NSF-ARCSS WORKSHOP
ON
ARCTIC SYSTEM HYDROLOGY

Meeting White Papers

18-20 September 2000
National Center for Ecological Analysis and Synthesis
Santa Barbara, CA

Compiled By

Larry Hinzman (University of Alaska Fairbanks)
Charles Vörösmarty (University of New Hampshire)

Table of Contents

Workshop Description

NSF-ARCSS WORKSHOP ON ARCTIC SYSTEM HYDROLOGY

DATES: 18-20 September 2000
LOCATION: National Center for Ecological Analysis and Synthesis
Santa Barbara, CA
ORGANIZERS: Charles Vörösmarty (University of New Hampshire)
Larry Hinzman (University of Alaska, Fairbanks)

BACKGROUND

Although there is widespread recognition that Arctic hydrology is sensitive to global warming, understanding the basic mechanisms that control the terrestrial water cycle is still a critical research need. Several NSF Arctic System Science (ARCSS) fora have identified Arctic hydrology and its feedbacks to the Earth system as a high-priority area for advancing the integration of NSF-sponsored high latitude research. These include the October 1998 and 1999 ARCSS Committee meetings, and the *ad hoc* gathering of arctic system scientists in March 1999 in conjunction with the ARCUS annual meeting of that year. In addition, the NSF SEARCH (Study of Environmental Arctic Change) Science Steering Committee recently met and developed its science plan, outlining several issues with respect to Arctic change which included consideration of the terrestrial water cycle.

These meetings recommended that the ARCSS Program convene a focused workshop involving experts drawn from a broad range of more disciplinary studies involving individual aspects of the Arctic water cycle. A steering committee (see list below) was convened to plan and carry out the workshop.

SCIENTIFIC ISSUES

A set of key issues emerges from current ARCSS research (summarized in numerous ARCSS, LAII, and OAII reports) that helps define the overall scope of the workshop and to guide in its organization:

- The effects of global change on the land-based hydrological cycle of the Arctic
- The influence of hydrological cycle change on:
  - the land-based system consisting of soil moisture, groundwater, glaciers, permafrost, vegetation;
  - atmospheric processes, including the time and space variations of precipitation;
  - the ice-ocean system of ice pack, ocean circulation, export of freshwater to the North Atlantic, and thermohaline circulation;
  - human systems from traditional to industrial; and,
  - biological productivity of terrestrial, inland aquatic, and Arctic Ocean coastal systems
- Feedbacks to the global system as affected by changes across Arctic hydrological systems.

WORKSHOP GOAL

The primary goal of this workshop was to assess the current state-of-the-art in Arctic systems hydrology and identify the appropriate roles that NSF-ARCSS could play in supporting the relevant science.

One measure of the ultimate success of the ARCSS research agenda would be an assessment of our collective ability to construct a consistent picture of Arctic basin hydrology from individual elements of ARCSS research. To this end, one focal point for the workshop was a feasibility study and conceptual design of a community-wide arctic hydrological system model, patterned after community-based GCMs and regional climate simulations (e.g. CCM2, MM5). The proposed model will be pan-Arctic in domain.

SUPPORTING OBJECTIVES

A specific set of target activities and objectives will support the overall goal:

(1) Judge our current capacity to synthesize ongoing NSF-funded hydrology research in the Arctic with respect to SEARCH-relevant change detection and process understanding;
(2) Assess the adequacy of measurement networks for hydrologically relevant variables such as precipitation, temperature, and discharge;
(3) Explore the feasibility of constructing a community-wide arctic hydrological system model (CAHSM);
(4) Using CAHSM as a framework, identify critical gaps in our knowledge of Arctic hydrology and in current NSF-funded projects;
(5) Design a research strategy to foster future synthesis studies of Arctic hydrology; and
(6) Publish a set of documents summarizing the principal workshop findings, including:
    (a) a strategic report to NSF highlighting progress to date, key gaps in our current understanding, and recommendations for future ARCSS research in hydrology;
    (b) a workshop summary to be published in AGU *EOS* or other widely distributed community journal;
    (c) a set of participant "white papers" detailing the individual presentations made at the workshop, published through ARCUS (this document); and
    (d) a synthesis review paper of key workshop findings to be published in the refereed literature.

WORKSHOP FORMAT

General Workshop. A 2.5-day ARCSS Hydrology Workshop was organized around a set of presentations by each of the participants, followed by thematic break-out sessions and plenary discussion.

Day 1. ARCSS Hydrology Program: Goals, development, current status
Brief introduction (5-10 min) by each workshop participant on current work/research
Poster presentations

Day 2. Working group activities in three thematic areas:
(1) Atmosphere
(2) Land Processes
(3) Ocean and Sea Ice
Discussion of CAHSM (a.m.) and SEARCH-relevant issues (p.m.)

Day 3. (1/2 day) Plenary reports of breakout groups
General discussion

Steering Committee Meetings. The Steering Committee met immediately after the general workshop for half a day to discuss key findings.

ARCSS HYDROLOGY WORKSHOP STEERING COMMITTEE

HYDROLOGY	Charles Vörösmarty, Chair	University of New Hampshire
	Larry Hinzman, Co-Chair	University of Alaska (Fairbanks)
ARCSS COMMITTEE	Bruce Peterson	Ecosystems Center (MBL)
PERMAFROST	Vladimir Romanovsky	University of Alaska (Fairbanks)
SEARCH COMMITTEE	Jamie Morison	University of Washington
ATMOSPHERIC DYNAMICS	David Bromwich	Ohio State University
SNOW DYNAMICS	Matthew Sturm	U.S. Army Corps (CRREL)
PALEOCLIMATOLOGY	Astrid Ogilvie	University of Colorado
HUMAN DIMENSIONS	Larry Hamilton	University of New Hampshire

List of Attendees and Contact Information

Carl Boggild
Geological Survey of Denmark and Greenland
Dept. of Hydrology and Glaciology
Thoravej 8, Copenhagen NV DK-2400 DENMARK
Tel.: 45 38 14 27 94
Fax: 45 38 14 20 50
E-Mail: ceb@geus.dk

David Bromwich
The Ohio State University
Polar Meteorology Group
Byrd Polar Research Center
1090 Carmack Road
Columbus, OH 43210
Tel.: (614) 292-6692
Fax: (614) 292-4697
E-Mail: Bromwich.1@osu.edu

David Brooks
Texas A&M University
Oceanography/College of Geosciences
College Station, TX 77843-3148
Tel.: (409) 845-3651
Fax: (409) 845-0056
E-Mail: dbrooks@ocean.tamu.edu

F. Stuart Chapin
University of Alaska Fairbanks
Institute of Arctic Biology
PO Box 757000
Fairbanks, AK 99775-7000
Tel.: (907) 474-7922
Fax: (907) 474-6967
E-Mail: fschapin@lter.uaf.edu

John Christensen
Bigelow Laboratory for
Ocean Sciences
180 McKown Point
West Boothbay, ME 04575
Tel.: (207) 633-9601
Fax: (207) 633-9641
E-Mail: jchristensen@bigelow.org

Andrew Fountain
Portland State University
Depts. of Geology and Geography
17 Cramer Hall, 1721 SW Broadway
Portland, OR 97201
Tel.: (503) 725-3386
Fax: (503) 726-3025
E-Mail: fountaina@pdx.edu

Steve Frolking
University of New Hampshire
Complex Systems Research Center
39 College Road, Morse Hall
Durham, NH 03824-3525
Tel.: (603) 862-0244
Fax: (603) 862-0188
E-Mail: steve.frolking@unh.edu

Barry Goodison
Environment Canada
AES-Climate Research Branch
4905 Dufferin Street
Downsview, ON M3H5T4
CANADA
Tel.: (416) 739-4345
Fax: (416) 739-5700
E-Mail: Barry.Goodison@ec.gc.ca

Pavel Groisman
University of Massachusetts at Amherst
Department of Geosciences
Morrill Science Center, Campus Box 35820
Amherst, MA 01003
Tel.: (413) 545-9573
Fax: (413) 545-1200
E-Mail: pgroisma@ncdc.noaa.gov

William Gutowski
Iowa State Univeristy
Dept. of Geological and Atmospheric Sciences
3021 Agronomy
Ames, IA 50011-1010
Tel.: (515) 294-5632
Fax: (515) 294-2619/3163
E-Mail: gutowski@iastate.edu

Lawrence Hamilton
University of New Hampshire
Dept. of Sociology
20 College Road
Durham, NH 03824-3509
Tel.: (603) 862-1859
Fax: (630) 862-3558
E-Mail: lawrence.hamilton@unh.edu

Larry Hinzman
University of Alaska Fairbanks
Water and Environmental Research Center
PO Box 755860
Fairbanks, AK 99775-5860
Tel.: (907) 474-7331
Fax: (907) 474-7979
E-Mail: ffldh@uaf.edu

Doug Kane
University of Alaska Fairbanks
Water and Environmental Research Center
P.O. Box 755900
Fairbanks, AK 99775-5860
Tel.: (907) 474-7808
Fax: (907) 474-7979
E-Mail: ffdlk@uaf.edu

Yuji Kodama
Hokkaido University
Institute of Low Temperature Science
N 19 W 8 Sapporo Japan
Tel.: 81-11-706-5509
Fax: 81-11-706-7142
E-Mail: kod@pop.lowtem.hokudai.ac.jp

Richard Lammers
University of New Hampshire
Institute for the Study of Earth, Oceans, and Space
Water Systems Analysis Group
39 College Road, Morse Hall
Durham, NH 03824-3525
Tel.: (603) 862-4699
Fax: (603) 862-0587
E-Mail: richard.lammers@unh.edu

Dennis Lettenmaier
University of Washington
Civil and Environmental Engineering
164 Wilcox Hall, Box 352700
Seattle, WA 98195-5270
Tel.: (206) 685-1024
Fax: (206) 685-3036
E-Mail: dennisl@u.washington.edu

Glen Liston
Colorado State University
Dept. of Atmospheric Science
Fort Collins, CO 80523-1371
Tel.: (970) 491-8220
Fax: (970) 491-8293
E-Mail: liston@iceberg.atmos.colostate.edu

Wieslaw Maslowski
Naval Postgraduate School
Dept. of Oceanography - Code OC/Ma
833 Dyer Road Room 331
Monterey, CA 93943-5122
Tel.: (831) 656-3162
Fax: (831) 656-2712
E-Mail: maslowsk@ucar.edu

James McNamara
Boise State University
Geoscience Dept.
Mail Stop 1535
Boise, ID 83725
Tel.: (208) 426-1354
Fax: (208) 426-4061
E-Mail: jmcnamar@boisestate.edu

James Morison
University of Washington
Polar Science Center
Applied Physics Laboratory
1013 NE 40th Street
Seattle, WA 98105-6698
Tel.: (206) 543-1394
Fax: (206) 616-3142
E-Mail: morison@apl.washington.edu

Frederick Nelson
University of Delaware
Department of Geography
216 Pearson Hall
Newark, DE 19716
Tel.: (302) 831-0852
Fax: (302) 831-6654
E-Mail: fnelson@udel.edu

Bruce Peterson
Marine Biological Laboratory
The Ecosystems Center
7 MBL Street
Woods Hole, MA 02543
Tel.: (508) 289-7484
Fax: (508) 457-1548
E-Mail: Peterson@mbl.edu

Terry Prowse
Environment Canada
National Water Research Institute
11 Innovation Boulevard
Saskatoon, SK S7N 3H5
CANADA
Tel.: (306) 975-5737
Fax: (306) 975-5143
E-Mail: terry.prowse@ec.gc.ca

Alan Robock
Rutgers University
Dept. of Environmental Sciences
14 College Farm Road
New Brunswick, NJ 08901-8551
Tel.: (732) 932-9478
Fax: (732) 932-8644
E-Mail: robock@envsci.rutgers.edu

Vladimir Romanovsky
University of Alaska Fairbanks
Geophysical Institute
P.O. Box 750109
Fairbanks, AK 99755-0109
Tel.: (907) 474-7459
Fax: (907) 474-7290
E-Mail: ffver@uaf.edu

Mark Serreze
University of Colorado at Boulder
Coop. Inst. for Research in Env. Sci.
Div. of Cryospheric and Polar Processes
Campus Box 216
Boulder, CO 80309-0216
Tel.: (303) 492-2963
Fax: (303) 492-1149
E-Mail: serreze@coriolis.colorado.edu

Michael Steele
Polar Science Center
Applied Physics Laboratory
1013 NE 40th Street
Seattle, WA 98105
Tel.: (206) 543-6586
Fax: (206) 616-3142
E-Mail: mas@apl.washington.edu

Marc Stieglitz
Columbia University
Lamont-Doherty Earth Observatory
Route 9W
Palisades, NY 10964
Tel.: (914) 365-8342
Fax: (914) 365-8156
E-Mail: marc@ldeo.columbia.edu

Matthew Sturm
Cold Regions Research and Engineering Laboratory
PO Box 35170
Ft. Wainwright, AK 99703-0170
Tel.: (907) 353-5183
Fax: (907) 353-5142
E-Mail: msturm@crrel.usace.army.mil

James Syvitski
University of Colorado
Institute of Arctic and Alpine Research
Campus Box 450
Boulder, CO 80309-0450
Tel.: (303) 492-7909
Fax: (303) 492-6388
E-Mail: james.syvitski@colorado.edu

Charles Vorosmarty
University of New Hampshire
Water Systems Analysis Group
39 College Road, Morse Hall
Durham, NH 03824-3525
Tel.: (603) 862-0850
Fax: (603) 862-0587
E-Mail: charles.vorosmarty@unh.edu

Robert Webb
NOAA/OAR/CDC
325 Broadway
Boulder, CO 80303
Tel.: (303) 497-6967
Fax: (303) 497-7013
E-Mail: rwebb@cdc.noaa.gov

Cort Willmott
University of Delaware
Geography Department
216 Pearson Hall
Newark, DE 19716
Tel.: (302) 831-2292
Fax: (302) 831-6654
E-Mail: willmott@udel.edu

Arctic Hydrology in Greenland With Special Emphasis on Processes in Cold Snow and on Glaciers

Carl Egede Bøggild
Geological Survey of Denmark and Greenland
Thoravej 8, DK-2400 Copenhagen NV
ceb@geus.DK

Run-off from seasonal snow covers in the Arctic provides the major source of stream flow in most non-glacierized catchments and is of importance for the run-off characteristics from glaciers. The first melt water to percolate through the snowpack is routed in a complex way due to re-freezing and rapid wet-snow metamorphism.

Motivated by discrepancies between modelled and observed hydrographs during the early melt period in the Tasersuaq basin in West Greenland, we have performed tracer experiments in several pits and at different levels below the snow surface, to improve our understanding of water flow and storage in cold snow. It is observed that vertical percolation more readily occurs the deeper in the snow pack the tracer is sprinkled. At places where preferential vertical flow is established, we believe the water will eventually reach the bottom of the snow pack once it has passed the wind crusts on the top of the snow pack.

From field observations, a parameterization of melt water retention in the cold snow is suggested. We propose a time dependent term for the thermal and the gravity component, respectively, of storage in the snow pack. This time dependent term describes the fraction of snow that is exposed to melt water at the time when the water reaches the base of the snow. Incorporating such a term in hydrological models for the Arctic would improve them by providing an explanation of the observed fast hydrological response in the early melt period and by limiting the magnitude of the modeled peak flow.

Melt water flow through cold snow is little understood. However, it provides a key to understanding and predicting the process of run-off since soils in early spring are frozen and so the snowpack constitutes the major retention for melt water drainage of Arctic catchments. The metamorphic state of the snowpack control the melt water percolation pattern, which in turn is a result of the winter precipitation and temperature. Climate change scenarios predict the greatest warming in winter in polar regions. There is therefore much reason to believe that run-off conditions may change under a changing climate.

The major gaps in our current understanding of the role of cold snow on run-off from Arctic catchments in the future are as follows:

1. A better understanding of melt water routing in relation to the physical properties of Arctic snow packs and its distributions in the Pan-Arctic region.

2. An improved ability to predict changes in storage and routing from the snow packs (under a changing climate).

Interannual Variability of the Atmospheric Hydrologic Cycle Over the Arctic from NCEP/NCAR Reanalyses

David H. Bromwich and Elizabeth N. Cassano
Polar Meteorology Group, Byrd Polar Research Center
The Ohio State University, Columbus, Ohio
bromwich@polarmet1.mps.ohio-state.edu

Previously, the atmospheric moisture budget over the Arctic basin as represented by reanalysis data from the National Centers for Environmental Prediction (NCEP) in conjunction with the National Center for Atmospheric Research (NCAR) (NCEP/NCAR Reanalysis) and from the European Centre for Medium-Range Weather Forecasts (ECMWF) were evaluated for the overlap period of 1979-1993 and found to be very similar to each other and to the available observations. Here emphasis is on the 50 years of the NCEP/NCAR Reanalysis (January 1949-May 1999) to depict the interannual variability of the atmospheric moisture fluxes across 70°N and their convergence farther north.

Precipitation minus evaporation (P-E) calculated from moisture flux convergence is compared with three large-scale circulation patterns that strongly impact the interannual variability of P-E over the Arctic and its environs: the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), and the North Pacific Oscillation (NPO). The impact of the NAO and the closely related AO on Arctic basin P-E is found to be marked with a P-E/NAO winter correlation of 0.49 (0.56 for the AO). On an annual basis, Arctic basin P-E is much more closely correlated with the NAO (0.69) than with the AO (0.49), consistent with the Atlantic Ocean domination of the northward flux across 70°N. Regional analysis confirms that the NAO impact on P-E is concentrated around the periphery of the North Atlantic Ocean and extends north into the Arctic Ocean in winter. The NAO and AO differ in their P-E modulation over the northern Eurasian sector with the AO being much more important for all seasons except summer (winter AO/P-E correlation 0.53, NAO/P-E correlation 0.16), consistent with its much stronger impact on the atmospheric circulation in that area. This result means that the variability of precipitation falling on the Eurasian rivers, which flow northward into the Arctic Ocean, is closely linked to the AO, but not to the NAO. The NPO was associated with a much more modest modulation of Arctic basin P-E (winter correlation of 0.33 and annual value of 0.10), with the regional signal being strongest over Alaska, northwestern Canada, and areas to the north. About 40% of the inter-winter variance of P-E over the sector that includes northeastern Canada is linked with the combined influence of the NAO/AO and NPO.

A region of large poleward moisture transport variability during summer was previously identified over western Siberia, east of the Urals, associated with the development of the Urals trough. It is shown that this is due to an opposing circulation pattern, with high (low) poleward moisture over the west Siberian plain during low (high) poleward moisture transport over Scandinavia. A pronounced trough/ridge pattern accompanies this circulation regime, which is primarily confined to July. Because the summer moisture transport dominates the annual total for this region, these circulation patterns produce this area's large interannual moisture transport variability.

The key gaps in process understanding for P-E over Arctic river basins include:

- The spatial and temporal variability of P-E around the Arctic and its decadal modulation.
- The controlling factors influencing the summer circulation regime near western Siberia.

The key gaps in monitoring and measurements include:

- The disagreement between reanalyses and radiosonde analyses of the poleward moisture transport across 70°N in summer.
- Limitations in reanalysis moisture flux convergence calculations between Greenland and Scandinavia due to deficiencies in the use of satellite data.

- Recent decline in the rawinsonde network in Eurasia and Canada.
- Quality and documentation of observing techniques/placement of precipitation measurements.

References:

Bromwich, D. H., R. I. Cullather, and M. C. Serreze, 2000: Reanalyses depictions of the Arctic atmospheric moisture budget. *The Freshwater Budget of the Arctic Ocean*, Lewis, E. L., ed., Kluwer Academic Publishers, pp. 163-196.

Cullather, R. I., D. H. Bromwich, and M. C. Serreze, 2000: The atmospheric hydrologic cycle over the Arctic basin from reanalyses. Part 1: Comparison with observations and previous studies. *J. Climate* 13:923-937.

Rogers, A. N., D. H. Bromwich, E. N. Sinclair, and R. I. Cullather, 2001: The atmospheric hydrologic cycle over the Arctic basin from reanalyses. Part 2: Interannual variability. *J. Climate* 14:2414–2429.

Modeling Freshwater Pathways in the Kara Sea, With Implications for Thinning of Arctic Sea Ice

David A. Brooks
Department of Oceanography
Texas A&M University
College Station, TX 77843
dbrooks@ocean.tamu.edu

Experiments with a numerical circulation model show that the Kara Sea is prominently influenced by runoff from Siberian rivers, vigorous tides, and seasonally variable winds. The semidiurnal (M-2) tidal response is quasi-resonant with an amplification factor of about four. Tidal energy enters the Kara Sea from the Arctic Ocean and follows a primary pathway leading to the Ob River estuary, which contains a full wavelength of the tide. The total rate of dissipation of tidal energy in the Kara Sea is about 5 GW, most of which occurs in the Ob and Yenisey River estuaries. Tidal stresses at the bottom appear to be sufficient to suspend fine sediments, making them available to be exported into the nontidal circulation.

Runoff from the principal rivers produces a freshened surface plume 10 to 20 m thick that spreads in both directions along the coast and several hundred kilometers offshore. A multibranched clockwise surface current associated with the plume boundary coalesces into a narrow eastward coastal current along the Taimyr mainland leading toward Vilkitsky Strait, which connects with the Laptev Sea to the east. Under typical winter wind conditions, the coastal current intensifies and an increased fraction exits to the Laptev Sea, compared to non-wind conditions when a larger share of the coastal current turns northward toward the Arctic Ocean.

Under present conditions of strengthened cyclonic polar winds, the model results suggest that increased export of freshened surface waters directly to the Laptev Sea may reduce the amount of cold, fresh shelf water available for export to the Arctic, thereby weakening the cold halocline layer thought to insulate Arctic sea ice from deeper water of Atlantic origin. If this mechanism is effective, it complements recent changes in sea ice motion that transport shelf water influence farther eastward than usual, possibly leading to increased upward heat fluxes and thinning of Arctic ice cover.

Role of Terrestrial Ecology in Arctic Hydrologic Systems

F. Stuart Chapin, III
Institute of Arctic Biology
University of Alaska Fairbanks
Fairbanks, Alaska 99775-7000
fschapin@bonanza.lter.uaf.edu

Hydrologic processes play a critical role in linking the land, atmosphere, and oceans of the Arctic System and in determining the role that terrestrial ecosystems play in feedbacks to climatic change. The land surface is coupled to the atmosphere through three fundamentally different mechanisms:

1. The exchanges of long-lived greenhouse gases (e.g., CO_2, CH_4) affect the atmosphere primarily at the global scale. These materials become globally mixed within a year, and their effects seldom change local radiative forcing by more than a few percent. Changes in high-latitude CO_2 and CH_4 fluxes are potentially important because of the large carbon stores and extensive areas of poorly aerated soils. Surface soil moisture is the primary factor governing the magnitude of high-latitude CO_2 and CH_4 fluxes, so any large changes in terrestrial hydrology will strongly affect trace-gas fluxes and the impact of arctic ecosystems on climate. For example, changes in thermokarst and the aerial extent of wetlands, lakes, and ponds would substantially alter high-latitude methane flux.

2. The land surface directly affects the atmosphere at the local to regional scale primarily through the energy and water vapor transferred to the atmosphere. These exchanges cause large proportional changes in the heat and moisture content of the overlying atmosphere and therefore directly influence local air temperature and the moisture available for precipitation. These fluxes are governed most strongly by vegetation and surface moisture and therefore are extremely sensitive to changes in terrestrial hydrologic processes. Tundra has a three-to-six-fold higher winter albedo than boreal forest, but summer albedo and energy partitioning differ more strongly among ecosystems within either tundra or boreal forest than between these two biomes. This indicates a need to improve our understanding of vegetation dynamics within as well as between biomes. If regional surface warming continues, changes in albedo and energy absorption would likely act as a positive feedback to regional warming due to earlier melting of snow and, over the long term, the northward movement of treeline. Surface drying and a change in dominance from mosses to vascular plants would also enhance sensible heat flux and regional warming in tundra. In the boreal forest of western North America, deciduous forests have twice the albedo of conifer forests in both winter and summer, 50 to 80% higher evapotranspiration, and therefore only 30 to 50% of the sensible heat flux of conifers in summer. Therefore, a warming-induced increase in fire frequency that increased the proportion of deciduous forests on the landscape would act as a negative feedback to regional warming.

3. The partitioning of incoming precipitation between evapotranspiration and runoff determines the freshwater input to the Arctic Ocean. This strongly influences the magnitude of deepwater formation in the North Atlantic and therefore the strength of the thermohaline circulation. This partitioning also influences the quantity of water returned to the atmosphere and therefore the quantity of atmospheric moisture available for precipitation.

The major gaps in our current understanding of the role of hydrology in arctic terrestrial ecosystems are as follows:

We lack process-based hydrologic models that operate at large scales and include realistic land-atmosphere exchange. In particular, we cannot adequately simulate soil moisture at large spatial scales. Given the sensitivity to moisture of most arctic and boreal ecosystem processes, including feedbacks to climate, it is critical that we improve our ability to simulate soil moisture.

The current land-surface schemes do not adequately represent hydrologic fluxes within soils and therefore the rates of surface evaporation and evapotranspiration. For example, many arctic land-surface packages lack organic soils and mosses and crudely represent permafrost, three factors that strongly influence land-atmosphere exchanges of water, energy, and trace gases.

Sub-grid-scale heterogeneity in vegetation is not well represented in arctic models of land-atmosphere exchange. There are large differences among arctic or boreal vegetation types in their hydrologic properties and responses to soil moisture. These within-biome patterns of heterogeneity often occur at the sub-grid-scale level and have not been adequately incorporated into hydrologic or land-surface models.

The boreal forest has not received adequate attention as a component of the arctic hydrologic system. The boreal forest occupies about 80% of the watershed area that provides fresh water to the Arctic Ocean. Fire and other disturbances strongly influence vegetation composition and therefore boreal water and energy exchange and runoff to the Arctic Ocean.

The Role of Glaciers in Arctic Hydrology

Andrew G. Fountain
Departments of Geology and Geography
Portland State University
Portland, OR 97212
fountaina@pdx.edu

Glaciers form an important component of the Arctic hydrologic system. They provide physical evidence for climate change in prehistoric and historic times. Melt water released from its long-term storage as ice affects global sea level and regional water supplies. On a seasonal basis, glaciers provide water during the hottest, driest months of summer and are particularly important during drought periods when seasonal snow packs are exhausted. Finally, water impounded by glaciers present a potential flood hazard because the water is typically released catastrophically. This report briefly summarizes these issues for the glaciers and ice caps in the Arctic, exclusive of the Greenland Ice Sheet. In this report glaciers and ice caps will be referred to as "glaciers."

1. Glacier-Covered Area and Distribution

The global distribution of glaciers is shown in Table 1. Glaciers, exclusive of the two large ice sheets of Greenland and Antarctica, cover about 680,000 km^2 of the earth (Dyurgerov and Meier, 1997). Roughly 60%, or 402,000 km^2, of that global glacierized area is inside or close to the Arctic Circle. Within the Arctic, the largest glacier-covered area is the arctic islands, including the Canadian Arctic, Russian Arctic, and the islands north of Iceland. The small glaciers surrounding the Greenland Ice Sheet and the glaciers of Alaska and Yukon cover roughly equal areas. Scandinavia and Iceland contain the smallest glacier-covered area.

Table 1. Glacier areas of the world exclusive of the Antarctic and Greenland ice sheets. (Dyurgerov and Meier, 1997). The area of the US/Canada is exclusive of Alaska and the Arctic Islands. Southern Hemisphere is exclusive of the glaciers along the margin of the Antarctic continent.

Region	Area $10^3 km^2$	Fraction %
Arctic Islands	244	35
Alaska and Yukon	75	11
US/Canada	49	7
Asia	119	18
Europe	18	3
Greenland, Antarctic glaciers	140	21
Southern Hemisphere	35	5
Global	**680**	**100**

Arctic Region	$10^3 km^2$	%
Arctic Islands	238	59
Greenland small glaciers	75	19
Alaska and Yukon	75	19
Scandinavia and Iceland	14	3
Arctic	**402**	**100**

Need: Information on glacier area is incomplete and many regions lack current maps of glacier extent. For example, depictions of glaciers on current topographic maps of the United States are at least 30 years out of date. To improve estimates of the effect of glaciers on hydrology, described below, improved estimates of glacier area are required.

2. Global and Regional Hydrological Effects

During the 20th century, glaciers have been largely losing mass and shrinking (Meier, 1984; Oerlemans and Fortuin, 1992; Dyurgerov and Meier, 1997). This mass wastage of glaciers has contributed significantly to a sea level rise of about 0.25 mm yr^{-1} over the past century. These values are consistent with a 0.6ºC warming in air temperature (Oerlemans, 1994). Although the total glacier area is small relative to that of the large ice sheets of Antarctica and Greenland, the glaciers have been losing mass at rapid rates (Dyurgerov and Meier, 2000). For the period 1961 to 1997, a global average of approximately –118 mm yr^{-1} of water averaged over the glaciers was lost. In the past several decades the rate of glacier mass wastage has accelerated. The 1976-1977 shift in the state of the atmosphere (Miller et al., 1993) changed circulation patterns over North America resulting in an increased rate of glacier mass loss (McCabe and Fountain, 1995; McCabe et al., 2000). From 1961 to 1977 the mass loss rate was –81 mm yr^{-1} and increased to –198 mm yr^{-1} during the 1977 to 1997 period (Dyurgerov and Meier, 2000).

Glacier mass wastage affects regional water supplies. Ecosystems and human communities that rely on water from glacierized basins have been receiving more water than expected from basins without glaciers. Once the glaciers come into equilibrium with the current climate, or if they continue to shrink, the volume of "extra" water to the watershed will disappear (Fountain and Tangborn, 1985). Moreover, glacial meltwater occurs during the hottest and driest parts of the summer, thus reducing the effects of droughts. Thus, runoff from glacierized basins exhibits less year-to-year variation.

Our knowledge of global and regional rates of glacier change is based on few observations. For example, in the period 1991 to 1995, detailed measurements of mass change in North America were limited to 14 glaciers; for Scandinavia including Iceland, 34 glaciers; and former Soviet Union, 14 glaciers (WGMS, 1998). This is insufficient to understand the pattern and rate of glacier change. No detailed measurements include very large glaciers (>100 km^2) found in Alaska and Asia. These glaciers are particularly important because they represent about 30% of the total global area of small glaciers.

Need: More measurements of glacier mass change are required. Because detailed surface-based measurements of glacier mass balance are expensive and relatively slow, new methodologies need to be developed and tested. These methods include reduced surface measurement strategies, geometric scaling, and application of remote sensing techniques of visible and radar satellite remote sensing (see papers in *Geografiska Annaler,* 1999). The surface-based and remote methods can then be combined to produce a reasonable picture of glacier change in any given region (Fountain, et al., 1997). As mention previously, we need to specifically develop methods to assess mass change on large (>100 km^2) glaciers.

One area of further research is the importance of rock glaciers to the local and regional water balance. These overlooked features on the Arctic landscape may also provide a stable and steady source of water during the late summer. The frequency and distribution of rock glaciers is not well known.

A GIS database should be constructed for Arctic glaciers to incorporate digital topographic information of glacier area. This would provide a common database for all investigators to use and one that could be continually updated with new information. In addition to maps of current glacier extent, historic maps should be incorporated as well as future mappings to define changes in glacier area and volume. Satellite images should also be incorporated. This data set would complement the scalar data set currently provided by the World Glacier Monitoring Service.

3. Short-term Hydrological Effects

Short-term runoff variations from a glacier result from variations in solar radiation and the overall energy balance (Hock, 1998). Whereas energy balance modeling on the ice surface is comparatively well known, subsurface processes of routing water through the glacier are still vaguely understood (Fountain and Walder, 1998). Processes internal to the glacier affect the onset of spring runoff and the daily variations throughout the melt season. Glaciers temporarily store and release water at time scales from days to seasons (Tangborn et al., 1975). Whether this is due to evolving internal hydraulic systems or to stable structures within the system is unclear. However, subglacial water flow is coupled to glacier movement (Iken and Bindschadler, 1986; Kamb, et al., 1985) such that one cannot understand subglacial water flow without also understanding glacier movement.

In some circumstances, storage and release processes result in catastrophic floods like those in Vatnajokull (Bjornsson, 1992), which inundate flood plains without warning. Water can be impounded along the ice margin, as ice dammed lakes, or within the body of the ice (Haeberli, 1983; Walder and Driedger, 1995). Moraine-dammed lakes, formed by a glacier retreating from its terminal moraine, also present a hazard. These lakes are present in many regions of the Arctic but are particularly catastrophic in the Himalayas, where rapid glacier retreat and large moraines impound large volumes of water and present significant hazards to villages in the valleys below (Ageta, et al., 2000). Engineering strategies to mitigate the flood hazard are currently underway (Rana, et al., 2000).

Need: To predict variations in runoff on time scales of months to hours we require a better understanding of the hydraulic routing through the glacier. Temporary storage locations in the near surface of the ice (Larson, 1978) and the firn (Schneider, 1994) are generally known but the impacts on the water movement through the glacier have yet to be worked out (Fountain and Walder, 1998). Englacial routing of water is understood by theoretical models, but empirical evidence is lacking except in rare cases. Subglacial hydraulic processes have been outlined theoretically, but the spatial distribution and seasonal evolution of the hydraulic systems are largely unknown (Fountain and Walder, 1998). Therefore, models of glacier runoff will not likely improve without substantially better information on the subsurface processes in glaciers.

References

Ageta, Y., Iwata, S., Yabuki, H., Naito, A., Narama, C., and Karma, K. 2000. Expansion of glacier lakes in recent decades in the Bhutan Himalayas. (abs). International Workshop on Debris-Covered Glaciers. Seattle, WA, Sept 13-15.

Bjornsson, H., 1992. Jokulhlaups in Iceland: Prediction, characteristics, and simulation. *Annals Glaciology,* 10, 95-106.

Dyurgerov, M. B. and Meier, M. F., 1997. Year-to-year fluctuations of global mass balance of small glaciers and their contribution to sea-level changes. *Arctic and Alpine Research, 29*(4), 392-402.

Dyurgerov, M. B. and Meier, M. F., 2000. Twentieth century climate change: Evidence from small glaciers. *Proceedings National Academy of Sciences, 87*(4), 1406-1411.

Fountain, A. G., Krimmel, R. M., and Trabant, D. C. 1997. A strategy for monitoring glaciers. U.S. Geological Survey Circular 1132, 19 pp.

Fountain, A. G., and Tangborn, W. V. 1985. The effect of glaciers on streamflow variations. *Water Resources Research, 21,* 579-586.

Fountain, A. G., and Walder, J. S. 1998. Water flow though temperate glaciers. *Reviews of Geophysics, 36*(3), 299-328.

Haeberli, W., 1983. Frequency and characteristics of glacier floods in the Swiss Alps. *Annals Glaciology, 4,* 85–90.

Hock, R. 1998. Modelling of glacier melt and discharge. Zürcher Geogrphische Schriften, 70, ETH Geographisches Institute, Zürich, 126 pp.

Iken, A., and R. Bindschadler, 1986. Combined measurements of subglacial water pressure and surface velocity of Findelengletscher, Switzerland: Conclusions about drainage system and sliding mechanism. *Jour. Glaciology, 32,* 101-119.

Kamb, B., Raymond, C., Harrison, W., Engelhardt, H., Echelmeyer, K., Humphrey, H., Brugman, M., and Pfeffer, T., 1985. Glacier surge mechanism: 1982-1983 surge of Variegated Glacier, Alaska, *Science, 227,* 469-479.

Larson, G., 1978. Meltwater storage in a temperate glacier: Burroughs Glacier, southeast Alaska. Report 66, Institute of Polar Studies, Ohio State University.

McCabe, G. J. and Fountain, A.G., 1995. Relations between atmospheric circulation and mass balance of South Cascade Glacier, Washington, U.S.A. *Arctic and Alpine Research, 27,* 226-233.

McCabe, G. J., Fountain, A. G., and Dyurgerov, M. 2000. Variability in winter mass balance of Northern Hemisphere glaciers and relations with atmospheric circulation. *Arctic, Antarctic, and Alpine Research, 22*(1), 64-72.
Meier, M. F., 1984. Contribution of small glaciers to sea level change. *Science,* 226(4681), 1418-1421.
Miller, A. J., Cayan, D. R., Barnett, T. P. Grahm. N. E., and Oberhuber, J. M., 1993. The 1976-77 climate shift of the Pacific Ocean. *Oceanography 7,* 21-26.
Oerlemans, J., 1994. Quantifying global warming from the retreat of glaciers. *Science, 264,* 243-245.
Oerlemans, J., and Fortuin, J. P. F. 1992. Sensitivity of glaciers and small ice caps to greenhouse warming. *Science 258,* 115-117.
Rana, B., Shrestha, A., Aryal, R., Pokhrel, A., Budathoki, K., 2000. Mitigation of Tsho Rolpa Glacier lake outburst floods in Nepal, Himalayas. (abs). International Workshop on Debris-Covered Glaciers. Seattle, WA, Sept 13-15.
Schneider, T., 1994. Water movement and storage in the firnn of Storglaciaren, northern Sweden. Stokholm University Forskningsrapport 99. Stockholm University, Stockholm, Sweden.
Tangborn, W. V., Meier, M. F., and R. M. Krimmel, 1975. A comparison of glacier mass balance by glaciolgical, hydrological, and mapping methods, South Cascade Glacier, Washington. *International Association of Hydrological Sciences, 104,* 185-196.
Walder, J. S., and Driedger, C. L., 1995. Frequent outburst floods from South Tahoma Glacier, Mounta Rainier, USA: Relation to debris flows, meteorological origin and implications for subglacial hydrology. *Jour. Glaciology, 41,* 1-10.
WGMS (World Glacier Monitoring Service), Fluctuations of Glaciers 1990-1995. Vol. VII. Compiled by Haeberli, W. and Hoelzle, M. Zurich.

Satellite Radar Remote Sensing for Monitoring Freeze/Thaw Transitions in Boreal and Arctic Region

Steve Frolking
University of New Hampshire
Complex Systems Research Center
Durham, New Hampshire 03824-3525
steve.frolking@unh.edu

The seasonal transition of the land surface between frozen and nonfrozen conditions affects a number of ecological and hydrological processes that cycle between wintertime dormant and summertime active states. The onset of the spring thaw period initiates snowmelt, leading to increases in runoff and stream discharge. Ecosystem responses are rapid, with soil heterotrophic respiration (CO_2 flux from soil decomposition activity) and photosynthetic activity of evergreen trees also increasing with the new presence of liquid water. As the snowpack ripens and melts away, the surface albedo drops. Absorption of this additional net solar radiation causes surface soil and air temperatures to rise dramatically, often 3 to 5˚C in a week. Increasing air temperatures, soil temperatures and day length finally induce vegetation out of dormancy and active growth of new leaves and shoots begins. The presence of liquid water also leads to a shift in the surface energy balance, with evapotranspiration increasing and sensible heat flux decreasing, affecting atmospheric boundary layer dynamics.

The meteorological and river gauge surface station network provides important data on the state of the land surface (air and soil temperature, snow depth, radiation). Unfortunately, the network density at high latitudes is neither good nor improving (Karl 1995). Alaska averages about one met station per 9000 km^2 (Kimball et al., 2001) and not all of these operate year-round. More generally, capabilities for monitoring boreal and arctic regions are severely hampered by the current state of surface weather and hydrological station networks; the numbers of reporting stations in these regions are extremely sparse, on the order of one per million km^2, especially in Canada and Siberia. Existing station networks are also deteriorating further due to station closures from limited funding and embargoes of national data (Karl, 1995). Nonetheless, by providing independent, ground-based data, contemporary and archived meteorological and river gage data will be an essential component in developing and evaluating freeze/thaw algorithms developed with archived remote sensing data.

Satellite-deployed radar sensors can monitor land surface conditions of remote regions. Radar has the substantial advantage for high latitudes of both seeing through clouds and not requiring solar illumination of the land surface. The microwave backscatter signature of a landscape is controlled by the landscape's structure and dielectric properties. Liquid water consists of highly polar molecules with a high dielectric constant that dominates the microwave response of natural landscapes. As water freezes, the molecules become bound in a crystalline lattice, and the dielectric constant decreases substantially. As landscapes undergo freeze/thaw transitions, the change in dielectric constant results in large backscatter shifts.

Two classes of active radar instruments have been applied, synthetic aperature radar (SAR) and scatterometry. SAR instruments (e.g., on RadarSat) generally have high spatial resolution (10 to 50 m) but typically have repeat cycles of ~30 days, so a freeze/thaw transition cannot be precisely delineated in time. Scatterometers (e.g., NSCAT and QuikScat) have lower spatial resolution (20 to 30 km) but at high latitudes generally pass over a point one or more times per day. Passive microwave sensors have also been used for freeze/thaw detection (e.g. Judge et al., 1997). High frequency/short wavelength instruments (e.g., K-band, X-band) are very sensitive to characteristics of the vegetation canopy or the ground/snow surface in regions of sparse vegetation, while lower frequency, longer wavelength instruments (e.g. C- band, L- band, or P-band) can penetrate deeper into the snowpack or soil.

Fig. 1 shows air temperature, snow depth, and NSCAT (K-band) backscatter for Thompson, Manitoba (Frolking et al., 1999). A large shift in backscatter was coincident with snowmelt, and smaller shifts during the winter may indicate changes in surface snow properties. Kimball et al. (2000) used a temporal change detection analysis of NSCAT daily radar backscatter measurements to classify surface freeze/thaw state across a 1.4

million km^2 region of Alaska from January through June 1997 (Fig 2a) and compared this with estimates based on a DEM-aided interpolation of daily maximum air temperature (Fig. 2b). The meteorological station density in Alaska was about one per 10,000 km^2, with a majority located below 100-m elevation, resulting in significant smoothing and a likely warm bias. Interpretation of the scatterometer data was particularly problematic along the coastlines, where pixels had significant ocean "contamination." Area estimates of frozen ground by ground station interpolation and by NSCAT interpretation were well correlated but biased with respect to each other (Fig. 3).

There are several complicating factors in the interpretation of radar freeze-thaw signals. For a complex surface (e.g., a terrestrial landscape) the frequency (and thus wavelength) of the radar instrument determines the physics of interaction of the electromagnetic radiation with the surface. As a landscape progresses through freeze/thaw transitions, different landscape components can be in different states (e.g., frozen soil but thawed above-ground vegetation, thawed vegetation canopy but frozen trunks, etc.), leading to complicated interpretation, particularly of low-resolution products. For the coarse resolution scatterometer data (~1000 km^2), each resolution cell is likely to contain an unknown mosaic of land-surface types, and in some regions, numerous small lakes and ponds. Different landscape components and different slopes/aspects will freeze and thaw at different rates. This sub-pixel heterogeneity will likely decrease the signal-to-noise ratio. The higher spatial resolution SAR instruments are generally in an orbital mode designed to study other phenomena, so their infrequent temporal repeats can make the timing of a freeze/thaw transition ambiguous. Many northern landscapes will undergo more than one freeze/thaw transition during spring thaw and/or fall freeze up. This complicates algorithm development for interpreting remote sensing signals. All of these factors point to the need for more research on instrumentation and algorithm development and evaluation. As the technology matures, however, it can provide a comprehensive, continuous, regional and pan-arctic data set of landscape freeze/thaw state.

Frolking, S., K. McDonald, J. Kimball, R. Zimmermann, J.B. Way, & S. W. Running. (1999). Using the space-borne NASA Scatterometer (NSCAT) to determine the frozen and thawed seasons of a boreal landscape, *J. Geophys. Res. 104:* 27,895-27,908.

Judge, J., J. F. Galantowicz, A. W. England, P. Dahl (1997). Freeze/thaw classification for prairie soils using SSM/I radiobrightness, *IEEE Trans. Geosci. Rem. Sens., 35:* 827-832.

Karl, T. R. (1995). Long-term climate monitoring by the Global Climate Observing System. *Climate Change*, 2-4.

Kimball, J. S., K. C. McDonald, A. R. Keyser, S. Frolking, & S. W. Running. (2001) Application of the NASA Scatterometer (NSCAT) for determining the daily frozen and non-frozen landscape of Alaska. *Remote Sens. Environ. 75:*113-126.

Fig. 1 - daily time series of snow depth, air and soil temperatures, and NSCAT backscatter.

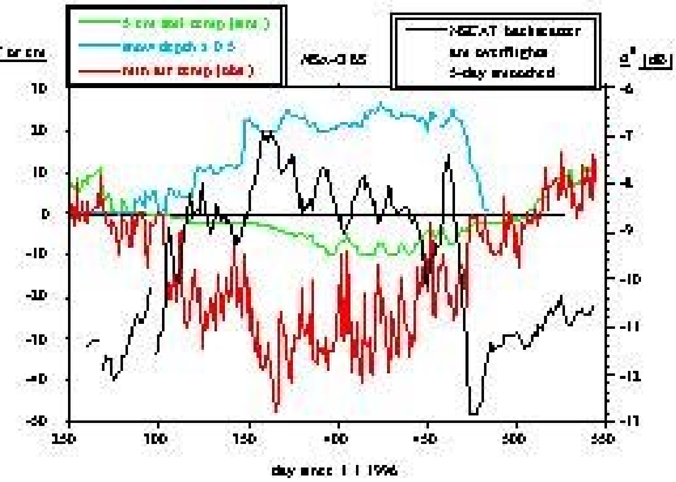
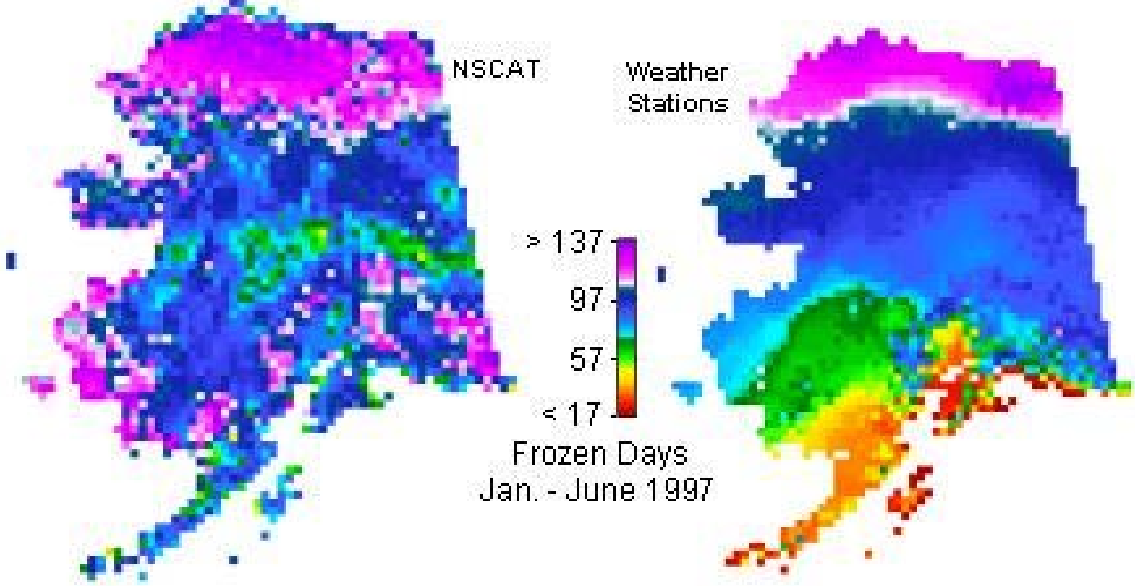


Fig. 2 - Estimates of number of days (Jan.-June 1997) that each 25-km cell was frozen.



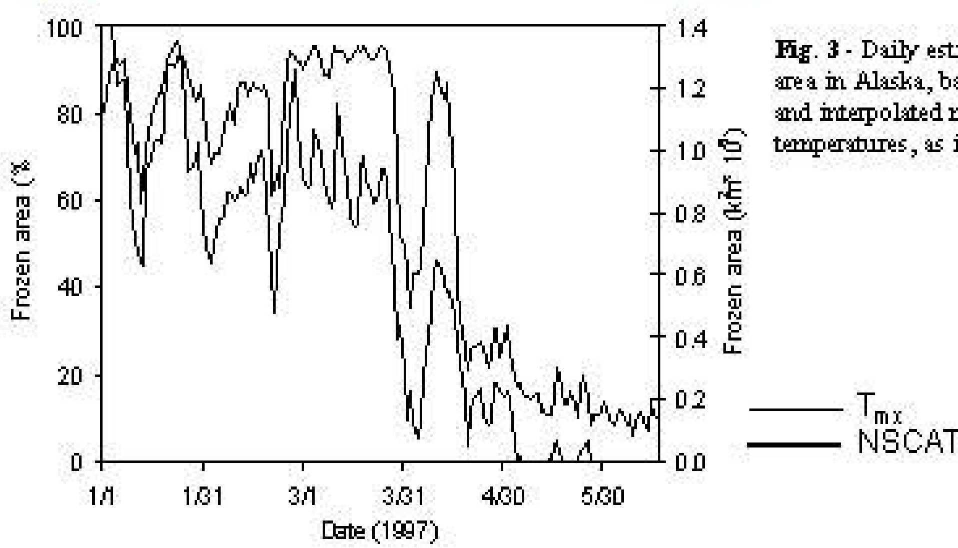


Fig. 3 - Daily estimates of frozen area in Alaska, based on NSCAT and interpolated maximum daily air temperatures, as in Fig. 2.

Some Considerations on Snow Cover and Precipitation for Hydrology in High Latitudes

B. E. Goodison[1], A. E. Walker[1], P. Y. T. Louie[1], D. Yang[2]
[1]Climate Research Branch, Meteorological Service of Canada
Downsview, Ontario, Canada
[2]University of Alaska, Fairbanks, Alaska
Barry.Goodison@ec.gc.ca

Snow cover has the largest areal extent of all components of the cryosphere, with most of the snow covered area being in the Northern Hemisphere and its temporal variability being dominated by the seasonal cycle. The interactions and feedback of terrestrial snow and ice, including temporal and spatial variability, in the current climate system, in land surface processes and in the hydrological cycle are specific issues requiring better understanding (Allisn, Barry, & Goodison, 2000; Goodison, Brown, & Crane, 1999). Snow water equivalent is arguably the most important physical property of snow cover in climate and hydrological models. Remote sensing provides invaluable and often unique observational data to complement *in-situ* data. The development of consistent, compatible data series for spatial and temporal analyses of snow cover, and especially SWE, is essential for these climatological and hydrological investigations. A critical issue for cold climate studies is the adequacy of observational networks to meet the science objectives. The traditional surface climate networks in the cold climate regions and especially in Arctic regions have been only marginally sufficient at best. The current global trend towards shrinking networks due to economic pressures on meteorological and hydrological services further exacerbates the problem. Precipitation, snowfall, and snow depth measurements are especially important for snow water equivalent determination.

In-situ observations of meteorological variables taken at conventional network stations are essential to all climate studies. They provide the basis for determining trends and variability and for developing and validating process models and other observational procedures. Researchers undertaking cold climate studies in high latitudes are faced with many problems in obtaining adequate *in-situ* observations to meet their science objectives. For example, knowledge of the amount and the spatial/temporal distribution of high-latitude precipitation has been a challenge for decades and is still a major challenge in our current efforts to quantify the water and energy cycle of northern regions. The lack of observing stations in the high-latitude regions certainly limits our ability to determine precipitation from conventional station measurements. Other major factors that contribute to uncertainties in the estimation of this precipitation field over land areas include the uneven distribution of measurement sites, biased toward coastal and the low-elevation areas, and the difficulty in measuring solid precipitation with precipitation gauges in windy and cold environments. As in other countries, the observing networks in Canada are under pressure and being rationalized for better efficiency and integration. This has significantly decreased the size of current networks and increased the use of autostations, which will result in the loss of some measurements and may have implications on the long-term compatibility of some data sets.

Compounding the problem in the northern hemisphere is the fact that Russia, Alaska, Canada and Greenland each use different instruments or methods to measure precipitation, and particularly solid precipitation and snowfall. The challenge for programs such as ACSYS/CliC is to reconcile these different observation sources and to assemble a consistent data set for climatological and hydrological studies. Significant under-measurement of snowfall precipitation has been documented for high latitude regions (e.g. Woo, et al., 1983). Little can be done about station location and local siting issues, but we can do something to adjust our existing and future data for systematic errors in measurement. We recommend that the results from the WMO/CIMO Solid Precipitation Measurement Intercomparison can provide a solid basis for methodology (Goodison, Louie, & Yang, 1998). The report provides not only the basis for the adjustments but also examples of applying the results in several countries. Subsequent papers (e.g. Yang et al., 1999a, b, c) demonstrate the application in high latitudes. For hydrological applications, average monthly corrections will not be suitable. In addition, before embarking on the adjustment, analysis, and application of precipitation data, we must have a very clear understanding of the science question we are trying to answer. Only by having a clear understanding of the question can we decide on the appropriate temporal and spatial scale for the analysis and hence the most appropriate adjustment procedures.

Satellite remote sensing provides an alternate information source for remote areas where conventional data are sparse or unavailable. These data sets provide some important and unique features, which can be used to enhance and complement conventional observations. They have a high repeat coverage of large regions and can detect diurnal trends from multiple daytime passes. Their wide areal coverage can provide detailed spatial delineation of surface field characteristics, which is not possible with sparse conventional observational networks. Satellite derived data sets are often in gridded form which make them particularly suited for model input and validation. In Canada, the Canadian project CRYSYS (Variability and Change in the Cryospheric System in Canada) has provided a mechanism for government and university researchers to address snow water equivalent determination, especially using remote sensing. One of the main objectives of the CRYSYS snow research is to develop, validate and refine empirical and theoretical algorithms of snow cover properties in varying climatic regions and landscapes of Canada using passive microwave data. Figure 1 gives an example of the snow water equivalent derived from SSM/I passive microwave for the Canadian Prairies and produced and delivered weekly in near real-time to users and the community via the CRYSYS web site (http://www.crysys.uwaterloo.ca/). As of December 1999, the forest snow water equivalent algorithms have been combined with the prairie snow water equivalent algorithm to produce a more representative weekly SWE map product for the entire three prairie provinces. The forest and prairie SSM/I snow water equivalent algorithms are also being tested over the Mackenzie river basin in northwestern Canada as part of the Mackenzie GEWEX Study (MAGS). The main goal of MAGS is to understand and model the energy and water cycles and related cold climate processes in this northern basin. The snow water equivalent algorithms are being validated for this region using available *in-situ* measurements and will be used to generate a 10 year time series of snow water equivalent over the basin to provide information on the spatial and temporal variability of the distribution of snow water equivalent in the basin and provide information for MAGS climate and hydrological modelling activities.

Continuing advances have been made in the development and evaluation of algorithms to derive SWE for different regions of Canada (DeSeve et al., 1997, 1999; Chang et al., 1997; Goita et al., 1997; Woo et al., 1995; Goodison and Walker, 1994). A single algorithm is not sufficient to characterize the snowpack/landscape variations across Canada. It is also recognized that the current passive microwave satellite sensors and associated algorithms may not be suitable for some areas, such as the western mountains, densely forested regions, and areas with deep snowpacks. Yet the demand for snow water equivalent information for operational (e.g., flood forecasting, hydro power) and climate (e.g., monitoring, detection, model validation) applications has increased significantly over the last few years, both to meet the needs for information in historically data sparse areas and to "replace" conventional *in-situ* snow measurements lost due to network reductions. There is a need for continuing algorithm development and validation to ensure users have reliable products. CRB will conduct special field experiments to assess the expected improvements in snow water equivalent determination that higher resolution AMSR data will offer. It is hoped that the improved spatial resolution will offer enhanced snow water equivalent information for operational and climate applications and allow further assessment in those regions where it is difficult to derive reliable SWE estimates. Finally, projects are underway to improve the use of the satellite-derived snow water equivalent information in flood forecasting, hydrological, regional climate, and land surface process models (e.g., GEWEX/MAGS). It will be essential that derived snow water equivalent information can meet the needs of a range of users working in different regions of the country and requiring information on different spatial and temporal scales. This research has always involved the user community, and this cooperation has been invaluable in advancing our research and its use in addressing important hydrological and climatological issues.

Challenges and Recommendations

Achieving a better understanding of the role of the Arctic in the global climate and of the related cryosphere-climate interactions will require an adequate observational basis to support the necessary process studies, model development/validation, and the assessment of long-term trends. To meet this requirement using both *in-situ* and remote sensing observations, we are faced with a number of challenges. These include the complexity of cryosphere-climate processes requiring both basic and specialized observations, the harsh operating environment for equipment and people, the sparse networks, and high cost for site access and equipment maintenance associated with operations in remote high-latitude regions, and the ongoing availability of remote sensing data suitable for determining cryospheric information in a timely and affordable manner.

Looking back on Canadian *in-situ* observations, we find that our conventional networks were better in the past; through long established procedures and standards, our archived data were more consistent; adjustment procedures for reducing systematic errors have been developed; and data sets were more accessible to researchers. Looking forward, we find our conventional networks decreasing in size and coverage; as well, the observational methods are changing with the introduction of new automatic sensors and data collection systems. This will cause some loss of climate parameters being measured, and with the changing standards of measurement, there will be a need for further assessment of measurement errors and the development of additional correction procedures to ensure consistent time series. Organizations will be more protective of their data sets and may restrict access to researchers.

Looking back with respect to remote sensing data, we have a 20 to 30 year record for algorithm development and for studying trends. However, there can be a mismatch of scales between process studies and remote sensing information. For example, low resolution sensors (SSM/I at 25 km and AVHRR at 1 km) cannot adequately describe some cryospheric parameters with high spatial variability (e.g. Arctic islands snow cover). Higher resolution data from LANDSAT are available but with restricted temporal coverage. RADARSAT data can also provide high resolution information, but the data are costly. Looking forward, there will be improvements as new satellite sensors come online with higher spatial resolution (AMSR at 10 km and MODIS at 500 m). This should alleviate some of the limitations in studying processes and state variables with high spatial and temporal variability in the Arctic. However, with the reductions in the *in-situ* observational network, validation and algorithm development with these new sensors will remain a challenge.

To meet these challenges, we need to optimize our *in-situ* observational networks in high latitudes. This will require a greater effort in standardizing our autostation observations and in determining their errors and developing adjustment procedures. We need to apply bias-correction of long-term (30 to 40 years) precipitation records in the Arctic using the WMO methods to develop improved regional precipitation databases and climatologies. There needs to be a rigorous comparative analysis of the bias-corrected precipitation data and products among Alaska, northern Canada, Siberia, Greenland, the Arctic basin, and other circumpolar countries to evaluate the validity of the bias-correction procedures. Further, we need to develop gridded, bias-corrected precipitation datasets and climatologies for the northern regions and for the Arctic as a whole. New remote sensing observations have much potential for application in high latitudes, and continuing efforts are required to combine these observations with conventional observations. It is essential to develop a strategy for combining observations and modelling to study high latitude processes. Focused field research programs such as GEWEX afford an opportunity to address this need and to fill in data gaps. The Canadian Mackenzie Basin GEWEX Study is a good example where observations, process studies, and modelling are brought together. This study is facing many challenges of studying cryosphere-climate interactions in a data-sparse high-latitude remote region. The study team is developing an enhanced observational strategy to meet its research needs. This provides a good case study on how it can be done. More details can be obtained from the web site: http://www.msc-smc.ec.gc.ca/GEWEX/MAGS_obs_strategy.html.

For data management and data availability, we need to encourage research field programs to have a data management system in place so that the valuable data collected will not be lost or neglected after the project is completed. The global data centres such as GPCC and NSIDC are providing an invaluable service to the research community by being custodians to global data sets and alleviating some of the problems with data access in the current "data protective" climate brought on by cost recovery/commercialization pressures.

A final very important consideration in assessing gaps and needs and approaches for Arctic hydrology is that pan-Arctic efforts must be cooperative among countries and international agencies/programs. One vehicle that is practical for coordinating countries' individual efforts is WCRP and its projects, including GEWEX and CliC. CliC, for example, has developed a science and co-ordination plan with a hydrological component, including definition of science issues and possible approaches. Arctic studies cannot be successful without engaging expertise in several countries.

REFERENCES

Allison, I., R. G. Barry, and B. E. Goodison (eds.). 2001. *Climate and the Cryosphere (CliC) Project: Science and Co-ordination Plan, Version 1.* World Climate Research Programme. WCRP-114, WMO/TD No. 1053. Geneva.

Chang, A. T. C., J. L. Foster, D. K. Hall, B. E. Goodison, A. E. Walker, J. R. Metcalfe and A. Harby. 1997. "Snow parameters derivede from microwave measurements during the BOREAS winter field campaign," *J. of Geophysical Research, 102,* (D24): 29,663-29,671.

De Sève, D., M. Bernier, J.-P. Fortin, and A. Walker. 1997. "Preliminary analysis of snow microwave radiometry using the SSM/I passive-microwave data: the case of La Grande River watershed (Quebec)." *Annals of Glaciology, 25:* 353-361.

De Sève, D., M. Bernier, J.-P. Fortin, and A. Walker. 1999. "Analysis of microwave radiometry of snow cover with SSM/I data in a taïga area: the case of James Bay area (Québec)," in Proc. 56th Eastern Snow Conference, Fredericton, Canada, 2-4 June 1999, pp. 31-41.

Goita, K., A. E. Walker, B. E. Goodison and A. T. C. Chang. 1997. "Estimation of snow water equivalent in the boreal forest using passive microwave data," in Proc. GER '97 (International Symposium: Geomatics in the Era of Radarsat, 24-30 May 1997, Ottawa, Canada), CD-ROM publication.

Goodison, B. E., R. D. Brown and R. G. Crane (eds.) 1999. “Cryospheric Systems”. In *EOS Science Plan – The State of Science in the EOS Program,* National Aeronautics and Space Administration, NP-1998-12-069-GSFC, pp. 261-307.

Goodison, B. E., P. Y. T. Louie, and D. Yang. 1998. *WMO Solid Precipitation Measurement Intercomparison: Final Report*. WMO/CIMO Report No. 67, WMO/TD No. 872, World Meteorological Organization, Geneva, 306pp.

Goodison, B. E., and A. E. Walker. 1994. “Canadian development and use of snow cover information from passive microwave satellite data” in Passive Microwave Remote Sensing of Land- Atmosphere Interactions. B. J. Choudhury, Y. H. Kerr, E. Njoku and P. Pampaloni, eds. VSP Press, The Netherlands, pp. 245-262.

Walker, A., B. Goodison, M. Davey, and D. Olson. 1995. *Atlas of Southern Canadian Prairies Winter Snow Cover from Satellite Passive Microwave Data: November 1978 to March 1986*, Environment Canada, Downsview, 191 pp.

Woo, M-k, A. Walker, D. Yang, and B. Goodison. 1995. “Pixel-scale ground snow survey for passive microwave study of the Arctic snow cover,” in Proc. 52nd Eastern Snow Conference, 7-8 June 1995, Toronto, Canada, pp. 51-58.

Yang, D., B. E. Goodison, J. R. Metcalfe, P. Louie, G. Leavesley, D. Emerson, V. Golubev, E. Elomaa, T. Gunther, C. L. Hanson, T. Pangburn, E. Kang, J. Milkovic. 1999a. Quantification of precipitation measurement discontinuity induced by wind shields on national gauge. *Water Resources Research*, *35* (2): 491-507.

Yang, D., Shig Ishida, Barry E. Goodison, and T. Gunther. 1999b. Bias correction of precipitation data for Greenland. *Journal of Geophysical Research-Atmospheres, 104,* (D6): 6171-6181.

Yang Daqing, Esko Elomaa, Asko Tuominen, Ari Aaltonen, Barry Goodison, Thilo Gunther Valentin Golubev, Boris Sevruk, Henning Madsen, Janja Milkovic. 1999c. Wind-induced Precipitation Undercatch of the Hellmann Gauges, *Nordic Hydrology*, 30, 57-80.

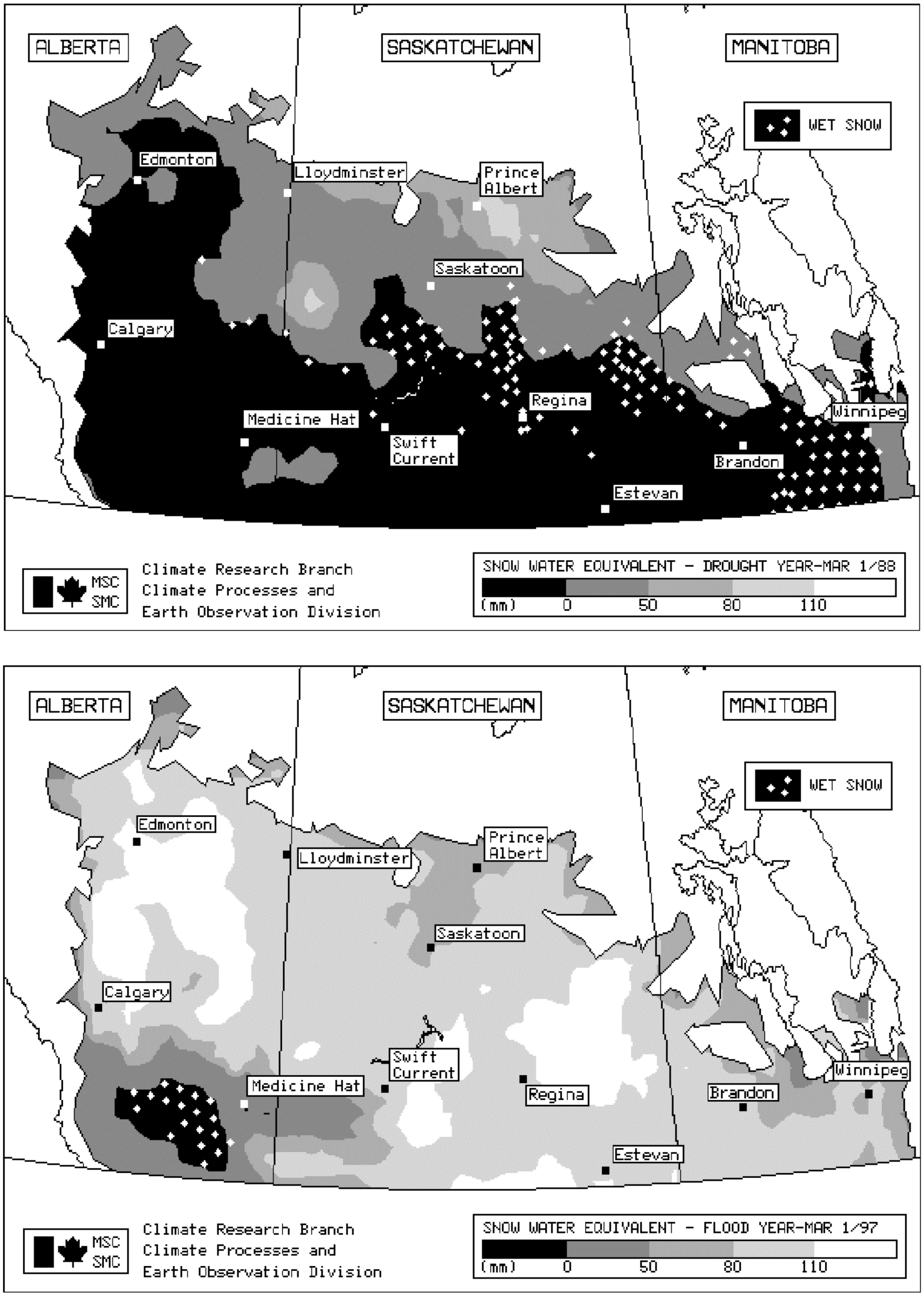


Figure 1. Passive microwave (SSM/I)-derived snow water equivalent for March 1, 1988 (drought year) and March 1, 1997 (flood year) on the Canadian prairies (shaded area).

Research Needs in Arctic Hydrology: Precipitation

Pavel Ya. Groisman
National Climatic Data Center
Asheville, North Carolina
pgroisma@ncdc.noaa.gov

Temperature in high latitudes has increased during the past 120 years by ~1K (annual zonally averaged temperature) with the largest increase in winter (~2K) and the smallest increase in summer (~0.5K). This increase was not steady and the warmest decade for annual temperature within the 60˚N to 90˚N zone was 1936-1945 rather than the 1990s (Figure 1).

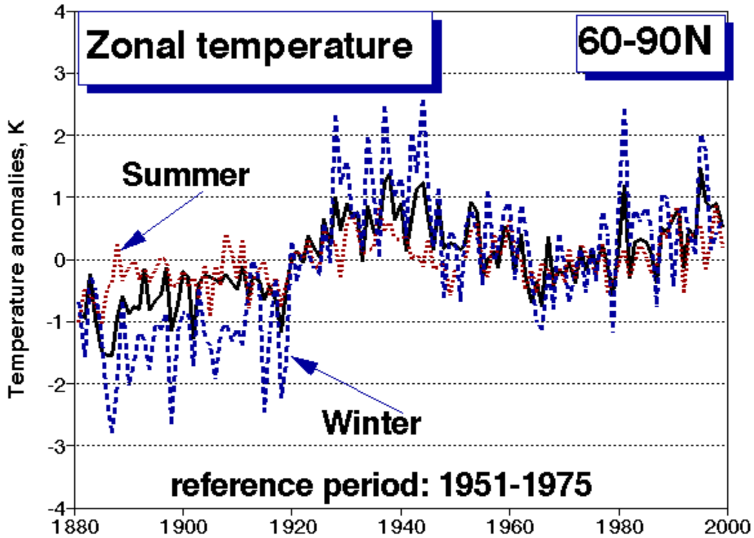


Figure 1. Arctic temperature variations by Lugina et al. (2001); update of Vinnikov et al. (1990)

Precipitation. During the past century there was a significant increase in precipitation over the Northern Eurasia (Groisman 1991) and for the second half of the century over the northern part of North America (Groisman and Easterling 1994). In eastern Russia (Siberia) during the past fifty years a decrease in summer precipitation was documented (Sun and Groisman, 2000). This decrease is accompanied by a decrease in stratiform and increase in convective cloudiness. The countrywide increase in convective cloudiness in turn affected the number of days with heavy precipitation over Russia. However, absolute values of precipitation in high latitudes are still not well measured due to instrument inaccuracy (WWB, 1974; Goodison, Louie, & Yang, 1998). This also can hamper conclusions about the precipitation changes in Arctic. Efforts are currently underway to fix this problem in Russia, Canada, and Nordic countries.

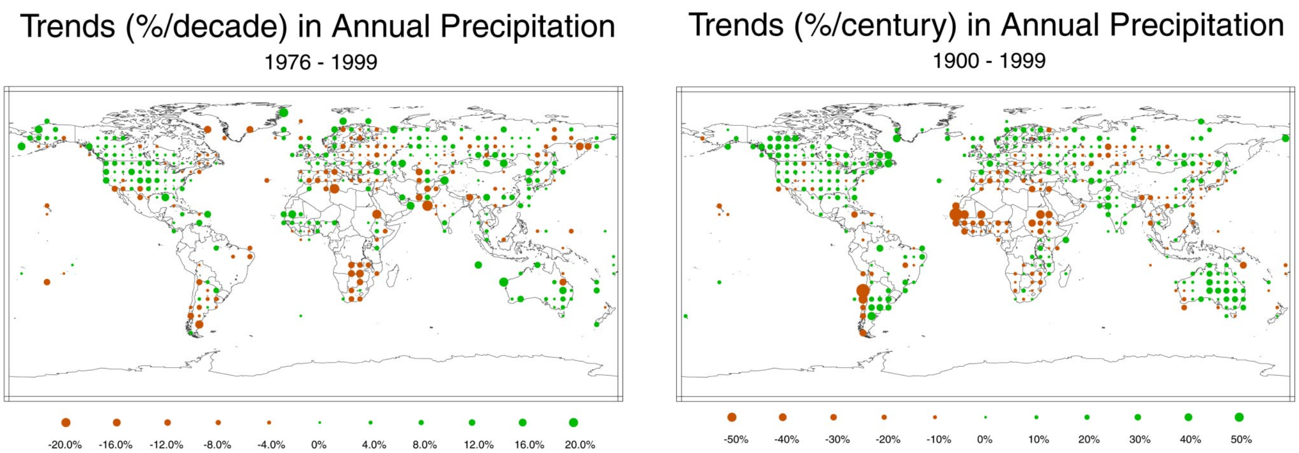


Figure 2. Annual precipitation trends based on the Global Climatology Network data set (Vose et al. 1992 updated).

Near-surface turbulent heat fluxes. They have noticeably changed in the cold season over Northern Eurasia during the past several decades. But their values are small and probably do not deserve much attention. A different picture arises if one were to consider these changes from the Arctic ocean where the recent sea ice retreat may generate a magnificent effect on the hydrological regime on the entire Arctic basin (Figure 3).

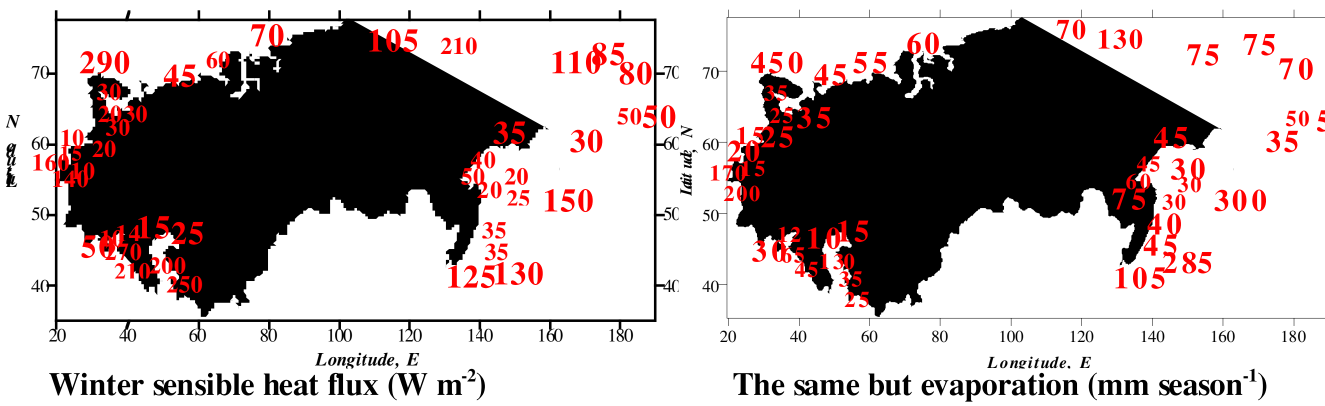


Figure 3. Turbulent winter heat fluxes from the leads and open sea calculated using the data of coastal stations by the method described in Groisman and Genikhovich 1997 with an assumption that leads occupy 10% of the sea ice area and climatological values of the open sea surface temperatures. Bowen ratio for these estimates varies in the range of 2 to 5 that is typical for polar oceans. Direction from the surface to the atmosphere is considered positive.

References

Goodison, B. E., Louie, P. Y. T., and Yang, D. 1998. WMO solid precipitation intercomparison, Final Report. World Meteorol. Organization, Instruments and Observing Methods Rep. 67, WMO/TD 872, 87 pp. + Annexes.

Groisman, P. Ya. 1991. Data on present-day precipitation changes in the extratropical part of the Northern hemisphere. In: *Greenhouse-Gas-Induced Climatic Change: A Critical Appraisal of Simulations and Observations,* pp. 297-310. Schlesinger M.E. (editor). Amsterdam: Elsevier.

Groisman, P. Ya., and D. R. Easterling: 1994: Variability and trends of precipitation and snowfall over the United States and Canada, *J. Climate*, **7,** 184-205.

Groisman, P. Ya., and Genikhovich, E. L.,1997. Assessing surface-atmosphere interactions using Russian standard meteorological network data. Part 1: Method. *J. Climate*, *10,* 2154-2183.

Groisman, P. Ya., E. L. Genikhovich, R. S. Bradley, and B.-M. Sun, 1999. Trends in turbulent heat fluxes over Northern Eurasia. In *Interactions Between the Cryosphere, Climate and Greenhouse Gases* (Proceedings of IUGG 99 Symposium HS2, Birmingham, UK, and July 1999), M. Tranter, R. Armstrong, E. Brun, G. Jones, M. Sharp, and M. Williams (eds.). *IAHS Publ.* No. **256**, Wallingford, England: IAHS Press, 19-25.

Karl, T. R., P. Ya. Groisman, R. W. Knight, and R. R. Heim Jr. 1993. Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations, *J. Climate, 6,* 1327-1344.

Lugina, K. M., P. Ya. Groisman, K. Ya. Vinnikov, V. V. Koknaeva, and N. A. Speranskaya. 2001. “Monthly surface air temperature time series area-averaged over the 30-degree latitudinal belts of the globe, 1881-1999.” Data set available at the DOE Carbon Dioxide Information Analysis Center, Oak Ridge, Tennessee [http://cdiac.esd.ornl.gov].

Sun, B.-M., and P. Ya. Groisman, 2000. Cloudiness variations over the former Soviet Union. *Internat. J. Climatol., 20,* 1097-1111.

Vinnikov, K. Ya., Groisman, P. Ya., Lugina, K. M., Golubev, A. A. 1987. Changes of mean surface air temperature in the northern hemisphere for 1841-1985 years, *Meteorology and Hydrology, 1,* 45-55 (in Russian, in English in *Soviet Meteorology and Hydrology*).

Vinnikov, K. Ya., Groisman, P. Ya. and Lugina, K. M. 1990. The empirical data on modern global climate changes (temperature and precipitation), *J. Climate, 3*(6), 662-677.

Vose, R. S. and six others. 1992. The Global Historical Climatology network: Long-term monthly temperature, precipitation, sea level pressure, and station pressure data. ORNL/CDIAC-53, NDP-041, Carbon Dioxide Information Analysis Center, Oak Ridge National Lab., Oak Ridge, Tennessee, 315 pp.

World Water Balance and Water Resources of the Earth, Gidrometeoizdat, Leningrad, p. 638, 1974 (in Russian), 1978 (in English by UNESCO Press).

Regional Climate Simulation for the Pan-Arctic Region Using MM5

William J. Gutowski, Jr. (1),* Helin Wei (1), Charles Vörösmarty (2), and Balazs Fekete (2)

(1) Iowa State University, Ames, Iowa
(2) University of New Hampshire, Durham, New Hampshire
gutowski@iastate.edu

* *Corresponding author address*: William J. Gutowski, Jr.,
3021 Agronomy, Iowa State University, Ames, IA 50011;
gutowski@iastate.edu; (515) 294-5632; (515) 294-2619 [fax]

1. INTRODUCTION

The watersheds surrounding the Arctic Ocean are significant contributors to the hydrologic cycle of the Northern Hemisphere's polar region. The land-based hydrologic cycle for this pan-Arctic region and its resultant freshwater discharges to the Arctic Ocean may play an important role in determining the ocean's thermal and salinity gradients, thereby affecting sea ice, regional ocean-circulation dynamics, and the formation of Atlantic deep water. Multi-year feedback links may exist that couple river discharge, ocean ice and temperature distributions, and the region's atmospheric circulation (e.g., Mysak 1995). The river flow also delivers to the Arctic Ocean dissolved constituents and sediments that could affect oceanic primary production and CO_2 uptake.

Global general circulation model (GCM) simulations show that the pan-Arctic region may be highly sensitive to global warming, with relatively large temperature increases, especially in winter (IPCC 1995). Because the region's hydrologic cycle can affect the formation of sea ice, cloud cover, and ultimately North Atlantic deep water, climate change in this region may in turn have global impact. Furthermore, climate warming in the pan-Arctic may also produce substantial thawing of permafrost and, as a consequence, alter the carbon cycle.

We have adapted MM5 for pan-Arctic simulation to evaluate interactions among processes controlling the land region's hydrologic cycle and freshwater input to the Arctic Ocean. One could use a GCM for such study, but model errors at lower latitudes could contaminate Arctic simulation and thus interfere with our analyses. Using a limited-area model allows us to specify pan-Arctic boundary conditions fairly accurately from reanalyses. This abstract describes adjustments made to MM5 for this purpose and gives a comparison of model performance with a wide variety of observations.

2. MODEL AND DATA

In order to simulate the coupled land-atmosphere hydrologic cycle of a region that experiences seasonally frozen soil, we have coupled to MM5 (Version 2) the Land Surface Model (LSM) of Bonan (1996). We have also coupled to MM5 a simple thermodynamic sea-ice model that evolves in conjunction with atmospheric input and specified, temporally varying sea-surface temperatures. The structure of the coupling has been chosen to ease adapting the fully coupled model for parallel-processor computation, an effort currently underway. From the suite of MM5's physical parameterizations, we have used the Grell cumulus convective scheme (Grell, Kuo, and Pash 1991, 1993), the adaptation of Blackadar's Planetary Boundary Layer model (Zhang and Anthes 1982), the explicit treatment of cloud water, rainwater, snow, and ice for resolved precipitation physics (Dudhia 1989), and CCM2 radiation.

The model domain covers the major Arctic watersheds of Asia and North America (Fig. 1). The lateral boundaries were also chosen so that much of the external forcing of the model comes from regions that are fairly well observed. Simulations reported here used horizontal resolution of 120 km on a polar stereographic projection. One-month test computations using 60-km resolution produced no significant differences from coarser resolution runs, so we retained 120-km resolution for economy. The model's vertical structure is fairly standard: 23 sigma levels with model top at 100 hPa and 9 levels in the layer $\sigma = [0.7,1.0]$.

We performed a series of simulations for October 1985 and July 1986 to calibrate the model versus observations and then performed a one-year simulation from October 1985 – September 1986 to validate model performance. This was a year of relatively large sea-ice changes near river mouths, implying a significant input of river discharge from land-atmosphere interaction. The NCEP/NCAR Reanalysis (Kalnay et al. 1996) provided initial and lateral-boundary conditions, with the latter updated every 12 hours. Before starting the long simulation, we also spun-up initial soil temperature and moisture by repeated simulation of September 1985.

Model development was guided by a wide variety of observations from sources such as the Historic Arctic Rawinsonde Archive (HARA; Kahl et al. 1992), the TOVS Pathfinder Path-P Daily Arctic Gridded Atmospheric Parameters (TOVS, 1999), the Polar Radiation Fluxes archive (Key, 1998), the Xie-Arkin (1997) precipitation data set based on surface observations and satellite retrievals, and the NCEP/NCAR Reanalysis. Analysis focused on behavior in three broad regions (Fig. 1).

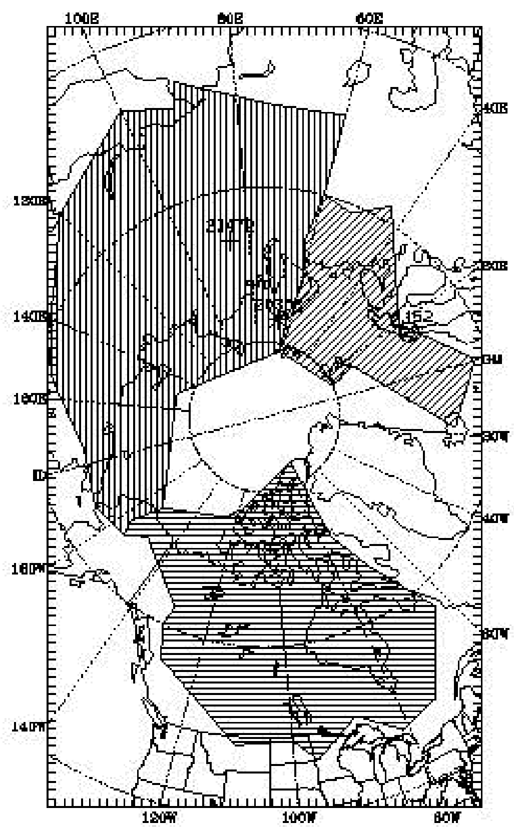


Fig. 1: Model domain and subregions for analysis (vertical line: Asian Arctic Watershed; horizontal line: North American Arctic Watershed; diagonal line: European Arctic Watershed.)

3. ISSUES FOR ARCTIC HYDROLOGY

(a) Atmospheric Water Cycle Dynamics
Model behavior, especially precipitation, was sensitive to simulated cloud cover. The one-month test simulations showed that cloud-cover diagnosis using the standard scheme based on relative humidity was inadequate. Comparison of model-produced cloud ice (C_I) and liquid water (C_L) with cloud cover climatology led to the adaptation of a scheme giving 90% cloud cover in a model layer whenever the layer's C_I or C_L passed prespecified thresholds that were constant in space and time. This produced marked improvement in cloud cover and precipitation simulation (Fig. 2).

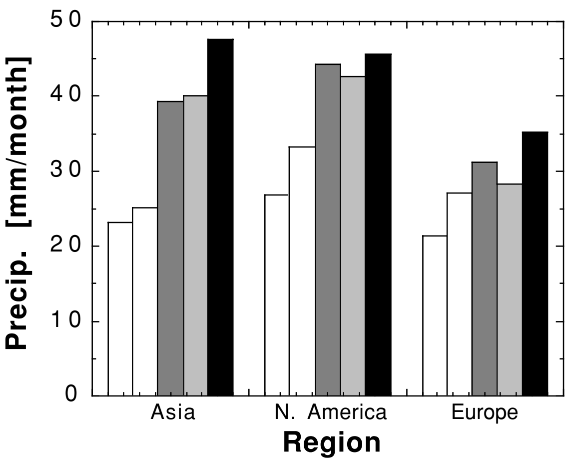


Fig.2: July 1986 precipitation using relative humidity based cloud schemes (unshaded) and cloud-water threshold schemes (shaded) and observed (solid)

Problems still remain for summer precipitation, when the model tends to produce too little. Also, cloud cover appears to be too low in the European Arctic sector in summer, as the model produces excessive incident solar radiation at the surface (Fig. 3). Water cycle processes in the atmosphere thus need further refinement.

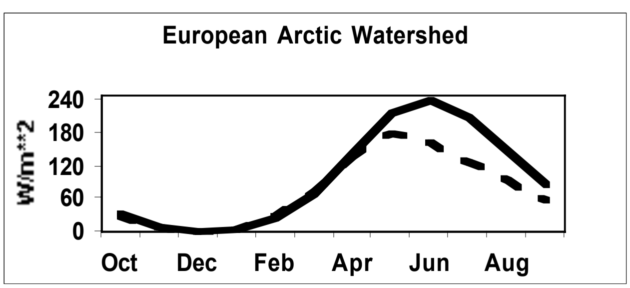


Fig.3: Monthly mean surface incident shortwave radiation for Jan.-Sept., 1986 from MM5/LSM (solid) and the Polar Radiation Fluxes archive (dashed).

(b) Atmospheric data sets
The model appears to simulate atmospheric circulation well. However, there is need for better circulation data sets that span the entire Arctic. Comparison of simulated 850 hPa winds versus NCEP/NCAR reanalysis and HARA rawinsonde winds shows that the model tends to agree better with HARA winds

than does the reanalysis (e.g., Fig. 4). Note that the reanalysis supposedly ingests soundings in the HARA archive and should thus tend to be close to HARA observations. Fig. 4 thus casts some doubt on the accuracy of the reanalysis winds away from the HARA sites. In addition, atmospheric water transports are not compared here because water vapor measurement remains a challenge, especially in extreme environments.

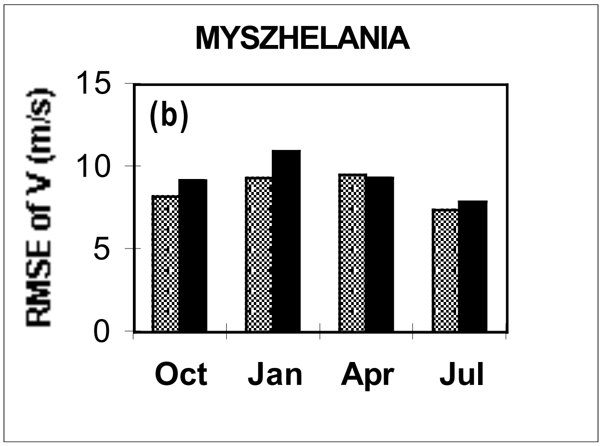


Fig. 4: Root mean square error vs. HARA observations in 850 hPa winds at a site in Russia for (a) zonal wind and (b) meridtional wind. [Hatched = MM5/LSM; Solid = NCEP/NCAR Reanalysis]

(c) Stable atmospheric boundary layers
Very stable atmospheric boundary layers occur when there is substantial flow of heat from the atmosphere to the surface. An important instance for regions experiencing seasonal snow cover is when warm air moving poleward melts snow on the ground. Related work has shown that very high resolution of the near-surface atmosphere is needed to simulate well heat flux into the snow. Specifically, a model needs at least one level in the atmospheric surface layer, which may be only a few meters thick (Wei et al. 2000). Failure to resolve this layer can result in significant negative bias in snow melt and thus runoff.

(d) Properties of frozen soil
The model uses a highly sophisticated sub-model for land-surface processes (Bonan 1996). However, the model's hydraulic conductivity does not change through freeze/thaw cycles, though its thermal conductivity does. This is a consequence of global application and testing of the model (Bonan 2000, personal communication). An outcome of this model property is that nearly all spring snowmelt infiltrates the soil and very little runs directly into rivers, even when the soil is frozen. Post-processing of the output to shunt snowmelt directly into runoff when soil is frozen yields reasonably good annual runoff cycles for the continental regions in Fig. 1. Discussion with permafrost experts reveals that improved understanding and modeling of seasonally frozen soil's hydraulic properties is needed.

4. CONCLUSIONS

A version of MM5 adapted for pan-Arctic simulation of the hydrologic cycle performs fairly well in a one-year simulation. Further improvements in spring runoff generation are needed to give a better match with the observed annual cycle of water flow through the land-atmosphere system. Directions for improvement have been described here.

ACKNOWLEDGEMENTS

This work has been supported by U.S. Dept. of Energy grant DE-FG02-96ER61473. We thank Dr. J. R. Key for kindly providing us with surface radiation fluxes from the Polar Radiation Fluxes Project. Computer support for this study was provided in part by the National Center for Atmospheric Research.

REFERENCES

Bonan, G. B. 1996. A land surface model (LSM) for ecological hydrological and atmospheric studies: Technical description and user guide, NCAR Tech. Note, NCAR/TN-417+STR, 150 pp.

Dudhia, J. 1989. Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. *J. Atmos. Sci*., *46,* 3077-3107.

Grell, A. G., Y.-H. Kuo, and R. Pash. 1991. Semi-prognostic tests of cumulus parameterization schemes in the middle latitudes. *Mon. Wea. Rev., 119,* 5-31.

------. 1993. Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev., 121,* 764-787.

IPCC. 1995. *Climate Change 1995. The Science of Climate Change*.. Houghton, J. T. L. g. Miera Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, ed., Cambridge: Press Syndicate of the University of Cambridge, 572 pp.

Kahl, J. D., M. C. Serreze, S. Shiotani, S. M. Skony, and R. C. Schnell. 1992. In situ meteorological sounding archives for arctic studies. *Bull. Amer. Met. Soc., 73,* 1824-1830.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A. Leetma, R. Reynolds, R. Jenne and D. Joseph. 1996. The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc., 77,* 437-471

Key, J. R., 1998. Polar Radiation Fluxes (PRF) Procedure Description. See http://stratus.ssec.wisc.edu/products/d1fluxes/fluxes3.html

Mysak, L. A. 1995. Interdecadal variability in the Arctic and northern North Atlantic: Observations and models. *Fourth Conference on Polar Meteorology and Oceanography*, Dallas, Texas, American Meteorological Society, (J9) 26–(J9) 27.

TOVS. 1999. TOVS Pathfinder Path-P Daily Arctic Gridded Atmospheric Parameters. Digital data available from nsidc@kryos.colorado.edu. Boulder, Colorado. EOSDIS NSIDC Distributed Active Archive Center, University of Colorado at Boulder.

Wei, H., M. Segal, W. Gutowski, Z. Pan, R. W. Arritt, and W. Gallus. 2000. Effect of surface layer resolution on simulation of rapid snowmelt. *J. Hydroclim.* (in press).

Xie, P., and P. A. Arkin.1997. Global Precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bull. Amer. Meteor. Soc., 78,* 2539-2558.

Zhang, D.-L., and R. A. Anthes. 1982. A high-resolution model of the planetary boundary layer - sensitivity tests and comparisons withSESAME-79 data, *J. Appl. Meteor., 21:* 1594-1609.

Human Dimension of Arctic Hydrological Change

Lawrence C. Hamilton
Sociology Department
University of New Hampshire
Durham, NH 03824
Lawrence.Hamilton@unh.edu

1. NAArc PROJECT OVERVIEW

The North Atlantic Arc (NAArc) project is a multi-method, comparative study of links between environmental and social change. Its focus includes four fisheries-dependent regions of the northern Atlantic: Newfoundland/Labrador, Greenland, Iceland, and Norway. The research integrates natural science (oceanography and biology) with social science (demography, social indicators, and community and individual life histories). A key aspect of this integration has been the assembly and analysis of time series databases containing biological, fisheries, and socioeconomic information for each of the four study regions and at relatively fine spatial scales. The project Web site lists publications and abstracts, and includes some downloadable datasets: http://pubpages.unh.edu/~lch/naarchom.htm

NAArc has been supported by grants from the Arctic System Science (1996–2000) and Arctic Social Sciences (2000–2003) programs of NSF.

The marine ecosystems that support northern fisheries have exhibited large-scale changes in recent decades. These changes are driven by interactions between environmental variation (e.g., temperature, salinity, currents) and the pressure of fishing. Figure 1, for example, shows correlations between cod catches, shrimp catches, and sea temperature off west Greenland.

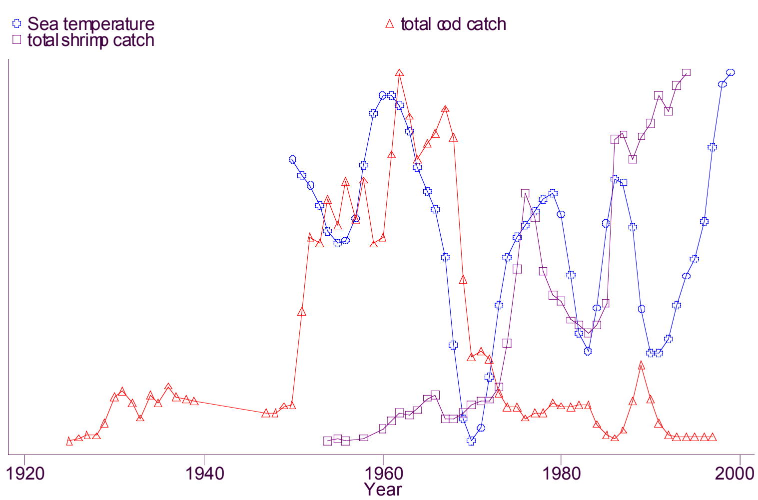


Figure 1: Smoothed Fylla Bank temperatures (data from Buch 2000), cod catches, and shrimp catches off west Greenland (Hamilton 2000).

Common patterns in resource changes and their social consequences can be seen across a variety of policy regimes. Such patterns can be viewed as “empirical models” that suggest likely human dimensions of future climatic change. For example, Figure 2 shows the contrasting population trends of 13 west Greenland municipalities, which partly reflect changes in adjacent marine ecosystems. Sisimiut grew during the cod-to-shrimp transition; Paamiut declined.

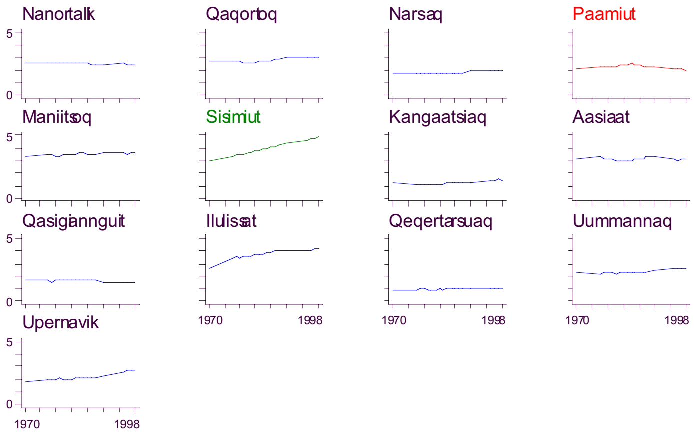


Figure 2: Greenland-born population (1000s) of 13 west Greenland municipalities, 1970–98 (Hamilton Lyster & Otterstad 2000).

2. GAPS IN UNDERSTANDING

Physical science and modeling work should aim to identify parameters of Arctic water cycles that have varied substantially in the recent past and/or appear likely to exhibit substantial change in the future. Human dimensions research could use this information as a starting point to ask further key questions:

2.1. For what specific parameters/locations/activities do we expect that human activities in the Arctic will be most sensitive to the projected hydrological changes? Possible issues:
- 2.1.1. impacts of permafrost changes on buildings, roads, and water systems;
- 2.1.2. erosion, water level, and other consequences for settlements from changes in fresh water flows, ice conditions etc.;
- 2.1.3. effects of changing ice, snow, and storm patterns on transportation by water, ground, and air;
- 2.1.4. other impacts on activities and infrastructure of primary resource industries (e.g., on pipelines, shipping, forestry, fishing); and
- 2.1.5. ecological changes affecting subsistence resources or traditional activities (e.g., hunting, fishing, herding).

2.2. Among contemporary Arctic societies, can we discern any effects related to hydrological changes that are occurring already? For example, analyzing observed physical/biological changes for possible:
- 2.2.1. effects on infrastructure or life in Arctic communities;
- 2.2.2. effects on industrial activities in the Arctic;
- 2.2.3. effects on transportation in the Arctic; or
- 2.2.4. effects on subsistence or traditional activities.

2.3. Integrating results from 2.1 (hypothesized/potential effects) and 2.2 (observed effects) with climatic projections: Can we suggest empirically based scenarios about the impacts of future hydrological changes on humans in the Arctic?

2.4. What consequences might Arctic hydrological changes have on societies outside the Arctic, for example through the mechanisms of:
- 2.4.1. the North Atlantic Oscillation;
- 2.4.2. Atlantic thermohaline circulation;
- 2.4.3. Arctic ocean ice cover/albedo; or
- 2.4.4. greenhouse gas sources/sinks.

A fundamental requirement in addressing these questions is to integrate socioeconomic with physical and biological research, at concrete levels of data, analysis, and modeling.

3. DATA NEEDS

Data required to address the human dimensions questions above would come from a variety of sources. These include:

3.1. Surveys, inventories, or databases assembled to assess the distributions of socioeconomic variables thought to be sensitive to hydrological variations. For example:
   - 3.1.1. settlements vulnerable to water-level or erosional effects;
   - 3.1.2. transportation links vulnerable to permafrost, runoff, snow, or ice cover effects;
   - 3.1.3. large- and small-scale economic activities likely to be affected by hydrological change;
   - 3.1.4. traditional activities likely to be affected by hydrological change.

3.2. Observational records associated with construction, maintenance, transportation, wildlife surveys, and other activities hypothesized as related to hydrological variations. What relevant time series already exist that could be assembled in integrated databases with objective hydrological/climatic data? What new observations/monitoring should begin?

3.3. Traditional, oral history, and first-hand knowledge of Arctic residents. For example:
   - 3.3.1. information about seasonal, storm, snow, ice, and runoff variations and how these affected people;
   - 3.3.2. information about variations in traditionally important resources, such as game animals.
   - 3.3.3. exploring how best to use such informal observations in the context of integrated interdisciplinary research;
   - 3.3.4. seeking effective ways to communicate research questions, procedures, and findings to Arctic residents.

4. A PAN-ARCTIC PERSPECTIVE

The Arctic is socially heterogeneous. Figure 3 illustrates one dimension of this heterogeneity, showing the distribution of population by settlement size in arctic and subarctic North America. The physical manifestations of climatic change could well be quite different (as are current climates) in different parts of the Arctic. Social responses to such change are likely to show even greater variation from place to place. For example, changes affecting the North Atlantic Oscillation could have immediate consequences for Sisimiut or Tromsø, but less importance in Kotzebue or Nome. Permafrost melting will, obviously, be of greatest concern where settlements are built on top of it. Opening the Northern Sea Route might bring economic opportunity to eastern Russia, while subsistence hunters in Alaska, Canada, and Greenland viewed sea ice declines as a threat. Certainly the different cultures and different governments have differential capabilities for adapting to changed conditions. A meaningful analysis of human dimensions of Arctic hydrological change must work from data at relatively fine spatial scales—where possible, at the level of individual communities and livelihoods.

The NAArc project has collected such data on northern Atlantic fishing societies challenged by large-scale change in their staple resources. Although changes such as the northwest Atlantic's cod collapses are generally viewed as adverse, we found some people and places have thrived amid these changes, while others struggled or declined. Change creates winners and losers. There are systematic elements to this process that provide propositions that could be tested with different kinds of data, on Arctic hydrology, and applied to the larger question of global climate change.

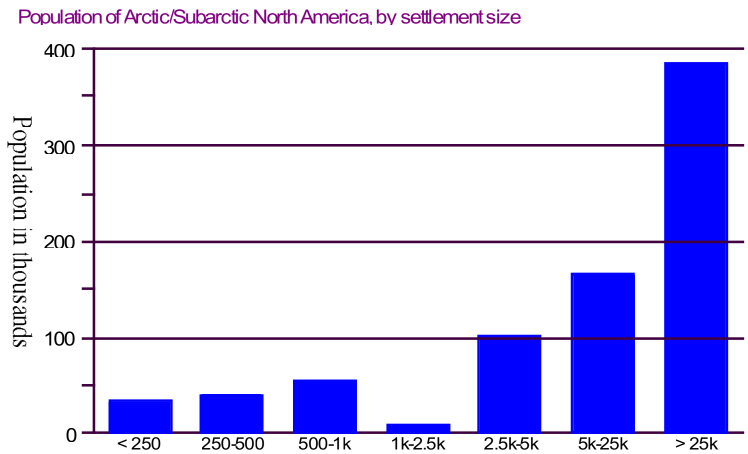


Figure 3: Distribution of current North American (Alaska/Canada/Greenland/ Iceland) arctic and subarctic population, by size of settlement (Rasmussen 1998).

5. REFERENCES

Buch, E. 2000. Oceanographic investigations off west Greenland, 1999. Copenhagen: Danish Meteorological Institute.

Hamilton, L. C. 2000. The NAO, AO and west Greenland fisheries. NAArc project working paper.

Hamilton, L. C., P. Lyster and O. Otterstad. 2000. Social change, ecology and climate in 20th century Greenland. *Climatic Change* 47(1/2):193–211.

Rasmussen, R. O. 1998. Settlement structure, resource management, and sustainable development: Megaprojects vs. local participation in Greenland. In *Sustainable Development in the North: Local Initiatives vs. Megaprojects*, pp. 47–87, G. Duhaime, R. O. Rasmussen and R. Comtois (eds.) Québec: GÉTIC, Université Laval.

Research Needs in Arctic Hydrology

Larry D. Hinzman
Water and Environmental Research Center
University of Alaska Fairbanks
Fairbanks, Alaska 99775-5850
ffldh@uaf.edu

The prospect of global climatic change has fueled the need to improve our understanding of many atmospheric, oceanic, and terrestrial processes. It has forced us to recognize the fact that most of these processes are interactive and that we must understand the linkages between them. Especially in the Arctic, many of these linkages have feedback effects that can greatly magnify their total impact upon the climatic system. The annual radiation balance in the Arctic yields a net loss in energy that is compensated by energy advected from warmer regions to the south. Thus the Arctic serves as a sink for excess energy radiated on more temperate regions. Anthropogenic climatic warming is expected to be greatest in the high latitudes, possibly three to four times the amount of mid-latitudes. The consequences of climatic warming in the high latitudes include longer snow and ice-free periods, resulting in higher absorbance of incoming shortwave radiation, effectively changing the annual surface energy budget and the global dynamics of energy redistribution. Ice and snowcover are critical parameters in understanding climatic dynamics and development of accurate simulation and measurement techniques of the cryosphere should be a top priority. In order to improve our understanding of the role of the Arctic in the global hydrologic and energy budget, we must develop a more dynamic view of the terrestrial, aquatic, oceanic, and atmospheric processes and their linkages.

Arctic environments provide a unique opportunity to unlock many clues about the recent past and present climates and their system responses, due to the memory stored in ice and frozen ground. It would be possible to resolve many of the complex interactions of atmospheric, terrestrial, and oceanic processes through an integrated examination of mass and energy flows through these systems, thus constructing a more complete picture of past climates and improving our understanding of climatic forcing mechanisms and feedbacks. The paleoclimate proxy indicators found in lake sediments and ice sheet cores provide paleoclimatic data needed to calibrate climate models. Integrating the process data with the paleoclimate data should provide a more powerful basis upon which to verify simulations of future climates and system responses to climate change. For example, impacts of soil moisture and trace gas feedbacks from the tundra and boreal forest regions, and ice sheet instabilities, are critical for accurate model simulations of future climates.

These analyses are possible due to a unique combination of events and processes that exist nowhere else on Earth. Glaciers in the Arctic are extremely sensitive to subtle changes in climate and display the effects of long-term trends through their impacts upon surface features. Also, it has been shown that records of previous climates may be extracted from temperature profiles of deep wells in permafrost because energy transfer is limited to conductive heat transfer only. Analysis of the fossil indicators of permafrost changes (including subsea, subglacial, and periglacial permafrost) and glacial history and dynamics with complementing paleothermometery analyses of permafrost can yield valuable information on temporal and spatial climatic dynamics. Given the fact that large parts of Alaska and Siberia were not glaciated during the last Ice Age, we now realize that many of the geomorphologic features that evolved under different climates are still evident.

If one studies the present drainage network of streams and rivers in the Arctic, it is apparent that these drainages do not conform to patterns established by rivers in more temperate regions. Mature drainages in temperate and tropical areas display better developed patterns as compared to those in the Arctic. However, ancient terraces may indicate a period of vastly different conditions. Regional analyses of the ancient drainages combined with geophysical dating techniques, lake sediment samples, and surface geomorphological analyses will provide insight into the moisture and thermal regimes of previous climates. This information, coupled with thermal profiles extracted from deep wells in permafrost, may yield complete climatic history of the Arctic up to the last 10 or 20 thousand years. The consequences of changing patterns of drainage networks extends beyond providing clues to previous climates. In the advent of a changing climate, we should expect that the patterns will change, yielding much higher sedimentation rates as rivers tend to a stable state. The ecologic consequences to aquatic and marine environments will be tremendous.

To carry this analysis further, sediments transported by arctic rivers under a warmer, wetter climatic regime would carry a signature of their source and time period. As the past climate warmed, erosion rates increased and oceanic circulation patterns changed. Regional analyses of sediments in the Arctic Ocean can reveal not only information regarding historical patterns of circulation but can also link terrestrial and oceanic processes. Recent analyses on climate variability have demon-strated that the changes in high-latitude air temperatures are related to oceanic heat transport. If oceanic circulation patterns were different under previous climatic conditions, and if these differences were incorporated into atmospheric general circulation models, it might be possible to simulate historical climates, such as the previous Ice Age. Freshwater runoff into the Arctic Ocean is critical since it affects sea-ice distribution, ocean stratification, heat transfer to the atmosphere, deep water formation, and hence climate. Sea-ice extent is also an important parameter involved in the flux of heat, mass, and momentum between the ocean and atmosphere.

The circumpolar Arctic has a sparsity of meteorologic and hydrologic data. This reinforces the need for reliance on historical data but also displays the necessity of improved data collection. The Greenland ice cores have presented good detail on previous climates, but the climate in Beringia appears to have been much different (not much colder, but drier); reconstructing this climatic record will require extensive field research and analysis. Although many oceanic sediment samples have been collected, they were not sampled for the purpose of tracking circulation with respect to arctic rivers; consequently a greater distribution of core samples must be obtained. We must develop a better understanding of physical processes controlling feedbacks, meaning we must develop better models of fresh water/sea-ice and seasonal snow impacts. Integrated models of hydrological processes, nutrient transport, and ecosystem and societal dynamics must be developed and verified within arctic regions and eventually around the entire arctic basin. There are many gaps in our understanding that prevent development of such models. Initial steps to eliminate some of these gaps are described below.

Recommendations

- Extensive soil moisture monitoring at established met stations and in other terrain types.
- Development of techniques of quantifying pixel size soil moisture levels in tussock tundra areas.
- Development of remote sensing methods to accurately measure soil moisture levels over large areas.
- Development of methods to quantify historic levels of soil moisture.

- Quantify historic and future changes in precipitation patterns and amounts.
- Improve understanding of the relationship of soil moisture to other processes.
- Determine if widespread drying of soils and ponds is occurring and if so, determine the subsequent climatic and ecosystem impacts.

- Improve understanding of mountain hydrology, including establishment of meteorological and soil thermal and hydrological monitoring stations in mountainous sites.
- Improve our spatial database and distributed modeling expertise on snowcover distribution and redistribution, permafrost ,and active layer dynamics and river discharge.
- Synthesize arctic water balance studies from around the circumpolar arctic.
- Given the sparsity of observational networks in the high altitudes, remote sensing and model simulation will play a major role in arctic hydrology and climate studies. Thus development of reliable databases and climatology will be very important for driving distributed hydrological models, for calibration of remote sensing data/products, and for validation of model outputs.

Figure 1. Area where the ice-rich permafrost has started to degrade, creating landscape and vegetation change as drainage channels develop and the surrounding tussock tundra converts to a drier shrub tundra.

Nutrient and Organic Matter Fluxes from the Pan-Arctic Watershed to the Arctic Ocean

Robert M. Holmes(1), Bruce J. Peterson(1), Viatcheslav V. Gordeev(2), Alexander V. Zhulidov(3), Charles Vörösmarty (4), Richard Lammers(4)

(1) Marine Biological Laboratory, Woods Hole, MA 02543
(2) Shirshov Oceanology Institute, Russian Academy of Sciences, Moscow, Russia
(3) Center for Preparation and Implementation of International Projects on Technical Assistance, Rostov-on-Don, 344104, Russia
(4) Complex Systems Center, University of New Hampshire, Durham, NH 03824
rholmes@mbl.edu

The constituents carried by rivers from continents to oceans are important indicators of changing conditions in the watersheds as well as controls on biotic activities in estuaries and coastal seas. A strong set of baseline data on nutrient and organic matter fluxes would position the scientific community to assess how climate and land-use changes are affecting this land-to-ocean linkage. In the Arctic these fluxes assume increased importance due to the large volume of riverine inputs relative to the volume of the shelf seas and the relatively small surface area of the Arctic Ocean relative to its drainage area. Whereas nutrients from major rivers exert control over productivity of estuarine and nearshore waters, organic matter and pollutants from land can serve as tracers of water masses throughout the Arctic Ocean. For example, even waters flowing through Fram Strait into the North Atlantic convey organic matter with a chemical signature of continental runoff.

A rigorous synthesis and analysis of these fluxes at the circumpolar scale does not exist. Work to date suggests that there are serious gaps and analytic errors in the materials available for attempting such a synthesis. There are three major sources of information for an assessment of nutrient and organic matter fluxes from Russia, Canada, and Alaska, respectively. The first is the Russian (formerly USSR) archives of the State Service of Observation and Control of Environmental Pollution (OGSNK, GSN after 1992). These archives include monthly values for nitrate, ammonium and phosphate for the major rivers draining the Eurasian portion of the arctic watershed. We have worked for several years with Russian colleagues to evaluate the quality of these data. After concluding that independent sampling was necessary, a trip last summer (2000) to the Ob and Yenesey Rivers resulted in a decision that the ammonium data are much too high due to the use of inappropriate methods. Nitrate and phosphate data appear to be better, but additional systematic comparisons will be needed to confirm their accuracy. These findings represent a severe blow to the effort to establish a baseline for nutrients fluxes because samples from past years cannot be replaced. Finally, the dissolved organic matter values that are available in the Russian data base are from indirect methods that are not comparable to modern chemical or high temperature oxidation methods.

The second source of information is for Canada. Some of this information is available from Canada Centre for Inland Waters (CCIW) as part of the GEMS-Water data base and includes rivers entering the Arctic Ocean proper, Hudson Bay, and the North Atlantic. The available data for phosphate, ammonium, and DOC is very limited in this data base and additional information has been collected. However, the quality of this data is not yet known and must be assessed with the aid of Canadian scientists familiar with the sample collection and analysis procedures.

The third source of data is from the U.S. Geological Survey for Alaska rivers. These data span a period of 10-20 years but the number of samples per river is very limited for nitrate, ammonium, phosphate, and especially DOC. About half of the entries are limited to 10 samples or fewer over many years. The data set is far too sparse to adequately estimate annual fluxes and obviously too limited to detect trends over time.

In summary, the available information falls well short of what is needed for rigorous estimation of continent to ocean fluxes. A strong argument can be put forward for a coordinated pan-arctic monitoring effort to assess nutrient and organic matter fluxes in major rivers. These fluxes represent one integrative means of assessing rates of change on the arctic landscape. The primary goal would be to provide a scientifically valid baseline against which to judge future changes in land to ocean fluxes arising from land-use or climate change impacts. A second important goal would be to provide accurate values for fluxes of nutrients supporting estuarine and near-shore fisheries and river-specific data on inputs of chemical tracers such as organic matter to the Arctic Ocean.

Arctic Hydrological Processes

Douglas L. Kane
Institute of Northern Engineering
University of Alaska Fairbanks
Fairbanks, AK 99775
ffdlk@uaf.edu

Hydrologic models used to study climate change should have two attributes: first, they should be able to model accurately the hydrologic response of a watershed now, and second, they should be able to predict future responses if there are changes in watershed structure or hydrologic inputs. This implies that such models be process and physically based models. Before this can be confidently accomplished, we need to have the capability of quantifying each of the hydrologic processes and storage reservoirs at the scale of interest (Figure 1). For high-latitude regions the relevant hydrologic processes are precipitation (both rain and snow), runoff, subsurface flow (sub- and supra-permafrost groundwater), evaporation, transpiration, sublimation, snowmelt, overland flow, storage (surface and subsurface), and redistribution of snow by wind. For routing water through the watershed, good quality digital elevation data are needed. The scales of interest range from small watersheds to the circumpolar Arctic.

Point estimates of precipitation in northern environments, which are often treeless and windy, have improved dramatically in the past decade. Numerous gauge types with varying catch efficiencies have been studied through intercomparison studies. Still, the density of such gauges is quite low and continually decreasing, especially in the Russian Arctic. Snow on the ground is difficult to quantify because of redistribution by wind, and estimates of sublimation are lacking. Although being used, true distributed precipitation estimates by radar are still not attainable. The distribution of measuring sites is biased towards low elevations and coastal areas.

Snowmelt is generally the most significant hydrologic event each year since it usually produces the peak flow and the surface albedo changes by a factor of four. Models based on energy balance computations produce very precise estimates of snowmelt; unfortunately there are few areas with sufficient data to perform energy balance computations. Simpler temperature index (degree-day) models work quite well but must be calibrated for each site. Field measurements of ablation are limited. Circumpolar snow distribution by remotely sensed methods is quite good; however, quantification of the snowpack (depth and water content) is still lacking.

Surface storage in wetlands, ponds, and lakes is significant, especially in low gradient watersheds. Quantification of storage is difficult because of poor existing topographic data. Subsurface storage in the active layer and in permafrost-free aquifers can also be significant. Active layer storage volume is of the same magnitude as annual precipitation, while the potential for much greater storage occurs in deeper aquifers in areas without permafrost. Active layer storage can readily be measured at the small watershed scale, but it is not practical at the large basin scale except potentially with remotely sensed methods.

Estimates of evaporation and transpiration are good in some small catchments, but at the larger scale there are no complementary data to confirm our estimates. Again, energy balance approaches work well where there are good data, but this is limited to a few select areas. Simpler methods also work, but they must be calibrated and the calibration changes with changing conditions. Measurements with evaporation pans are good indices, but they must also be calibrated to estimate the actual evapotranspiration (ET). Water balance methods yield good seasonal or annual estimates if the storage terms can be accurately determined.

The likelihood that existing data collection networks in northern environments will be increased is nil. Well-funded research projects may contribute to the database but only in experimental watersheds. It is possible that much higher density of measuring stations can exist in experimental watersheds. Remotely sensed data collection methods represent our greatest hope for additional data.

Future Research

We need to develop better physically based hydrologic models; the rationale being that in a changing environment it is not necessary to continually recalibrate these models. This is critical if one is trying to use these models for predicting future hydrologic responses to changing conditions. One characteristic of these models is that they should be spatially distributed to address varying land uses and the associated thermal and hydrologic fluxes. Another future attribute of these models is that they should be capable of being coupled with atmospheric, biological, and chemical models.

To support spatially distributed models we need spatially distributed data. Spatially distributed data sets could be developed from a network of measuring sites or by remotely sensed methods. Advances in remote sensing are critical to research progress in circumpolar hydrology. Near-surface processes such as snow cover distribution, snowmelt, and soil moisture are excellent candidates for spatial monitoring. To develop confidence in physically based hydrologic models, it is imperative that distributed data sets be used to evaluate model performance.

While the main hydrologic processes have been adequately studied, there are numerous processes that have only been examined superficially. The role of surface storage in low-gradient watersheds, and the hydrologic importance of redistributed snow and the evolution of drainage networks in permafrost environments are samples of processes needing further study. Many processes can individually be modeled, but we need to examine the interactions between processes. How will changes in air temperature and precipitation impact soil moisture and evapotranspiration, including vegetation?

The question of how to take results at the relatively small experimental watershed and scale them up to a large basin or the entire circumpolar Arctic is one that will provide a challenge for some time. The lack of good spatially distributed data on land use, soils, vegetation, and topography will further handicap progress in this arena.

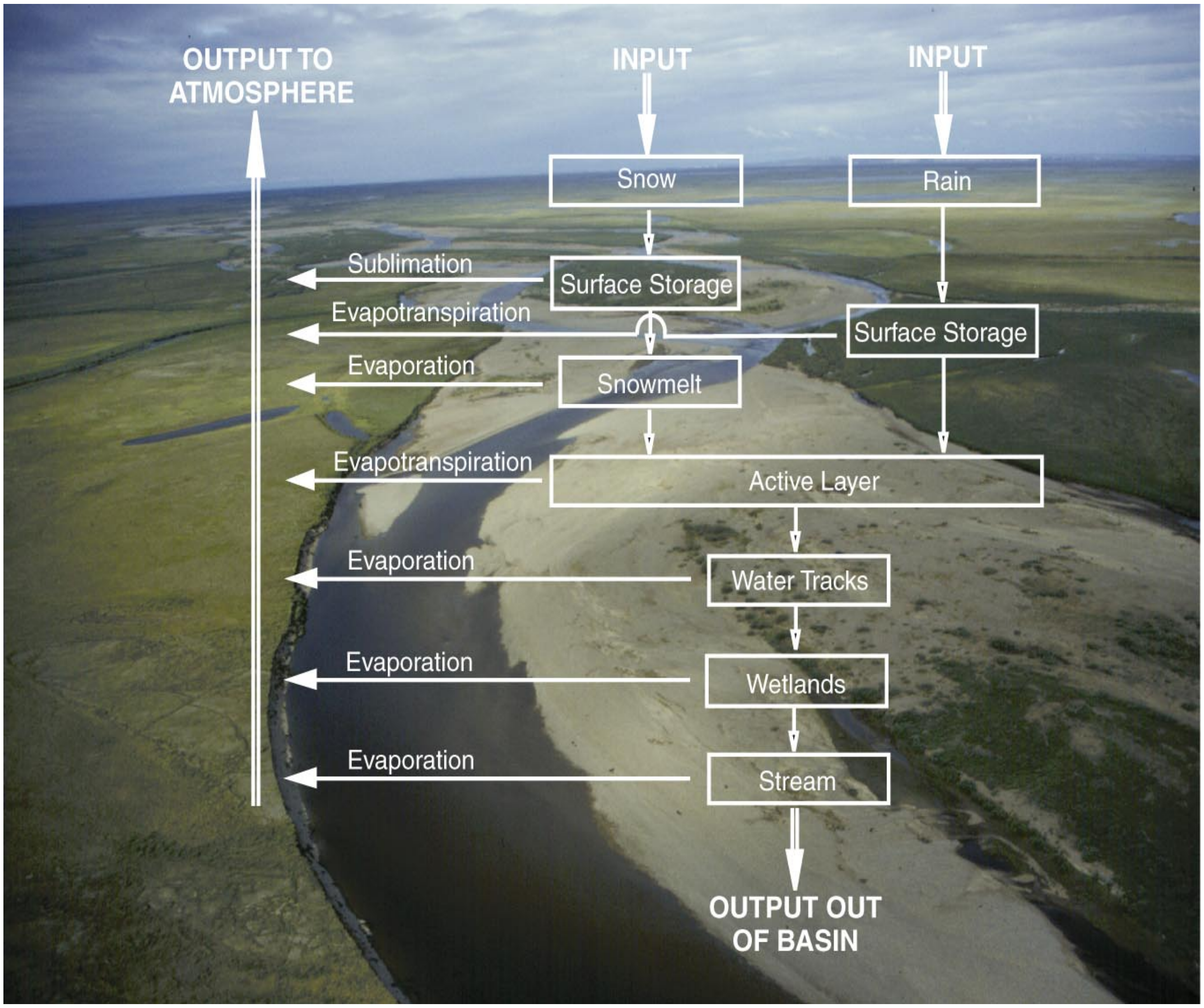


Figure 1. Schematic of the arctic hydrological cycle in a region of thick ice-rich permafrost where groundwater interactions is not a consideration.

Water Cycle in Eastern Siberia

Yuji Kodama
Institute of Low Temperature Science
Hokkaido University
Sapporo Japan
kod@pop.lowtem.hokudai.ac.jp

1. Introduction

In developing a better understanding of hydrologic and climatic dynamics of Arctic regions, it is critically important not to ignore two-thirds of the Arctic. The Russian Arctic represents a huge land area that influences global climatic dynamics; yet, in many senses, it remains a mystery. In order to better understand the water cycle in Eastern Siberia, the GAME study of the Siberian region was started in 1996. Three observational sites were set up in the Lena River basin, near Tiksi as tundra area, at Spaskayapad near Yakutsk as plain taiga area, and at Tynda as mountainous taiga. The rivers of this area flow into the Arctic Ocean, supplying the fresh water, that influences the amount of sea ice through lowering the salinity. The meteorological and hydrological study over Siberia is important since it combines modern field research with remote sensing analyses and modeling studies.

2. Precipitation and Discharge

The Lena River sub-basins are characterized by the relationship of the annual precipitation with annual discharge. The precipitation minus discharge (PMD) in tundra and mountainous taiga areas is insensitive to the precipitation change, whereas in plain taiga area the PMD is increasing with the increase of precipitation. When compared with the North Slope of Alaska, it is like the plain taiga and it is different from the results of Siberian tundra.

Monthly discharge of the Lena River at Kusur was analyzed. In the last 50 years, there has been an increase of discharge in winter months, whereas there is no obvious change in summer month discharge.

In both Siberia and Northern Alaska, a general tendency towards warming was found. However, in Siberia (and most of Russia), summer precipitation is increasing, whereas in Alaska, summer as well as annual precipitation is reported to be unclear: one report says decreasing and another says increasing. Precipitation in cold environments could be erroneous due to wind-induced gauge undercatch.

3. Turbulent Fluxes Over Tundra

Turbulent fluxes over tundra in summer have wind directional preference. A southwesterly wind is hot and dry, making the temperature difference between air and land surface small, resulting in smaller sensible heat flux. Northeasterly wind is cold and humid, making sensible heat flux larger. These on- and off-shore winds are not with land-sea breeze circulation. They are due to cyclone activities and could be related to the AO.

4. Key Gaps

- bias correction in precipitation,
- assessment of synoptic pattern change due to warming,
- AO variation with land-atmosphere interaction change,
- quantitative understanding of the relationship among hydrologic processes over all scales, and
- regional comparison in hydrologic cycle, in the results as well as the observation methods.

Continental Paleohydrology of Eurasia During the Last Glacial Maximum

Richard B. Lammers
Complex Systems Research Center
University of New Hampshire
Durham, NH 03824
Richard.Lammers@unh.edu

One of the goals of our arctic-related projects is to quantify the impact of very long term changes in pan-Arctic-scale hydrology in response the major glaciations (Forman and Johnson, 1998). This includes identifying alternative hypotheses regarding the Eurasian ice extent and documenting the potential impact of ice sheet extent on land-to-ocean water flux. There is currently a great deal of uncertainty regarding the eastern extent of the Eurasian ice mass during the last glaciation (Forman et al., 1999, Thiede and Mangerud, 1999). This uncertainty has profound implications for the continental paleohydrology of Eurasia and the Arctic Ocean.

Placing massive ice sheets over currently ice-free regions of the north has two effects on the large-scale hydrology. The first is the blockage and rerouting of major rivers and the second is an increase in the continental land area at ocean margins due to the lowering of sea level. In central Asia, this effect is particularly important due to the large northern flowing rivers and due to the large continental shelf in the Eurasian Arctic Ocean.

Three scenarios of Eurasion ice extent are presented:

> **Minimum.** This scenario sees the Barents Sea ice sheet covering Novaya Zemlya and Franz Josef Land on its eastern side. The present day Kara Sea is effectively ice free.
>
> **Medium.** The medium scenario seeks to investigate the effects of a Barents Sea ice sheet extending across the present day Kara Sea and reaching the Taymyr Peninsula.
>
> **Maximum.** This is an unlikely scenario for the Late Weichselian since it better represents the situation during the Early/Middle Weichselian. In this scenario the Barents Sea Ice Sheet extends to the Central Siberian Upland.

Under the Minimum scenario, all the north-flowing river water in the European part of Russia is diverted to the Kara Sea via a system of proglacial lakes. The Ob and the Yenisei Rivers converge on the exposed continental shelf and form a drainage basin larger than the contemporary Amazon River.

The Medium scenario sees the blockage of the combined Ob/Yenesi drainage system and the formation of a large proglacial lake roughly equal in surface area to the present-day Caspian Sea. This lake drains to the northeast through the North Siberian Plain and enters the Arctic Ocean in the Laptev Sea. In our scenario the Lena River joins this basin on the exposed continental shelf before entering the ocean.

In the Maximum scenario, the larger ice sheet blocks the North Siberian Plain and a massive proglacial lake is formed that drains over the low divide at the southern end of the Ob basin through the Turgai Gates. This lake is formed principally by the Ob and Yenisei Rivers and is up to 2.5 times the surface area of the present-day Caspian Sea. The Lena continues to flow to the Laptev Sea. Given enough water, the south-flowing Ob/Yenisei Rivers will fill the Aral Sea and then the Caspian Sea basins (both currently endorheic) and enter the Black Sea near the mouth of the present day Don River.

Key Knowns and Unknowns

Well known:

- Laurentide and Fenno-Scandian Ice Sheet extent well defined
- Timing of major events in North America
- Degree of sea level lowering and exposed continental shelf

Poorly known:

- Paleoclimatic fields for driving land surface paleohydrological models
- Eurasian ice extent over Kara Sea
- Timing of Eurasian glacial events
- Geomorphological and sedimentological evidence of Eurasian proglacial features

These poorly known items are essential for identifying the location and timing of the diverted river courses and proglacial lakes.

References

Forman, S. L. and G. L. Johnson, eds. (1998). *Prospectus for the Russian-American Initiative on Shelf-Land Environments in the Arctic (RAISE),* Arctic Research Consortium of the United States (ARCUS), Fairbanks, AK, 50 pp.

Forman, S. L., Ingólfsson, V. Gataullin, W. F. Manley and H. Lokrantz. (1999). Late Quaternary stratigraphy of the western Yamal Peninsula, Russia: New constraints on the configuration of the Eurasian ice sheet, *Geology, 27*(9):807-810.

Thiede, J., and J. Mangerud. (1999). Eurasian Ice Sheet Extent, *EOS Transactions, 80*(42):493-494, American Geophysical Union, Oct. 19, 1999.

Research Needs in an Arctic Hydrology Program

Dennis Lettenmaier
Civil and Environmental Engineering
University of Washington
Seattle, WA 98105
lettenma@ce.washington.edu

1. The focus needs to be pan-Arctic, which is a term that needs to be defined geographically. As a minimum, the extent should be the ACSYS definition, which includes all of the land area draining to the Arctic. Of particular concern is that the boreal regions not be neglected (60% of the runoff to the Arctic originates south of latitude 60 N) and that the defining unit be based on watersheds, rather than an arbitrary latitude, or ecoregion.

2. There needs to be a strong focus on hydrological processes, including land-atmosphere energy exchange. Furthermore, the program must foster approaches that link process understanding at the scale of direct observation to the larger Arctic hydrological system.

3. There should be a strong link to international programs and in particular ACSYS/CliC and GEWEX. The NSF program should be viewed as a U.S. contribution to international activities. As plans for the NSF activity evolve, consideration should be given to the CliC Science Plan, which addresses many of the issues discussed in Santa Barbara.

4. There must be an observational focus, but this needs to be accompanied by a strategy that will facilitate use of the observations in development and testing of models not only of local processes, but also of the entire Arctic hydrological system. This plan should recognize and leverage from the unique attributes of the Alaska portion of the Arctic drainage, but must also include strategies to supplement, leverage, and otherwise transfer information to the much larger portion of the Arctic drainage that lies outside the U.S. The observational strategy should include a partnership with Canadian scientists that can leverage from the GEWEX/MAGS activity, but also must consider development of better observations and models applicable to the Canadian Archipelago. Furthermore, the strategy must recognize that any viable pan-Arctic modeling efforts must demonstrably represent processes in the Eurasian Arctic drainage, which is now deficient in both long-term and intensive observation activities.

5. The observational strategy should explicitly determine the appropriate balance between long-term observations and the loss over the last decade of many observing stations in Canada and the Former Soviet Union, as well as the role of new observing methods (e.g., remote sensing) and intensive field campaigns.

6. There should be a focus on development of retrospective data products, including data rescue where appropriate. Precipitation products that include best current understanding of solid precipitation gage catch deficiencies urgently need to be implemented to facilitate water balance diagnostic studies and other large-scale modeling. The program should take an active role in the planning for new global and regional reanalyses that could supplement historic surface observations.

The Role of Arctic Snow Distributions in Atmospheric, Hydrologic, and Ecologic Interactions

Glen E. Liston
Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado 80523
liston@iceberg.ATMOS.ColoState.EDU

Arctic snow distributions influence numerous components of the high-latitude hydrologic cycle. Snowcover affects soil-moisture conditions, runoff, and active layer characteristics (Kane et al. 1991; Hinzman et al. 1996; Marsh 1999). It influences atmospheric and ground temperatures by moderating the conductive, sensible, and latent energy transfers between the atmosphere, snowcover, and ground (Liston 1995, Hinzman, Goering, & Kane 1998; Nelson et al. 1998). Snow indirectly controls stream channel pattern, morphology and fluvial processes through thermal controls on permafrost and active layer thickness (McNamara, Kane & Hinzman 1999), and impacts active-layer enrichment through thermal regulation of active-layer depth and water/nutrient supply (McNamara, Kane & Hinzman 1997). It scavenges pollutants and contaminants from the atmosphere throughout the winter and concentrates their release during spring melt (Everett et al. 1996). In arctic Alaska, snow can account for as much as 80% of the annual runoff (McNamara, Kane & Hinzman 1998).

Arctic tundra snowcovers are typically thin, and the frequent occurrence of blowing snow leads to significant snow redistribution, causing it to accumulate in the lee of ridges, in topographic depressions, and in taller shrubby vegetation (Benson and Sturm 1993; Pomeroy, Gray & Landine 1993; Liston and Sturm 1998; Liston et al. 2000a; Sturm et al. 2000a, b, c). A further consequence of these blowing-snow events is that significant portions (10 to 50%) of the snowcover is returned to the atmosphere by sublimation of the wind-borne snow particles (Benson 1982; Liston and Sturm 1998; Essery, Li & Pomeroy 1999; Pomeroy and Essery 1999). The result of these processes and interactions is a highly variable end-of-winter snow distribution. When this nonuniform snow distribution melts in the spring, a patchy mosaic of snow and vegetation evolves as the snowcover is removed. This variable snowcover influences energy and moisture flux interactions between the land and atmosphere, and impacts energy and moisture balances (Liston 1995; Essery 1997; Newmann and Marsh 1998; Liston 1999). In addition, blowing-snow redistribution can significantly impact spring snowmelt-runoff timing, magnitude, and spatial variability (Luce, Tarboton & Cooley 1998). All of these moisture-related factors influence the hydrologic response of the region as well as land-atmosphere energy and moisture interactions.

In the coming years the following items should emerge as arctic hydrology research priorities:

(1) We need to address impacts and feedbacks within the completely coupled and interacting earth-atmosphere system. This includes addressing issues related to how vegetation interacts with the atmosphere and land-surface hydrology in a coupled manner. For example, we know that vegetation influences the atmosphere and the atmosphere influences the vegetation, thus, future models must account for these feedbacks. Other examples include soil moisture effects, cloud-radiation interactions, snow-atmosphere-hydrology interactions, ocean-atmosphere feedbacks, and teleconnections from other regions of the globe. While many current studies focus on many of these kinds of interactions, the next phase of our general research effort must move in this “fully interactive” direction.

(2) Many hydrospheric and biospheric processes interact with the atmosphere at spatial scales that are smaller than those represented within current (and likely future) models. Because of this, there needs to be additional efforts to develop subgrid representations of the relatively high-resolution processes that occur the land surface. For example, the end-of winter subgrid snow distribution is largely responsible for the depletion of snow-covered area within a model grid cell during spring snowmelt. Since this snow-covered area is a first-order influence on the surface energy budget during this period, a realistic subgrid snow distribution representation is crucial to the successful simulation of arctic melt by a regional or global climate model.

(3) Arctic hydrology research would benefit from more involvement with the atmospheric science community. It is clear that in order to simulate realistic land-surface hydrologic interactions, key outputs from the atmospheric models must be improved, including precipitation timing and quantities, and radiation and associated cloud fields.

(4) The weather, climate, and hydrology problem is inherently a global problem. As such, remote-sensing technology is bound to be of value in addressing issues that include remote areas of the world like the arctic. Efforts that develop ways to include remote sensing products in their models should be encouraged. These remote-sensing products need to be thoroughly validated against ground-based observational data sets.

References Cited

Benson, C. S. 1982. Reassessment of winter precipitation on Alaska's Arctic Slope and measurements on the flux of wind blown snow. Geophysical Institute, University of Alaska Report UAG R-288, September 1982, 26 pp. [Available from Geophysical Institute, University of Alaska, P.O. Box 757320, Fairbanks, AK 99775-7320.]

Benson, C. S., and M. Sturm. 1993. Structure and wind transport of seasonal snow on the Arctic slope of Alaska. *Annals of Glaciology*, **18**, 261-267.

Essery, R. L. H., 1997: Modelling fluxes of momentum, sensible heat and latent heat over heterogeneous snow cover. *Quart. J. Royal Meteorol. Soc.*, **123**, 1867-1883.

Essery, R., L. Li, and J. Pomeroy. 1999. A distributed model of blowing snow over complex terrain. *Hydrological Processes*, **13**, 2423-2438.

Everett, K. R., D. L. Kane, and L. D. Hinzman. 1996. Surface water chemistry and hydrology of a small Arctic drainage basin. In: J. F. Reynolds and J. D. Tenhunen (Eds.), *Landscape Function: Implications for Ecosystem Response to Disturbance. A Case Study in Arctic Tundra*. Berlin and New York: Springer-Verlag, Ecologic Studies Series, Vol. **120**, 185-201.

Hinzman, L. D., D. L. Kane, C. S. Benson, and K. R. Everett. 1996. Energy balance and hydrological processes in and Arctic watershed. In: J. F. Reynolds and J. D. Tenhunen (Eds.), *Landscape Function: Implications for Ecosystem Response to Disturbance. A Case Study in Arctic Tundra*. Berlin and New York: Springer-Verlag, Ecologic Studies Series, Vol. **120**, 131-154.

Hinzman, L. D., D. J. Goering, and D. L. Kane. 1998. A distributed thermal model for calculating soil temperature profiles and depth of thaw in permafrost regions. *J. Geophysical Research*, **103** (D22), 28,975-28,991.

Kane, D. L., L. D. Hinzman, C. S. Benson, and G. E. Liston. 1991. Snow hydrology of a headwater Arctic basin 1. Physical measurements and process studies. *Water Resources Research*, **27**, 199-1109.

Liston, G. E. 1995. Local advection of momentum, heat, and moisture during the melt of patchy snow covers. *J. Applied Meteorology*, **34** (7), 1705-1715.

Liston, G. E. 1999. Interrelationships among snow distribution, snowmelt, and snow cover depletion: Implications for atmospheric, hydrologic, and ecologic modeling. *J. Applied Meteorology*, **38** (10), 1474-1487.

Liston, G. E., and M. Sturm. 1998. A snow-transport model for complex terrain. *J. Glaciology*, **44** (148), 498-516.
Liston, G. E., J. P. McFadden, M. Sturm, and R. A. Pielke, Sr. 2000a. Modeled changes in arctic tundra snow, energy, and moisture fluxes due to increased shrubs. *Global Change Biology*, in press.
Luce, C. H., D. G. Tarboton, and K. R. Cooley. 1998. The influence of the spatial distribution of snow on basin-averaged snowmelt. *Hydrological Processes*, **12**, 1671-1683.
Marsh, P., 1999: Snowcover formation and melt: recent advances and future prospects. *Hydrological Processes*, **13**, 2117-2134.
McNamara, J. P., D. L. Kane, and L. D. Hinzman. 1997. Hydrograph separations in an Arctic watershed using mixing model and graphical techniques. *Water Resources Research*, **33** (7), 1707-1719.
McNamara, J. P., D. L. Kane, and L. D. Hinzman. 1998. An analysis of streamflow hydrology in the Kuparuk River Basin, Arctic Alaska: a nested watershed approach. *J. Hydrology*, **206**, 39-57.
McNamara, J. P., D. L. Kane, and L. D. Hinzman. 1999. An analysis an arctic channel network using a digital elevation model. *Geomorphology*, **29**, 339-353.
Nelson, F. E., K. M. Hinkel, N. I. Shiklomanov, G. R. Mueller, L. L. Miller, and D. K. Walker. 1998. Active-layer thickness in north central Alaska: Systematic sampling, scale, and spatial autocorrelation. *J. Geophys. Res.*, **103** (D22), 28,963-28,973.
Neumann, N., and P. Marsh. 1998. Local advection of sensible heat in the snowmelt landscape of Arctic tundra. *Hydrological Processes*, **12**, 1547-1560.
Pomeroy, J. W., and R. L. H. Essery. 1999. Turbulent fluxes during blowing snow: field test of model sublimation predictions. *Hydrological Processes*, **13**, 2963-2975.
Pomeroy, J. W., D. M. Gray, and P. G. Landine. 1993. The Prairie Blowing Snow Model: characteristics, validation, operation. *J. Hydrology*, **144**, 165-192.
Sturm, M., J. P. McFadden, G. E. Liston, F. S. Chapin, III, C. H. Racine, and J. Holmgren. 2000a. Snow-shrub interactions in Arctic tundra: A hypothesis with climate implications. *J. Climate*, in press.
Sturm, M., J. Holmgren, and G. E. Liston. 2000b. Regional snow distribution patterns in arctic Alaska: Results from oversnow traverses 1994-2000. In review.
Sturm, M., G. E. Liston, C. S. Benson, and J. Holmgren. 2000c. Characteristics and growth of three arctic Alaska snow drifts. In review.

Role of Hydrology in the Arctic Ocean and Sea Ice System

Wieslaw Maslowski
Department of Oceanography
Naval Postgraduate School
Monterey, California 93943
maslowsk@ucar.edu

One way to look at the arctic hydrological cycle is to consider the ocean as its end point, receiving fresh water mainly via river runoff and precipitation, and also due to sea ice melt and the Bering Strait inflow. This fresh water input is first of all important locally because it defines water mass properties and dynamics of many arctic shelf regions. At the same time fresh water is crucial in maintaining the multiyear ice cover over the whole basin, because it creates a fresh and cold layer in the upper water column (i.e. halocline), which separates sea ice from warm Atlantic Water below. The existence of halocline in the Arctic Ocean prevents the heat at the Atlantic layer from reaching the surface and melting the ice pack. The upper ocean circulation, to a large degree driven by atmosphere-ice-ocean interactions, distributes fresh water over the Central Arctic and exports it into the North Atlantic. Large-scale ocean currents determine fresh water residence time over the shelves and in the deep basins, shelf-basin communication, and inter-basin exchanges. Fresh water export through Fram Strait and through the Canadian Archipelago has a strong influence on deep water formation in the Greenland and Labrador seas, respectively. Deep waters from these regions are source waters for North Atlantic Deep Water, one of the main water masses of the global ocean. Hence, through its influence on the northern high-latitude convective activities, fresh water exported from the Arctic Ocean becomes an important player in the global ocean thermohaline circulation and climate.

Variability of fresh water fluxes through the two main exits from the Arctic Ocean is the key to understanding its linkages and interactions with the global ocean. Recent observational and modeling studies indicate that the convective activities in the Greenland and Labrador seas might be negatively correlated, due to the out-of-phase relationship between the fresh water transports through Fram Strait and through the Canadian Archipelago. This hypothesis points to at least two significant issues. One is the need for long-term monitoring of the outflow through the Canadian Archipelago and Fram Strait, and the other is the requirement for proper representation of these passages in ocean general circulation models. The Pan-Arctic coupled ice-ocean model developed and run at the Naval Postgraduate School resolves the Canadian Archipelago. The annual cycle of fresh water flux into the northern Baffin Bay calculated from this model shows two maxima, one in summer and one in winter season. The summer maximum can be explained by the local sea ice melt. The winter maximum is suggested to originate from the large scale advection from the Arctic Ocean. The upper ocean circulation appears to determine not only the residence time of fresh water in the central basin but also the shift of its maximum transport within the annual cycle between the spring/summer entrance into the ocean (i.e., river discharge) and the winter exit from the Canadian Archipelago. Such a hypothesis requires a critical verification with observations, but if true it will have significant consequences for future global ocean and climate modeling, since it argues for a proper representation of exchanges through the archipelago. It also suggests that changes in timing and amounts of river runoff delivered to the arctic shelves may be felt down stream all the way around the central basin and outside of it. A quantitative measure of terrestrial inputs of fresh water into the Arctic Ocean and its spatial and temporal variability is needed to adequately account for its influence on ice-ocean conditions in models.

Another important component of the hydrological cycle that needs an improved representation in models of the Arctic Ocean is precipitation. Incorporation of other terms such as ice melt and the Bering Strait inflow depends mainly on the model resolution, domain size, and complexity but precipitation needs to be prescribed explicitly, unless an atmospheric model is fully coupled to an ice-ocean model. Satisfying this requirement is quite difficult, since there are not too many precipitation observations, especially over the Arctic Ocean. The spatial coverage of precipitation data is only part of the problem; another issue is their temporal distribution. One way to deal with this issue is to use reanalyzed output from operational weather prediction models, such as run at the European Center for Medium-range Weather Forecasts (ECMWF) or National Centers for Environmental Prediction (NCEP). A problem with this approach is that the northern high latitudes have not been very well represented in these models, so their output over these regions has problems on its own. Another way to account for the surface buoyancy flux often used in ice-ocean models is to restore the model surface salinity to climatology. This is done by using monthly surface salinity climatology to correct model-predicted surface salinity fields when they depart too much from the observed values over some specified time period. Such an approach acts to provide a buoyancy flux to the model subsurface layers. It has been commonly used in ice-ocean models, until model integrations became much longer (decades to centuries) and it became a limiting factor in investigations of long-term ocean variability.

The need for improved hydrological data with sufficient spatial and temporal resolution to help modeling interannual to decadal variability of the Arctic Ocean and its sea ice is obvious. Recent advances in computer technology allow us to build and run high-resolution, large domain, and physically complex models to address many scientific questions about the workings of the Arctic Ocean system and its linkages with global climate. Observations of hydrologic processes seem to be needed most now to allow long integrations and verification of those models and to facilitate further progress in understanding the pan-arctic region.

The Role of Watershed Geomorphology in Arctic Hydrologic Processes

James P. McNamara
Department of Geosciences
Boise State University
Boise, ID 83725
jmcnamar@boisestate.edu

A watershed is a natural partition in a landscape that transfers precipitation to streamflow and has morphologic properties that are dynamically adjusted by erosion to accommodate that transfer process. Permafrost exerts significant controls on nearly all physical processes in the arctic including erosion. By restricting erosion, permafrost influences watershed morphology and the consequent relationships between precipitation and streamflow. If permafrost degrades, we can expect a dynamic readjustment of the shape of the watershed and consequent changes in hydrologic response and sediment production as the watershed seeks out a new equilibrium form. A model of hydrologic change in response to a warming climate must include a dynamic landscape with physical properties that evolve as erosional processes engage that are currently suppressed by permafrost and ice. A model of hydrologic change cannot simply impose a new climate on the same landscape, or even the same landscape with a thicker active layer. Permafrost controls watershed morphology and hydrologic response in at least two ways. Changes in either one will alter the pathways that water takes through a watershed, which will influence the timing and magnitude of floods and the mechanisms of nutrient delivery from terrestrial to aquatic environments.

1. The shallow active layer has reduced storage capacity and limited subsurface flow. Headwater streams tend to be flashy. A thicker active layer in a warmer climate will allow for more hydrologic interaction between the surface and subsurface.

2. River basins typically evolve to self-organized critical states that possess certain universal properties regarding the spatial arrangement of slopes and channels. Headwater basins in the Kuparuk River basin in arctic Alaska do not possess those universal properties, suggesting that the basin has not been allowed to evolve as it should. Perhaps the presence of permafrost that restricts erosion is the cause. Degrading permafrost might therefore unleash erosional processes and allow slopes and channels to readjust.

The major gaps in our current understanding and monitoring of the role of watershed geomorphology in arctic hydrology are as follows:

1. Few studies have conducted rigorous experiments on hillslope and fluvial erosion in arctic watersheds. We therefore do not know the explicit controls that arctic conditions have on hillslope and fluvial erosion and consequent watershed form.

2. Accurate representation of watershed geomorphology in hydrologic models requires accurate, high-resolution digital elevation models. Many regions in the arctic lack this information.

Arctic Hydrology and the Study of Environmental Arctic Change

James Morison
Polar Science Center
Applied Physics Lab, Univ. of Washington
Seattle, WA 98105
Morison@apl.washington.edu

The Study of Arctic Environmental Change (SEARCH) has been conceived as a broad, interdisciplinary, multiscale program with a core aim of understanding the recent and ongoing, decadal (for example 3 to 50 year), pan-arctic complex of intertwined changes in the arctic physical system (SEARCH SSC, 2000). These changes include among other things a decline in sea level atmospheric pressure, increased surface air temperature, cyclonic ocean circulation, and decreased sea ice cover. The physical changes produce changes in the ecosystem and living resources and impact the human population. We have given the name Onami (Iñupiat for "tomorrow") to the complex of intertwined, pan-arctic changes. Part of gaining this understanding will be to determine the full scope of Onami.

Activities undertaken as part of SEARCH will guided by a series of hypotheses. The first hypothesis is that Onami is related to or involves the Arctic Oscillation (AO), which is a natural mode of atmospheric variation that is potentially active over a broad range of time scales including climatic time scales (Thompson and Wallace, 1998). A key objective of SEARCH will be to understand the interactions inherent in Onami in a rigorous quantitative way. Testing this hypothesis will tell us much about the interaction of the atmosphere, ocean, and land. It will allow us to tell how Onami is tied to the global atmosphere.

The second hypothesis is that Onami is a component of climate change. The AO is a fundamental mode of atmospheric variability and may be tied to climate change. Onami may be tied to climate change along with it or with the other large-scale patterns of atmospheric variability. The objective is to understand how Onami fits into the larger climate change picture.

The third hypothesis is related to the first two. It is that yet unknown feedbacks amongst the ocean, land, and the atmosphere are critical to Onami. These feedbacks could determine whether the Onami, and the Arctic, play critical roles in climate change.

The final hypothesis is that whether or not the recent Onami is tied to long-term climate change, the physical changes have effects on arctic ecosystems and societies. Ultimately we hope to predict not only the course of Onami, but also its impact on society.

SEARCH includes four major types of activities:

- long-term observations to track the environmental changes;
- modeling to test ideas about the coupling between the different components of Onami, and to predict its future course;
- process studies to test hypotheses about critical feedbacks; and
- application of what we learn to understand the ultimate impact of the physical changes on the ecosystems and societies.

Arctic hydrology is an important element of SEARCH. We need to learn the changes in the hydrology of the north that are a part of Onami. Perhaps the most important element is the overall hydrologic balance. It affects the freshwater cycle, and through Onami the arctic freshwater cycle may have a significant role on global climate through its effect on the thermohaline circulation. This is illustrated in Figure 1. The hypothetical process can be described as being initiated by an increase in the AO index. As hypothesized by SEARCH (SEARCH SSC, 2000), such an increase advects warm air and moisture into northern Europe and Russia. This increases precipitation in the watersheds of the Russian rivers and in turn increases river discharge.

Increased discharge is enough in itself to decrease the surface salinity of the Arctic Ocean. However, the ultimate effect is enhanced by the cyclonic circulation associated with a rising AO. The cyclonic circulation moves river-derived low salinity water on the Russian shelves along the coast into the western Arctic. This reduces cross-shelf exchange and mixing of the river water with Atlantic water to feed the cold halocline layer. In the 1990s the reduction of the cold halocline has been observed at a time of enhanced AO (Steele and Boyd, 1998).

The freshwater that is advected eastward is mixed with waters of Pacific origin that, even before entering the basin, have a lower salinity than Atlantic waters. Thus the salinity at the surface of the Beaufort Sea is decreased as has been observed in the 1990s (McPhee et al., 1998).

The surface water of the western Arctic, being the lowest density water in the basin, has always been an important contributor to the Arctic surface water exiting western Fram Strait and the Canadian Archipelago. The increased cyclonic circulation associated with a positive AO has enhanced this tendency. As a result we have seen surface waters with the character of the Beaufort Sea as far east as the northern tip of Ellesmere Island in recent years (Newton and Sotirin, 1997). As a result of the Onami process forcing greater amounts of freshwater around the periphery of the basin, the surface salinity decreases in the waters entering the Greenland Sea and Labrador Sea through Fram Strait and the Canadian Archipelago. The enhanced stratification that results is hypothesized to inhibit convection in these areas and reduce the rate of thermohaline circulation, thereby impacting the global ocean circulation.

References

McPhee, M. G., T. P. Stanton, J. H. Morison, and D. G. Martinson. 1998. Freshening of the Upper Ocean in the Central Arctic: Is Perennial Sea Ice Disappearing?, *Geophys. Res. Lett.*, 25, 10, 1729-1732.

Newton, J. L. and B. J. Sotirin. 1997. Boundary undercurrent and water mass changes in the Lincoln Sea, *J. Geophys. Res., 102,* C2, 3393-3403.

SEARCH SSC, 2000, SEARCH Science Plan, draft available at http://psc.apl.washington.edu/search/index.html

Steele, M. and Boyd, T. 1998. Retreat of the cold halocline layer in the Arctic Ocean*, J. Geophys. Res. 103,* 10,419- 10,435.

Thompson, David W. J. and John M. Wallace. 1998. The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters, 25*(9), 1297-1300.

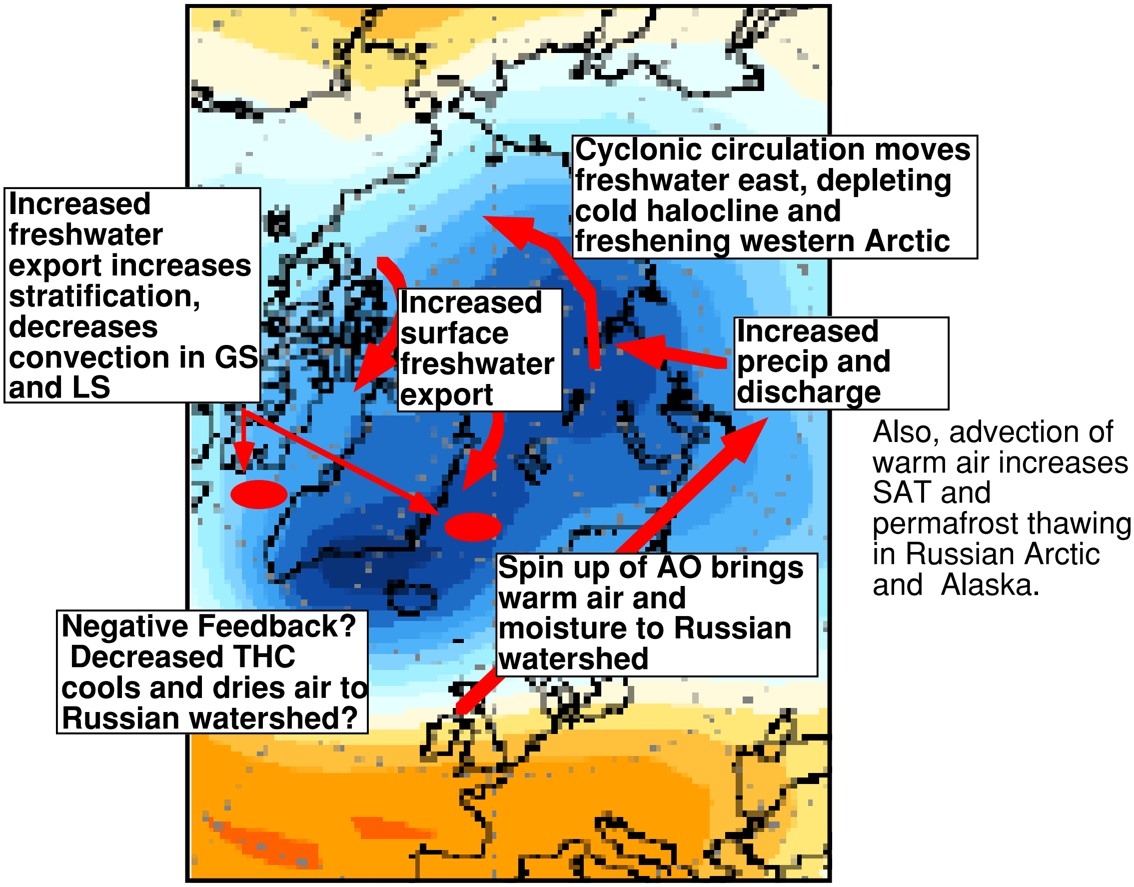


Figure 1. Scenario for the role of the arctic hydrologic cycle on the thermohaline circulation under a positive AO regime.

Spatial and Temporal Variability of the Active-Layer Thickness Record at Multiple Spatial Scales, North-Central Alaska

Frederick E. Nelson (1), Nikolay I. Shiklomanov (1), and Kenneth M. Hinkel (2)

(1) Department of Geography
University of Delaware, Newark, DE 19716
fnelson@UDel.Edu

(2) Department of Geography
University of Cincinnati, Cincinnati, OH 45221

A climatically induced increase in the thickness of the seasonally thawed (active) layer above permafrost could result in widespread thawing of ice-rich permafrost and lead to subsidence of the ground surface. This possibility has implications for hydrological, biological, and biogeochemical processes and could result in extensive damage to human infrastructure.

End-of-season thaw depth has been monitored at seven 1 km^2 CALM (Circumpolar Active Layer Monitoring) sites in northern Alaska since 1995 (Nelson et al., 1998). Grid nodes are spaced at 100 m intervals, yielding a regular array of 121 (11 x 11) data collection points. Three sites (Toolik Lake, Imnavait Creek, and Happy Valley) are located in the Foothills physiographic province, and four are on the Arctic Coastal Plain (Betty Pingo, West Dock, Barrow, and Atqasuk.) Air and soil temperature measurements are made at each site, and soil moisture is monitored at most.

Five years of record permit several general conclusions: (1) Sites on the North Slope of Alaska respond consistently to forcing by air temperature on an interannual basis. All sites experienced maximum average thaw depth in 1998 and a minimum in 1996, consistent with the warmest and coolest summers during the period of record. (2) There is significant intrasite variation in thaw depth and near-surface soil moisture content within each 1 km^2 grid, reflecting the impact of vegetation, substrate, snowcover dynamics, and terrain. Sites on the Coastal Plain generally show less spatial variation than those in the Foothills (Nelson, Shiklomanov & Mueller, 1999). (3) On the Coastal Plain, thaw depth is significantly greater in drained thaw-lake basins, where soils are typically at or near saturation. Figure 1 illustrates the bimodal distribution of thaw depths, which is related to primary landscape elements. (4) Foothill sites demonstrate large spatial and interannual variability resulting from local factors, whereas the spatial pattern of thaw depth across Coastal Plain sites is relatively consistent.

Several prior studies in the Kuparuk River basin have demonstrated the feasibility of mapping active-layer thickness over extensive areas, using field-based, analytic, and numerical methods (Nelson et al., 1997; Hinzman et al., 1998; Shiklomanov and Nelson, 1999; Klene, 2000). Most regional thaw depth estimates are based on one year of data, however, and do not include interannual variability, which can significantly alter spatial patterns of active layer distribution. To estimate the effect of climate variability on the spatial distribution of the thaw depth, all climate data available for the Kuparuk region from 1987 to 1999 were used with a "climatically aided interpolation" scheme (Willmott and Matsuura, 1995) to create annual thawing degree-day fields. These climate fields were used in turn to create a series of active-layer fields for the Kuparuk region based on Stefan's solution for the depth of thaw. Although climate directly influences the depth of annual thaw, its influence can be reduced or magnified by soil surface and subsurface conditions. The spatial pattern of the active layer over this 13-year period is shown in Figure 2. Thaw depth beneath different land-cover and landform categories has distinct sensitivity to climatic parameters and is reflected by changes in the spatial active layer pattern.

The two series of maps represented by Figures 1 and 2 are separated by a wide divergence of spatial scale. This gap could, in principle, be narrowed or eliminated by parameterizing soil moisture in complex topography. Field evidence (Figure 3) indicates that variations of active-layer thickness in the foothills are linked closely to slope curvature through the soil moisture regime. Experiments are underway using derivative mapping to examine relations between thaw depth, soil moisture, profile curvature, and plan curvature. Detailed, spatially extensive soil moisture data sets are a high priority in active-layer mapping.

Figure 4 shows hazard potential in the circum-Arctic permafrost regions associated with thaw settlement and development of thermokarst terrain. This map is based on the climate-change scenario provided by the ECHAM1-A general circulation model (Cubasch et al., 1992) and was constructed by creating an "index of thaw settlement" based on the product of relative changes of active-layer thickness and the volumetric proportion of ground ice in the upper permafrost. Although useful for identifying areas in which more localized simulation experiments are warranted, the coarse grid of the active-layer calculations limits the map's practical applicability. Standardized, high-resolution data bases for soil properties, soil moisture, and vegetation would be useful for improving such maps.

References

Anisimov, O. A., Shiklomanov, N. I., and Nelson, F. E. 1997. Effects of global warming on permafrost and active-layer thickness: results from transient general circulation models. *Global and Planetary Change* **15**: 61-77.

Brown, J., Ferrians, O. J. J., Heginbottom, J. A., and Melnikov, E. S. 1997. *International Permafrost Association Circum-Arctic Map of Permafrost and Ground Ice Conditions*. U.S. Geological Survey Circum-Pacific Map Series, Map CP-45. Scale 1:10,000,000.

Cubasch, U., Hasselmann, K., Hock, H., Maier-Reimer, E., Santer, B. D., and Sausen, R. 1992. Time-dependent greenhouse warming computations with a coupled ocean-atmosphere model. *Climate Dynamics* **8**: 55-69.

Hinzman, L. D., Goering, D. J., and Kane, D. L. 1998. A distributed thermal model for calculating soil temperature profiles and depth of thaw in permafrost. *Journal of Geophysical Research*, *103:* 28,975-28,991.

Klene, A. E. 2000. The n-factor in natural landscapes: Relations between air and soil-surface temperatures in the Kuparuk River basin, northern Alaska. *Publications in Climatology 53*(1): C.W. Thornthwaite Associates, Pittsgrove, NJ, 85 pp.

Nelson, F. E., Shiklomanov, N. I., Mueller, G., Hinkel, K. M., Walker, D. A., and Bockheim, J. G. 1997. Estimating active-layer thickness over a large region: Kuparuk River basin, Alaska, U.S.A. *Arctic and Alpine Research, 29:* 367-378.

Nelson, F. E., Hinkel, K. M., Shiklomanov, N. I., Mueller, G. R., Miller, L. L., and Walker, D. A. 1998. Active-layer thickness in north-central Alaska: systematic sampling, scale, and spatial autocorrelation. *Journal of Geophysical Research, 103:* 28963-28973.

Nelson, F. E., Shiklomanov, N. I., and Mueller, G. R. 1999. Variability of active-layer thickness at multiple spatial scales, north-central Alaska, U.S.A. *Arctic, Antarctic, and Alpine Research*, *31:* 158-165.

Shiklomanov, N. I., and Nelson, F. E. 1999. Analytic representation of the active layer thickness field, Kuparuk River basin, Alaska. *Ecological Modelling*, *123:* 105-125.

Willmott, C. J.,and Matsuura, K. 1995. Smart interpolation of annually averaged air temperature in the United States. *Journal of Applied Meteorology*, *34:* 2577-2586.

Figure 1. Five-year series of active-layer thickness maps for 1 km^2 grid at Atqasuk on the coastal plain. Note consistent pattern, in which drained thaw-lake basin (red) experiences consistently higher thaw-depth values than uplands (blue).

Figure 2. Active-layer thickness maps for Kuparuk River basin, 1987-99.

Figure 3. Active-layer thickness along slope profile at Imnavait Creek in northern Brooks Range foothills. Note general increase in thaw depth with decreasing convexity and increasing concavity.

Figure 4. Map of hazard zonation under ECHAM1-A GCM climate scenario. Hazard zones are derived from a "thaw-settlement index," based on product of relative changes in active-layer thickness (Anisimov, Shiklomanov & Nelson, 1997) and volumetric proportion of ground ice in upper permafrost (Brown et al., 1997). Map is constructed on a 0.5 x 0.5° lat/long grid.

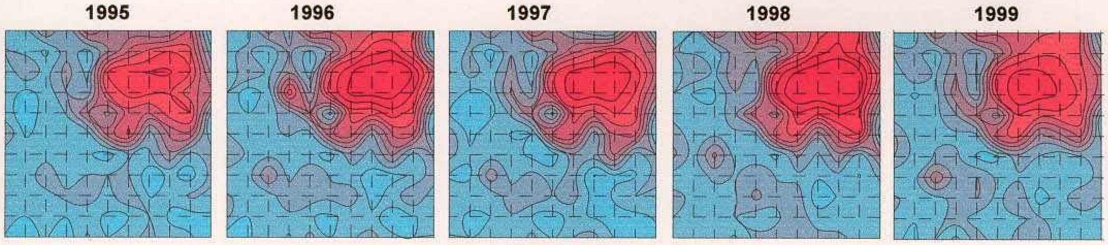


Fig. 1

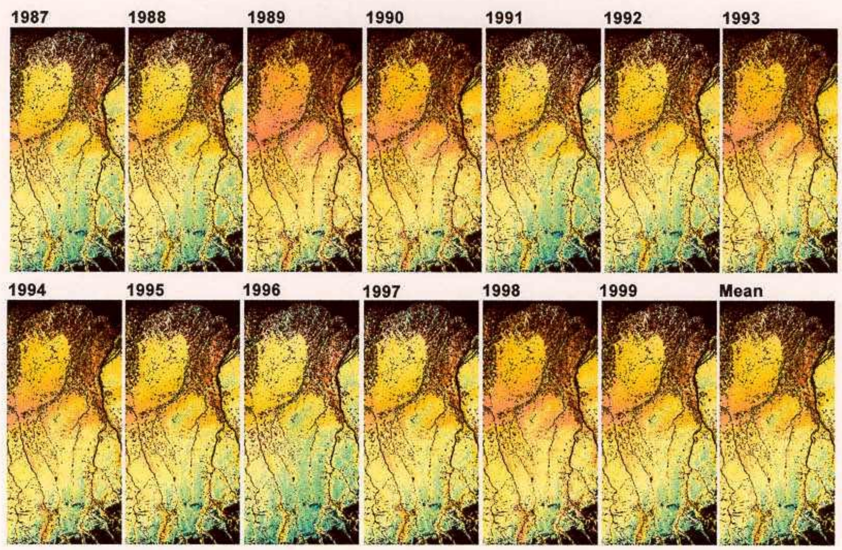


Fig. 2

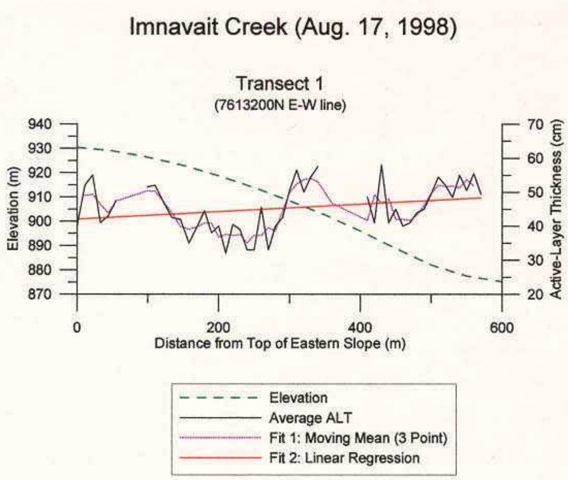


Fig. 3

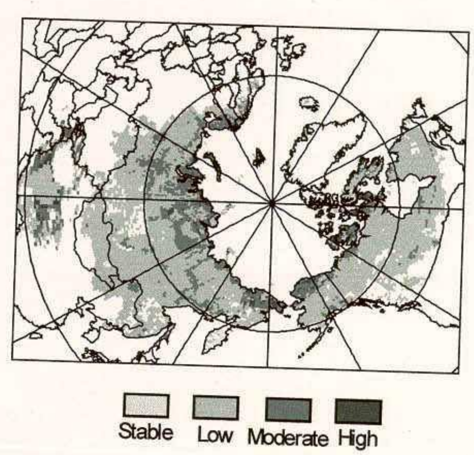


Fig. 4

Significance of Cold-Regions River Dynamics to Arctic Hydrology

Terry D. Prowse, Ph.D., P.Geo
National Water Research Institute
11 Innovation Blvd., Saskatoon, SK, CANADA
S7N 3H5
terry.prowse@ec.gc.ca

The dynamics of river flow in cold-regions rivers is greatly influenced by the presence of an ice cover, particularly during the periods of freeze-up and break-up (Figure 1). Both events are capable of producing hydrologic extremes that far exceed those experienced during the open-water period. In the case of freeze-up, the formation of an additional resistance boundary to the flow results in an increase of river stage and, during the period of ice cover progression, an abstraction of flow to satisfy the increase in hydraulic storage (Figure 2). As a result, locations downstream of the advancing cover will experience a period of *low flow*. In some documented cases, the discharge during this abstraction period is lower than the low flow that is normally believed to occur later in the winter when flow from the landscape is at a minimum (see magnitude of November depression compared to late-winter discharge in Figure 1).

Although changes may occur to the ice-cover roughness over the winter, by the time of spring ice break-up most hydraulic storage is still in place. With the fracturing and movement of the ice cover, the resistance is effectively removed and the water comes out of storage. This volume of water has never been accounted for in the measurement and modelling of spring discharge and has probably led to an overestimate of the volume of water originating from snowmelt which occurs concomitantly with breakup on most large northern rivers (Figure 1). In one case study of the Mackenzie River main stem, freeze-up storage was assessed as making up 15 to 19% of the total spring freshet (not including the additional water from ice melt).

Depending on the type of breakup, relatively high water temperatures often accompany the downstream progression of breakup on northward flowing rivers. Rapid rates of heat transfer at the breakup front then result in accelerated melt of the ice cover and a sudden input of additional flow to the spring freshet. Although some field experiments have assessed the additional flow produced by ice melt to be equal to that of a major tributary (e.g., to the Liard River, Canada), no calculation of its relative significance has been made for a full basin.

Both the formation and break-up of river ice produces rapidly varying flow, usually the result of the formation and release of ice jams (Figure 3). The steep energy gradients associated with jams usually lead to surges, the celerity and water velocity for which far exceed those for the open-water months. Given that water-level/discharge relationships are not constant during these dynamic periods, most hydrometric stations are rendered inoperable by ice scour, and direct discharge flow measurements are impractical, discharge can only be crudely estimated for these periods. Such estimates are usually based on flow values from upstream and/or downstream of the site of interest, but these locations are usually several hundred widths distant and, hence, only crude extrapolations can be made. As a result, the published values of "daily discharge" do not reflect the peaks and troughs in discharge that accompany such events. When only medium to long-term estimates of flow (i.e., greater than multiday) are required, this is probably not of concern. For event analysis of extreme events, however, accurate short-term discharge and water level information is critical. It should also be pointed out that floods on many cold-regions rivers are not highly correlated with discharge. High stages produced by backwater from ice jams often develop from relatively low discharge compared to peak open-water flows but are regularly responsible for the greatest and most frequent floods on ice-covered rivers (Figure 4). While this has been demonstrated at a number of northern sites, no regional analysis of ice-induced versus open-water floods has been conducted.

In addition to controlling the flow and level dynamics of cold-regions rivers, river ice has also been recently recognized as a significant modifier of fluvial geomorphology whereby it directly influences the erosion and deposition of sediment and results in the formation of unique morphological features. Similarly, through the process of ice scour it is responsible for vegetation succession within the channel and on floodplains. Break-up in particular is an important modifier of overall river ecology, affecting the biodiversity of riparian landscapes to the quality of the water chemistry and in-channel habitat.

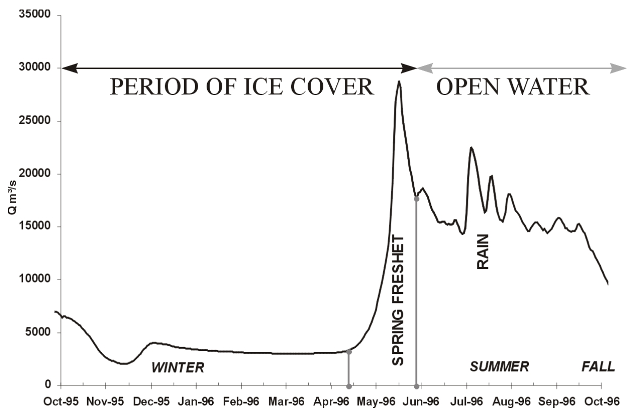


Figure 1. Typical hydrograph for large northern river.

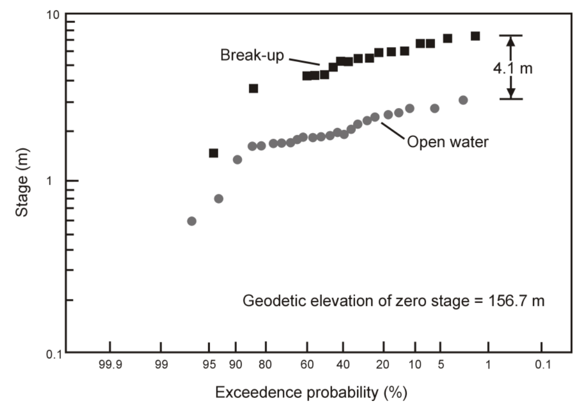


Figure 3. Configuration of a break-up ice jam. Note steep gradients.

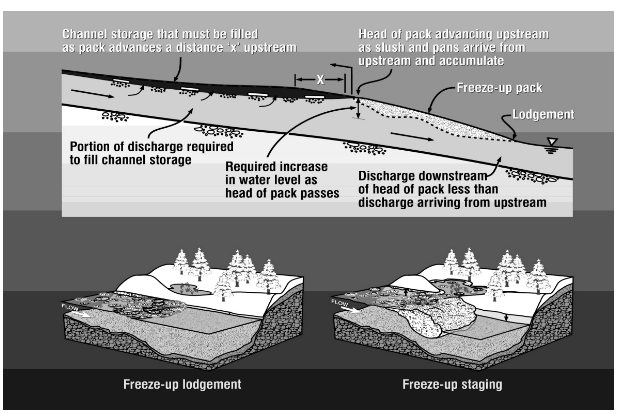


Figure 2. Abstraction of flow into hydraulic storage during freeze-up.

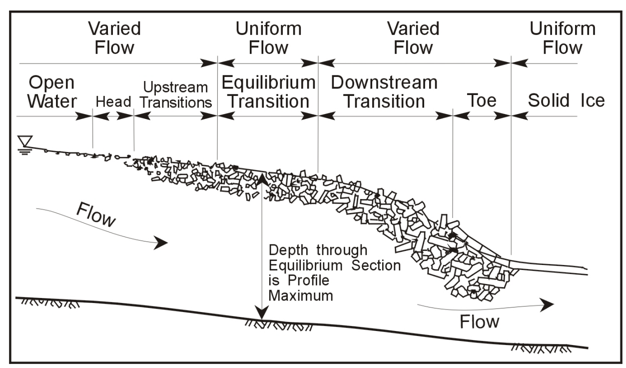


Figure 4. Exceedance probability of ice versus open-water conditions.

Detection and Attribution of Anthropogenic Global Warming Using Observed Trends in Northern Hemisphere Soil Moisture, Snow Cover, and Sea Ice Areas

and

Land Surface Modeling in Regions with Seasonally Frozen Soil

Alan Robock (1) and Konstantin Y. Vinnikov (2)

(1) Department of Environmental Sciences
Rutgers University
New Brunswick, New Jersey
robock@envsci.rutgers.edu

(2) Department of Meteorology
University of Maryland
College Park
kostya@atmos.umd.edu

Most attempts to detect global warming and attribute it to anthropogenic causes have used temperature, both observations and climate model projections. The hydrological component of the climate system, however, offers opportunities to address this problem by examining parameters that may have amplifying effects on temperature changes or that have temperature-sensitive thresholds (such as melting) that are easy to observe. Here we describe approaches to this problem using snow, sea ice, and soil moisture. In the case of soil moisture, certain cold weather aspects, such as partitioning of snow melt into infiltration or runoff, deserve special attention. In all cases, it is crucial to recover and maintain long homogenous observational records.

Sea ice. Vinnikov et al. (1999) assembled all the time series of observed annual-average Northern Hemisphere (NH) sea ice extent for the past several decades and after quality control showed that NH sea ice extent has been decreasing. By comparing the observations to control and greenhouse gas-forced climate model simulations, they showed that the observed decrease is larger than would be expected by natural variations and is likely caused by anthropogenic global warming. This exciting result needs further investigation to examine seasonal and spatial patterns of sea ice changes and to address sea ice thickness changes. While the climate model simulations of sea ice thickness changes are similar to the observations of Rothrock, Yu & Maykut (1999), better data sets of sea ice thickness changes will be required, if it is possible to recover them from secret military records.

Snow cover. Preliminary analyses of snow cover trends show a similar result to those for sea ice, but long-term records require satellite observations, and they are shorter than surface-based records. Working with David Robinson (Rutgers University) and Richard Armstrong (NSIDC), we are just completing an analysis of snow cover extent from 1967 to the present. We will then compare these records to simulations from different climate models. These variations may also be related to the Arctic Oscillation (which may or may not be changed by global warming)

Soil moisture. Soil moisture is the only parameter expected to behave in a non-monotonic manner in response to global warming. Climate models predict that both precipitation and evapotranspiration will increase, but evapotranspiration will increase exponentially, while precipitation will only increase linearly, but faster than evapotranspiration initially. Therefore, soil moisture is expected to first increase, but then decrease as evapotranspiration exceeds precipitation. Most climate models predict summer drying because of this effect, but observations so far of summer soil moisture in the middle latitudes (Figure 1; Robock et al., 2000) show increasing soil moisture.

Land surface schemes in climate models so far have been shown to not do a good job in simulating observed soil moisture (Robock et al., 1998; Entin et al., 1999). In particular, the problem of partitioning of snow melt into runoff or infiltration has not been adequately addressed, although results from the Project on Intercomparison of Land-surface Parameterization Schemes (PILPS) Phase 2(d) experiment using observations from a grassland at Valdai, Russia (Schlosser et al., 2000) provide such an opportunity for one location using 18 years of observations. While Slater et al. (2000) examined different snow formulations in the 21 land surface schemes that participated in this experiment, the frozen soil formulations are only now being studied by us. Experiments from the other two catchments at Valdai for which we have observations, a mature forest and a growing forest, would be very important to address this issue with different vegetation.

The above discussion is summarized in the requested categories as follows:

<u>Key Gaps in Process Understanding:</u>

- How is spring meltwater partitioned into infiltration and runoff?
  [Needs snow and land surface modeling experiments, constrained by actual in situ observations.]

- What determines the seasonal cycle and regional distribution of sea ice and snow trends? Is there an Arctic Oscillation signal?

<u>Key Gaps in Monitoring/Measurements:</u>

- Continued observations of soil moisture at stations with long records and ancillary meteorology, hydrology, and radiation observations, especially in the former Soviet Union, Mongolia, and China.

- Data rescue of hydrology observations (including soil moisture, snow, runoff, water table) from stations in the former Soviet Union and eastern Europe.

References

Entin, Jared, Alan Robock, Konstantin Y. Vinnikov, Shuang Qiu, Vladimir Zabelin, Suxia Liu, A. Namkhai, and Ts. Adyasuren. 1999. Evaluation of Global Soil Wetness Project soil moisture simulations. *J. Meteorol. Soc. Japan, 77,* 183-198.

Robock, Alan, C. Adam Schlosser, Konstantin Ya. Vinnikov, Nina A. Speranskaya, Jared K. Entin, and Shuang Qiu. 1998. Evaluation of AMIP soil moisture simulations. *Global and Planetary Change, 19,* 181-208.

Robock, Alan, Konstantin Y. Vinnikov, Govindarajalu Srinivasan, Jared K. Entin, Steven E. Hollinger, Nina A. Speranskaya, Suxia Liu, and A. Namkhai. 2000. The Global Soil Moisture Data Bank. *Bull. Amer. Meteorol. Soc., 81,* 1281-1299.

Rothrock, D. A., Y. Yu, and G. A. Maykut. 1999. Thinning of the Arctic sea-ice cover, *Geophys. Res. Lett.*, 26, 3469-3472.

Schlosser, C. A., A. G. Slater, A. Robock, A. J. Pitman, K. Y. Vinnikov, A. Henderson-Sellers, N. A. Speranskaya, K. Mitchell, and the PILPS 2(d) contributors. 2000. Simulations of a boreal grassland hydrology at Valdai, Russia: PILPS Phase 2(d). *Mon. Weather Rev., 128,* 301-321.

Slater, A. G., C. A. Schlosser, C. E. Desborough, A. J. Pitman, A. Henderson-Sellers, A. Robock, K. Ya. Vinnikov, N. A. Speranskaya, K. Mitchell, A. Boone, H. Braden, F. Chen, P.Cox, P. de Rosnay, R. E. Dickinson, Y-J. Dai, Q. Duan, J. Entin, P. Etchevers, N. Gedney, Ye. M. Gusev, F. Habets, J. Kim, V. Koren, E. Kowalczyk, O. N. Nasonova, J. Noilhan, J. Schaake, A. B. Shmakin, T. Smirnova, D. Verseghy, P. Wetzel, Y. Xue, Z-L. Yang, and Q. Zeng. 2000. The representation of snow in land-surface schemes: Results from PILPS 2(d). Submitted to *J. Hydrometeorology*.

Vinnikov, Konstantin Y., Alan Robock, Ronald J. Stouffer, John E. Walsh, Claire L. Parkinson, Donald J. Cavalieri, John F. B. Mitchell, Donald Garrett, and Victor F. Zakharov. 1999. Global warming and Northern Hemisphere sea ice extent. *Science, 286,* 1934-1937.

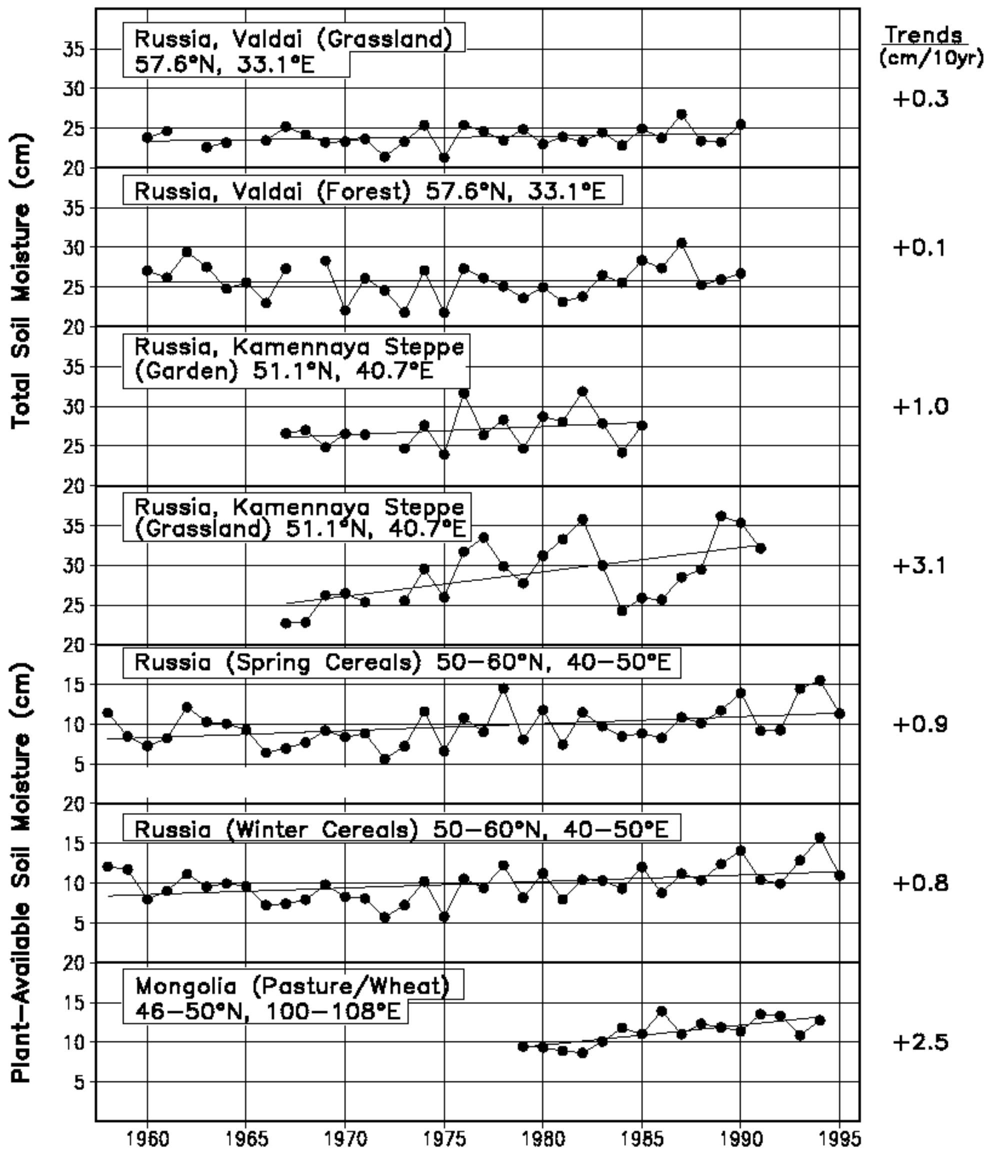


Figure 1. Trends of summer soil moisture from stations or regions with the longest records. [Figure 6 from Robock et al. (2000).]

Permafrost Related Problems in Arctic Hydrology

Vladimir E. Romanovsky[1], Thomas E. Osterkamp,[1] and Nikolai N. Romanovsky[2]

[1] Geophysical Institute
University of Alaska Fairbanks
ffver@uaf.edu

[2] Department of Geocryology
Moscow State University

Our temperature measurements made over the last two decades show that permafrost has warmed at all sites along a north-south transect that spans the continuous and most of the discontinuous permafrost zones of Alaska from Prudhoe Bay to Glennallen. Modeling indicates that in the continuous permafrost zone, mean annual permafrost surface temperatures vary inter-annually within the range of more than 5 K. In the discontinuous permafrost, the observed warming is part of a warming trend that began in the late 1960s. Total magnitude of the warming at the permafrost surface since then is about 2 K (Figure 1). The last "wave" of the recent warming according to the observed data began on the Arctic Coastal Plain, in the Foothills and at Gulkana in the mid-1980s (typically 1986 or 1987) and in areas of discontinuous permafrost about 1990 (typically 1989 to 1991). The magnitude of the observed warming at the permafrost surface is about 3 to 4 K at West Dock and Deadhorse, Prudhoe Bay region, about 2 K over the rest of the Arctic Coastal Plain and south into the Brooks Range, and typically 0.5 to 1.5 K in discontinuous permafrost. At some sites in discontinuous permafrost south of the Yukon River, permafrost is now thawing from both the top and bottom. Thawing of ice-rich permafrost is presently creating thermokarst terrain which has a significant effect on sub-arctic ecosystems and infrastructure. Consequently, for any future warming, the greatest impacts of thawing permafrost will occur in areas of warm ice-rich discontinuous permafrost.

Also, permafrost is currently warming in many other regions of the earth (Haeberli et al. 1993; Pavlov 1994; Wang and French 1994; Osterkamp 1994; Ding 1998; Sharkhuu 1998; Vonder Mühll, Stucki & Haeberly 1998; Romanovsky et al. 1998; Weller and Anderson 1998; Osterkamp and Romanovsky 1999; Serreze et al., 2000). This warming occurs most rapidly in the mountain regions where convective heat transfer accelerates changes in the thermal regime of permafrost and permafrost degradation. Changes in permafrost distribution will affect surface and sub-surface hydrology through changes in subsurface water storage and subsurface water fluxes. The area with mountain permafrost covers a significant portion of the watersheds in the upper and mid flow of most Siberian rivers. So, the changes in permafrost distribution in these regions can significantly affect the seasonal variations in the river discharge, increasing the winter discharge and possibly slightly decreasing the summer discharge.

In mountain areas within the permafrost zone, the active layer is usually constructed by blocks, boulders, debris, and gravel. This creates a very rough surface topography. On slopes and tops of hills and mountains, the coarse-grained material forms periglacial slope phenomena like "rock rivers," "rock streams," "rock fields," and "rock glaciers." These formations, known in the Russian literature by the general term "kurums," cover the upper belt of hills and mountains (Romanovskiy et al.,1989). This upper belt has no continuous cover of vegetation, only patches of small shrubs and grasses. Mountains occupy the main part of the territory in east Siberia. These regions are characterized by a very severe and continental climate with thin snow cover and extremely cold windless winters.

The active layer of kurums and other coarse-grained deposits is completely drained during autumn and does not contain ground ice in the winter. The cavities in the active layer remain open until spring. Snow cover on the rough surface of kurums is discontinuous and has many holes. Cold and heavy winter air penetrates through these holes into the active layer and cools down the active layer and the upper part of permafrost to the same temperature as the outside air. During spring, the melting snow water percolates into the active layer and refreezes on the surfaces of blocks and debris. High porosity and low temperatures trap all the amount of water from the melted snow in the active layer in a form of "crust-infiltrated" ground ice. This causes a significant decrease in spring flooding in the mountain areas.

During summertime, the intensive condensation of water vapor takes place in the active layer of kurums. In accordance with data of Magadan hydrologist I. T. Rei'nuk, condensation on the mountains of northeast Siberia can reach 80 mm/year or 2.52 $l/(sec \cdot km^2)$ on average (personal communication). For kurums and other coarse grained deposits in the mountains of East Siberia, it is typical to have very low water content in the upper part of the active layer and low moisture at the ground surface. Because of that, the level of evaporation during the summer is very low. A combination of low evaporation and high condensation in coarse-grained active layer increases the surface water runoff from the mountain areas. Summer rainfalls provoke melting of the "crust-infiltrated" ground ice in the active layer. As a result, the late summer and fall rainfalls cause high floods in rivers and streams.

In summary, the effects of coarse-grained deposits in the active layer in areas with severe continental climate are:

- redistribution of surface water storage and discharge (or runoff) during summer time, and
- increase of the runoff due to intensive water condensation and decrease of evaporation.

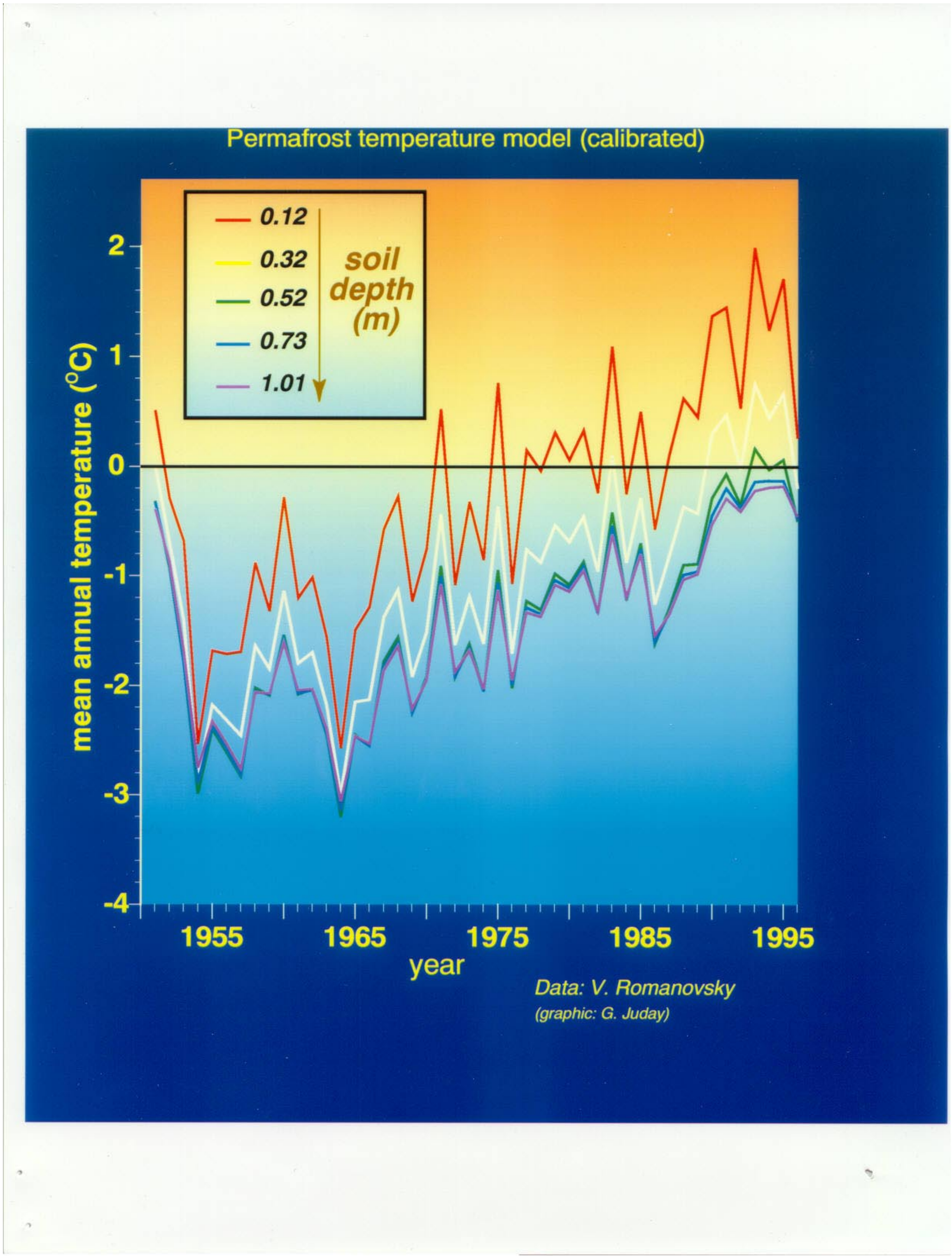


Figure 1. Calculated mean annual temperature dynamics in the active layer and near-surface permafrost at the Bonanza Creek LTER site (Fairbanks) in 1951–1996 (Osterkamp and Romanovsky, 1999).

References

Ding, Y. (1998). Recent degradation of permafrost in China and the response to climatic warming. Proceedings of the Seventh International Conference on Permafrost, Yellowknife, Canada, pp. 221-224.

Haeberli, W., Cheng, G., Gorbunov, A. P., and Harris, S. A. (1993). Mountain permafrost and climatic change. *Permafrost and Periglacial Processes, 4,* 165-174.

Osterkamp, T. E. (1994). Evidence for warming and thawing of discontinuous permafrost in Alaska. *EOS Transactions,* American Geophysical Union, *75*(44), 85.

Osterkamp, T. E., and V. E. Romanovsky (1999). Evidence for warming and thawing of discontinuous permafrost in Alaska. *Permafrost and Periglacial Processes, 10*(1), 17-37.

Pavlov, A. V. (1994). Current changes of climate and permafrost in the Arctic and Sub-Arctic of Russia. *Permafrost and Periglacial Processes, 5*: 101-110.

Romanovsky, V. E., Osterkamp, T. E., Balobaev, V. T., Rusakov, V. G., and Fukuda, M., Measurements and Modeling of the Active Layer and Permafrost Temperature Regime in Fairbanks, Alaska (USA) and Yakutsk, Sakha Republic (Russia). Paper presented at the AAAS, Arctic Science Conference, Fairbanks, AK, October 1998, p. 66.

Romanovskiy, N. N., Tiurin, A. I., and Sergeev, D. O. (1989). Kurums of Bold Mountains Belts. Novosibirsk: NAUKA Publisher, Siberia Division, p. 151 (in Russian).

Serreze, M.C., Walsh, J. E., Chapin, F. S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W. C., Morison, J., Zhang, T., and Barry, R. G. 2000. Observational evidence of recent change in the northern high-latitude environment. *Climatic Change 46*(1-2): 159-207.

Sharkhuu, N. (1998). Trends of permafrost development in the Selenge River Basin, Mongolia. Proceedings of the Seventh International Conference on Permafrost, Yellowknife, Canada, pp. 979-986.

Vonder Muehll, D., Stucki, T., and Haeberly, W. (1998). Borehole temperatures in Alpine permafrost: a ten years series. Proceedings of the Seventh International Conference on Permafrost, Yellowknife, Canada, pp. 1089-1096.

Wang, B. and French, H. M. (1994). Climate controls and high-altitude permafrost, Qinghai-Xizang (Tibet) Plateau, China. *Permafrost and Periglacial Processes, 5,* 87-100.

Weller, G., and P. A. Anderson (eds.). (1998). Implications of Global Change in Alaska and the Bering Sea Region. Proceedings of a Workshop, June 1997. Center for Global Change and Arctic System Research, University of Alaska Fairbanks, Fairbanks, Alaska. 157 p.

Towards Assessing the Hydro-Climatology of the Pan-Arctic Land Mass

Mark C. Serreze
CIRES
Campus Box 449
University of Colorado
Boulder, Colorado 80309-0449
serreze@kryos.colorado.edu

Understanding historic variability in the hydro-climatology of the pan-Arctic landmass, monitoring hydrologic variables, and predicting future change promises to be a daunting task. Outstanding problems include the following:

(1) Precipitation is a fundamental input to hydrologic models. However, existing precipitation time series contain large error due to under-catch of blowing snow, changes in instruments, and other factors such as wetting losses. Efforts have been made to correct such errors. However, correction techniques are varied and there as yet exists no temporally consistent data base covering the Arctic drainage.

(2) Existing station networks providing precipitation time series are relatively sparse, posing fundamental difficulties in developing gridded fields at adequate spatial resolution.

(3) Obtaining timely updates of precipitation is difficult and the existing network is degrading. Many stations in the former Soviet Union and Canada have closed. Canada is also seeing a trend toward automation.

(4) Information on evaporation for model validation and for closing the hydrologic budget is extremely sparse. Evaporation represents perhaps the single greatest unknown in the Arctic hydrologic system.

(5) Existing data sets for snow water equivalent are at present limited to station estimates providing insufficient coverage.

Potential avenues to address some of these problems include the following:

(a) Precipitation (and evaporation) fields from numerical weather prediction models.

Research at University of Colorado has examined the veracity of precipitation forecasts from “reanalysis” efforts by the National Centers for Environmental Prediction (NCEP) and the European Center for Medium Range Weather Forecasts (ECMWF). Reanalysis relies on a “frozen” numerical weather prediction model whereby inconsistencies introduced by changes in model physics inherent to operational systems are eliminated. Inconsistencies can still be present due to changes in the amount and quality of assimilation data through time.

While recognizing the errors in available validation data sets, it appears that the model-predicted precipitation totals are seriously in error. By comparison, temporal variability is reasonably well captured. A new generation reanalysis recently initiated by ECMWF (known as ERA-40) using a better model with high spatial resolution is expected to provide significantly improved fields. Major advantages of reanalysis are that timely updates will be available and the problem of precipitation under-catch is avoided. However, with reference to point 1 above, validation requires sufficiently long time station time series of precipitation adjusted to remove biases. Assessing the accuracy of evaporation forecasts in turn requires a comprehensive effort to assemble all available observed evaporation estimates.

(b) Precipitation fields based on multivariate statistical approaches

The University of Colorado is also active in this area. A series of predictor variables from reanalysis is used to provide a best fit to observed precipitation time series. Once the regression coefficients are determined, precipitation fields can be compiled as soon as new reanalysis data come on line. The predictors include forecast precipitation from the reanalysis along with variables related to precipitation. These include the vapor flux convergence, precipitable water, winds, positive vorticity advection at 500 mb, and indices of convection. Initial results using NCEP data are quite good, but there are some problem areas (e.g., the Kolyma lowlands). Use of ERA-40 data is expected to yield improvements. Again with reference to point 1, validating the reconstructed fields requires station time series of precipitation adjusted to remove biases.

(c) Applications of precipitation minus evaporation (P-E) based on aerological methods.

The vertically integrated vapor flux convergence, when adjusted by the time change in precipitable water, yields P-E. Through efforts at The Ohio State University (D. Bromwich), monthly fields of P-E have been compiled using wind and humidity data from the NCEP reanalysis. P-E is a relevant hydrologic variable in its own right and on an annual basis is closely allied with river discharge. Estimates of evaporation can also be obtained by subtracting P-E from precipitation (precipitation based on observed or modeled fields). Initial results from University of Colorado using uncorrected precipitation totals from different observed data sets yields spurious negative evaporation rates (i.e., condensation) for large areas during winter. While expected given gauge under-catch, this problem may also reflect errors in the P-E fields. Results using bias-corrected precipitation totals are better.

(d) Snow water equivalent from passive microwave satellite data.

Algorithms have been developed to provide estimates of snow water equivalent at 25 km resolution from the Special Sensor Microwave/Imager. However, the accuracy of these fields remains largely untested. Furthermore, passive microwave systems cannot estimate the water equivalent of wet snow. Extensive validation efforts are planned. Procedures for blending passive microwave estimates with observed precipitation totals and other data are also being explored.

The Treatment of River Discharge in Arctic Ocean Modeling

Michael Steele
Polar Science Center, Applied Physics Laboratory
University of Washington
Seattle, WA 98105
mas@apl.washington.edu

The Arctic Ocean is the freshest major ocean basin in the world, owing in large measure to its high volume of river discharge (Aagaard and Carmack, 1989; Vörösmarty et al., 2000). This discharge is quite seasonal and variable along the Eurasian and North American coastlines. It flows onto some of the world's broadest and shallowest continental shelves, where it undergoes mixing, advection, and interaction with sea ice and atmosphere. A portion continues out into the deep Arctic Ocean, where it overrides cold, salty ambient waters to create the highly stable cold halocline layer. Recent evidence suggests that atmospheric climate variability can force drastic changes in shelf-derived water pathways and thus perhaps in the stability of the Arctic Ocean (Steele and Boyd, 1998; Martinson and Steele, 2001). Finally, riverine-influenced waters follow the main surface circulation towards the North Atlantic via the Canadian Archipelago and through Fram Strait and the Barents Sea (Steele et al., 1996).

Unfortunately, it has been shown (Zhang et al., 1998; Steele et al., 2000) that many ocean models provide a poor representation of Arctic Ocean sea surface salinity (SSS). The reason is presently unknown. A realistic simulation of SSS is commonly obtained only by adding an unphysical term to the equation for salinity S known as "climate restoring." This has the form of a Newtonian spring constant, i.e., $(S - S_c)/\tau$, where S_c is the climatological (i.e., long-term mean) salinity and τ is an adjustable time scale that typically ranges from 30 days to 5 years. The smaller the time constant, the faster the solution is restored back towards climatological "reality." This technique obviously suffers from a limited ability to simulate changes relative to the long-term mean.

Numerical models of the arctic sea ice-ocean system include river discharge in a variety of ways. Some have no explicit discharge at all, including this effect purely via strong climate restoring, which near river mouths tends to lower SSS. Others include discharge for some or all of the major rivers at the appropriate ocean model grid points, while still others attempt to account for ungauged flows by distributing an additional amount either at these same grid points or uniformly around the domain at all grid points. Models that use explicit discharge data also employ a variety of climate restoring techniques, including no restoring at all (which as noted above tends to produce unrealistic SSS).

Models with explicit discharge almost always use these data to modify the salinity of the surface waters in the appropriate coastal ocean grid cell. Few if any models use auxiliary information on river current speed, temperature, or dissolved chemical concentrations. However, there is increasing interest in including these additional variables, especially chemical constituents, since these can be used as ocean circulation tracers.

The major gaps that remain in accurately representing the effects of riverine inflow to the Arctic Ocean are numerous. They include:

1. **River discharge data in a format that is "friendly" to ocean models.** This means gridded time series of discharge at a spatial resolution of several tens of kilometers along the arctic coastlines, for as long a period as possible. Typical climate studies are several decades long,

with simulations that start in the 1950s becoming more common. Missing data in space and time need to be filled in some way, e.g., with climatological values.

2. **Coordinated time series of discharge, chemical tracer concentrations, and temperatures.** Chemical tracers such as barium are used to great effect in tracing riverine-influenced waters within the Arctic Ocean. Variability in the input signal to the ocean should be accounted for in these calculations. Similarly, the temperature of the discharging waters may affect the timing of sea ice melt-back.

3. **Better shelf physics.** There are a host of shelf processes that few ocean models capture. These include the effects of grounded sea ice keels (stamuhki), which can trap river discharges close to the mouth and thus delay freshwater entry onto the shelf by as much as several weeks. In some instances, this might be long enough to change the wind forcing regime and thus the ultimate fate of these waters. Another generally neglected effect is the interaction between sediment and river/ocean/sea ice circulation.

4. **Better shelf-basin physics.** The physical mechanisms that transport riverine waters off the shelf and into the deep basin are complex and generally not well-modeled. An example is bottom-trapped gravity currents, which are difficult to accurately simulate in a large-scale, relatively low-resolution numerical model. Continental slopes in the Arctic Ocean are some of the steepest in the world, which also presents a difficult numerical challenge.

References

Aagaard, K. and E. C. Carmack. 1989. The role of sea ice and other fresh water in the Arctic circulation, *J. Geophys. Res., 94,* 14,485-14,498, 1989.

Martinson, D. G., and M. Steele. 2001. Future of the arctic sea ice cover: Implications of an antarctic analog, *Geophys. Res. Lett*., 28, 307-310.

Steele, M. and T. Boyd. 1998. Retreat of the cold halocline layer in the Arctic Ocean*, J. Geophys. Res., 103,* 10,419-10,435.

Steele, M. and the AOMIP team. 2000. Salinity drift in Arctic Ocean models: An intercomparison, manuscript in preparation.

Steele, M., D. Thomas, D. Rothrock, and S. Martin. 1996. A simple model study of the Arctic Ocean freshwater balance, 1979-1985, *J. Geophys. Res., 101,* 20,833-20,848.

Vörösmarty, C. J., B. M. Fekete, M. Meybeck, and R. B. Lammers. 2000. Global system of rivers: Its role in organizing continental land mass and defining land-to-ocean linkages, *Global Biogeochem. Cycles, 14,* 599-621.

Zhang, J., W. Hibler, M. Steele, and D. Rothrock. 1998. Arctic ice-ocean modeling with and without climate restoring, *J. Phys. Oceanogr., 28,* 191-217.

Current Research on Regional Scale Hydrology

Marc Stieglitz
Lamont Doherty Earth Observatory
Palisades, NY 10964
marc@ldeo.columbia.edu

To date, a catchment-based land surface model (LSM) that accounts explicitly for the topographic control over subgrid soil moisture variability has been developed (via TOPMODEL formulations; Beven et al., 1994; Beven and Kirkby, 1979). The model—the NSIPP (NASA Seasonal-to-Interannual Prediction Project) global catchment-based LSM (Ducharne et al., 2000; Koster et al., 2000)—incorporates ground thermodynamics as well as a three-layer snow model (Lynch-Stieglitz, 1994; Stieglitz et al., submitted). The three-layer snow model accounts for snow melting and refreezing, dynamic changes in snow density, snow insulating properties, and other physics relevant to the growth and ablation of the snowpack. Validating with 1987-1988 ISLSCP data sets at over 5000 catchments representing North America indicates that the model is capable of simulating the spatial coverage of snow. More importantly, the model's treatment of the insulation properties of snow cover leads to an accurate simulation of the permafrost front, relative to the NSIDC digital permafrost map (Figure 1) (Stieglitz et al., submitted). This successful large-scale application of the model for North America suggests that the global application of the model is within reach, and more specifically, that application at high latitudes will be successful. Finally, by including for the role that topography plays in the development of soil moisture heterogeneity and the critical, perhaps overwhelming, impact of this heterogeneity on surface energy, water, and trace gas fluxes, we hope to improve seasonal and interannual variability in coupled climate simulations.

With regard to development and application of the model at high latitudes, we intend to use historical hydro-met data to model the hydrologic cycle of the Kuparuk Basin (8140 km^2), located in the north slope of Alaska—NSF-OPP Collaborative Research: Modeling Hydrologic Processes in the Arctic: A Watershed Approach for Regional and Global Climate Modeling. This project attempts to explore the control that high-latitude processes, specifically the growth and ablation of the seasonal snowpack, and ground freeze-thaw dynamics, have on Arctic tundra hydrology. The starting point for this work is the NSIPP LSM. Further, it is the goal of this study to identify those critical land-atmosphere interaction processes that need to be represented in modeling the arctic ecosystem at large scales and to determine the degree to which small-scale variability needs to be represented. Historical climate data covering the last 40 years will be used to force the LSM. Model-generated discharge, snow extent, snow depth, ground temperatures, etc., will be validated with site data across a range of spatial scales. Ultimately, it is the intention of this pilot study that this LSM serve as the basis for Pan-Arctic implementation, coupling to the ARCSyMs Regional Climate Model (RCM), and have model-generated soil moistures and ground temperatures be used as drivers for the suite of ecological models currently funded by the ATLAS program. Project collaborators for this project are Eric Wood at Princeton and Colin Stark at LDEO.

There are still several research obstacles to be overcome with regard to Pan Arctic application of hydrologic models. One such problem is that even at small spatial scales, snow heterogeneity significantly impacts the timing and quantity of snowmelt-related discharge and poses a real obstacle towards application on an arctic-wide basis (Stieglitz et al., 1999). Unfortunately most models currently ignore the role topography plays in the development of snow cover heterogeneity and the impact that this heterogeneity has on the terrestrial albedo, surface energy fluxes, and snowmelt discharge. Gradients in elevation, differences in aspect, and the interactions between wind, topography, and vegetation will also result in snow cover heterogeneity. As an ongoing part of this effort, we will improve the models' representation of sub-grid scale snow heterogeneity. To account for elevation effects in regions of high relief, a temperature lapse rate will be used along with binned elevation bands to distribute snow cover and snow melt throughout the landscape (Bowling and Lettenmaier, 1998; Hartman et al., 1999). To account for the effects that wind, vegetation, and topography have on the distribution of snow cover, we will adapt the work of Liston and Sturm (1998) and Hartman et al. (1999) to our modeling framework. Empirical equations for wind-blown snow will be used to treat snow distribution in much the same way we currently treat soil moisture heterogeneity; through a statistical representation in which valleys are regions of snow accumulation and uplands are regions of snow ablation. Finally, this new model development will be incorporated within the overall data assimilation effort

References

Beven, K., P. Quinn, R. Romanowicz, J. Freer, J. Fisher, and R. Lamb. 1994. TOPMODEL and GRIDATB, A users guide to the distribution versions (94.01), Cent. for Res. on Environ. Syst. and Stat., Lancaster Univ., Lancaster, U.K., England.

Beven, K. J., and M. J. Kirkby. 1979. A physically-based variable contributing area model of basin hydrology, *Hydrol. Sci. J*, *24(1)*, 43-69.

Bowling, L. C., and D. P. Lettenmaier. 1998. A Macroscale Hydrological Model for the Arctic Basin, in *FALL AGU*, San Fransisco.

Ducharne, A., R. D. Koster, M. J. Suarez, M. Stieglitz, and P. Kumar. 2000. A catchment-based approach to modeling land surface processes, 2, Parameter estimation and model demonstration, *J. Geophys. Res., 105*, (D20) 24809-24822.

Hartman, M. D., J. S. Baron, R. B. Lammers, D.W. Cline, L.E. Band, G.E. Liston, and C. Tague. 1999. Simulations of snow distribution and hydrology in a mountain basin, *Water Resources Research*, *35* (5), 1587-1603.

Koster, R. D., M. J. Suarez, A. Ducharne, M. Stieglitz, and P. Kumar. 2000. A catchment-based approach to modeling land surface processes in a GCM. Part I: Model structure, *JGR-Atmos 105*, D20 24809-24822.

Liston, G. E., and M. Sturm. 1998. A snow-transport model for complex terrain, *Journal of Glaciology*, *44* (148), 498-516.

Lynch-Stieglitz, M. 1994. The development and validation of a simple snow model for the GISS GCM, *Journal of Climate*, *7* (12), 1842-1855.

Stieglitz, M., A. Ducharne, R. Koster, and M. Suarez, The Impact of Detailed Snow Physics on the Simulation of Snow Cover and Subsurface Thermodynamics at Continental Scales, *Journal of Hydrometerology*, submitted.

Stieglitz, M., J. Hobbie, A. Giblin, and G. Kling. 1999. Hydrologic modeling of an arctic tundra watershed: Toward Pan- Arctic predictions, *J. Geophys. Res.*, *104* (D22), 27,507-27,518.

Zhang, T., R. G. Barry, and K. Knowles. 1999. Statistics and characteristics of permafrost and ground ice distribution in the Northern Hemisphere, *Polar Geography, 22* (2), 147-169.

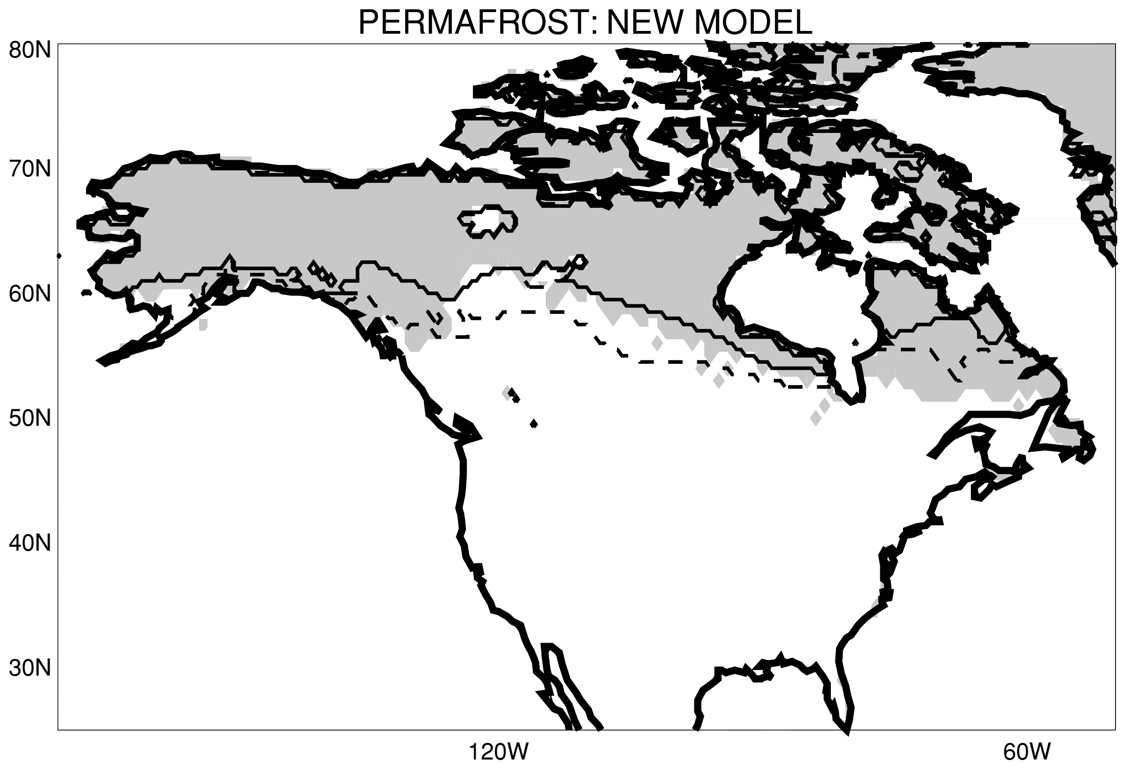


Figure 1: Model-generated and observed (NSIDC digital permafrost maps, Zhang et al., 1999) permafrost regions. A catchment is considered to be within a permafrost region and thereby shaded gray if the deepest model layer within that catchment is frozen throughout the 1987–1988 simulation period. The solid line refers to the observed permafrost line corresponding to 50% permafrost coverage whereas the dashed line corresponds to 10% permafrost coverage. With few exceptions, the permafrost boundary generated by the new scheme appears highly accurate.

Arctic Snow Cover and its Role in Arctic Hydrology: Gaps in Our Knowledge and Abilities

Matthew Sturm
USA-CRREL-Alaska
Ft. Wainwright, Alaska 99703
msturm@crrel.usace.army.mil

Snow covers most of the arctic between 6 and 10 months of the year. It is arguably one of the most important components of the hydrologic system. Because it is both a source of run-off and also a widespread land surface cover, it impacts the hydrologic cycle in several ways, all of which are important. Depth and density distribution determine the amount of snow melt run-off that will pass down the streams and rivers at breakup, while the areal extent of the snow and the length of time the snow is on the ground dominate the local and regional albedo and therefore the annual energy balance. The stratigraphic and grain properties of the snow determine how good an insulator it is, and therefore the depth and distribution of winter freezing and magnitude of heat losses from the underlying plants and ground. Because of its superb insulating qualities, the snow is important in determining the permafrost condition and has an important impact on arctic ecology through its effects on plants and the active layer.

Many of the critical snow measurements needed to understand key processes and predict responses in arctic hydrology are relatively easy to make if they were needed at only one point or for a short period of time, and if a human was always available to make them. For example, it takes only a few seconds to probe the snow depth. Difficulties arise because what is really needed for understanding or modeling arctic hydrologic processes is fields or maps of these simple measurements covering wide areas for long periods of time. Unfortunately, in most of the major types of terrain found in the Arctic the distribution of snow depth and density is extremely heterogeneous. In the boreal forests, interception by the canopy creates a distribution that depends on stand density and canopy structure, with interaction with the wind and melt complicated by the shadowing of the trees. On the tundra, wind redistributes the snow, creating deep drifts and areas of scour. In addition, local variations in precipitation, temperature and wind also impose on the snow cover variations in depth and density at a scale that is slightly larger than the landscape scale imposed by trees or topography. Combined, the resulting variations in snow cover depth and density are tough to predict or measure. An alternate approach, deriving snow depth and density maps from atmospheric forcing, also tends to be difficult and leads to inaccurate values and erroneous maps of depth and density. In part, this is because winter precipitation is difficult to measure, often under-measured, but to a larger extent it is because the network of stations where these measurements are made is sparse. If accurate maps of snow depth or snow water equivalent are needed, the only reliable way to produce them is by collecting extensive amounts of data, or using detailed physically based models of snow transport and energy exchange on a grid scale that resolves the bumps and hollows of the landscape, along with input from research-grade atmospheric forcing data.

Other snow properties of importance are more difficult to measure. For example, both snow thermal and hydraulic conductivity are determined by the layered nature of the snow pack and the grain characteristics of each layer. Other than by digging a snow pit and examining the snow pack layer by layer, or perhaps by running a detailed and complex energy-balance metamorphic model such as CROCUS, these critical physical parameters cannot be determined. Yet they control winter conductive heat losses from the ground and the rate at which melt water will be transferred to the ground during the melt. They are fundamental physical parameters that need to be known in order to predict critical fluxes of energy and water, but which are currently taken from look-up tables of dubious validity. In addition, virtually no spatial variability in these parameters is assumed in most modeling efforts, yet we know that the properties can vary greatly over short distances.

Finally, there are a number of fundamental process that take place in the snow or snow pack that remain poorly understood. First, under certain conditions, the air in the snow can convect. When this occurs, heat transfer increases by a factor of three or more. Convection has been documented in the snow pack found in the boreal forest, but it is not clear if the air in the snow pack of the tundra, which typically contains layers of dense wind slab with low permeability, also convects. This introduces a uncertainty in assigning a value of thermal conductivity to the snow pack that could be large. Second, sublimation is estimated to remove as much as 50% of the winter snowfall in the windier places of the Arctic, a substantial part of the annual water balance. But these loss estimates are based on semiempirical formulations that have only been tested in a limited number of locations. Most sublimation is thought to occur when the wind is moving the snow and snow grains are saltating. Potentially, if the air between saltating snow grains is supersaturated (as there is some reason to assume), then the rate of sublimation could be much lower than estimated. This uncertainty in the water balance needs to be resolved. Finally, the processes that determine whether wind-blown snow will be deposited as dense flat-lying layers of wind slab or sculpted into snow dunes and sastrugi are not understood. Slabs have a major impact on foraging by caribou, success of predators on caribou, and in determining patterns of snow melt run-off in the spring.

A few of the critical gaps in our understanding of snow, or our ability to map snow cover in a way necessary for understanding or modeling the arctic system, can be summarized as follows:

1. Knowledge and Abilities Gaps: Fundamental Measurements

- Accurate and widespread measurement of winter precipitation not yet achieved
- Wind-blown flux of snow important, but hard to measure, thus rarely measured
- Sublimation rarely (never?) measured
- Winter wind speed & direction often unreliable due to riming/icing of sensors
- Stratigraphy hard to measure widely but determines critical bulk thermal & physical properties

2. Knowledge and Abilities Gaps: Critical Products

- Snow cover depth maps difficult(!) to derive from remote sensing or meteorological input
- Sub-grid variations in distribution important to run-off but rarely captured by modeling or remote sensing
- Spatial variation of snow cover insulation and density (SWE) rarely mapped

3. Knowledge and Abilities Gaps: Processes

- Vegetation-snow feedback process poorly understood
- Hard slab and surface dune formation processes not understood
- Lateral transfer of heat during snow melt not understood, not modeled
- Wind-pumping and air convection in arctic depth hoar; is it important?

Rapid Integrated Monitoring System for the Pan-Arctic Land Mass (Arctic-RIMS)

Charles Vörösmarty
Water Systems Analysis Group
University of New Hampshire
Durham, NH 03824
charles.vorosmarty@unh.edu

The geography and dynamics of freshwater across the pan-Arctic are important elements of the larger Earth system, made especially timely given growing evidence of the vulnerability of the Arctic climate and terrestrial biosphere to global change. Nonetheless, accurate estimation of the pan-Arctic freshwater balance has proven to be problematical given significant uncertainties in its key components such as precipitation (P), evapotranspiration (E), P-E, and soil water variations. A recently initiated project funded by NSF and NASA and involving several U.S. and foreign collaborating groups seeks to develop a coherent framework for assessing the spatial and temporal variations of the pan-Arctic terrestrial water cycle. A near-real time capability is sought combining the use of numerical weather prediction and reanalysis products and river discharge to the Arctic Ocean.

A spatially and temporally harmonized data set for pan-Arctic hydrology and meteorology we believe to be essential to any future monitoring of global change in this region. This is the primary focus of this project work having three primary goals:

GOAL 1 *To develop and implement an Arctic-RIMS (Rapid Integrated Monitoring System) for acquiring near-real-time data and producing "quick-look" outputs that characterize terrestrial and aerological water budgets across the pan-Arctic drainage region.*

GOAL 2 *To create hydrologically based reanalysis products using Arctic-RIMS and to analyze these time series in our continuing work on spatial and temporal variability of the pan-Arctic land mass.*

GOAL 3 *To use NASA Earth Observing System data in near real time to compile hydrological products for the pan-Arctic terrestrial regions, including snow extent and water equivalants (from SSM/I, MODIS, AMSR) and near surface freeze-thaw timing and spatial distributions (from SeaWinds on QUICKSAT and ADEOS II, SSM/I and AMSR).*

Arctic-RIMS integrates several well-established data sets and tools developed by the co-Investigators to produce time-varying, region-wide aerological and land surface water budgets including river inputs to the Arctic Ocean and its 18 subsidiary seas (Bromwich, Cullather, and Serreze 1999, Serreze and Maslanik 1998, Lammers et al. 2000). We are now coupling algorithms developed at Ohio State University and the University of Colorado to compute vapor flux convergence and other fields through the Vapor Transport Analysis System (VTAS), the NSIDC NISE satellite-derived snow product, the University of New Hampshire/Russian Arctic/Antarctic Research Institute Permafrost Water Balance Model (P/WBM) (Vörösmarty, Federer and Schloss 1998, Fekete, Vörösmarty and Grabs 1999), the UNH Water Transport Model (WTM) and simulated river networks (STN-30) (Vörösmarty et al. 2000). The algorithms are integrated within the UNH Global Hydrological Archive and Analysis System to provide a coherent geographic and temporal framework.

Real-time river discharge data has been underutilized within the ocean-atmosphere modeling community, with typical three to five year delays in data posting. There also has been a deterioration in gauge networks even in previously well-monitored parts of the globe. The situation is particularly troublesome across the Russian Arctic. In contrast, there are reliable sources of operational meteorological and oceanological data for the purposes of weather forecasting. The mismatch between river discharge and meteorological data availability interferes with the construction of validated pan-Arctic water budgets. The timely identification and interpretation of changing Arctic hydrology is thus becoming increasingly difficult. Despite these problems, the Arctic appears to be an ideal setting to develop an integrated water cycle monitoring capacity since most of the river discharge into the Arctic Ocean is delivered through but a small number of large rivers (Shiklomanov et al. 1999). Only 12 hydrological gauges are required to capture 91% of total monitored area and 85% of discharge. Some gauge data (for North America) are already available through the Internet.

Both an operational capacity (GOALS 1, 3) and scientific analysis (GOAL 2) are sought. Provisional data sets are being released in near-contemporary time (one to two month delay) and reanalyzed at yearly intervals to produce higher quality output fields. Operational and reanalysis products will include all components of the water cycle across the entire pan-Arctic land mass (atmospheric convergence, precipitation, evapotranspiration, change in soil, snowpack, and shallow groundwater, runoff, and river discharge) plus estimates of potential error. Nominal resolution is 30' spatial (long. x lat.) with weekly and where possible daily time steps.

Arctic-RIMS reflects our ongoing commitment to make Arctic data sets available freely and without restriction. All operational data are therefore distributed through freely accessible web sites at the collaborating institutions (e.g., see: http://www.R-arcticnet.sr.unh.edu/). CD-ROMs will contain yearly updates of the RIMS reanalysis products and be distributed by the NSIDC.

References

Bromwich, D. H., Cullather, R. I. and Serreze, M. C. 1999. Re-analysis depictions of the Arctic atmospheric moisture budget. In: E. L. Lewis (ed.), *The Freshwater Budget of the Arctic Ocean,* NATO Meeting/NATO ASI Series, Dordrecht, Germany: Kluwer Academic.

Fekete, B. M., C. J. Vörösmarty, and W. Grabs. 1999. *Global, Composite Runoff Fields Based on Observed River Discharge and Simulated Water Balances.* WMO-Global Runoff Data Center Report #22. Koblenz, Germany.

Lammers, R. B, A. I. Shiklomanov, C. J. Vörösmarty, and B. J. Peterson. 2000. An assessment of the contemporary gauged river discharge and runoff in the pan-Arctic region. *J. Geophysical Research.* In press.

Serreze, M. C. and Maslanik, J. A. 1998. Arctic precipitation as represented in the NCEP/NCAR re-analysis. *Annals of Glaciology, 25,* 429-433.

Shiklomanov, I. A., A. I. Shiklomanov, R. B. Lammers, C. J. Vörösmarty, B. J. Peterson, and B. Fekete. 1999. The dynamics of river water inflow to the Arctic Ocean. In: E. L. Lewis (ed.), *The Freshwater Budget of the Arctic Ocean.* NATO Advanced Study Institute Series. Dordrecht, Germany: Kluwer Academic.

Vörösmarty, C. J., C. A. Federer, and A. Schloss. 1998. Potential evaporation functions compared on U.S. watersheds: Implications for global-scale water balance and terrestrial ecosystem modeling. *J. of Hydrology 207:* 147-69.

Vörösmarty, C. J., B. M. Fekete, M. Meybeck, and R. Lammers. 2000. A simulated topological network representing the global system of rivers at 30-minute spatial resolution (STN-30). *Global Biogeochemical Cycles, 14:* 599-621.

Improving Observational Records for Arctic Hydrology

Cort J. Willmott
Geography Department
University of Delaware
Newark, Delaware 19716
willmott@UDel.Edu

One of our main goals should be the accurate (quantitative) description and prediction of seasonal, interannual, and spatial variability and change in the important hydroclimatic variables. To achieve this, we need a much better understanding of the spatial and temporal scales at which the key processes and variables operate and should be resolved. Obtaining this knowledge will require both model- and data-based evaluations of Arctic climate and hydrology, with special attention to their sub-grid-scale and sub-time-step variability. Without sufficient understanding, we will continue to unknowingly estimate (from data) or simulate (with models) biased or inconclusive hydroclimate fields and time series.

Many more reliable observations are needed to help clarify the predictive strengths and weaknesses of our models, as well as to accurately quantify historical, hydroclimatic variability in the Arctic. A major initiative, in turn, should set in motion to provide a much more extensive set of reliable observational records. Included among the important variables should be: snowfall and rainfall, snow water equivalent, evapotranspiration, runoff, soil moisture, active-layer depth, and river discharge. Such observations also should be useful as model boundary and initial conditions. Our data-acquisition efforts should be prioritized according to the promise that each holds for improving our model-prediction or estimation skill.

Several targeted efforts--which could fill significant gaps in the Arctic instrumental record and are feasible--are outlined below.

1. Additional effort should be made to augment the store of historical, observational records by finding, collecting, encoding, and making available previously unencoded observations. Both archival research and data-rescue missions are needed. This work ought to include the encoding (e.g., digitization) of a wide variety of currently on-paper information, including weather observers' written records and published maps and graphs.

2. Better procedures should be developed to make disparate instrumental records (e.g., those derived from different measurement techniques or times of observation) commensurate across the Pan-Arctic.

3. Significant improvements are needed in our techniques for estimating gridded hydroclimatic fields from sparse in-situ measurements and other observational records.

4. A few selected, intensive field campaigns (somewhat like NASA's FIFE, but at basin scales) are called for to provide the multivariate suites of measurements needed to refine and test our more sophisticated process-based models.

5. Dramatic improvements in satellite coverage of the Pan-Arctic should be a high priority.

6. A spatially high-resolution, low-cost sampling of the between-station hydroclimatic variability (even if only for a relatively short period of time) is needed to help us understand currently unsampled spatial variability, especially as it exists at shorter-than-a-month time scales.

7. Many more in-situ measurements of some very poorly sampled but important variables are required as well, such as of evapotranspiration, snow water equivalent, surface wind, and blowing snow.