

Alteration of land surface hydrology in the Arctic imposes both direct and indirect effects on "downstream" components of the arctic system. Important direct impacts are conveyed on terrestrial ecosystems and human society. Indirect effects constitute feedbacks through which hydrological changes in turn cause changes to atmosphere and ocean dynamics. We treat two broad classes of feedback in this chapter, one involving the physics and biology of the Arc-

tic and another considering human dynamics.

Recent hydrological changes impact permafrost structure and stability, the distribution of arctic vegetation, and soil processes including CO₂ flux (Table 5-1). Data from an extensive set of boreholes indicate that permafrost temperatures have warmed 2 to 4°C across the broad region of North-

ern Alaska during the last century (Lachenbruch and Marshall 1986). Farther south in regions of discontinuous permafrost, 1 to 1.5°C of warming has been observed over the last 20 years (Osterkamp and Romanovsky 1999). In some places, the warming is sufficient to thaw the permafrost, resulting in significant landscape changes as massive buried ice melts. Where the thawed ground sinks below the water table, new swamps are created (Figure 5-1). In upland areas, drainage can be enhanced, converting wetlands to a drier ecosystem (Figure 5-2). Drier soils no longer support the plant and animal communities formerly adapted to live there—None of the many challenges to arctic ecosystems posed by climate change (Krajick 2001).

Recently observed changes in temperature, soil moisture, snow cover, and precipitation have resulted in spatially and temporally rich shifts in vegetation. Mosses and other tundra species insulate the ground and reduce active layer thickness (Luthin and Guymon 1974). When disturbed by fire or a warming climate, this ground cover is replaced by shrubs or even trees (Brown and Grave 1979). Local birch and black spruce trees have been advancing in some places. Field studies have



Figure 5-1. The hydrologic consequences of climate warming are very much site dependent. The Tanana Flats (Lat. 64°40' N Long. 147°50' W) is an area of rich permafrost and upwelling groundwater. As the permafrost degrades with climate warming, the surface collapses, and areas that were once birch and black spruce forests become flooded and are replaced by fens and bogs (photo from Jorgenson et al. 2000).

demonstrated a transition in land surface cover from graminoid-dominated to shrub-dominated tundra (Chapin et al. 1995, Henry and Molau 1997, Jones et al. 1997, Walker et al. 1999, Silapiswan in press), which could have important consequences for snow accumulation and winter biogeochemical processes (McFadden et al. 2001, Sturm et al. 2001, Liston et al. in press). Satellite remote sensing of NDVI (Normalized Difference Vegetation Index) records an increase in arctic plant growth and growing season between 1981 and 1991 that is consistent with an increase in shrubs (Myneni et al. 1997). A major challenge will be to monitor the progression of successional changes and their impact on seasonal evapotranspiration and runoff (Shiklomanov and Krestovsky 1988, Eugster et al. 1997, McFadden et al. 1998, Chapin et al. 2000), especially since vegetation changes occur on decadal time scales that are long relative to observational records,



Figure 5-2. Thermokarst formation near Council, Alaska, has resulted in variable impacts to the local hydrologic regime. New riparian channels form as ice-rich permafrost degrades. As drainage improves in adjacent tussock tundra, soils become somewhat drier and the proportions of shrubs increase (photo courtesy of L. Hinzman).



Figure 5-3. Waterfowl that migrate to the Arctic each year depend on tundra ponds. Ice-rich permafrost prevents percolation of surface water to groundwater and maintains these ponds despite relatively low rates of precipitation (photo by L. Hinzman).

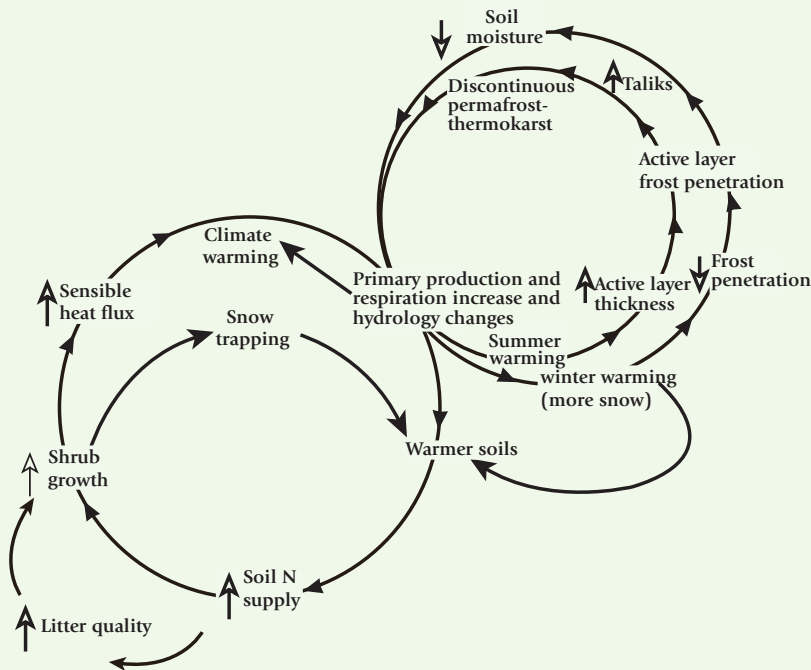
and thus difficult to detect. Box 5-1 schematically summarizes a few of the ways in which biotic and abiotic systems might respond to climate change.

The arctic terrestrial system plays an important role in global carbon dynamics and may possibly be one of the so-called “missing sinks” needed to balance the atmospheric carbon budget (Tans et al. 1990, Ciais et al. 1995, Schimel 1995). Changes in arctic air temperatures and precipitation impacting soil moisture and snow cover have had an important effect on the efflux of CO₂ from the land, with global-scale climate implications. In recent years there has been a shift in parts of the Arctic from a net annual sink to a net source of carbon (Oechel et al. 2000). During the growing season the system continues to take up carbon (Figure 4-8), but this uptake is more than bal-

anced by winter losses (Jones et al. 1997, Fahnestock et al. 1998, 1999, Vourlitis et al. 1997, 1999, Oechel et al. 1997, Zimov et al. 1993a, b).

Whether the arctic land surface is a “missing sink” or not, the efflux and sequestration of carbon in arctic soils is intimately linked with hydrology. Soil moisture determines the rate of organic matter decomposition, with cold, wet soils generally limiting the decomposition process (Oberbauer et al. 1989). At the same time, much of the plant growth in the Arctic is nitrogen-limited (Chapin et al. 1995). Warming and drying not only promotes greater carbon efflux through decomposition (Oechel et al. 2000), but also increases nitrogen mineralization, promoting a shift in plant community composition toward more productive functional groups

Box 5-1. Postulated Land Surface Hydrology Responses to Greenhouse Warming



The hydrologic response of the arctic land surface to changing climate is dynamically coupled to the region's surface energy balance, thermal regime, and ecology. The coupling between hydrology and ecology takes place primarily through changes in the active layer of the permafrost. One likely consequence of climate warming will be that soil conditions will improve for shrubs, creating both winter (snow holding) and summer (increased nitrogen mineralization) conditions more favorable to shrub growth and dispersion (Sturm et al. 2001). Changes in land surface cover will change the energy partitioning and carbon cycling, thereby affecting both local weather and global climate. At the same time, as suggested by the upper cycle, the climate change will affect the active layer and permafrost character. Summer warming, or winter warming with increased snow, will have different outcomes, though for large and long-term changes in climate, they will probably converge. The two cycles are shown linked through soil thermal conditions, but they are also linked through soil moisture. Both cycles have a direct impact on the hydrologic response of the landscape, including water storage for subsequent evaporation and runoff (Kane 1997). This scenario applies to upland ecosystems. Lowlands and wetlands may respond differently.

(Chapin et al. 1995). The whole ecosystem response is complicated and still under investigation (Shaver et al. 2000), but the role of water, particularly in the form of soil moisture, is well established as critical to carbon cycling in the Arctic.

Arctic animals have adapted to their particular niche, and changes in the environment will influence all creatures. Terrestrial herbivores must be able to graze beneath the winter snowpack. Midwinter warming or rain events can introduce ice layers that prevent caribou and musk oxen from cratering the ice-encrusted snow. Similarly, such ice layers can prevent adequate wind pumping of fresh air to small rodents living under the snow. The circumpolar arctic serves as a breeding ground for dozens of species of waterfowl and other birds (Figure 5-3), and the condition of the arctic environment determines the size of populations that migrate to more temperate winter ranges. The timing of their migrations and very existence is strongly affected by local hydrological conditions. Water conveys obvious controls on aquatic habitat. Recent work in the Kuparuk River in Alaska shows an additional, close linkage between fish production and river discharge (Figure 5-4).

Marine life in the Arctic is conditioned by physical factors including circulation, temperature, salinity, and ice. Changes in these factors inevitably affect marine ecosystems. For example, cold low-salinity surface water anomalies originating in the Arctic can reduce vertical mixing, negatively affecting

Table 5-1: Examples of how observed environmental changes may affect arctic ecosystems. Note that some changes can reverse direction depending on the local context.

CHANGING PHYSICAL ENVIRONMENT	ECOSYSTEM IMPACTS					
	Vegetation	Wildlife	Biogeochemical Fluxes	Trace gas	Fire	Lakes and Streams
Permafrost thaw	Slumping soils disrupt vegetation	Decrease in trafficability	Increased export of C, N, P and sediments	Increasing flux to atmosphere	Drainage promotes fire	Increased productivity/sediment load
Soil moisture changes	Shifts in species distribution	Mixed response depending upon species	Increased export if runoff increases	CO ₂ flux increases in drier soils, methane flux increases in wetter soils	Fire frequency and severity increases in drier soils	If runoff increases, productivity will increase
Summer temperature increase	Higher gross primary production and respiration	Increase in insects	Increased decomposition liberates nutrients	Decomposition leads to increases in fluxes	Fire frequency and severity increase	Lake trout and grayling growth decline
Snow cover decline	Shifts in vegetation stature and species	Less insulation for rodents. Predator species become more advantaged	Greater winter export	Fluxes may decrease if soils are colder due to lack of insulation	Increased fire	Less spring input of organic matter and nutrients lowers productivity
Winter temperature increase	Northward migration of species, increase in shrubs	Winter mortality decreases. Ice layers reduce fresh air to rodents	Decomposition rates increase during winter increasing soluble nutrients in spring	Fluxes increase	Longer fire season	Increases in baseflow throughout winter

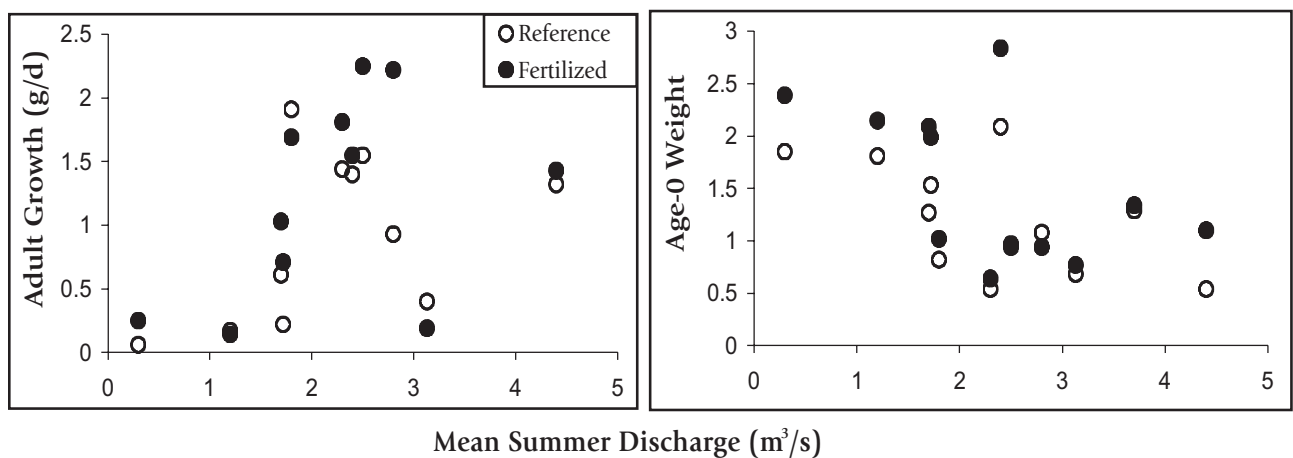


Figure 5-4. Discharge versus fish production in the Kuparuk River, Alaska. Instream biotic systems are linked closely to the behavior of river systems, with dependencies on both the physical (scouring, habitat) and chemical (oxygen status, primary production) setting. These dependencies on biotic systems are translated into dependencies on human society, both industrial and indigenous. Above is a plot of the average arctic grayling adult growth and young-of-the-year weight at 40-d versus mean discharge in the reference and fertilized reaches of the Kuparuk River, 1986, 1988–1998 (adult growth was not available for 1993). The impact of hydrological processes on biological processes is evident (Linda Deegan, Arctic LTER database).

nutrient flows and hence phytoplankton production on which marine food webs—and northern Atlantic commercial fisheries—depend (Gudmundsson 1998, Astthorsson and Gislason 1995, 1998, Hamilton and Allanson 2001). Marine mammals have a close dependence on sea ice for mobility and access to food sources.

Arctic Water Cycle Change and Humans

Environmental change across the Arctic influences human societies. Table 5-2 shows some of these “points of contact” between humans and the linked hydrological system. Industrial enterprises such as energy development, transportation, or commercial fisheries, and

more traditional livelihoods and communities of the Arctic’s indigenous peoples, are intimately connected to elements of the arctic hydrologic cycle. Changes to precipitation quantity and timing, fog, snow, river and sea ice, sea level, temperature, ocean circulation, and contaminants have, and will continue to affect individual livelihoods, the viability of settlements, and national economic prosperity for many who live in the Arctic. Precipitation changes associated with climate warming, such as that which killed thousands of reindeer on Svalbard (Aanes et al. 2000), point to the vulnerability of human-managed arctic ecosystems. Changes in permafrost could affect thousands of structures built on frozen ground—including houses, hospi-

tals, pipelines, and community water systems—well into the future as the thermal and structural stability of soils continues to degrade (Figures 5-5, 5-6, 5-7). While the true impact of each of these changes requires an understanding of the complex interactions between physical, biological, and human systems, current studies are mostly limited to educated guesswork. Because arctic physical processes are tightly coupled to global processes, shifts in arctic water cycles could also have consequences for people far outside the Arctic. As an example, freshwater from the Arctic basin is important to global ocean circulation, including the North Atlantic Current that moderates the climate of northern Europe and perhaps aridity in central North America.

Table 5-2: Points of contact, and areas of needed research, where changing physical environment parameters are likely to affect human activities in the Arctic.

CHANGING PHYSICAL ENVIRONMENT	HUMAN DIMENSION IMPACTS				
	Infrastructure	Transportation	Other Economic Activities	Subsistence, Traditional Activities	Health
Permafrost	Buildings, water & power systems	Roads, runways	Pipelines	Overland travel, subsistence resources	Water supplies, waste disposal
Precipitation, runoff	Riverbank erosion, flooding, water supplies	Roads, navigable waters	Mining & industrial wastes	Overland travel, subsistence resources	Water-borne illness
Storms, fog	Coastal wave erosion	Sea, air	Fire prevention	Subsistence hunting & fishing	Accidents
Snow cover	Snow removal	Winter travel avalanches	Water supply	Overland travel, subsistence resources	Water supply
River & sea ice	Coastal/riverside erosion	Shipping routes & season	Hydropower	Subsistence hunting, travel	Accidents
Summer temperature	Foundation instability	Permafrost and ice-road degradation	Tourism	Changes in species and migration routes	Insects, vector-borne illness
Sea level	Coastal flooding, erosion	Shipping facilities	Village relocation	Coastal cemeteries or artifacts	Freshwater salinization
Ocean circulation	Harbor siting	Shipping	Commercial fisheries	Subsistence hunting & fishing	Contaminant transport
Contaminants	Water supply/treatment	Spill prevention remediation	Commercial fisheries	Subsistence hunting & fishing	Human exposure

Land-Atmosphere-Ocean Feedbacks

Atmospheric circulation patterns change seasonally and have complex interactions with ocean circulation, sea ice, and land-surface

energy and water fluxes. Among these interactions, the link between the atmosphere and snow cover extent is relatively well established. Snow cover influences the surface energy budget in winter by insulating the surface and in

spring by recharging rivers. Clark et al. (1999; citing also Thompson and Wallace 1998) found that the Arctic Oscillation (AO) correlates with Eurasian surface air temperatures. Temperatures in turn affect snow cover. The observed recent decrease in Northern Hemisphere spring/summer snow cover (Groisman et al. 1994) thus likely reflects large-scale atmospheric events. Box 5-2 outlines some of the evidence linking northern hemisphere snow cover to atmospheric dynamics.

In chapter 4, we reviewed evidence for decadal-scale variability in Arctic Ocean ice. Recent data show significant losses of sea ice, especially in coastal and marginal seas. Several geophysical phenomena, including ventilation of the Arctic Ocean, deep-water formation, oceanic albedo, roughness, and evaporation, are dramatically altered by the presence or absence of sea ice. Box 5-3 illustrates some of these linkages.



Figure 5-5. Structures can be dramatically affected if the underlying ice-rich permafrost thaws (photo by L. Hinzman).



Figure 5-6. 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 (photo by L. Hamilton).



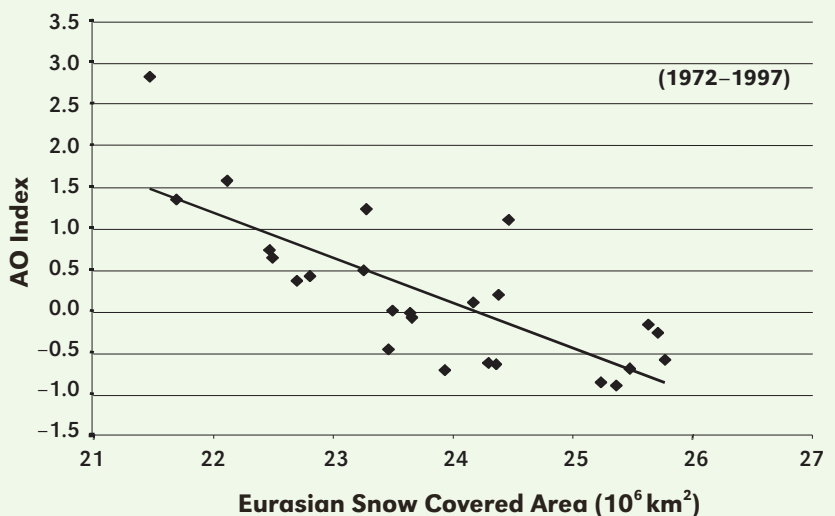
Figure 5-7. Ice-rich permafrost thawing and surface and groundwater intensive flow created this thermokarst pit in a parking lot in Fairbanks, Alaska (photo by V. Romanovsky).

Arctic land-atmosphere-ocean feedbacks extend far beyond coastal seas and influence the Arctic Ocean as well as other oceans of the world. Recent analysis of periodic atmospheric phenomena such as the AO and NAO suggest interconnections among the major land, ocean, and atmospheric components of the larger arctic system (Hilmer and Jung 2000, Morison et al. 2000). Salinity anomalies originating with freshwater pulses from the Arctic have had oceanographic, climatic, and economic consequences around the northern Atlantic (Malmberg et al. 1999). Such observations give hints about how the system is woven together and its potential sensitivities to global change (Box 4-1).

Land-Atmosphere-Ocean-Human Feedbacks

The commercial fisheries of the North Atlantic, important economically to more than a dozen nations and as food sources to many more (Figure 5-8), are immediately “downstream” from the Arctic Ocean. Often, they have been directly affected by the arctic hydrologic cycle (see Box 5-4). It is possible to trace causal links from arctic winds and precipitation, to arctic and Atlantic oceanographic changes, to primary biological production and key fisheries resources. The health of these resources in turn affects the well-being of people, enterprises, communities, and even nations. The cold-ocean ecosystems of the northern Atlantic support some of the most fisheries-dependent societies on Earth. Marine resources are critical as well to many arctic and sub-arctic indigenous commu-

Box 5-2. Large-Scale Circulation/Snow Cover Linkages



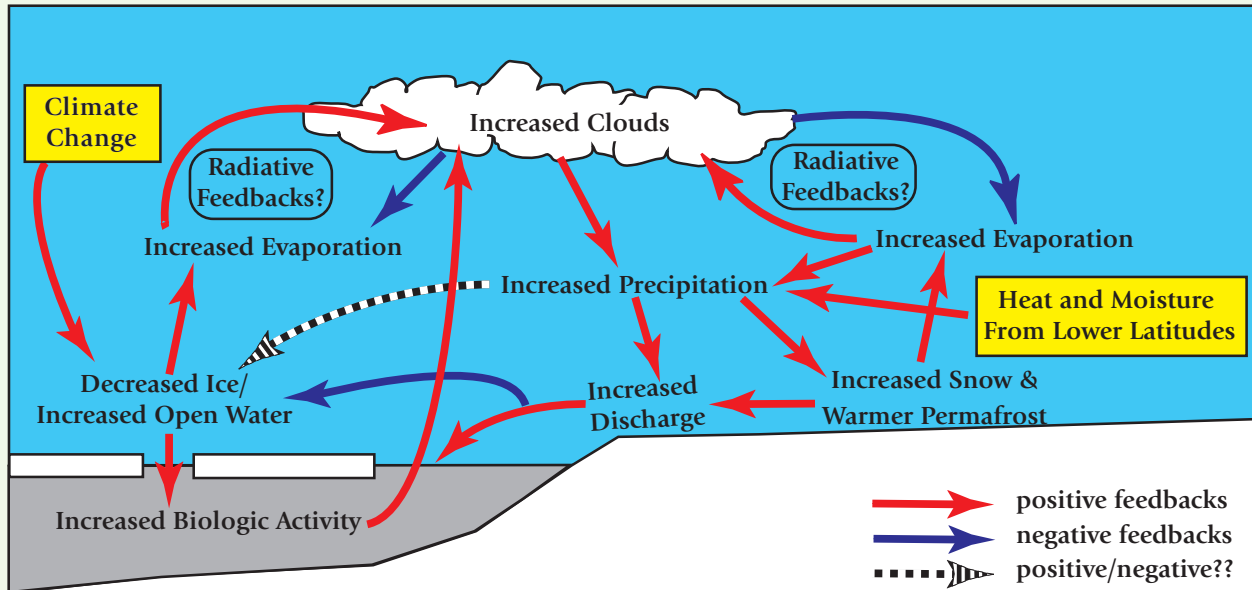
Interactions between the arctic land mass and overlying atmosphere have been found to have an important impact on the development and sustainability of snow cover and on arctic weather patterns. Several studies have shown how the atmosphere affects Eurasian snow cover (e.g., Clark et al. 1999). Other investigations have emphasized the atmospheric response to snow such as the relationship between anomalous Eurasian snow cover extent and the strength of the Asian monsoon (e.g., Douville and Royer 1996). Cohen and Entekhabi (1999) showed a statistically significant impact of autumn Eurasian snow cover patterns on the strength and spatial coverage of the Siberian high and how that can affect the position of the Icelandic low, resulting in shifts in the North Atlantic-Arctic atmospheric circulation. Large negative (positive) snow extent anomalies that exist in autumn can act as a heating (cooling) mechanism through albedo conditions and have an effect on the following wintertime atmospheric conditions (Watanabe and Nitta 1999). Figure is from Arsenault (2000).

nities, for whom subsistence hunting and fishing provide cultural continuity and significant sources of food. Water fluxes also regulate the spread and bioaccumulation of contaminants, originating both from northern and more distant sources, in arctic wildlife (AMAP 1999). Such contaminants are understandably of great concern to

arctic residents (Figure 5-8). Airborne transport of pollutants and deposition through precipitation constitute a major transboundary environmental issue (Figure 5-9).

Other important land-atmosphere-ocean-human connections linked through the water cycle affect arctic industrial activities and

Box 5-3. Feedbacks Among Sea Ice, Precipitation, River Runoff, and Coastal Oceans



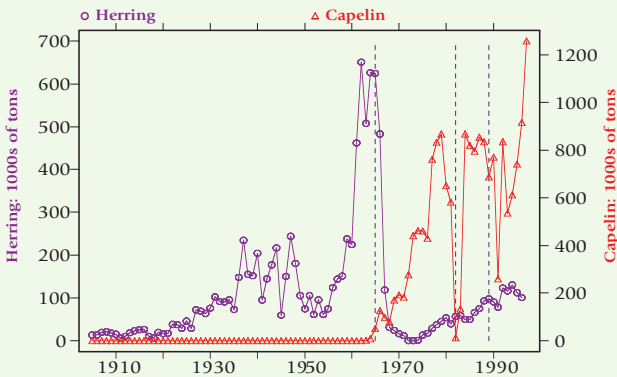
Recent studies indicate the presence of decadal-scale variability in the extent and thickness of arctic sea ice. Recent trends show decreasing sea ice, especially in coastal and marginal seas. The box diagram shows some potential land-ocean-ice-atmosphere feedbacks and interactions that might occur in such a changing environment.

We start with an assumption of decreasing sea ice cover near the coast in response to climate warming, which would encourage cloud formation and increased precipitation. More open water fosters a potential biotically mediated positive feedback on clouds through production of dimethyl sulfide (DMS) by marine phytoplankton. DMS then serves as a source of cloud condensation nuclei. We also note the potential for additional water vapor advected to the coastal region from the central Arctic Ocean and/or lower latitude areas. In summer, increased precipitation would create more runoff and thus more discharge of fresh waters to the coastal ocean. A potential negative feedback might then result, since all other effects being constant, freshwater tends to stratify the coastal ocean and

encourage sea ice growth. (In fact, the annual volume of river discharge to the Arctic Ocean approximately equals the volume of sea ice exported southward through Fram Strait.) However, positive feedbacks could also occur as the stratified ocean warms (Macdonald 2000).

The above scenario assumes that the land surface is fixed. In reality, increased precipitation might encourage a warming of the land surface, for example, as the insulating effects of snow cover act to warm permafrost. This might lead to plant community changes, increased evaporation and thus more clouds, more precipitation, and so on. We also note the potential for radiative feedbacks in this scenario, yet predicting cloud properties and their specific response to perturbation will constitute a major challenge. An important caveat is the presence of lateral advection, which would certainly produce a three-dimensional structure that is not captured by this two-dimensional schematic. The unknowns and uncertainties are many, and the hydrological cycle figures prominently in each.

Box 5-4. Freshwater Fluxes, Ocean Salinity, and Fisheries



The graph above shows total catches in Icelandic waters of herring and capelin, 1905 to 1997. Dashed vertical lines show approximate arrivals of cold, low-salinity arctic water anomalies (GSA '70s and GSA '80s) off North Iceland. These anomalies have strong linkages to the water cycle and affect biological production of importance to humans.

The "Great Salinity Anomaly" (GSA '70s), a low-salinity surface water mass that circulated around the North Atlantic ca. 1968–82, is thought to have originated with a freshwater/sea ice pulse from the Arctic via Fram Strait. A second North Atlantic salinity anomaly (GSA '80s) that circulated ca. 1982–89 had different origins, forming in the Labrador Sea/Baffin Bay due to severe winters and possibly arctic freshwater outflow through the Canadian Archipelago (Belkin et al. 1998). Arctic hydrological factors, including precipitation and runoff in northern Canada, and the sea-ice extent in the western Arctic Ocean, are thus linked (Power and Mysak 1992, cited in Belkin et al. 1998) to a phenomenon that has been described as "one of the most persistent and extreme variations in global ocean climate yet observed in this century" (Dickson et al. 1988). As they moved for years through the North Atlantic, both GSAs had effects on marine life, commercial fisheries, and human societies.

The seas north of Iceland are characterized by relatively large variations in temperature and salinity in comparison with seas to the south. These variations affect phytoplankton production: a cold, fresh surface layer inhibits vertical mixing, reducing the nutrients available to maintain the spring phytoplankton blooms (Gudmundsson 1998). Phytoplankton production controls the biomass of zooplankton, which in turn provides food for larval cod, capelin, and herring (Astthorsson and Gislason 1995). The cold, relatively fresh water of GSA '70s was first observed northeast of Iceland in 1965–71, coinciding with the collapse of Iceland-waters herring catches seen in the graph above (Hamilton and Allanson 2001). Herring stocks never fully recovered from this collapse. In subsequent years another forage species, capelin, played a larger commercial role. GSA '80s circulated through North Icelandic waters in 1982, and again in 1989–90. Both these events were followed by steep falls in capelin catches.

Onshore in Iceland, fluctuating fisheries catches translated into economic hardship for individuals and businesses who count heavily on these resources. Some employers were forced to shut down and some communities lost inhabitants as well as jobs.



A capelin catch in southeast Iceland (photo by Larry Hamilton).

settlements. Development and maintenance of infrastructure in arctic regions is thoroughly intertwined with permafrost-dominated hydrological processes. Facilities built over permafrost remain stable only so long as the permafrost remains frozen. A weak understanding of hydrologic science and a warming climate combine to make construction and maintenance of infrastructure tenuous.

Construction of roads or bridges requires knowledge of the biogeophysical characteristics of the drainages that must be traversed. These include the frequency of floods, average high and

low flows, potential for icing, rainfall distributions, snow loads and dominant drift directions, soil properties, and vegetation. For most regions of the Arctic, such information is essentially nonexistent. This often leads to costly mistakes and extensive re-engineering. Construction or removal of roadways also threatens to damage fragile ecosystems that will require decades or centuries to recover. Roads create impoundments of water, which if not properly drained can result in extensive thermokarsting (Figure 5-7). All of these issues become especially problematical under rapid environmental change and highlight the role of humans in the interacting arctic biogeophysical system.

Central Questions: What are the impacts of arctic hydrological changes on ecosystems and humans? How does the hydrologic cycle feed back to the oceans and atmosphere?

Key Gaps in Current Understanding and Needed Studies:

- Synthesis studies coupling atmosphere-land-ocean dynamics
- Permafrost impacts on vegetation, biogeochemistry, and trace gas exchanges
- Documentation of changes in the distribution and dynamics of arctic vegetation
- Documentation of changes to arctic animal populations, many of importance to humans
- Altered weather and human response
- Sensitivity of human infrastructure to permafrost warming and associated hydrological change
- Synthesis studies embedding human dimension issues into coupled atmosphere-land-ocean system studies



Figure 5-8. Fish are an important part of the subsistence diet and the commercial economy for many arctic people. This Native family is harvesting salmon on the Arctic Red River in the Northwest Territories, Canada (photo by L. Hinzman).



Figure 5-9. Sulfur dioxide and other pollutants from this smelter in the Murmansk region of Russia have killed forests in an area more than 40 kilometers across and caused measurable damage well into Norway and Finland (photo by L. Hamilton).