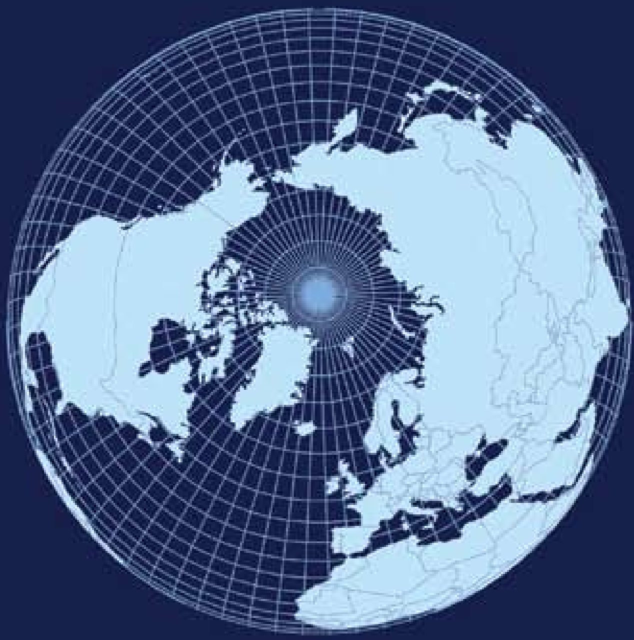
Arctic-HYDRA

The Arctic Hydrological Cycle

Monitoring, Modelling and

Assessment Programme



SCIENCE AND IMPLEMENTATION PLAN

Arctic-HYDRA

Science and Implementation Plan

2010

Acknowledgments

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Árni Snorrason *Charles J. Vörösmarty*

Arctic-HYDRA

A New International Effort for the Study of the Arctic Hydrological Cycle and its Role in the Global Climate System

The Arctic region of our planet consists of a deep, largely ice-covered ocean surrounded by the land masses of Eurasia and North-America. The physical geography of the region encompasses the mountainous regions of Alaska, the ice masses of Greenland and Arctic Canada and the flat plains and tundras of Siberia. Population centers include developed parts of Northern Europe and remote, sparsely inhabited regions where hunters live off the land. Arctic seas contain rich fishing grounds, mineral reserves are exploited in several regions and the rising interest in rich oil and gas reserves is attracting international attention.

Records of past climate variations and modelling of future climate provide strong indications that the Arctic region is particularly vulnerable to ongoing global warming. Air temperatures have increased twice as much in the Arctic as in the rest of the world over the past half century and a warming of three times the global average is predicted for the Central Arctic by the end of the 21st century. In recent years, declining sea ice cover has attracted the attention of policy makers and the general public and scientists continue to debate the future effects of increasing freshwater runoff from Arctic land masses on oceanic circulation. In the future, processes involving Arctic marine and terrestrial systems can be expected to exert influence far beyond the boundaries of the Arctic region.

Studies of the Arctic Hydrological Cycle form a key component of ongoing scientific research aimed at increasing our understanding of the region's role in Earth's climate system. The past 20 years have seen a decline in observational networks in most regions of the Arctic and no monitoring systems exist within large areas that contribute runoff. Modelling efforts aimed at advancing our understanding of the causes and impacts of climate changes in the Arctic are still limited by a lack of knowledge relating to hydrological characteristics of water basins.

In this context, the national hydrological institutes in all Arctic countries have teamed up with several academic departments, the World Meteorological Organization and other international bodies in a new consortium that will aim to provide a new, quantitative picture of the state of the pan-Arctic Hydrological Cycle at a time when rapid Arctic warming is affecting several domains of the climate system. Because water cross-cuts all elements of the Arctic system, the programme will include studies of hydrology and meteorology, sea ice and oceanography, glaciers and ice caps, cold land processes, ecosystems, changes and variability, environmental impacts and people. Because Arctic freshwater in its various states is so deeply embedded into the behavior of the larger Earth system, the domain of Arctic-HYDRA will be fully pan-Arctic. Focus will be on defining the state and fluxes of freshwater systems and their geographic and temporal variations that characterize the Arctic in the first two decades of the 21st century.

Arctic-HYDRA

The Arctic Hydrological Cycle Monitoring, Modelling and Assessment Programme

www.arcticportal.org/arctichydra

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1.

Issues and Rationale

1.1. The Arctic is a Recipient and Amplifier of Climatic and Environmental Change

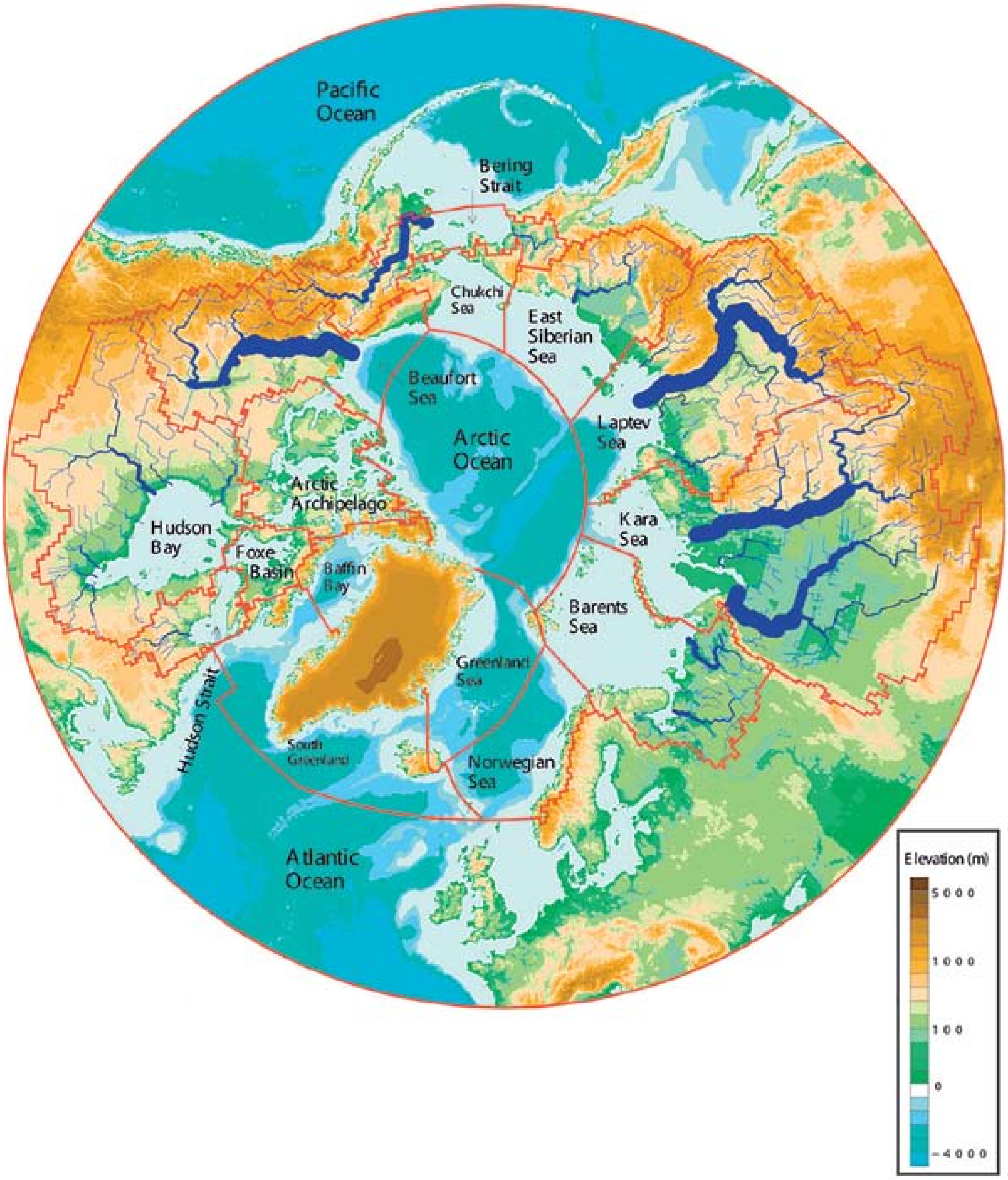


Figure 1.1 – A view of the pan-Arctic region, showing drainage basins in Eurasia and North America that contribute runoff to the Arctic Ocean and surrounding seas. The thickness of blue lines drawn along river courses represents relative river discharge. The Arctic Ocean is the most river-influenced and landlocked of all oceans and although it contains only 1% of the world's ocean water, it receives about 10% of world river runoff.
Source: R.B. Lammers, University of New Hampshire, modified from Forman et al. (2000).

The Importance of the Arctic in the Climate System

The Arctic constitutes a complex system uniting physical, chemical, biological and human social domains. Normally, the Arctic region is defined as the area north of the Arctic Circle (66°33' N), but is sometimes referred to as the region where the average temperature for the warmest month (July) is below 10°C. The Arctic and its hydrology play a central role in regulating Earth's climate. The Arctic Ocean is an unusually fresh part of the world ocean system, owing to large amounts of net convergence of atmospheric moisture from the lower latitudes, as well as discharge by huge rivers in Siberia and North America reflecting its place as the most land-dominated of all ocean basins. Sustained influx of freshwater is crucial to maintaining a relatively fresh surface layer, which helps to retain the Arctic Ocean's sea ice cover by insulating the surface layers from deeper warm waters. However, pathways and variability of freshwater circulation within the Arctic Ocean are still poorly understood, despite concerns regarding surface freshening in the North Atlantic and its influence on global thermohaline circulation.

Hydrological processes in the Arctic have a large impact on the water and energy balances at a range of spatial scales. Runoff, groundwater, soil moisture, snow cover, glacier mass balance and permafrost in this region all influence the natural environment at the local scale through their impacts on biological activity and water chemistry. Furthermore, water is a primary weathering agent for rocks and soils, breaking them down, dissolving them, and transporting the resulting sediments and dissolved solids to the sea. Freshwater discharge and energy fluxes to the Arctic Ocean, latent and sensible heat fluxes, glacier mass balance, snow cover and permafrost conditions influence the global climate through feedback effects involving atmospheric and ocean circulation. Interactions

How the Arctic System Can Amplify Global Climate Change

The Arctic exerts a special influence over global climate through feedback mechanisms, by which Arctic processes can cause additional climate change for the planet.

The first is through the change in surface reflectivity (albedo) that occurs when the area of snow and ice surfaces is reduced by melting. An increased amount of solar energy is then absorbed by the darker land/ocean surface, leading to increased melting and thus amplifying the warming trend. The northward expansion of forests into tundras in a warmer climate will also lead to a reduction in reflectivity.

Alteration in oceanic circulation patterns is another important feedback mechanism, through which Arctic processes can amplify changes in global climate. The sinking of cold, dense seawater (deepwater formation), driving the thermohaline circulation in the world's oceans, primarily occurs in the North Atlantic Ocean and in the Labrador sea. Sea ice formation also influences this process, by making near-surface water saltier and denser as salt is rejected from the ice. In a warmer climate, deepwater formation can be reduced by an increase in freshwater input through greater precipitation and runoff from adjacent continental areas, as well as by reduced sea-ice formation. The resulting slowdown in the thermohaline circulation would slow the transport of carbon dioxide to the deep ocean and thereby allow more rapid buildup of CO_2 in the atmosphere, thus amplifying global warming. A slower oceanic circulation could lead to regional cooling in areas adjacent to the North Atlantic Ocean, at least temporarily, even as warming continues throughout the rest of the planet.

Finally, climatic warming is expected to influence the exchange of greenhouse gases between the atmosphere and Arctic soils and sediments. Vast amounts of carbon have been accumulated in peat bogs in Siberia and parts of North America and summer thawing of the surface layer of permafrost leads to the release of methane and carbon dioxide to the atmosphere. These releases are thus intimately connected to the disposition of water, frozen water, energy and carbon. Greater release in a warmer climate may create an amplifying feedback loop, whereby more warming causes additional releases, leading to more warming and so on.

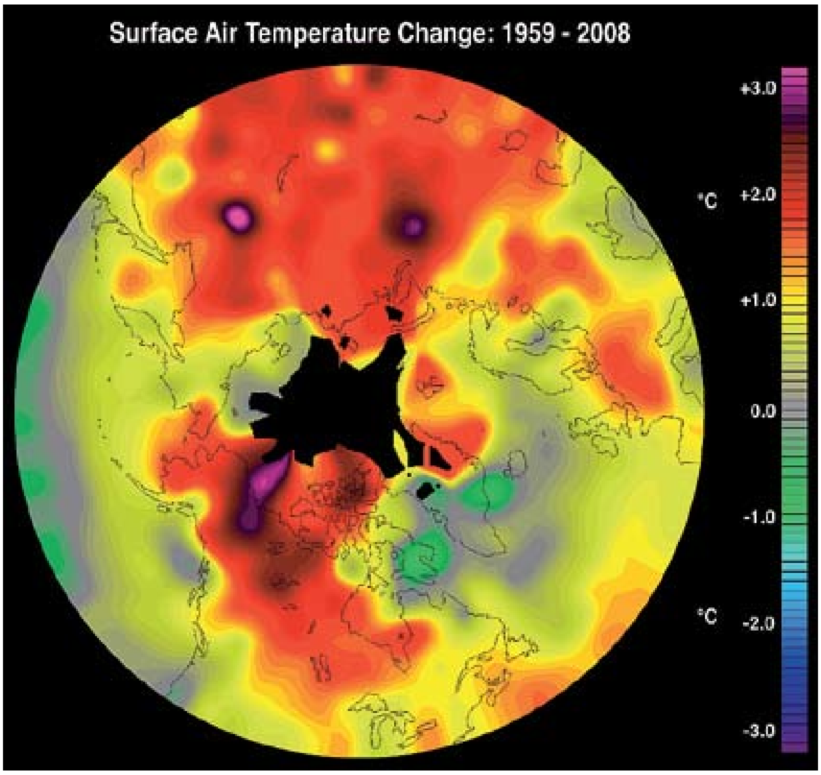


Figure 1.2 – Arctic temperature changes 1959-2008. *Source:* http://arctic.atmos.uiuc.edu/

between different processes in the Arctic, e.g. the extent of snow cover, glaciers and permafrost, groundwater discharge and streamflow require that impact studies consider the simultaneous functioning of all parts of the system.

Recent Climate Change in the Arctic

Temperature records, hydrological data, glacier and permafrost observations and data on sea ice extent and thickness all provide strong evidence for Arctic warming in the past decades. Figure 1.2 shows the change in temperature in the Arctic region over the 50 year period 1959-2008. A warming of 2-3 °C is observed in most of Alaska, in NW Canada and parts of Siberia. On average, annual Arctic temperature has increased by almost twice the rate measured for the rest of the world, with some variations across the region. Precipitation in the Arctic has, on average, increased by 8% in the past century.

Remarkable changes have been observed in the spatial patterns of Arctic temperature anomalies at the beginning of the 21st century (2000-2007) as compared with most of the 20th century. The year 2007 was the warmest on record for the Arctic and some authors suggest calling this recent interval the Arctic Warm Period. Figure 1.3 shows satellite-derived summer-mean sea surface temperature (SST) anomalies since 2000. Warm anomalies during 2002–2005 are evident north of Alaska, the Bering Strait and eastern Siberia and temperature anomalies in 2007 are much larger than in any other year, reaching a maximum of 5°C in the Chukchi Sea. The summers of 2005 through 2007 all ended with extensive areas of open water, leading to absorption of extra heat from solar radiation and unusually late ice freeze-up. A strong negative trend in summertime sea-ice extent has been observed over the last 30 years and a record minimum occurred in 2007 (Figure 1.4). This minimum was set up by sustained winds blowing from the North Pacific across the North Pole, whereas the near record minimum in 2008 occurred in a summer with more variable winds (Figure 1.5). In September

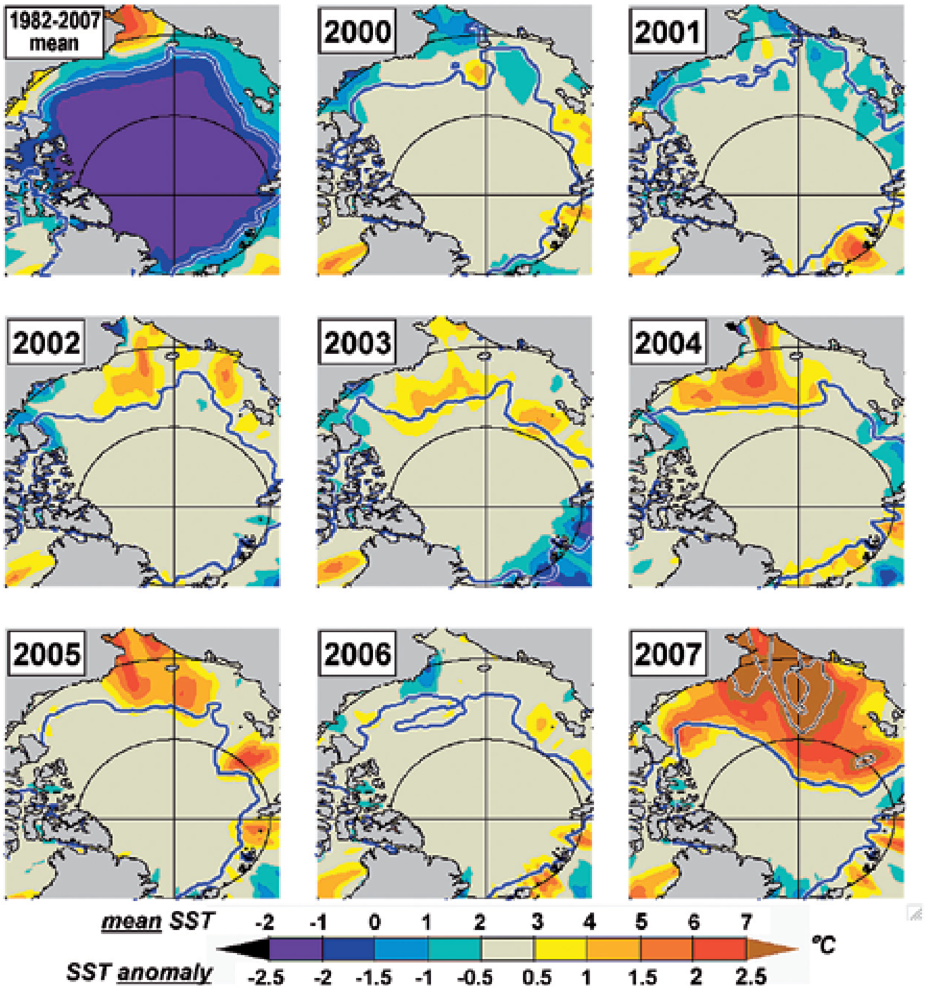


Figure 1.3 – Mean satellite-derived summer sea surface temperatures over the Arctic Ocean 1982-2007 (top left), and anomalies from this mean in the years 2000-2007. For 2007, extra contours for 3°C and 4°C are provided. Also shown is the September-mean ice edge (blue contour) from the Hadley Centre (1982–2006: http://badc.nerc.ac.uk/data/hadisst/) and from the National Centers for Environmental Prediction (2007: ftp://polar.ncep.noaa.gov/pub/cdas/). *Source*: Steele et al. (2008).

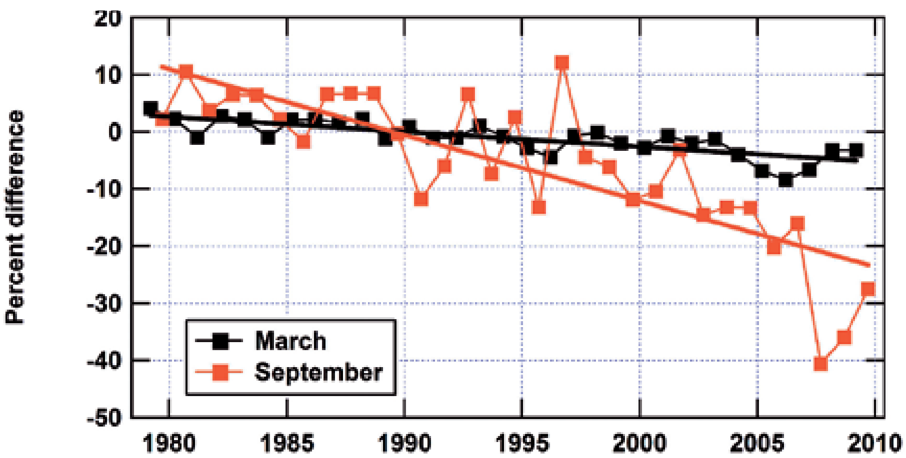
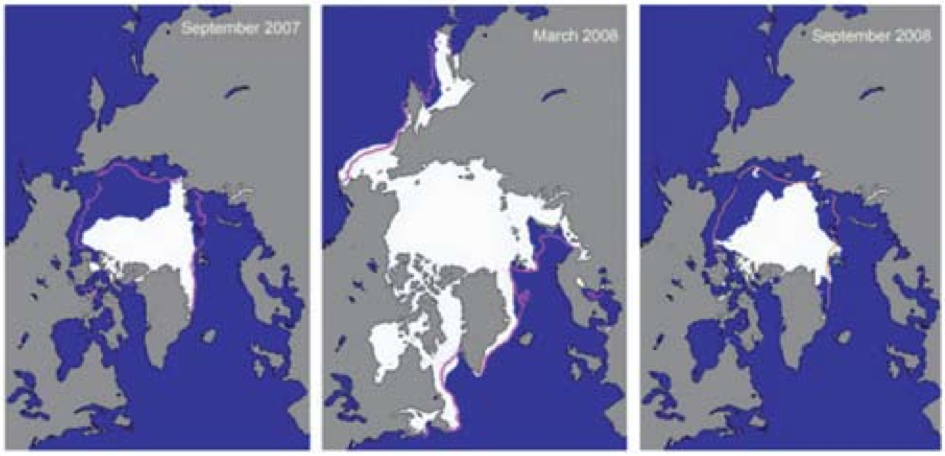


Figure 1.4 – Time series of the difference in sea-ice extent in March (the month of ice extent maximum) and September (the month of ice extent minimum) from the mean values for the time period 1979–2000. Based on a least squares linear regression for the period 1979-2009, the rate of decrease for the March and September ice extents was –2.5% and –8.9% per decade, respectively. *Source*: Perovich et al. (2009).



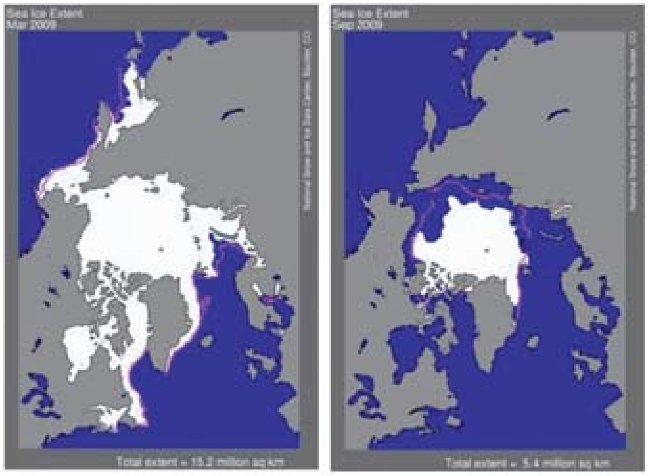


Figure 1.5 – Sea ice extent in September 2007 (top left), March 2008 (top center), September 2008 (top right), March 2009 (bottom left) and September 2009 (bottom center), illustrating the winter maximum and summer minimum extents. The magenta line indicates the median maximum and minimum extent of the ice cover, for the period 1979–2000. The September 2007 minimum extent marked a record minimum for the period 1979–2008. [Figures from the US National Snow and Ice Data Center Sea Ice Index: nsidc.org/data/seaice_index].

2009, more ice cover remained at the end of the Arctic summer than in 2007 and 2008, but sea-ice extent has not recovered to previous levels and the past five years have seen the five lowest ice extents in the satellite record. Satellite derived sea-ice thickness estimates indicate that the ice has thinned significantly between 1982 and 2007 and helicopter-borne and ice-based electromagnetic measurements indicate a reduction of mean sea-ice thicknesses in the region of the North Pole of up to 44% between 2001 and 2007.

Widespread changes in the terrestrial cryosphere throughout the Arctic region are well documented. Most Arctic glaciers and ice caps have been in decline since the early 1960s, with this trend speeding up in the 1990s (Figure 1.6). There is more uncertainty about recent changes in the state of the Greenland ice sheet, but recent gravitational observations from space (the GRACE experiment) are making it possible to determine the rate of mass loss from the ice sheet with reasonably good accuracy. The most recent assessments indicate accelerating mass loss from the ice sheet during the

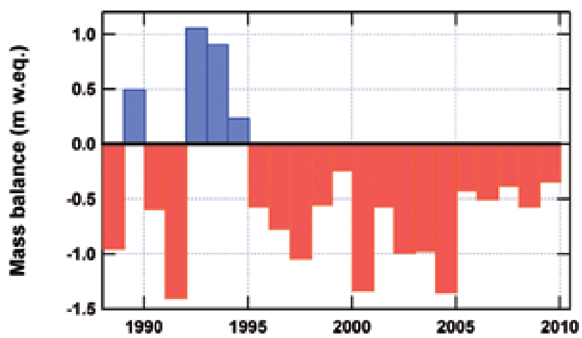


Figure 1.6a – The annual mass balance of Sátujökull, a representative transect of the Hofsjökull ice cap, Central Iceland, has been negative since 1995. The ice cap lost approximately 5% of its total volume in the period 1995-2008.

Sources: Sigurðsson et al. (2004), Thorsteinsson (2009). Data accessible at the World Glacier Monitoring Service (http://www.geo.unizh.ch/wgms/).

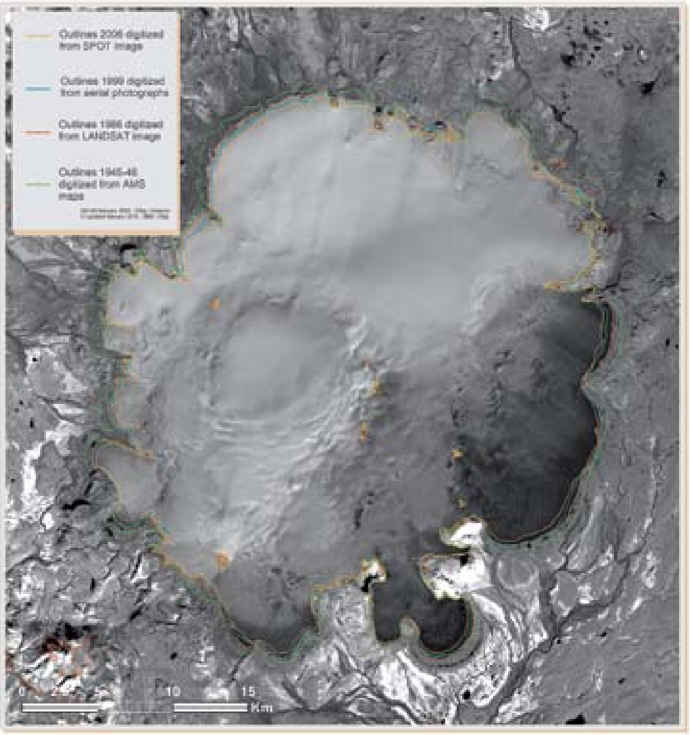


Fig. 1.6b – Changes in the outlines of the Hofsjökull ice cap during the period 1946-2006.
Prepared by O. Sigurðsson and Bogi B. Björnsson, Icelandic Meterological Office, 2010.

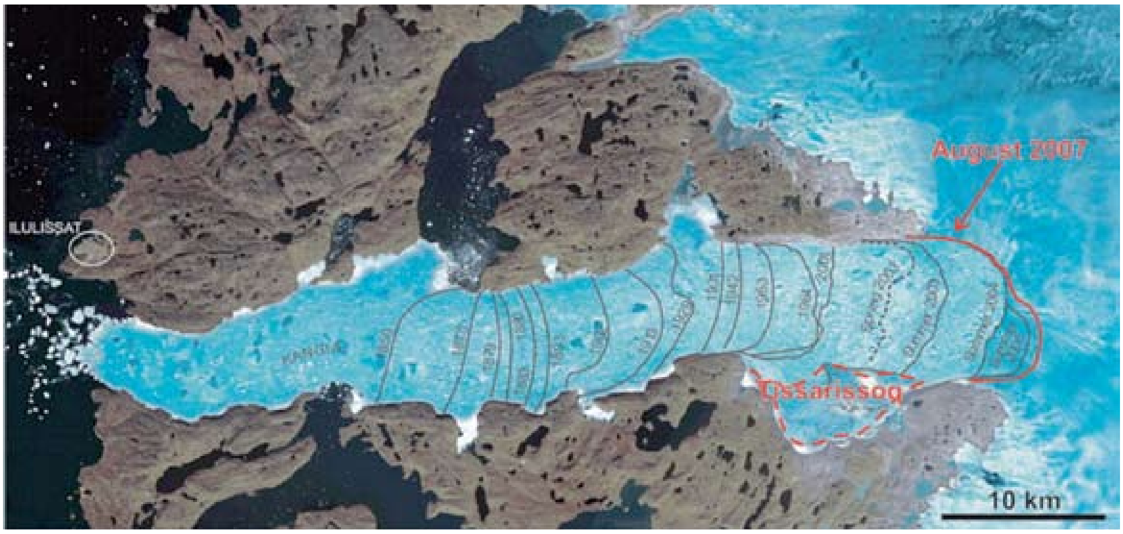


Figure 1.7 – Front position of the Ilulissat (Jakobshavn Isbræ) glacier, West Greenland, in 2007 (thick red line) and earlier years, based on Weidick and Bennike (2007). The image mosaic is from June 2003 Landsat and ASTER images. The large ice lagoon Tissarissoq at the south side of the fjord became ice-free at the end of the summer 2007, probably for the first time since the Medieval Warm Period.

1990s up to 2008. According to the latest IPCC Assessment report, Greenland was in 1996 losing about 96 km³ per year in mass from its ice sheet. In 2005, this had increased to about 220 km³ a year due to rapid thinning near the coast, while in 2006 it was estimated at 239 km³ per year. Drastic retreat of several major outlet glaciers like the Jakobshavn Isbræ (Figure 1.7) has been documented in recent years, but this retreat has unexpectedly been accompanied by a rapid increase in flow velocities of several glaciers and hence increased rates of calving. In SE-Greenland, the higher velocities may be related to an increase in ocean temperatures near the coast of Greenland, which reduced the sea ice cover and hence the buttressing effect of sea ice on calving glaciers. Another contributing factor is increased percolation of surface meltwater which enhances glacier sliding through buildup of water pressure at the bed.

Scenarios for Arctic Warming in the 21st Century

Possible scenarios of 21st century climate change have been obtained through model calculations and analyzed in the Arctic Climate Impact Assessment Report (ACIA, 2005). Figure 1.8 shows the projected worldwide change in annual mean temperature for three 21st century periods: 2011-2030, 2041-2060 and 2071-2090 (average of 5 ACIA models). On average, the models predict greater temperature changes at high northern latitudes than anywhere else in the world. By 2071-2090, the central Arctic will, according to these projections, have warmed by 5°C (about three times the global average). Precipitation is projected to increase by between 7.5% and 18% between the periods 1981-2000 and 2071-2090, as compared with a projected mean global precipitation increase of 2.5% (ACIA Report, Chapter 4.4.3).

The ACIA models have also been used to predict hydrological changes in the Arctic during the 21st century. For example, earlier break-up and later freeze-up of rivers and lakes is projected. The reduction in ice cover thickness on lakes and rivers is expected to continue due to atmospheric warming, although modifications due to precipitation changes may occur.

The total Arctic river runoff is projected to increase by 10-20% by 2050 and may thus exceed 5000 km^3/year by the middle of the century.

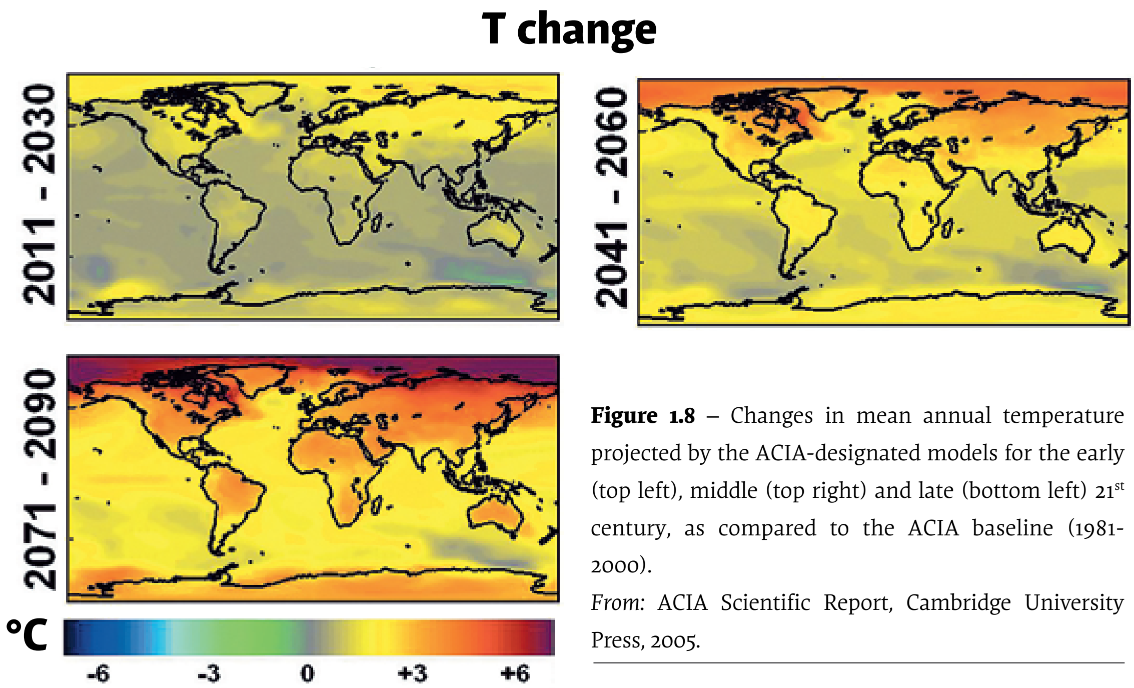


Figure 1.8 – Changes in mean annual temperature projected by the ACIA-designated models for the early (top left), middle (top right) and late (bottom left) 21st century, as compared to the ACIA baseline (1981-2000).

From: ACIA Scientific Report, Cambridge University Press, 2005.

ARCTIC AMPLIFICATION ALREADY OBSERVED?

Box 1 highlighted how processes in the Arctic may increase the rate of global atmospheric warming. Climate models predict that temperature rise will be more pronounced in the Arctic than elsewhere on the planet under increasing greenhouse warming; this is commonly referred to as “Arctic amplification”.

In a recent paper, Serreze et al. (2009) provide evidence that surface-based Arctic amplification has already been occurring within the last decade. The recent surface temperature anomalies (Figure 1.3) align with the observed reduction in September sea ice extent as predicted. Moreover, the recent autumn warming, which also affects the overlying atmosphere, is stronger in the Arctic than in lower latitudes. The effects of Arctic amplification on the atmospheric circulation are not well understood, but the loss of sea ice cover may lead to changes in storm tracks and rainfall patterns over Europe or the American West.

1.2. Arctic Changes Affect Humans, Ecosystems and Earth Systems

Water is a fundamental component linking many of the environmental changes in the Arctic region, and society demands answers to how a changing Arctic Hydrological Cycle impacts humans, ecosystems, and Earth systems. The Arctic Climate Impact Assessment (ACIA, 2005) summarized many of these changes, and stressed that not only are many of them already taking place, but they are also expected to accelerate over the next 100 years and beyond. Furthermore, Working Group II of the *IPCC Fourth Assessment Report* stated with high confidence that climate change (e.g. temperature increase) is affecting natural systems, including changes in snow, ice, and frozen ground/permafrost. There is also high confidence that impacts will include increasing coastal erosion, increasing seasonal permafrost thawing depth, reduced extent of permafrost (Figure 1.9) and sea ice and decrease of river and lake maximum ice thickness (Figure 1.10). While there are both projected benefits and negative impacts of these changes, there is increasing concern about the extent to which the inhabitants of Arctic regions will be able to adapt to these changes in the future. The traditional way of life of the indigenous peoples of the North is intricately connected with the environment and changes in the water regime of rivers and lakes will strongly impact their way of life and local economies. And while reduced sea-ice extent will likely expand opportunities for shipping and offshore oil extraction in the Arctic, such industrial activities will also increase the risk of environmental degradation resulting from oil spills and other industrial accidents.

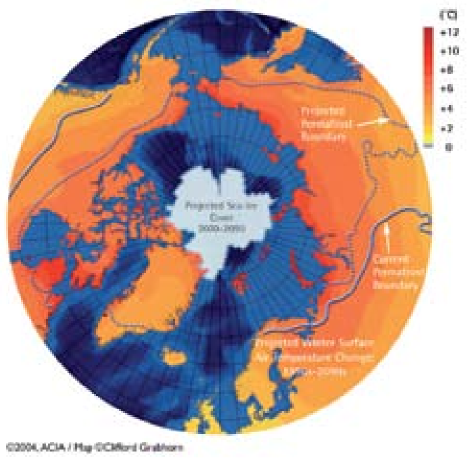


Figure 1.9 – Current and projected permafrost extent in the Arctic (ACIA, 2005).

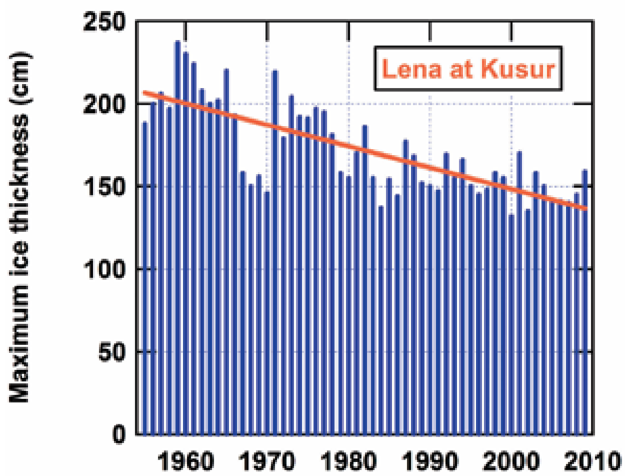


Figure 1.10 – Changes in the maximum ice cover thickness in the Lena river (Asian Russia) 1955-2009. From: A. Shiklomanov.

Recent studies have found evidence for considerable increase in winter runoff carried by Arctic rivers, accompanied by a reduction in summer runoff, and these trends are expected to continue throughout the 21st century (Figure 1.11). These changes and other substantial hydrosphere changes (e.g. permafrost thawing) are expected to affect Arctic ecosystems in various ways. As a whole, the Arctic ecosystem is part of the higher-level global biosphere and changes in its characteristics will undoubtedly affect properties of ecosystems near the boundaries of the Arctic. The influence of the Arctic is firstly reflected through changes in heat and moisture exchange, which in turn affect other properties of the natural system. Changes in the Arctic ecosystem have already become evident not only as changes of the natural properties of the ecosystem itself, but have affected the conditions of management in different branches of the Arctic economic complex.

Changes in river discharge regimes, their intensity and flood frequency have direct consequences for the transfer of pollutants to the Arctic Ocean. Through changes in hydrology, fine river sediments carrying contaminants can spread even further into open waters. Thawing permafrost will release sediment, nutrients and organic carbon which will enter hydrological and biological cycles. Solid

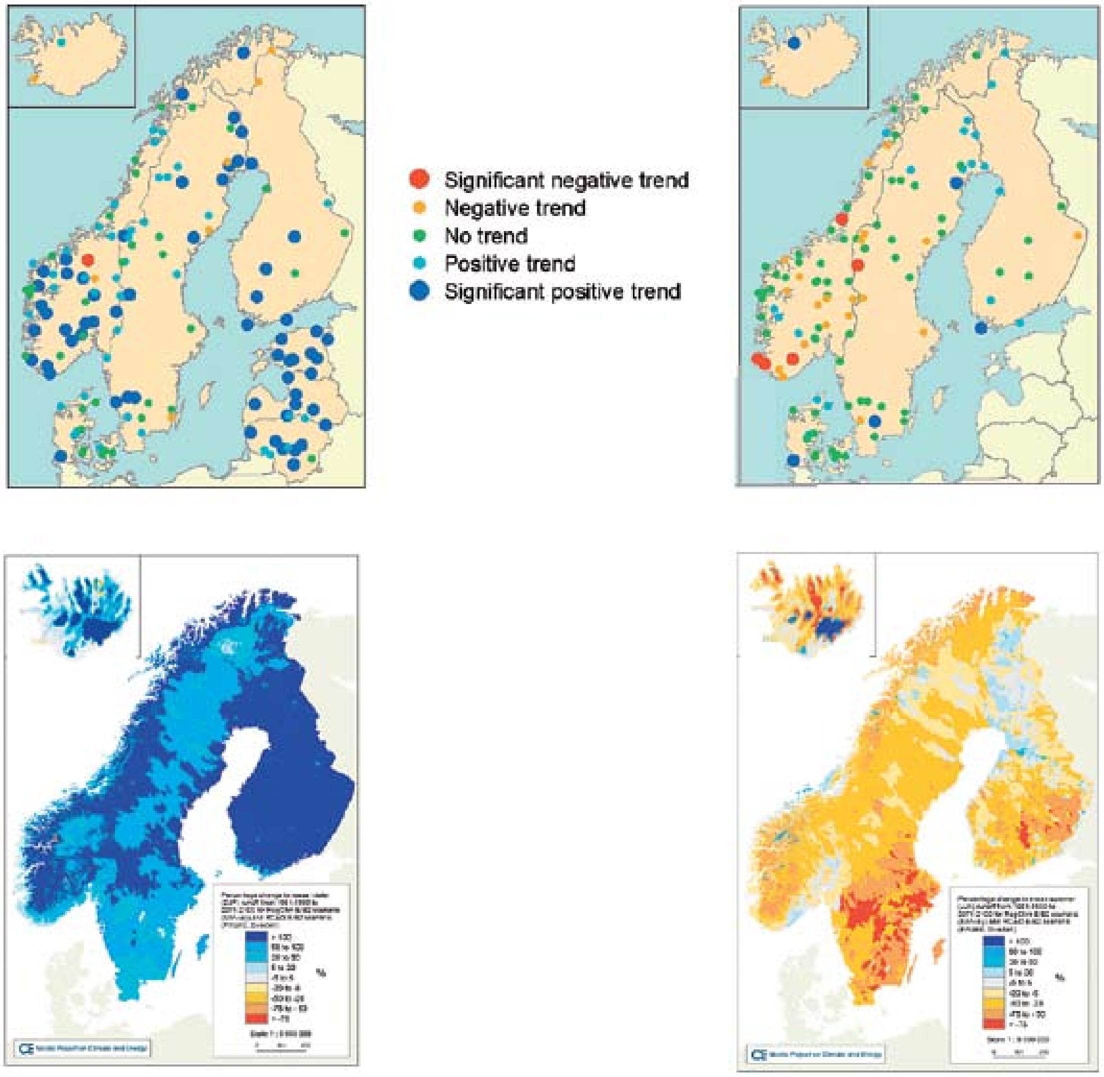


Fig. 1.11 – Trends in historical data and future projections in winter and summer runoff for the Nordic countries. A substantial part of the runoff from this region forms a component of the Arctic Hydrological Cycle.
Top left: Trends in observed runoff for winter (Dec., Jan., Feb.) for the period 1941-2002.
Top right: Trends in observed runoff for summer (Jun., Jul., Aug.) for the period 1941-2002.
Bottom left: Percentage change in runoff for winter (Dec., Jan., Feb.) from 1961-1990 to 2071-2100, predicted by the Max-Planck Institute's ECHAM4/OPYC3 atmospheric general circulation model, using the SRES B2 emission scenario.
Bottom right: Percentage change in runoff for summer (Jun., Jul., Aug.) from 1961-1990 to 2071-2100, predicted by the Max-Planck Institute's ECHAM4/OPYC3 using the SRES B2 emission scenario.
Source: Nordic Climate and Energy Project (see: www.os.is/ce and Fenger, 2007).

waste dumps in small Arctic communities, mine tailings and oil drilling sumps will be washed away with thawing permafrost into the rivers flowing into the Arctic Ocean. There is evidence that climate change will be accompanied by the increased flux of heavy metals and organochlorine compounds. Finally the leading concern for the Arctic is the risk of oil spills from both onshore and offshore exploration and production. This problem may be accelerated by leakages from corroded pipelines due to permafrost melting and by more frequent incidence of oil spills in rivers and estuaries.

Intensive commercial activities such as oil and gas production, navigation, fishery, mining operations, water and hydraulic engineering and transport of freight by winter roads are conducted in the Arctic river basins. All above mentioned activities are in one way or another associated with moistening of the basins, their water resources, rivers' hydrologic and water conditions and water pollution. The changes in these characteristics that have occurred during the last 20-25 years and will occur in the future may seriously disturb the functioning of these industries.

Society demands answers to questions of how a changing Arctic Hydrological Cycle will impact humans, ecosystems, and earth systems

Buildings Dawson, Yukon Territory, slumping together because of thawing of underlying permafrost.

The Trans-Alaska pipeline is designed to keep permafrost frozen by the use of thermosiphons. Permafrost is warming in interior Alaska, where this picture was taken.

Saami herder in a boat leads his reindeer herd to summer pastures on an island. Norway.

The Chukochiye River meanders through the tundra of the Kolyma delta region, Siberia, Russia.

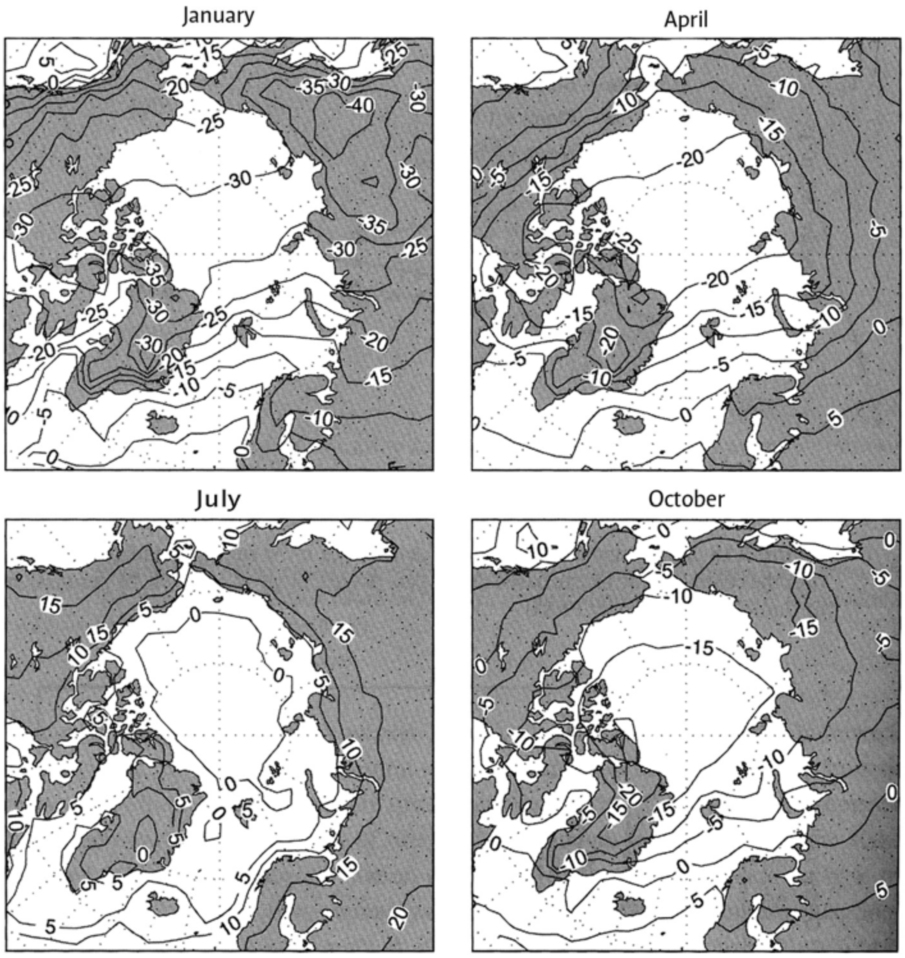


Figure 1.12 – Mean surface air temperature (°C) in the Arctic region for January, April, July and October. *From:* Serreze and Barry: The Arctic Climate System. (Cambridge, 2005). *Adapted and updated from:* Rigor et al. (2000).

1.3. Studying Water is Fundamental to our Understanding of Arctic Climate Change

Climate of the Arctic

The strong summer-winter contrast in solar radiation affects the climate in all Arctic areas (Figures 1.12 and 1.13). The summertime absorption of solar energy is generally low due to the high reflectivity (albedo) of snow and ice surfaces and solar radiation is small or absent in winter. Maritime conditions prevail over the Arctic Ocean, coastal Alaska, Iceland, coastal Northern Norway and adjoining parts of Russia whereas continental climate dominates the interior regions of Siberia, Arctic Canada and Central Alaska. The winter climate is characterized by the frequent occurrence of inversions, whereas Arctic weather patterns during summertime are dominated by the movement of low pressure systems (cyclones) across Siberia and into the Arctic Ocean basin. In many Arctic and sub-Arctic regions, the weather is controlled by semi-permanent low pressure systems that are weakly developed in summer, but stronger in winter. The most important of these low pressure systems are the Icelandic Low and the Aleutian Low. In winter, eastern Eurasia is dominated by the semi-permanent Siberian High. High pressure is also prevalent over the Canadian Arctic Archipelago during the cold season.

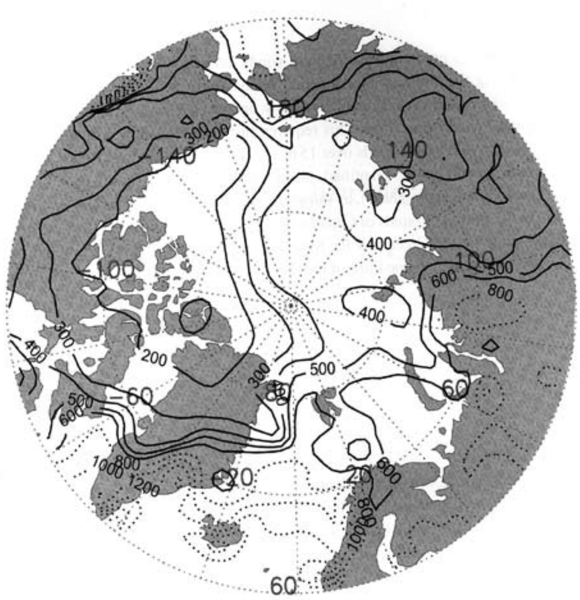


Figure 1.13 – Mean annual precipitation (mm) based on available bias-adjusted data sources. Contour intervals are 100 mm (solid, for amounts up to 600 mm) and 200 mm (dotted, for amounts 800 mm and greater).
From: Serreze and Barry: The Arctic Climate System. Cambridge University Press 2005.

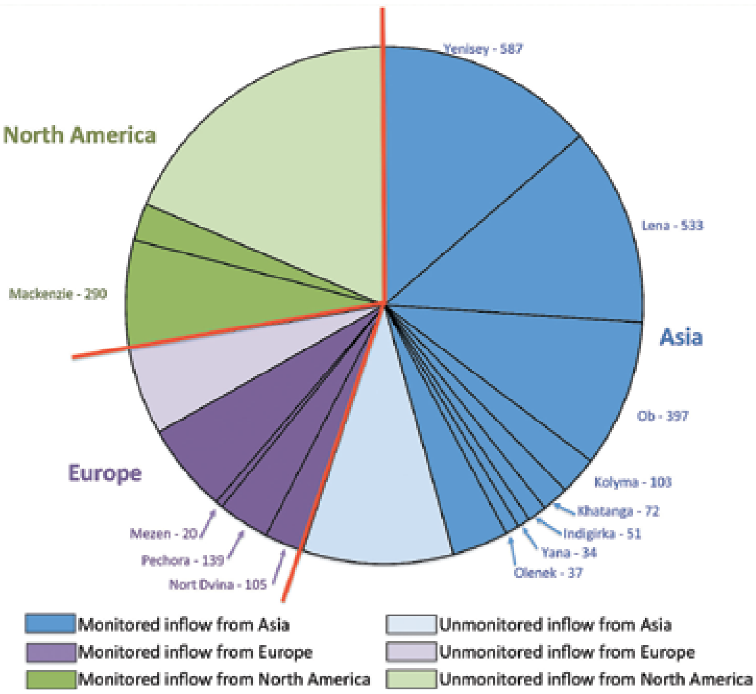


Figure 1.14 – Surface inflow into the Arctic Ocean (4270 km^3/year in total). *From:* A. Shiklomanov.

Water in liquid form

Water is a fundamental component linking many of the environmental changes in the Arctic region. About 65% of the total terrestrial Arctic drainage area (without Hudson Bay) of 19*10^6 km^2 is monitored at present. The mean annual drainage is estimated to be 4300 km^3 and the four largest drainage basins, the Ob, Yenisey, Lena and Mackenzie, contribute about 63% of the total gauged volume discharge to the Arctic Ocean (Figures 1.14 and 1.15).

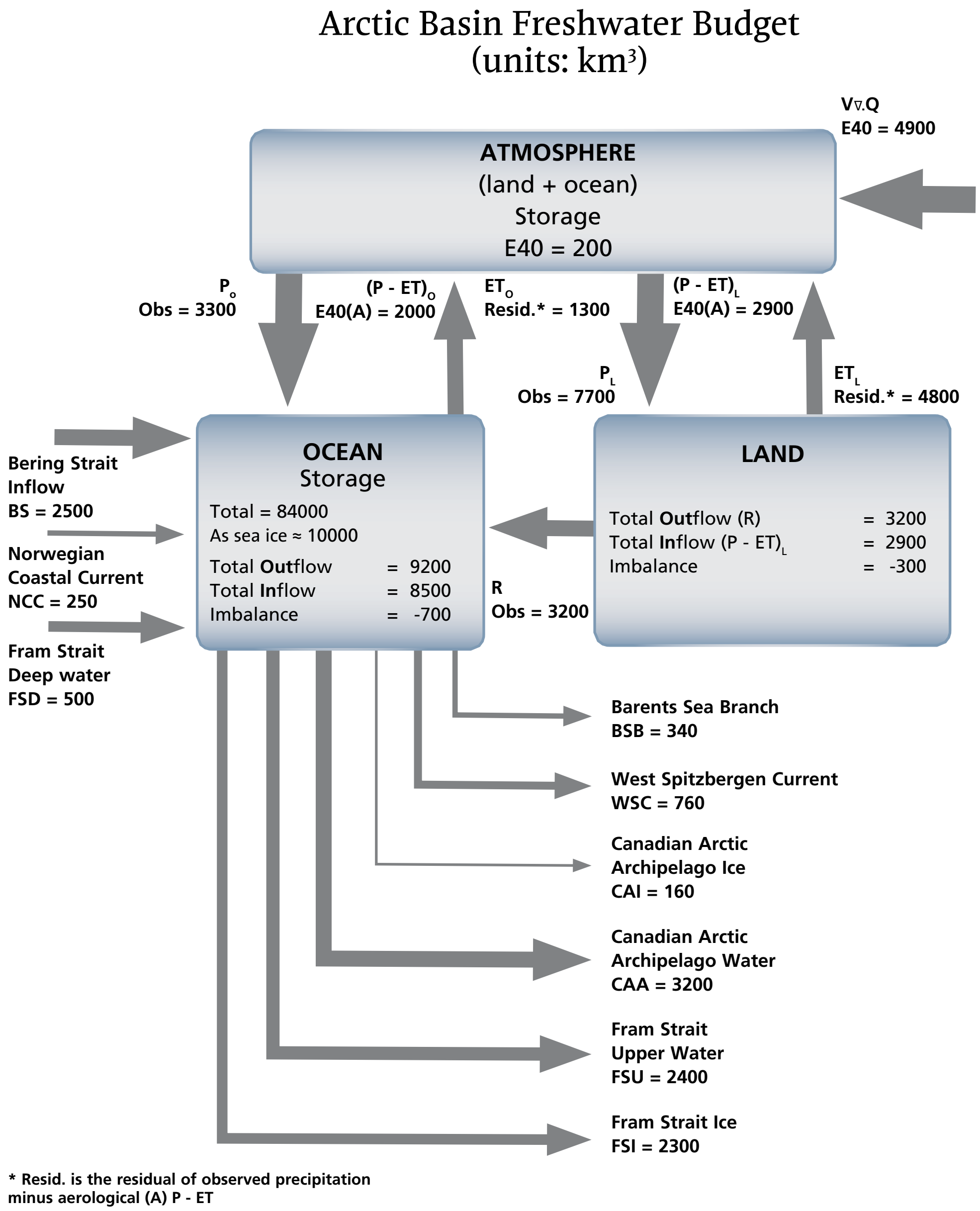


Figure 1.15 – Storage and flux estimates for the pan-Arctic water cycle, synthesizing existing literature-based estimates and modelling results. Arrows show direction and relative sizes of fluxes linking major domains. A dominant pathway for fresh water into the pan-Arctic is atmospheric moisture transport, then deposited on land and sea by net convergence (snow and rain minus evaporation). Freshwater then moves to the Arctic and ultimately to the North Atlantic Ocean. Budget closure has been relatively well-established but required substantial interpretation, extrapolation of existing information and expert judgment. Through its integrated monitoring systems, including integrated hydrographic stations, Arctic-HYDRA will help to provide a new level of consistency not previously available in the baseline information, from which future syntheses can be drawn. *Modified from:* Serreze et al. (2006).

The Arctic is dominated by long cold winters with many months of snow accumulation, but the hydrological cycle is much more dynamic in the summer months when liquid water abounds. Most watersheds in the region receive more precipitation in the summer months than during the entire cold season. Both runoff and evapotranspiration compete to be the largest exporters of water from a basin. Although many terrestrial areas of the Arctic appear to have copious amounts of water after snowmelt, this vision is deceptive since in one short summer this water disappears. Major floods are rainfall and snowmelt generated, except for the largest basins (those of the Lena, Ob, Yenisey and

Mackenzie rivers), in which basin-wide rainfall is never attained and thus snowmelt only produces the floods of record.

In areas of continuous permafrost, storage reservoirs of liquid and solid water are limited. The active layer above the permafrost has a storage capacity roughly equivalent to annual precipitation, but much of the storage is already occupied by soil water. Lakes, ponds and wetlands are often plentiful in low-gradient watersheds and provide surface storage. Water is stored in the snowpack for a few months in all catchments and many small Arctic rivers freeze up to the bottom during wintertime. Aufeis deposits (floodplain icings) and glaciers are capable of storing water in solid form from a few months to thousands of years. In areas of discontinuous permafrost or permafrost free areas, substantial subsurface storage is available and changes are hard to quantify.

The terrestrial part of the pan-Arctic water cycle feeds large quantities of freshwater and water-borne substances from land to sea. With the Arctic experiencing relatively large climate change effects, associated changes in water release from the cryosphere to the local and regional hydrology will modulate erosion, nutrient release and downstream sediment and solute/pollutant transport by surface and subsurface waters, and thereby the biogeochemistry of both inland and recipient coastal and marine water systems.

Recent studies of long-term hydrometric data for the Eurasian Arctic indicate that the annual discharge to the Arctic Ocean from the six largest Eurasian rivers increased by 7% between 1936 and 1999, implying that the annual freshwater inflow to the Arctic Ocean is is now about 130 km^3 greater than it was in the mid-1930´s.

Snow, ice and permafrost

The cryosphere is the frozen part of the Earth system, in which frozen water is bound in snow, ice sheets, ice caps, glaciers, snow, lake and river ice, frozen ground (seasonally or as permafrost) and sea ice. Water as ice has a strong influence on surface and subsurface water and energy fluxes, as well as vegetation, thereby influencing land surface-atmosphere interactions. It affects gas and particle fluxes, clouds, precipitation, hydrological conditions, and atmospheric and oceanic circulation. There are strong and complex relations between the cryosphere and climate systems, including feedback mechanisms. In the polar areas, the hydrological cycle is strongly affected by the spatial and temporal variation in ice. For example, precipitation is stored as snow for a relatively long duration before being released as runoff during a short period of time in the spring. This controls water flow and river ecology, floods and droughts, hydropower production, agriculture, transport on rivers, etc.

The Greenland ice sheet and glaciers and icecaps in the Arctic (Figure 1.16) provide a substantial freshwater flux to the Arctic Ocean. Data on the coupled glacier-river freshwater input to the Arctic Ocean and changes in variation and magnitude is important to climate modelling and for understanding the total effects of changes in the freshwater cycle in the Arctic. Seasonally or permanently frozen ground is characteristic of a large part of the Arctic basin. Changes in this regime due to climate change, for example air temperature or snow cover may have profound changes to the temporal and spatial distribution of frost. Melting of permafrost will change the regional fluxes of methane, and affect river sediment fluxes, ecology and habitats, infrastructure and transport. River and lake ice affect the energy fluxes, flow of water and biological production and diversity in the river-lake systems.

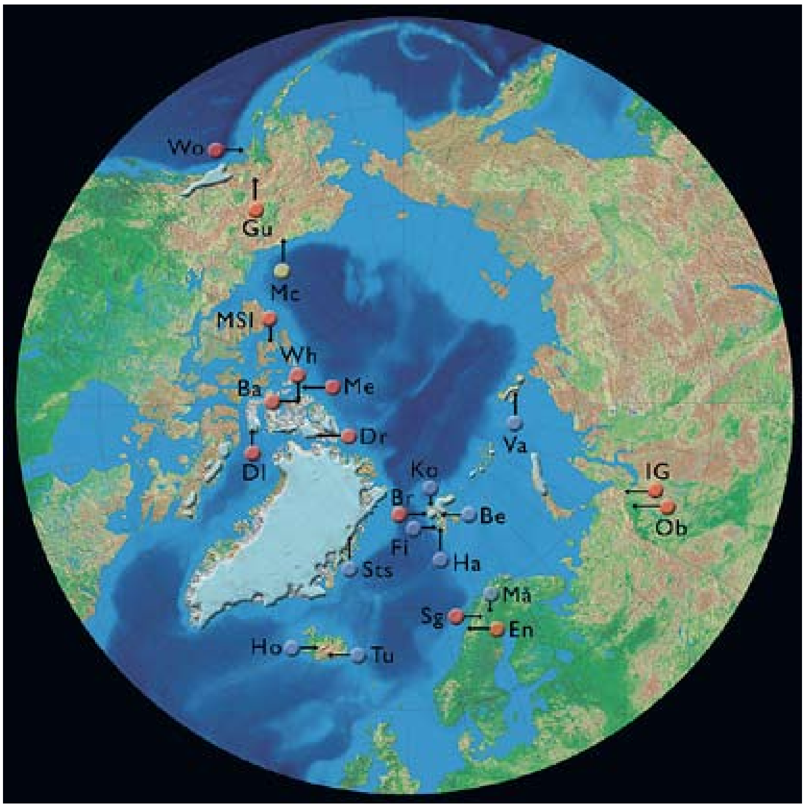


Fig. 1.16. – Ice-covered areas in the Arctic and the location of glaciers and ice caps for which mass balance data are available. Wo: Wolverine Glacier, Gu: Gulkana Glacier, Mc: McCall Glacier, MSI: Melville South Ice Cap, Ba: Baby Glacier, Me: Meighen Ice Cap, DI: Devon Ice Cap, Dr: Drambui Glacier, Ho: Hofsjökull, Tu: Tungnárjökull, Br: Austre Brøggerbreen, Ko: Kongsvegen, En: Engabreen, Sg: Storglaciären, IG: Igan, Ob: Obruchev, Va: Vavilov, Ha: Hansbreen, Wh: White, Be: Bear Bay, Fi: Finsterwalderbreen, Ma: Märmaglaciären, Sts: Storstrømmen.
Source: ACIA (2005).

Table 1.1 – Ice coverage in Arctic regions with extensive glaciation (Dowdeswell and Hagen, 2004).

	x 10^3 km^2
Greenland Ice Sheet	1640.0
Canadian Arctic (>74° N)	108.0
Canadian Arctic (<74° N)	43.4
Alaska	75.0
Iceland	10.9
Svalbard	36.6
Franz Josef Land	13.7
Novaya Zemlya	23.6
Severnaya Zemlya	18.3
Norway/Sweden	3.1

1.4. An Integrated, International pan-Arctic Approach is Necessary

The Arctic-HYDRA concept envisions systematic quantification of the Arctic Hydrological Cycle during the early 21st century through more effective collaboration of national hydro-meteorological services, numerical weather prediction and modelling centers and space agencies in the Arctic countries. The current lack of integration impedes the assembly of a system-wide picture. Basic stocks and fluxes of water throughout the pan-Arctic water system (Fig. 1.15) have only recently been assembled, attesting to the difficulties inherent in distilling fragmentary data (both spatially and temporally) from several sources, whose original intent may not have been to contribute directly to synthesis.

In this context, Arctic-HYDRA will provide a framework to:

- Design and execute a systematic process to evaluate the utility of key historical and operational data sets depicting the geospatial distribution of water cycle variables, using information generated over the satellite era and capable of assessing the fully pan-Arctic domain.
- Apply the evaluation process to create optimal deployments of monitoring network and remote sensing resources to construct an operational, contemporary depiction of the pan-Arctic water cycle.
- In concert with regional and global modelers, assess the effectiveness of current monitoring resources to detect plausible scenarios of Arctic environmental change.
- To provide feedback to data providers on the efficacy and value of their data sets to the user communities and to propose concrete suggestions on ensuring their relevancy.

Systematic planning, to unite in situ monitoring, remote sensing, and geospatial modelling is necessary to ensure that efforts such as the 2007-09 International Polar Year (IPY) and the longer term ICARP-II (to 2020) map directly to the improvement of our understanding of the Arctic as a system and as part of a larger set of global water and energy cycle systems. With this objective in mind, the value of integrated water cycle observing and analysis systems becomes obvious. The structure of such a system, to be implemented within the framework of the Arctic-HYDRA collaboration, is described in Chapter 3.

2.

Challenges

2.1. Severe Decline in Observational Networks has Reduced the Scientific Community's Ability to Detect the Nature of Changes in the Arctic Hydrological System.

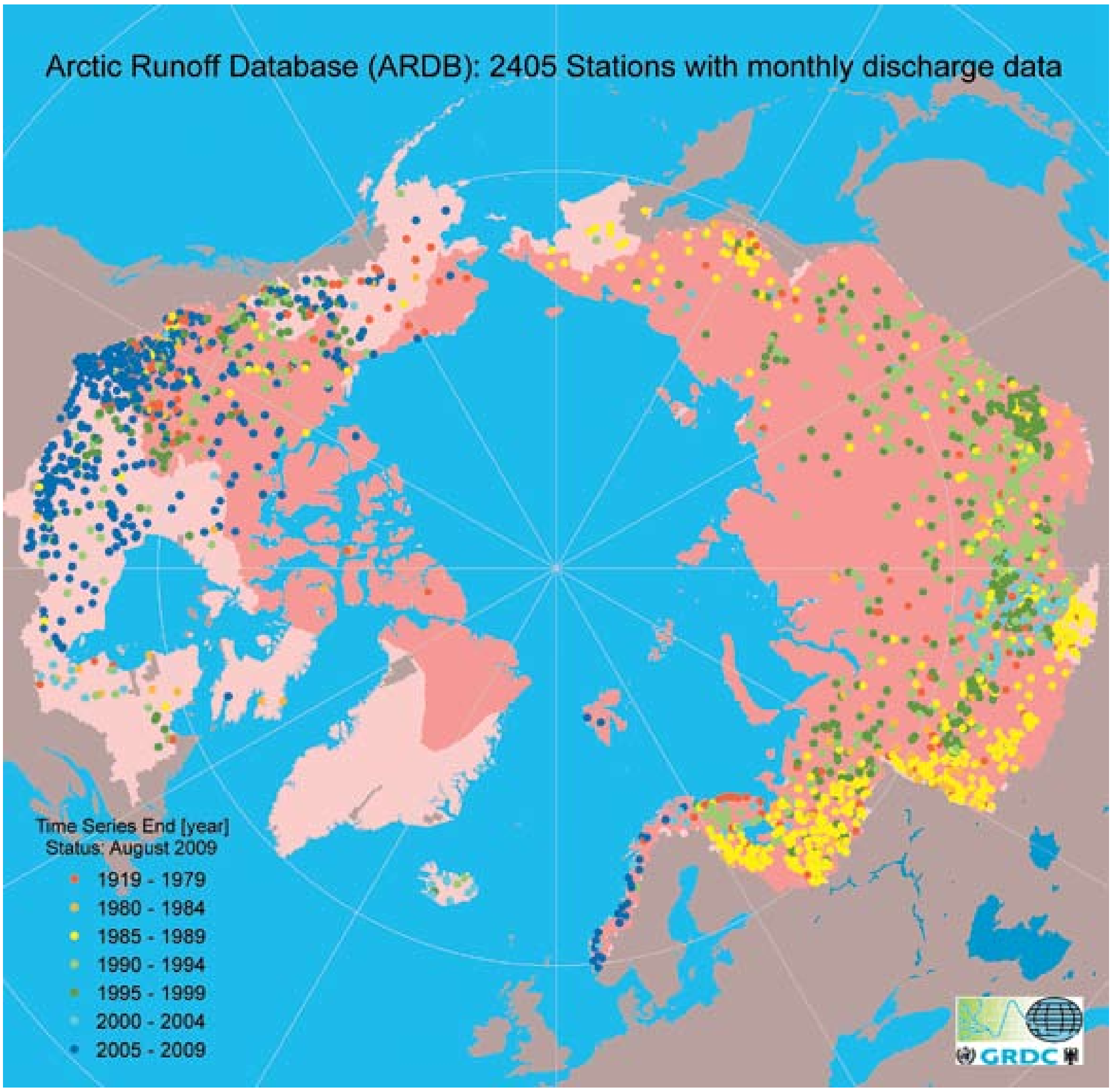


Figure 2.1 – Hydrological stations represented in the Arctic Runoff Data Base, maintained by the Global Runoff Data Centre (see: http://www.bafg.de/GRDC/EN/02__Services/05__Special__DBs/ARDB/ardb.html). The drainage basin of the Arctic Ocean occupies a total area of $18.9*10^6$ km^2 [Shiklomanov and Shiklomanov, 2003; Table 2 – but $22.5*10^6$ km^2 if adjoining areas are included, see their Table 1] and the total river runoff into the ocean is estimated to be 4270 km^3/yr. The network of hydrometric stations operated within the AO basin is very uneven and no observations are carried out in one-third of the region. The observation series are of unequal lengths, covering 55-65 years in Eurasia but mostly not longer than 40 years (2003) in the North American part of the Arctic drainage basin. Numerous gaps exist in the North American observation records, particularly in Canada, where many observations at hydrometric stations are carried out only during the warm period of the year.
Source: Global Runoff Data Centre

Status of Hydrological Monitoring in the Arctic

Access to comprehensive and reliable data sets on Arctic hydrology is of crucial importance for studies focusing on the role of the Arctic in the climate system. The rivers draining to the Arctic Ocean redistribute moisture from temperate regions to the high latitudes, and also connect very large and heterogeneous areas to the Arctic Ocean and its shelf seas.

The Arctic Runoff Data Base, ARDB, which is collected and maintained at the Global Runoff Data Centre, GRDC, in Koblenz, Germany, provides station information and data series of runoff gauging stations in the Arctic region. With more than 2400 stations represented (Figure 2.1), this is the most complete international dataset on daily (1024 stations) and monthly (2405 stations) runoff in the Arctic. Another service, maintained by the University of New Hampshire, USA, provides freely available pan-Arctic river runoff data from nearly 60 stations, in near-real time.

Although Arctic nations currently expend about $100 million annually on the collection of hydrologic data, the number of sites at which data are collected has been declining (Figure 2.2). Many sites with long-term records have been discontinued in the past several years as funding has failed to keep pace with costs. As development and resource extraction in the Arctic increases, the need for hydrologic data will increase.

In the United States, the U.S. Geological Survey (USGS) is the primary agency that monitors streamflow; although many of these stream gauges are funded through partnerships with other Federal, State, and local agencies. Throughout the U.S. from 1980s through 2000, about 1,790 stream gauges, including a few in the Arctic, with more than 30 years of record, were decommissioned due to a lack of funding. To reduce the loss of critical stream gauges, the US Congress funded the National Streamflow Information Program (NSIP) of the USGS in 2001. That funding allowed the USGS to add about 500 stream gauges to the network, but funding has not kept pace with costs and in 2004 and 2005 there was a net loss of about 150 stream gauges. The USGS currently operates more than 120 stream gauges in Alaska, however, fewer than 20 are funded through NSIP and the rest rely on funding partners.

In Canada, the majority of climate, hydrometric and water quality stations are located in the southern half of the country, where the population and economic pressures are greatest. As a result, the adequacy of the network to describe hydrological and climatological characteristics, both spatially and temporally, decreases significantly in the northern part of the country and is particularly poor in the Canadian Arctic Archipelago. For example there are significant limitations in Canada's ability to estimate freshwater streamflow within Arctic Ocean tributaries, past, current or future. There is relatively good information on flows from large rivers (f.ex. the Mackenzie) which may constitute roughly 60-80% of discharges to the Arctic. There is great uncertainty associated with the estimates

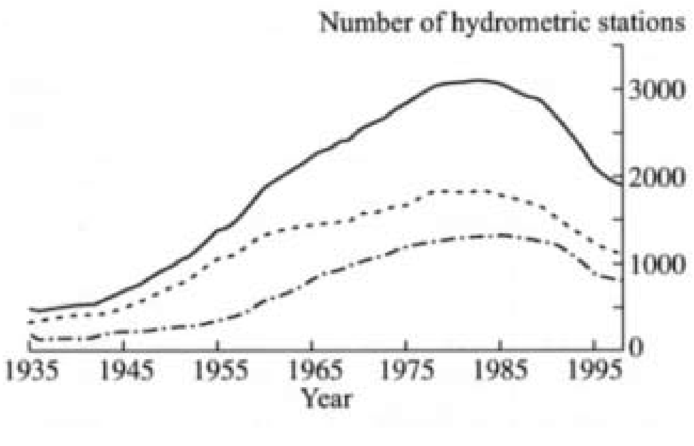


Figure 2.2 – Changes in the number of observational points for the river runoff into the Arctic Ocean from 1935 to 2000 according to data from the State Institute of Hydrology, Russia, the Environment Agency of Canada, and the U.S. Geological Survey. Solid, dashed and dot-dashed lines are the entire Arctic drainage basin and its Russian and North American parts, respectively. *From:* Shiklomanov & Shiklomanov (2003).

of ungauged streamflow to the Arctic Ocean, largely due to the paucity of monitoring. Furthermore, streamflow estimates for small catchments across northern Canada are particularly poor. Therefore present estimates of the total Canadian flow to the Arctic, and the proportion that is gauged, can currently be considered uncertain.

The discharge to the Arctic Ocean from Eurasia is better monitored than from North America because most of the river inflow is delivered through a small number of large rivers with long-term operating downstream gauges. Only 10 hydrological gauges are sufficient to capture 80% of the total Arctic Ocean drainage area in Russia. Hydrometric observations on small and medium size rivers in the Russian Arctic are sparse and ungauged or poorly monitored areas dominate many parts of the region. Over the last 10 years the accessibility of river discharge data for the pan-Arctic has been significantly expanded by the release and regular updates of the University of New Hampshire's R-ArcticNet database (http://www.R-ArcticNet.sr.unh.edu). However, sharp declines in Russian hydrometric gauging networks in the 1990´s and delays in data reporting hamper research progress. Since 2000 governmental funding of Russian monitoring networks has improved and as a result the number of operating gauges has stabilized or even slightly increased. There are still significant delays in the timely delivery of Russian hydrological data to the international research community and the Arctic Rapid Monitoring System for the pan-Arctic (ArcticRIMS, http://rims.unh.edu/) was developed to facilitate and accelerate data reporting for the most important Russian river gauges.

Patterns in the reported decline of monitoring have recently been analyzed, to see how they compare with the geographical distribution of observed and predicted Arctic-wide climate changes. Figure 2.3 shows how station density has changed since the 1970s, in relation to observed temperature change. The vertical axis is the fraction of stations with accessible data for 1995-1999, as a proportion of the stations with accessible data for 1975-1979. A fraction of 1 means that the station density is the same today, and a fraction of 0.2, for instance, means that only 20% of the stations operational in the 1970's still provided data in the 1990's. The horizontal axis shows the mean observed temperature increase during 1995-2002, relative to the 1961-1990 average. It is evident that the decline in network density has been greatest for four Eurasian basins. For the Kara Sea drainage, data from 520 stations is no longer available.

Figure 2.4 shows the change in density of hydrological stations in the Arctic in relation to predicted 21st century temperature changes. The vertical axis again indicates the change in station density since the 1970's but the horizontal axis now shows the modeled temperature increase, for the 2050's and IPCC's A2 emission scenario. Here, it appears that the largest future temperature increase is expected in the four basins with the greatest decline in discharge monitoring, and that uncertainty of the future temperature change, as reflected by the range is also particularly large in these basins.

In order to quantify mass fluxes of, e.g., carbon and nutrients, water chemistry monitoring, used in concert with water discharge monitoring, is crucial. Unfortunately, such data for the Arctic region are even more sparse than runoff data. A recent study has quantified the spatial and temporal extent of water chemistry monitoring of four important constituents in the pan-Arctic drainage basin. Results indicate that accessibility to water chemistry data is severely lacking, both spatially and temporally (Figure 2.5). Accessible nitrogen and phosphorus monitoring covers 62% of the non-glaciated Arctic Ocean drainage basin area, sediment monitoring covers 63%, and carbon monitoring covers only 51%. The relatively low accessibility to water chemistry data means that important budgets of carbon, sediment and nutrients cannot be closed for large areas of the Arctic.

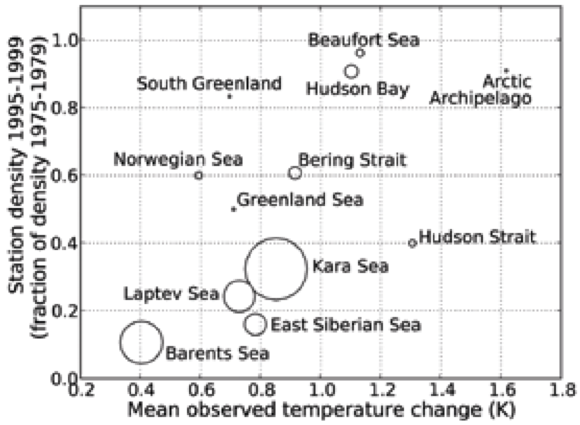


Figure 2.3 – Change in density of hydrological stations in relation to observed temperature changes. Circle sizes correspond to the absolute number of closed stations. *Adapted from:* Bring and Destouni (2008).

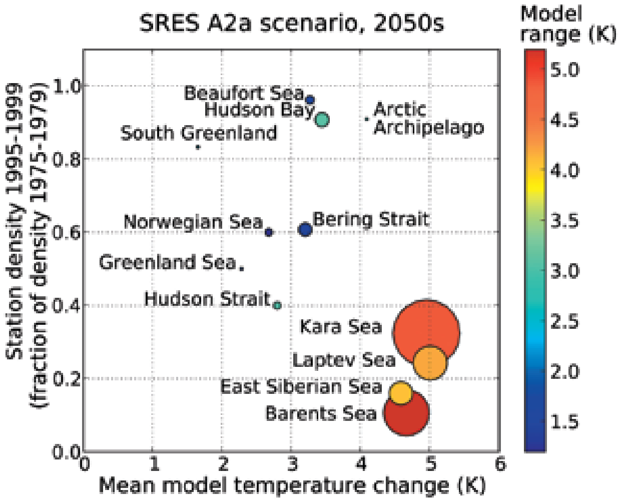


Figure 2.4 – Change in density of hydrological stations in relation to predicted 21st century temperature changes. Circle sizes correspond to the absolute number of closed stations and the colour of the circles indicates the range in temperature between the three models used for the study. *Adapted from:* Bring and Destouni (2008).

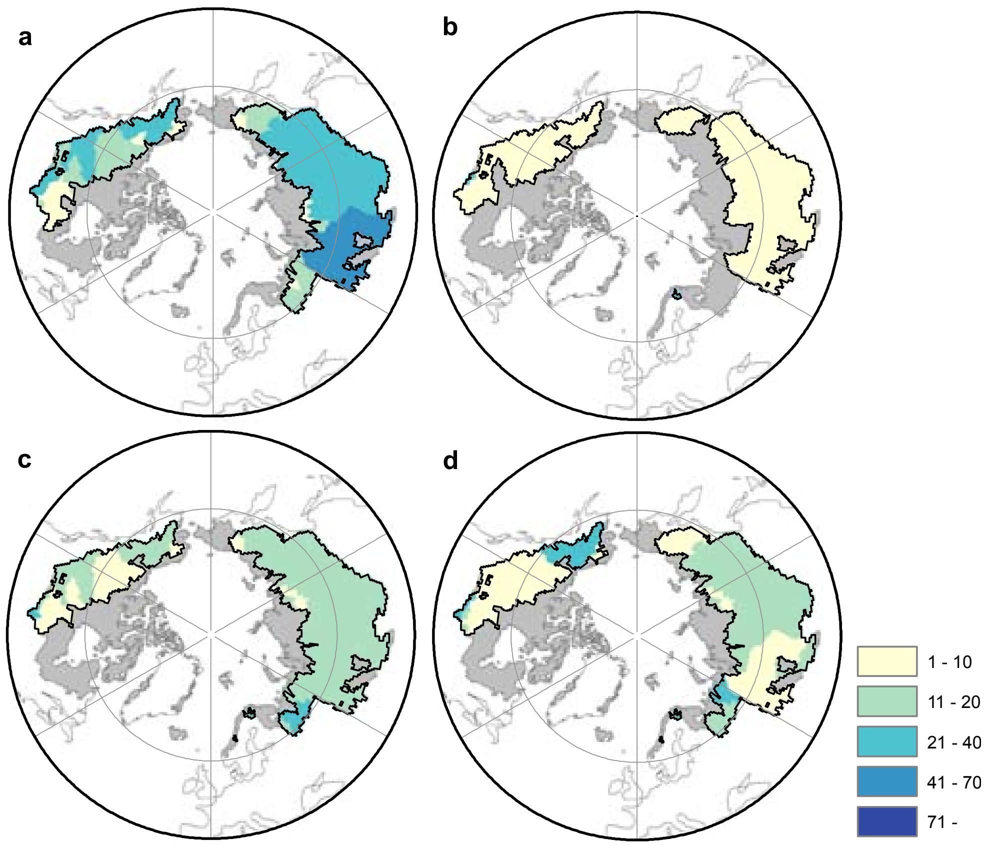


Figure 2.5 – Overview of the maximum length of accessible data series (years) for pan-Arctic monitoring of (a) sediment, (b) carbon, (c) nitrogen and (d) phosphorus. *Adapted from:* Bring and Destouni (2009).

2.2. Loss of Monitoring Capacity Hampers Advance in the Understanding and Interpretation of the Causes and Impacts of a Changing Arctic Hydrosystem

Improved knowledge of the Arctic Hydrological Cycle is of crucial importance to efforts aimed at understanding the Arctic as an integrated system. The Arctic is unlikely to ever have the density of streamflow monitoring sites seen in more developed areas. Poorly developed infrastructure and extreme conditions make access and data collection using traditional methods a challenge. Large ungauged areas will continue to exist and as such, a strategy for maximizing the value of data collection is called for. Within constraints of funding partners, a network should be designed that adequately characterizes defined sets of landscape variables so that runoff models may be developed that utilize existing data and new, remotely sensed data. Arctic-HYDRA offers the opportunity to examine characteristics of gauged basins in the pan-Arctic and develop a network analysis that identifies gaps and potential redundancies in coverage of various landscape types. Such a network analysis would allow the individual hydrological services agencies to best prioritize locations for additional data collection that maximizes the value of the data to the overall network.

In view of the sparse (and declining) station networks, scientists are forced to rely on results, often divergent, from runoff models to analyze the state and variability of the land surface hydrologic cycle across the pan-Arctic system. Land Surface Models (LSM´s) are forced with gridded time series of downwelling shortwave and longwave radiation, precipitation, near-surface winds, humidity and surface-air temperature. Output variables include soil moisture and temperature, snow water equivalent, runoff, latent and sensible and ground heat fluxes and upward shortwave radiation.

Although models offer great potential for enlightenment regarding large scale hydrological changes, recent modelling efforts have revealed substantial deficiencies in the ability of models to capture various key aspects of pan-Arctic hydrology (Figures 2.6 and 2.7). Comparison between results from five different LSM´s revealed up to a 30% difference in annual partitioning of precipitation between evaporation and runoff within major Arctic watersheds such as the Lena. Capturing the correct baseflow of the large rivers is a consistent problem and modeled hydrographs are often out of phase, peaking too early in comparison with observations (Figure 2.6). Sufficient monitoring data is critical for narrowing these ranges in estimates.

Models used to produce the results shown in Figs. 2.6 and 2.7:

- CHASM (Combined Hydrology and Stability Model) – Bristol Innovations Software (UK)
  http://chasm.info/
- NOAH (The Community NOAH Land-Surface Model) – NOAA (US)
  http://www.emc.ncep.noaa.gov/mmb/gcp/noahlsm/README_2.2.htm
- CLM (Community Land Model) – UCAR (US)
  http://www.cgd.ucar.edu/tss/clm/components/hydrocycle.html
- VIC (Variable Infiltration Capacity Macroscale Infiltration Model) – University of Washington (US)
  http://www.hydro.washington.edu/Lettenmaier/Models/VIC/
- ECMWF (European Centre for Medium-Range Weather Forecasts) – Reading (UK)
  http://www.ecmwf.int/about/

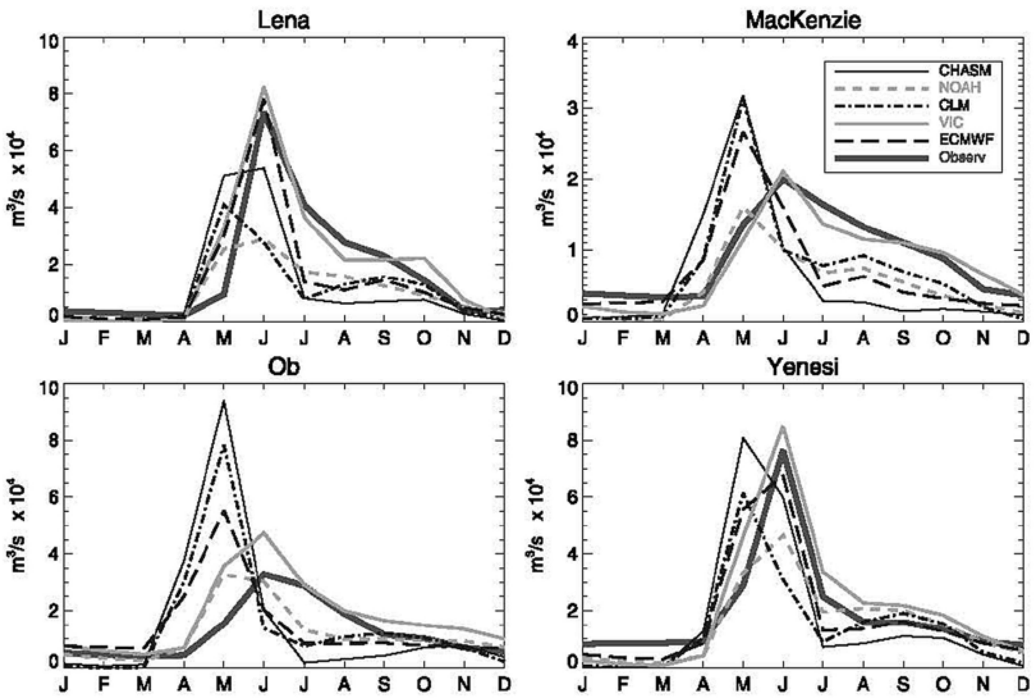


Figure 2.6 – Modelled mean monthly discharge (five different models) in the four main Arctic river basins compared with data from observations. *From:* Slater et al. (2007).

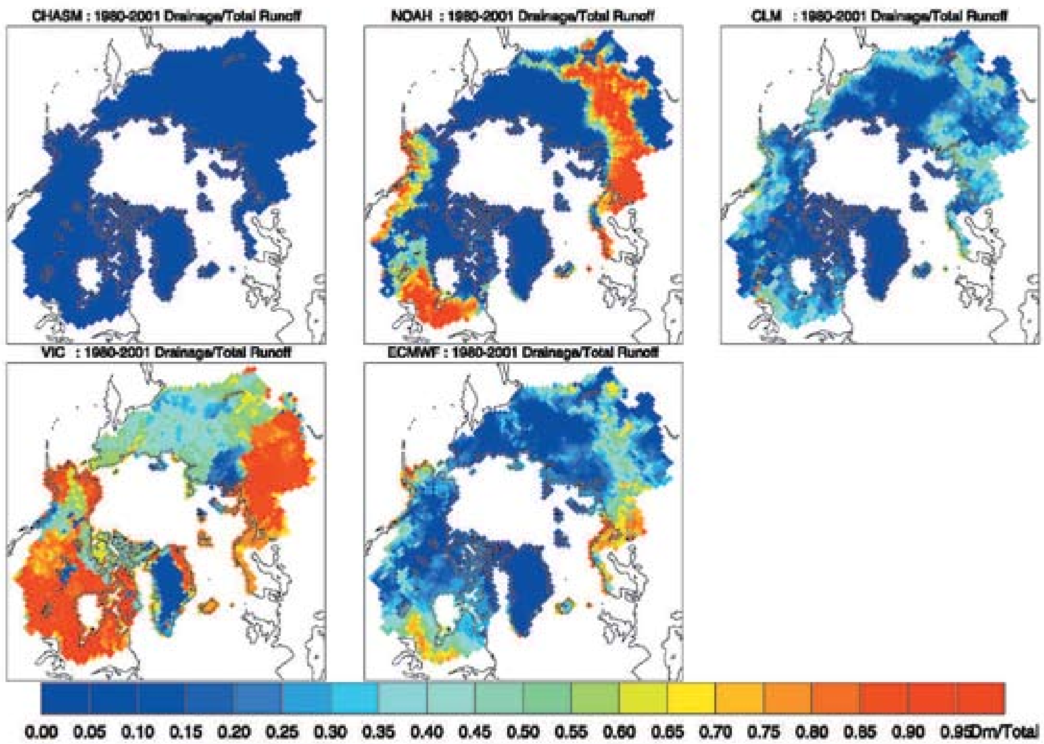


Figure 2.7 – Annual average of drainage from the base of the soil column as a proportion of total runoff. One of the models (the VIC model) produces strikingly higher soil drainage than the other models, reflecting the ability of this model to allow for soil infiltration during the spring snowmelt period. *From:* Slater et al. (2007).

Extensive comparison of LSMs has been carried out under the Project for Intercomparison Study of Land Surface Parameterization Schemes (PILPS). Some results from one such study are summarized in Figures 2.8 and 2.9, comparing simulations of land surface processes from 21 models run for the Torne-Kalix (58,000 km^2) catchment in Northern Scandinavia. From Fig. 2.8, a large scatter in the predicted March snow water equivalent (SWE) is evident, with averaged modeled SWE over the basin ranging from 119-268 mm. Models with high latent heat flux and an average downward sensible heat flux (a heat source for the surface) tend to have the lowest snow accumulation. Fig. 2.9 shows that the modelled mean annual runoff in the Torne-Kalix basin is found to differ substantially, from 301 to 481 mm. For some models subsurface runoff dominates, while for others, runoff is solely from the surface. Differences in modeled snow accumulation and surface-subsurface runoff partitioning contribute to large variations in the shapes of mean hydrographs.

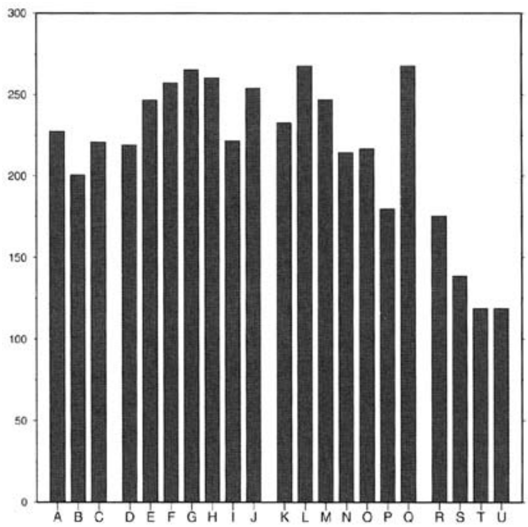


Fig. 2.8 (left) – Basin averaged snow water equivalent (SWE) for March from the 21 PILPS 2e land surface models (listed as A-U), over the period 1989-1998. *From:* Bowling et al. (2003).

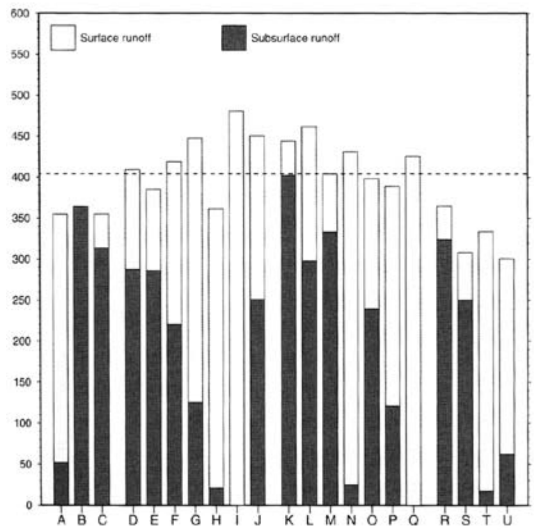


Fig. 2.9 (right) – Total basin mean annual surface and subsurface runoff from the 21 PILPS 2e land surface models (listed as A-U) over the period 1989-1998. The dashed horizontal line is the observed mean annual runoff at the mouths of the Torne and Kalix rivers combined. *From:* Bowling et al. (2003).

3.

Arctic-HYDRA: Integration and Implementation

3.1. Arctic-HYDRA: An Integrated System for Arctic Hydrology studies

Previous sections have highlighted the importance of hydrological studies for our understanding of past, present and future change in the Arctic. Moreover, further research progress is hampered by the decline in monitoring systems and participants in Arctic-HYDRA are thus proposing to launch a new research effort focusing on the following major overarching questions:

- **What is the role of the unified Arctic Hydrological Cycle in the global climate system?**
- **What are the feedbacks of changes in the Arctic Hydrological Cycle on the regional and global climate systems?**
- **What are the impacts of changes in the Arctic Hydrological Cycle on biology, biogeochemistry, and human society?**

The Arctic-HYDRA programme will form a large umbrella for hydrological research in the Arctic. As a multidisciplinary effort, it will link hydrology with many other fields of science in geophysical, environmental and social sectors. The spatial focus is the Arctic Ocean drainage basin, but climate, ocean and land-atmosphere processes connect Arctic-HYDRA with global studies. The initial networking phase of the programme was contemporaneous with the International Polar Year (IPY) period 2007-2009, combining various project ideas submitted to the IPY management office.

Given the scope of these objectives and the relatively short time-frame of the IPY, Arctic-HYDRA was also conceived to form part of the parallel longer term (10-15 yr) objectives of the ICARP-II (International Conference on Arctic Research Planning) and its Working Group 7 project, "Terrestrial Cryospheric & Hydrologic Processes and Systems". Thus, the Arctic-HYDRA consortium has been using IPY as a steppingstone to longer-term, comprehensive water cycle studies (e.g. ICARP-II) and within ISAC (International Study of Arctic Change).

As an extensive and multi-dimensional activity Arctic-HYDRA calls for integration. There are many possibilities to implement integration and gain synergy: between operational hydrological services, between disciplines, between regions, between data controlling systems – and between combinations of these components. Effective use of integration is an important strategic goal of Arctic-HYDRA, and it can be applied widely within the programme.

Figure 3.1 illustrates the principle of an integrated hydrological system, a concept that has been developed for the planning of Arctic-HYDRA. The basic blocks of this concept are observation systems, process studies, models, and data-information systems that are effectively linked to produce synergy benefits. Within the framework of this system, Arctic-HYDRA consists of a core network for observation of the Arctic Hydrological Cycle (AHC), coupled with a suite of intensive, focused process studies that are based on in-depth measurements and modelling of the individual components of the AHC. Furthermore, large scale hydrological models and data assimilation techniques will be developed to generate a comprehensive, integrated description of the AHC including the key variables necessary to quantify feedbacks between the atmosphere, cryosphere and the oceans. The project will establish links with other projects with focus on meteorology, climatology, the cryosphere (including permafrost, snow cover and glaciers), the biosphere and on societal issues affected by the AHC.

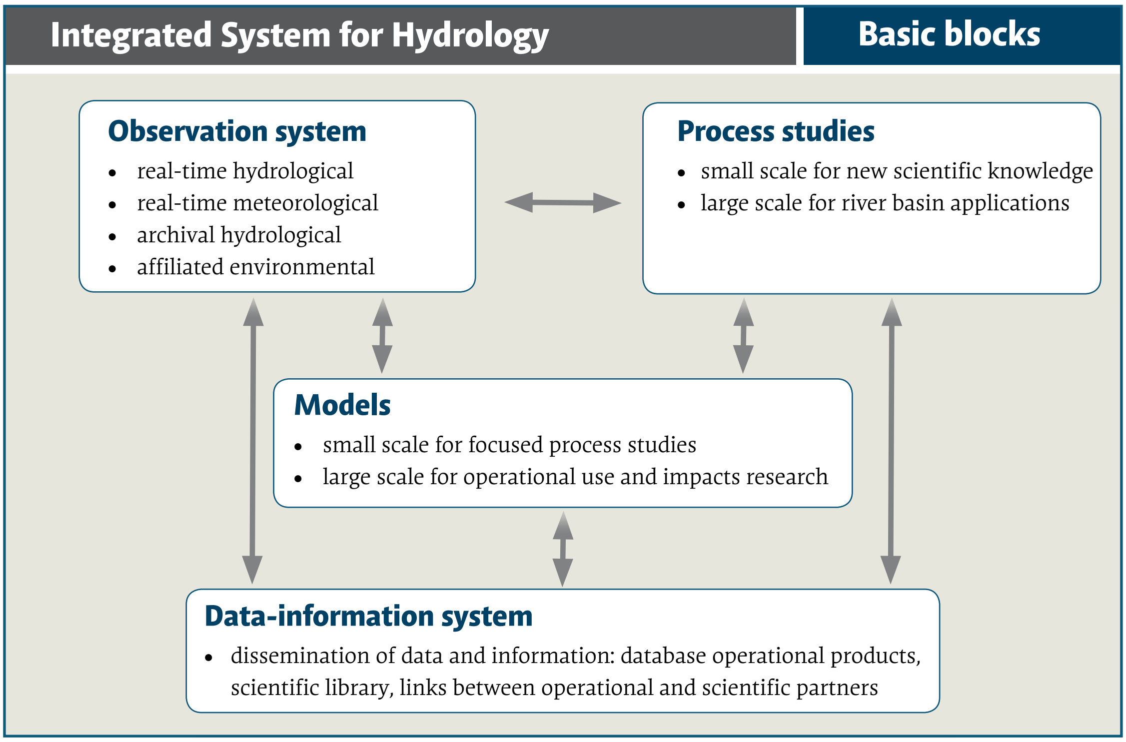


Figure 3.1 – Basic components of the Integrated System for Arctic Hydrology.

The basic blocks of the integrated hydrological system interact at several levels. The monitoring and data systems continuously transfer almost real-time data into operational hydrological models, and if models diagnose some data as inconsistent, this feedback is communicated into the data and monitoring systems. Most ground observations are point measurements, while models produce regional values for precipitation, snow, evaporation and other variables. As wide scale models also simulate run-off for a high number of sub-basins, in-situ measurements are not always needed. On the other hand, real-time observations at important sites keep the status of large scale models correct. Satellite images of snow cover are used in the snow calculations of hydrological models. Good quality geo-information on water resources is essential basic information for hydrological models, and map interfaces have proven to be applicable, informative and user friendly. The list of examples could be continued.

In addition to the operational components (observation, real-time modelling and data systems), the integrated concept includes process studies. Process studies are made for various purposes, but two main objectives and categories can be marked out. On one hand, large scale process studies aim at better modelling at a river basin scale. This work can be considered as model development, and to be successful, it should seek for balance between relevant science aspects and simple, applicable solutions. On the other hand, small scale process studies produce new information on hydrological processes. During the project phase, large and small scale studies are separate processes, but in the long run, they interact. Thus both categories of process studies are linked with operational modelling and furthermore with observation and data systems. Figure 3.2 shows some main interactions within the integrated hydrology system.

The above discussion emphasises that structures and contents of monitoring programmes should support both modelling and process studies, and vice versa, new scientific knowledge should be used for the optimization of monitoring systems. This integration is cost effective – both from the point of view of systems operation and scientific relevance.

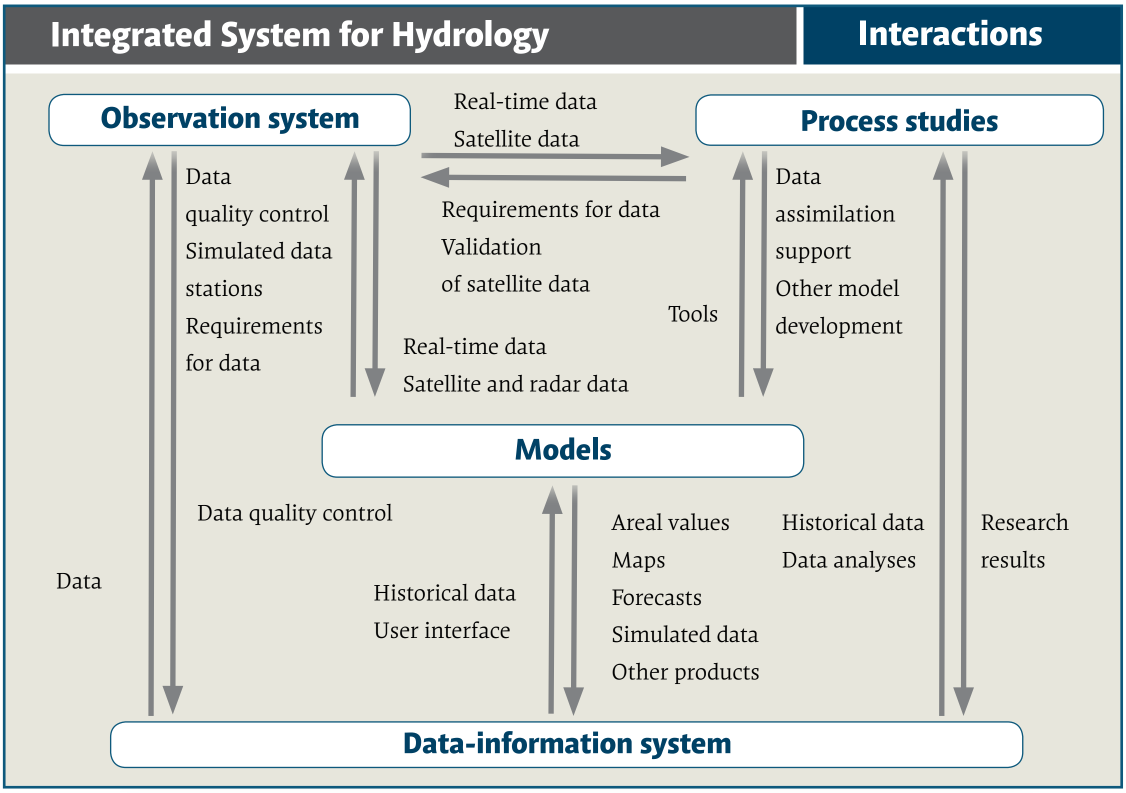


Figure 3.2 – Interactions between the main components of the Integrated System for Arctic Hydrology.

3.2 Components of the Integrated System

Observation System

There are well-recognized uncertainties in observations of many elements of the Arctic Hydrologic Cycle including evapotranspiration, precipitation, soil and groundwater. At the same time river discharge as an integrated characteristic of hydrological changes is one of the most accurately measured components of the cycle. Recent comprehensive assessment of river discharge accuracy for large Russian rivers showed that uncertainty of annual discharge is only ± 2-7%.

Despite the value of existing discharge information (Figure 3.3), ungauged or poorly monitored areas dominate many parts of both the North American and Eurasian Arctic, as discussed in Section 2.1. During the last decade, the accessible discharge coverage for the pan-Arctic was significantly expanded by releasing the R-ArcticNet database (http://www.R-ArcticNet.sr.unh.edu). However, recent sharp declines in Russian and Canadian hydrometric gauging networks and delays in data reporting, especially for Russia, hamper the research progress. Sparse or lacking monitoring networks in the northern, remote regions, experiencing most dramatic climate changes (IPCC, 2007; ACIA, 2005) constitute another major gap in our knowledge (Section 2.1). The similar situation is typical for other ground observational networks.

During the last decades, significant progress has been achieved in remote sensing technology. Remote sensing products can provide critical observational support to study the hydrological cycle in the pan-Arctic and can reveal complex spatial variations that cannot be readily obtained through traditional in situ approaches. The precipitation data from the Global Daily and Monthly Merged

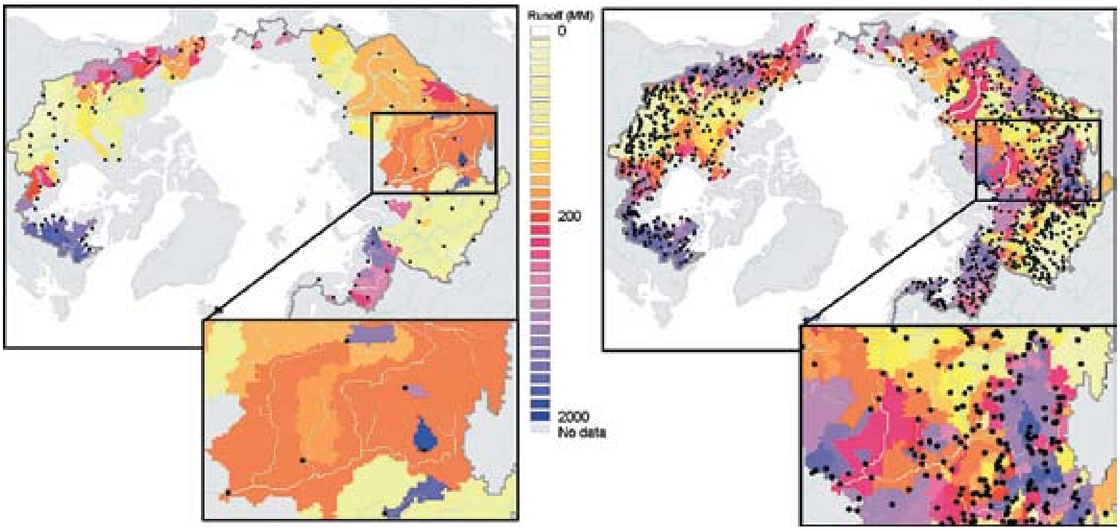


Fig. 3.3 - Long-term mean annual runoff in the pan-Arctic from observational data. This graphic is based on data from the Global River Discharge Database RivDis v1.0 [UNESCO/University of New Hampshire (1996) - data from 1998] and from the R-ArcticNET v4.0 database: A Regional, Electronic Hydrometeorological Data Network For the pan-Arctic Region [University of New Hampshire (2005) - data from 2006]. Only gauges and watersheds larger 5000 km^2 are shown. *From:* Shiklomanov et al. (in press).

Precipitation Analyses being produced by the Global Precipitation Climatology Project (GPCP) along with snow water equivalent information from active and passive microwave platforms (SMMR-SSM/I, AMSR-E) are very important to improve our knowledge about precipitation and spring snow storage across the pan-Arctic. Satellite altimetry over lakes and reservoirs, started in the 1990's, is another critical instrument to track changes in water level/storage of medium and large water bodies and is an important complement to ground based stations. Remote sensing information characterizing the conditions and changes in land cover is very important for the understanding of large-scale hydrological processes.

There is a clear need to establish a more balanced operational system for the monitoring of Arctic hydrology. An important contribution in this direction will be the Arctic Hydrological Cycle Observing System (Arctic-HYCOS), based on the WHYCOS concept developed by WMO, which is intended to become the basic monitoring component within Arctic-HYDRA (see section 3.4).

The main goal of Arctic-HYCOS will be to improve monitoring, data accuracy, availability and dissemination for the pan-Arctic drainage basin. To address this goal the HYCOS will be organized around several research objectives:

- Develop an optimal design for hydro-meteorological monitoring networks to capture the essential variability of the Arctic hydrological system and to enable accurate and efficient assessment of water cycle change.
- Estimate uncertainty of available in-situ and remote sensing data, including analysis of accuracy and systematic errors of new observational technologies.
- Develop an integrated pan-Arctic data consolidation and analysis system for the water cycle, uniting data from in situ, model, and remote sensing sources to generate an integrated view of key components of the pan-Arctic hydrosphere.

Process studies

Process studies have been an important focus of hydrologists studying the Arctic, yielding critical knowledge on dynamic linkages in the water cycle. However, the studies have generally been performed over short time periods and at a small scale and the short duration of most studies has resulted in failures to capture both the natural variability of processes and the occurrence of extreme events.

For process studies, the uniqueness of the Arctic lies in the presence and impact of permafrost, and in the extreme climates that generate the dominance of frozen soils. In the recent period of Arctic warming, there has been a renewed and growing interest in how the magnitude of many of these fluxes and storage domains may be changing and how these changes may influence other aspects of the hydrological cycle of these extreme cold environments. A number of relevant scientific issues can be raised due to the foreseen change – issues that have profound environmental and social importance.

Because of the increased awareness of climate change, there has been a reinvigorated realization of the need to enhance hydrological observations. Past simplified cause and effect approaches to addressing water resource issues are not going to be up to the task in a world with a changing climate. There is a need to develop physically based hydrological models that do not need to be calibrated. Such models need to be able to predict the hydrological response at watershed scales that can also be coupled with atmospheric models; to accomplish this, the research watersheds will need to be at least 10,000 km^2 or larger.

This will require process studies both over a wider range of spatial settings and longer durations where the natural variability is captured. From the point of view of data availability, the current status needs to be improved: although the hydrological data available from the northern research basins is the best available, it will not be sufficient to address issues pertinent to climate change. For example, data collection needs to be designed both spatially and temporally, so that basic monitoring stations (such as snow stations) can be located at or very close to research catchments, and high time resolution of modern equipment can be utilized during dynamic times of hydrological seasons.

The above conclusion stresses the need for integration between various scientific approaches and communities. Well designed and managed observation programmes and data systems are crucial for process studies and it is in the common interest of process studies and monitoring to develop technologies and practices for hydrological measurements. Coordination between basic monitoring and targeted monitoring experiments is important as well.

Models

Models serve both operational and scientific purposes, and their spatial scales and structures vary considerably. Both small and large scale models will be extremely important within the integrated Arctic-HYDRA programme.

Large scale modelling will be composed of river basin, regional and global/pan-Arctic models. As the Arctic Ocean drainage basin is very large, the current models should be mapped and evaluated, and the scientific community should set targets for pan-Arctic hydrological models and their integration with atmospheric and Arctic Ocean models. From the hydrological point of view, one of the greatest challenges is to include adequate ground and river system description into large scale models.

A basic model must also have high operational capacities. This type of a system can be continuously updated by use of real time observations, and it can assimilate satellite image information on snow, soil moisture or flooding areas to produce still more accurate and real time hydrological forecasts and reports. In this way observations (e.g. water level, snow depth or equivalent) produce relevant real time hydrological information covering large areas. A large scale modelling system can also be used to produce real time hydrological maps of spatial precipitation, spatial temperature, water equivalent of snow, soil moisture, run-off etc., based also on real time or near real-time observations. The applicability of hydrological models is high – they can be successful e.g. in the simulation of climate change scenarios.

The Finnish National Watershed Simulation and Modelling System (WSFS) offers one example of this approach (www.environment.fi/waterforecast). The WSFS is used both for hydrological forecasting and warning, and simulation of the hydrological cycle (historical, real time, future scenarios). This system covers the whole country, and is automatically updated by real time observations, weather radar data, and satellite information.

Modelling systems benefit from all available geographical, hydrological and meteorological data as well as information on catchment area, basin subdivision, lake and river network maps and geographical data of lakes and flooding areas. A digital elevation map or area elevation information of the catchments is also needed to simulate the spatial distribution of precipitation and snow.

The above discussion serves to outline the strong and multi-level connections between modelling and monitoring. On the other hand, physically based modelling is an increasingly important tool in hydrological process studies. Operational modelling can be connected to the data-information system in a very effective manner. Thus the point of view of an integrated concept is relevant in many ways.

Data information system

As the core of an integrated system, the Arctic-HYDRA data-information system will operate a number of processes: data collection and transmission, data processing, scientific calculation applications, visualization applications, data storage (database), maintenance of a web-based scientific library, and updating and presentation of general programme information. The data-information system will also serve as the main user interface for Arctic-HYDRA.

The data-information system will communicate most of the scientific results achieved within Arctic-HYDRA. They will include: real time monitoring data, prediction of the AHC, assessment reports based on monitoring and modelling, and results of process studies.

The data-information system should include the following components:

- Local Area Networks in sub-regional centers, and in a Main Data-Information Centre
- Data Transfer Interface
- Flexible, secure and reliable software
- Relation database, and
- Wide Area Network for user communication.

New technologies

Newer technologies covering a wide range from ground measurements to remote sensing are continually being developed and tested to allow safer and more cost-effective monitoring, while at the same time improving accuracy and reliability of the data. Examples include fully automated and robust data collection and distribution systems designed for remote hydrological monitoring networks. These are operational as stand-alone units or as a network of systems, allowing for expand-ability for future sensor and station additions. Typical sensor configurations provide water level, discharge, precipitation, and water quality parameters such as turbidity, DO, temperature, pH and conductivity plus a wide array of meteorological sensors such as wind speed, wind direction, relative humidity, air temperature, barometric pressure, dew point, rainfall, and solar radiation. Such networks can be remotely managed from a PC and measured information can be e-mailed, or posted to a web or FTP site in real-time. Telemetry choices include VHF and UHF, Iridium, Inmarsat D+, GOES, ARGOS, Globalstar, Orbcomm, cellular phone (GSM or CDMA), and landline.

For deployment in water, environmental monitoring buoys have been designed for use in coastal areas, lakes, reservoirs and rivers. The measurement platforms can be configured with a wide range of sensors for monitoring weather, air & water quality, waves and currents. Special ice buoys with subsurface mooring systems have been designed for Arctic lake monitoring.

Acoustic Doppler technology is now in common use for measuring stream velocity in Europe and North America. This technology may also be incorporated with an instrument package that includes ground-penetrating radar and is mounted from a helicopter. This platform eliminates the need for human operations on the river surface during dangerous ice-break up conditions. Stage sensors now include both radar and laser technology as well as the traditional pressure transducers.

The Russian hydrometeorological agency "Roshydromet" is realizing a project with support from the International Development Bank and a guarantee from the Russian government to organize several mobile groups equipped with these new instruments to provide better discharge observations on remote large and medium size rivers, particularly in Siberia.

The water balance of large river basins can now be monitored from space on timescales ranging from days to decades. The remote sensing techniques include satellite altimetry on surface waters (rivers and their tributaries, wetlands and floodplains) and space gravity missions that provide spatio-temporal variations of terrestrial water storage in soils and surface water reservoirs. These observations from space can significantly improve our understanding of hydrological processes affecting large river basins in response to climate variability.

Satellite altimetry missions launched over the last 15 years include ERS-2 (1995-), Jason-1 (2001-) and ENVISAT (2002-). The GRACE twin satellites launched in 2002 measure spatio-temporal variations of the gravity field with an unprecedented resolution (2°x2°) and precision (1 cm in terms of geoid height), over time scales ranging from 1 month to several years. The main application of GRACE is quantifying the land-based hydrological cycle, providing vertically integrated water mass change over large river basins with a precision of a few mm of water. Combination of observations from GRACE, satellite altimetry, and other space systems (e.g., active and passive radiometry, SAR and INSAR, etc.), used together with in situ measurements and hydrological modelling through assimilation schemes, will greatly improve our understanding of the continental branch of the Arctic Hydrological Cycle.

3.3. The Science and Monitoring Requirements of Arctic-HYDRA Demand an International Coordinated Effort Involving the National Operational Services, Agencies, Academia, Industry, Communities and International Bodies

Arctic-HYDRA represents an opportunity to advance the science of the Arctic Hydrological Cycle (AHC) and to establish a legacy of novel and comprehensive pan-Arctic observational networks that will contribute to global Earth observing systems.

The Arctic-HYDRA project is based on interdisciplinary integration within the field of operational and scientific hydrology. Furthermore, integration with biochemical, ecological and in general environmental studies related to the AHC will be implemented. In addition, traditional integration with meteorology and climatology, as well as with cryospheric clusters will be considered. There is a long tradition of co-operation and joint monitoring of the classical hydrological variables with those of the atmosphere and the climate as well as with snow measurements, permafrost and glacial mass balance measurements and modelling in many of the Arctic National Hydro and Hydro-meteorological Services (NHMS).

The original Arctic-HYDRA project idea (2006) was endorsed by the ICSU/WMO Joint Committee for the International Polar Year 2007-2009, which stated that the project idea 'includes very strong scientific, education and outreach components and demonstrates a high level of adherence to IPY themes and goals', and that the activity would represent a 'prominent and valued part of the IPY program'. The initial networking phase of Arctic-HYDRA (2006-2008) was funded by the Nordic Council of Ministers and received endorsement from the WMO Hydrology and Water Resources (HWR) Programme. The effort includes participation from all Arctic countries and Japan, involving all Arctic National Hydrological Services. Table 4.1 lists the primary partners of the Arctic-HYDRA effort and illustrates prominent international affiliations and linkages that have already been made.

To enable a wide list of hydrological and related applications, analyze water and energy cycle variability and change, develop meaningful seasonal predictions for mid- and high-latitudes, and generate less uncertain climate projections, a logical, efficient, all-encompassing multi-disciplinary system of observations, data (re-) analysis, modelling, and interpretation is required. In practice, however, such a system cannot be designed and built using a top-down approach, and, therefore an attempt will be made by Arctic-HYDRA to integrate useful contributions by already existing programs and to contribute to studies of water and energy cycle on a global scale. Due to the importance of the Arctic and its hydrological cycle, Arctic-HYDRA will be an important contributor to many programs and projects involved in global change research.

Arctic HYDRA will contribute to the WCRP CEOP (Coordinated Energy and water cycle Observing Programme), initially developed by the WCRP Global Energy and Water Cycle Experiment (GEWEX). CEOP has been accepted as the main water data processing engine of the future Global Earth Observations System of Systems (GEOSS). Arctic-HYDRA data will contribute both directly and also in processed way, through CEOP, to the goals of the Earth System Science Partnership (ESSP) Global Water System Project (GWSP).

Members of the Northern Research Basins (NRB) Working Group, the IHP northern network, are key proponents of Arctic-HYDRA. The Arctic Monitoring and Assessment Programme (AMAP), through

Arctic-HYDRA Lead Partners

Name	Organization	Country
Árni Snorrason	Icelandic Meteorological Office	Iceland
Charles J. Vörösmarty	City University of New York	USA
Georgia Destouni	Stockholm University	Sweden
Markku Puupponen	SYKE, Freshwater Centre	Finland
Stein Beldring	Norwegian Water Resources and Energy Directorate	Norway
Alain Pietroniro	National Water Research Institute	Canada
Alexander Shiklomanov	University of New Hampshire	USA
Arne Tollan	Norwegian Water Resources and Energy Directorate	Norway
Arvid Bring	Stockholm University	Sweden
Barry Goodison	Environment Canada	Canada
Bent Hasholt	University of Copenhagen	Denmark
Dan Rosbjerg	Technical University of Denmark	Denmark
Douglas Kane	University of Alaska Fairbanks	USA
Eduard Sarukhanian	WMO	WMO
Fred Wrona	Environment Canada	Canada
Igor Shiklomanov	State Hydrological Institute, St. Petersburg	Russia
Jean-Guy Zakrevsky	Environment Canada	Canada
Jim Bogen	Norwegian Water Resources and Energy Directorate	Norway
John Pomeroy	University of Saskatchewan	Canada
Jonathan Pundsack	Arctic CHAMP, University of New Hampshire	USA
Jukka Käykhö	University of Turku	Finland
Larry Hinzman	University of Alaska, Fairbanks	USA
Lars Otto Reiersen	AMAP	Norway
Odd Rogne	AMAP	Norway
Richard Lammers	University of New Hampshire	USA
Steven A. Frenzel	USGS Alaska Science Center, Water Resources Office	USA
TBD	ASIAQ	Greenland
Terry Prowse	University of Victoria & Environment Canada	ICARP-II
Tetsuo Ohata	JAMSTEC	Japan
Thorsteinn Thorsteinsson	Icelandic Meteorological Office	Iceland
Ulrich Looser	Global Runoff Data Center	Germany
Valery Vuglinsky	State Hydrological Institute	Russia
Verne Schneider	USGS	USA
Vladimir Ryabinin	WCRP/CliC	WMO
Volker Rachold	IASC - International Arctic Science Committee	Sweden
Wolfgang Grabs	WMO HWR	WMO
Yuri Sychev	Polar Foundation	Russia

its affiliation to the Arctic Council, is the only regional environmental programme enjoying intergovernmental status. Recognition of the importance of the Arctic hydrology for global change stimulates interest and involvement of the World Bank and its subsidiary bodies in supporting the monitoring of rivers delivering freshwater to the Arctic Ocean.

Arctic-HYDRA will facilitate the development of both research and sustained hydrological observations in the Arctic, to the benefit of climate change diagnosis and climate prediction. Thus, Arctic-HYCOS, the main operational branch of Arctic-HYDRA observations, will not only be a regional constituent of the WHYCOS, but also a crucial component of the Global Climate Observing System (GCOS) and Global Terrestrial Observing System (GTOS), and a crucial contributor of the Coastal Module of the Global Ocean Observing System (GOOS). Implementation of Arctic-HYCOS is called for in the GCOS Implementation Plan. Worldwide coordination of this work is ensured through the Global Terrestrial Network for Hydrology (GTN-H), coordinated by the WMO Water Resources Programme and the City College of New York.

Lack of adequate resources for sustained observing systems forces cognizant research programs and funders to initiate and support long-term monitoring through research observations. For example, Arctic-HYCOS was proposed by the WCRP Arctic Climate System Study (ACSYS) Project (1994-2003). Attempts to generate continuous support to most important observations are therefore made through coordination of efforts of main research and operational environmental programs, such as the Integrated Global Observing Strategy Partnership (IGOS-P). The WCRP/SCAR Climate and Cryosphere Project (CliC), jointly with its co-sponsor SCAR, leads the development of the IGOS Theme on Cryosphere. This Theme and as well the IGOS Integrated Water Cycle Observations Theme will provide the foundations for coordination of Arctic-HYDRA observations with the rest of hydrological and cryospheric programs.

As a regional activity, Arctic-HYDRA will contribute to goals of the International Arctic Science Committee (IASC) and its several programs such as the International Study of Arctic Change (ISAC). The Northern Eurasia Earth Science Partnership Initiative (NEESPI), a consortium of research projects interested in studying the manifestations of global change in the Northern Eurasia, is potentially a valuable partner for Arctic-HYDRA.

3.4. Implementation of the Arctic-HYCOS Observing System

The main activities of Arctic-HYCOS will be:

- To establish and operate regional networks for measuring basic hydrological components within the territory of the Arctic drainage basin. Existing observation networks should be fully utilized, and the decline of networks in some countries should be counteracted.

- To establish and operate a hydrological information system. The information system shall generate and provide regularly reliable data on the hydrological cycle, and information needed for water resources management and research. Data management practices must respect the WMO Resolution 25 on hydrological data exchange.

- To provide reliable assessments of freshwater inflow and energy flux into the Arctic Ocean in both the short and longer term. Longer-term objectives should include sediment transport and other selected water quality parameters.

The system will provide data collection, processing, storage and distribution in accordance with the appropriate procedures accepted by the countries of the region using WMO standards. It will provide hydrological information of high quality and processing and distribution will occur in near real-time (with no longer than a 1-month delay). The system will be based on existing appropriate national observation systems available in the Arctic countries, without duplicating them. A major part of the Arctic-HYCOS will be the Basic Network of Hydrological Stations (BNHS).

The BNHS should involve, firstly, the stations with long-term observation series covering at least 50 years on the large rivers discharging to the Arctic Ocean, on their tributaries as well as stations with long-term observation series on small rivers within the permafrost zone. The requirements of the participating countries and regional priorities would be the driving factors for the design of the network as well as for the selection of the variables for measurements and exchange. The stations to be included in the regional network would be identified jointly by the Hydrological Services of the participating countries, according to the established WHYCOS criteria.

The creation of a complete regional hydrological cycle observing system within the Arctic Region would take at least 8 to 10 years and therefore, the implementation of the Arctic-HYCOS project will have to be subdivided into several phases. The Arctic-HYCOS observation system should be managed by a Regional Centre, which would coordinate the regional co-operation activities.

The Arctic-HYCOS will be designed to take account of the requirements of the latest information technologies, means of communications and data transmission, including Internet and GIS-technologies. Innovative technology would also be used to transfer information and exchange data within the region, to reinforce the national and regional agencies concerned, so that they can improve their capacity to generate products needed by end users at the national and regional levels. Newer technologies are continually being evaluated to allow safer and more cost-effective monitoring, while at the same time improving accuracy and reliability of the data. As the core observation network, Arctic-HYCOS provides an opportunity to expand the individual networks in a strategic manner such that each additional station describes a region or set of characteristics under-represented in the current compendium of stations. To enhance these networks stations that are currently not in service due to funding constraints may be reactivated so that previous data from such sites can be used to analyze trends. As stations are added to networks, telemetry will be incorporated so that the data are available in near real time.

From the point of view of integration, the Arctic-HYCOS observation system will form the main source of input for process studies as well as for modelling. As the monitoring network has good spatial coverage, and data are collected in almost real time, some new possibilities will be opened both in process work and modelling. Real time data and up-to-date data reports will highlight the importance of data-information system for wide groups of interest. Thus the observation system will have strong and diverse links with all other main components of the Arctic-HYDRA system.

3.5. Arctic-HYDRA Workshops and Outreach Activities

Execution of a viable plan that functions across borders requires broad input, assessment, review and revision. Implementation of these synthesis activities will require substantial preplanning and coordinated organization throughout the exercise. A series of workshops will be convened to assure the best approach is being applied to meet the stated goals. International workshops will be organized yearly to examine specific aspects of the scientific questions defined in Arctic-HYDRA. Advanced graduate students, who will benefit from the close interaction with experts from the essential disciplines, will participate in each workshop. The product of each workshop will be a high quality, multi-authored report detailing the outcome of the particular workshop theme.

Additionally, Arctic-HYDRA will create opportunities for creating a more comprehensive understanding of spatial and temporal variations in hydrological processes. This understanding will culminate primarily through semi-annual workshops focused upon specific scientific questions. Biannual conferences dedicated to examining the circumpolar inter-connections of the hydrological cycle will yield a greater understanding of the role of the Arctic water cycle in global climate dynamics. For example, inter-comparison of coordinated watershed studies on such processes as snowmelt or rainfall, which are then analyzed with complementary satellite remote sensing imagery, would enable an accurate assessment of mass and energy fluxes on pan-Arctic scales.

The project synthesis, integration, and outreach issues are complex and multi-faceted. Necessary collaboration and coordination among and between project participants and other related research activities towards a broad-scale understanding of different system connections through the freshwater cycle of the pan-Arctic will be supported by dedicated involvement and efforts of an international Arctic-HYDRA secretariat. The secretariat will foster cooperation between partners in USA, Canada, the Nordic Countries, Russia, Greenland and form liaisons with partners in other countries involved in Arctic studies. The secretariat will be structured to foster not only research, but also graduate education, post-graduate training and outreach to policy-makers and the public. Data dissemination and informative websites and newsletters will help to broaden interest in Arctic environmental change in general, and provide updates on specific research programs.

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The Chukochiye River meanders through the tundra of the Kolyma delta region, Siberia, Russia

Scientific goals of Arctic-HYDRA:

- To characterize variability in the Arctic Hydrological Cycle (AHC).
- To examine linkages between atmospheric forcing and continental discharge to the ocean.
- To assess the historical response of the Arctic Ocean to variations in freshwater input from rivers and net precipitation over the ocean.
- To attribute to specific elements of the AHC or to external forcing the sources of observed spatial-temporal variability in the land-ocean-ice-atmosphere systems.
- To detect emerging changes in the contemporary state of the AHC in near real time and to interpret such changes in a broader context.