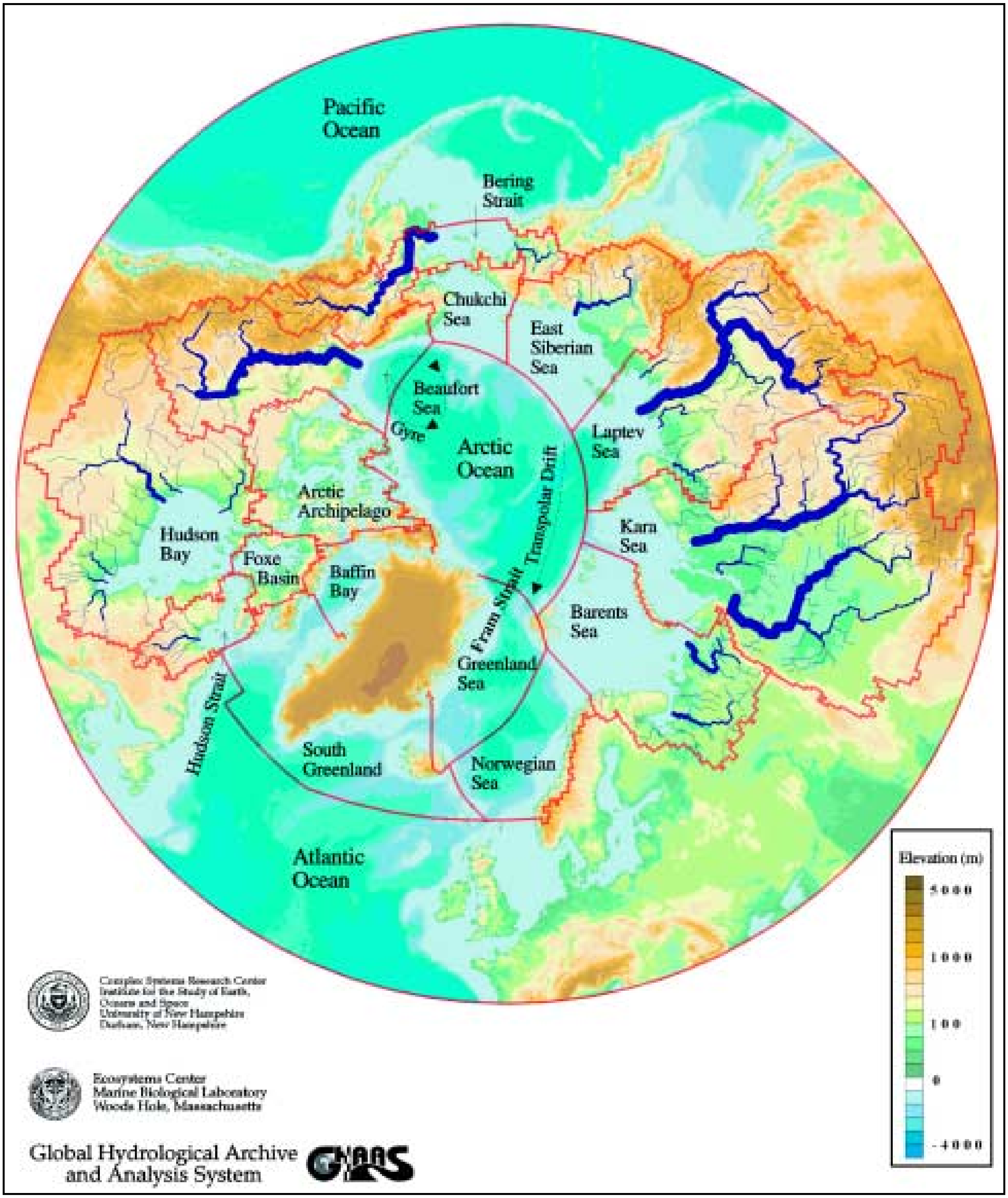


*Figure 3-1. A view of the pan-arctic region, showing the contributing drainage basin of the Arctic Ocean and its numerous seas. Blue lines represent relative river discharge. The coupling of atmosphere-land-ocean is strong, and knowledge of the region's hydrologic cycle is central to our understanding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

3

# Role and Importance of Water in the Arctic System

## The Integrated Water Cycle of the Pan-Arctic

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

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

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

## Land

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

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

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

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

## Box 3-1. Unique Water Cycling in the Arctic

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

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

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

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

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

### Atmosphere

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

## Ocean

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

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

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

## Importance of Arctic Hydrology to the Arctic System

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

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

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

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

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

## Importance of the Arctic to the Earth System

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

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

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

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

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

**Key Gaps in Current Understanding and Needed Studies:**

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

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

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