

The Arctic Freshwater System in a Changing Climate



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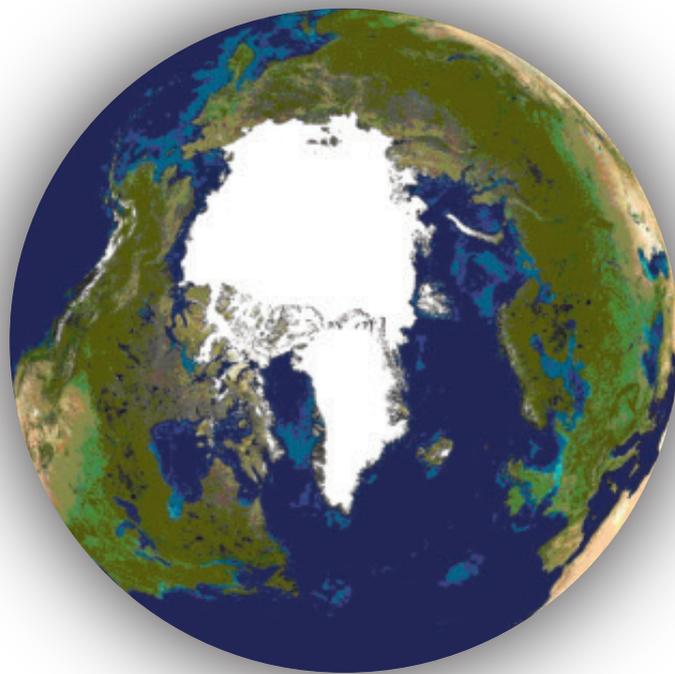
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Preface

The Arctic Freshwater Synthesis (AFS) project was led and coordinated by the World Climate Research Programme's (WCRP) Climate and Cryosphere (CliC) Project, in partnership with the International Arctic Science Committee (IASC) and the Arctic Council's Arctic Monitoring and Assessment Program (AMAP). The AFS is a contribution to the 3rd International Conference on Arctic Research Planning (ICARP III), the WCRP's Grand Challenges, and AMAP's 2016 update assessment of Snow, Water, Ice and Permafrost in the Arctic (SWIPA). The AFS was prepared by an international group of experts. Scientific publications arising from the AFS are published in a special edition of *The Journal of Geophysical Research: Biogeosciences* ([http://agupubs.onlinelibrary.wiley.com/agu/jgr/journal/10.1002/\(ISSN\)2169-8961/](http://agupubs.onlinelibrary.wiley.com/agu/jgr/journal/10.1002/(ISSN)2169-8961/)). Lead authors of the AFS have also prepared a chapter for the SWIPA update assessment currently under preparation by AMAP. These peer reviewed scientific documents constitute the background materials for this summary report.

CliC, AMAP and IASC would like to thank the following lead authors and contributors to the AFS assessment for their contributions to the work to prepare this summary: A. Bring (Sweden); E. Carmack (Canada), M. Holland (USA), A. Instanes (Norway), M. Johansson (Sweden), J. Mård (Sweden); T. Prowse (Canada), T. Vihma (Finland), F.J. Wrona (Canada). Special thanks are due to the science-writer, Mark Nicholls (United Kingdom), who authored this summary based on the AFS technical background materials and Gary Wesche (Polar Educators International) for his comments and suggestions).

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Why the Arctic Freshwater System is important

Flows of freshwater funneled into the Arctic means the region has a crucial role in regulating the global climate and ocean currents – but the Arctic environment, and its freshwater system, is changing rapidly.

How freshwater cycles through Earth's atmosphere, oceans and land is central to life on our planet. Water carries heat, nutrients and other chemicals that influence all the physical, chemical and biological processes on which life depends.

Freshwater is crucial to the Arctic's unique and fragile ecosystems. But the Arctic region also plays a key role in the hydrological systems that drive its ocean currents and control the planet's climate.

The Arctic Ocean is relatively small – containing just 1% of the world's ocean water. However, rivers flowing into it from the North American and Eurasian landmasses that surround it account for 10% of the total flow from the world's rivers.

Because freshwater is less dense than saltwater, this huge volume of freshwater mixes with seawater to form a less saline seawater layer that sits on top of denser saltwater.

The resulting 'stratification' has several important effects, but importantly it restricts mixing between surface and deeper ocean layers. The lower salinity of surface waters in the Arctic means they are more liable to freeze and produce sea ice. This sea ice, as well as ice on lakes and river and snow cover on land, helps to cool the Earth through its high 'albedo', that is, its ability to reflect solar radiation.

Meanwhile, relatively warm ocean currents flow into the Arctic from the Atlantic and Pacific, where

the water is cooled, sinking and driving global ocean circulation.

The cool and relatively fresh surface water of the Arctic Ocean also plays an important role in the northern hemisphere's weather systems, influencing the position of the jet stream and storm tracks over North America, Europe and Asia. Decreases in sea ice cover, in particular, are believed to have such an effect.

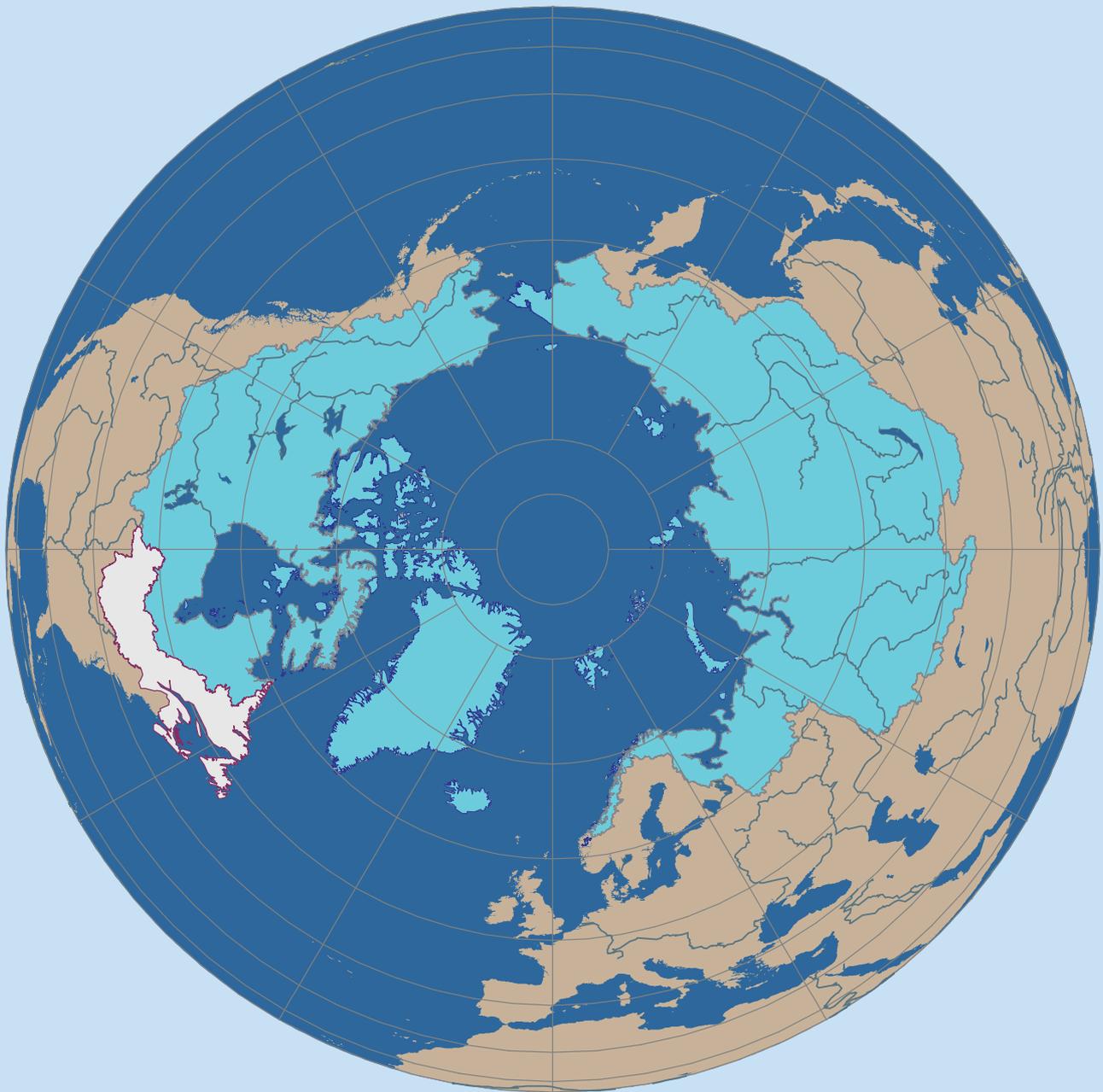
In addition to its influence on global climate, the Arctic region provides a unique environment for a wide range of migratory and non-migratory species. Its inflowing ocean currents and rivers supply nutrients that form the basis of marine food webs of global importance. It is home to about 4 million humans, living in both traditional and modern societies.

The Arctic is changing at a startling pace, with global warming raising temperatures in the region at twice the global average. Understanding the role of freshwater in these changes – both how Arctic freshwater systems are affected by climate change, and how changes to the Arctic freshwater system will affect other environmentally relevant processes – is critical to understanding how these changes will affect the lives of people living in the Arctic and beyond.

This report is intended to inform the non-expert reader about these changes to the freshwater systems in the Arctic, and their implications. It is based upon the work of the Arctic Freshwater Synthesis project (see box), and draws on the work and research of hundreds of scientists studying the region.

About this report

This report is an output of the Arctic Freshwater Synthesis project. The project is a review of the latest scientific literature on the sources, fluxes, storage and effects of changes in freshwater resources in the Arctic. It comprises six chapters, covering the atmosphere, oceans, terrestrial hydrology, ecosystems, Arctic resources and infrastructure, and modeling. It is intended to be used by the scientific community and to develop policy recommendations for local, regional and national governments.



Defining the Arctic Freshwater Domain

In the past, the Arctic hydrological system was understood as a more narrowly geographically defined area, bordered by, for example the southern limits of watersheds draining directly into the Arctic Ocean, or by convenient 'gateways' through which ocean currents must pass while moving into and out of the Arctic Ocean.

However, this Arctic Freshwater Synthesis takes a wider view, adopting an expanded hydrological regime that includes shelf and coastal regions, freshwater recirculated back into the Arctic Ocean, and terrestrial drainage systems that extend further south than those considered before.

Specifically, it defines the Arctic Marine System as the pan-Arctic domain north of the Bering Strait in the Pacific, and the Greenland-Scotland Ridge in the Atlantic. It considers the Norwegian, Iceland and Greenland seas south of Fram Strait and west of the Barents Sea Opening as the Nordic Seas, and the remainder, bounded by Fram Strait, the Barents Sea Opening, Bering Strait and Davis Strait as the Arctic Ocean. In terrestrial terms, it adds the area that drains into the Laurentian Great Lakes and St. Lawrence river system (shown in white) to the All Arctic Regions terrestrial contributing area (shown in blue).

This classification also includes the subarctic Labrador and Irminger seas south of the David Strait as part of the Arctic Marine System, and recognizes the role of freshwater inputs from more southerly watersheds, such as those draining into the Hudson Bay and the St. Lawrence Seaway.

This approach allows for a more complete understanding of how the Arctic hydrological system operates, how it is linked to systems in the mid-latitudes, and attempts to explain the forces and processes that influence it.

Climate change is affecting the Arctic Freshwater System

Global warming is increasing the intensity of the Arctic freshwater system, creating feedbacks and changing ecosystems, landscapes, environmental systems and human society.

One effect of climate warming is that it puts more energy into the Earth's hydrological system. This intensifies the water cycle, meaning that more freshwater moves through the system. This has consequences for the Arctic freshwater system, its oceans, and for the climate and life in the Arctic and much further afield.

Warmer air temperatures, especially during summer and early autumn, mean that the atmosphere can hold more water. Climate change is also leading to the transport of more moisture from lower latitudes towards the pole. This is contributing to increases in precipitation in the Arctic, falling either as rain or snowfall. In many parts of the region, the proportion of precipitation that falls as rain, as opposed to snow, has increased, and the period of snow-cover has become shorter.

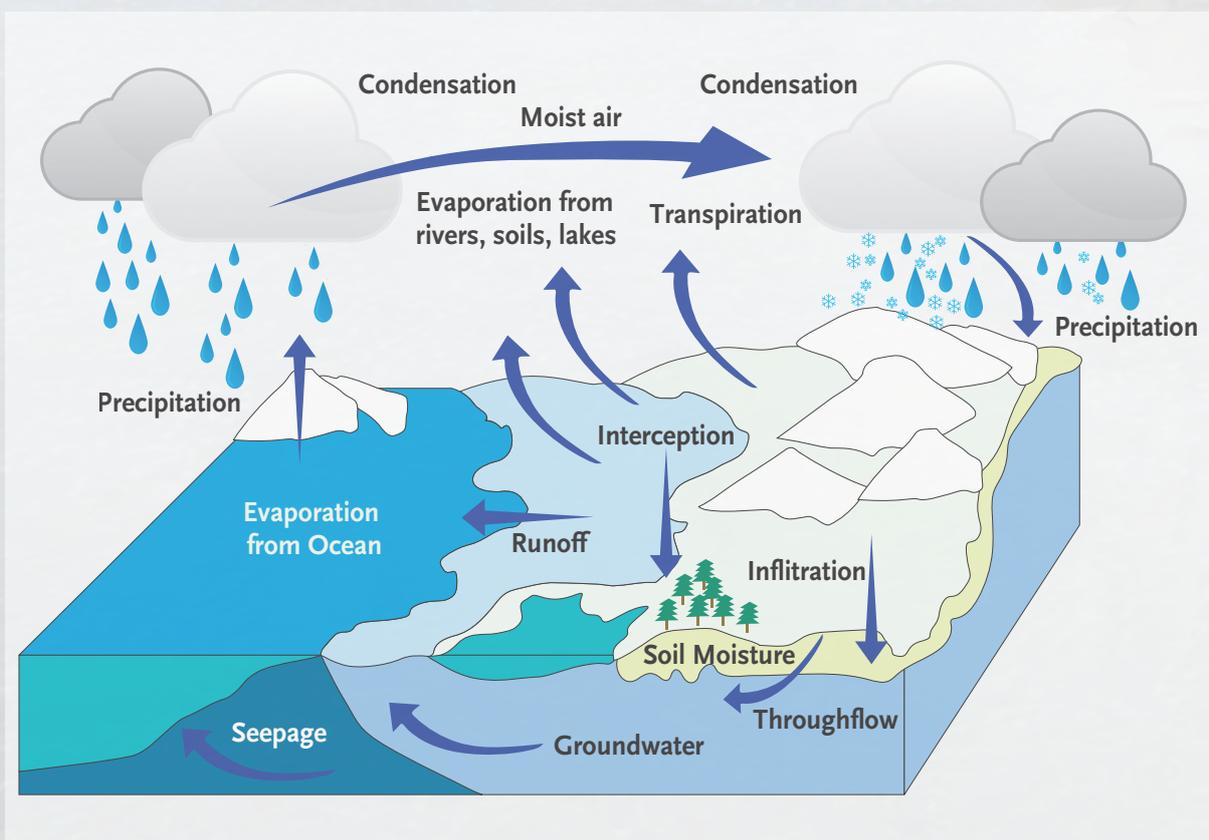
Generally speaking, Arctic river flow has increased and the timing of peak flows and river ice

cover is changing, reflecting the altered patterns of precipitation and snow- and ice-melt. These trends are expected to continue, although to variable degrees between different parts of the Arctic and over different seasons.

Increased precipitation, river flow and discharge from melting glaciers and ice sheets are channeling growing volumes of freshwater into the Arctic Ocean. For example, estimates of river flows have increased to 4,200 km³ (±420 km³) during 2000-2010 from 3,900 km³ (±390 km³) during 1980-2000. These changes are forecast to continue: by 2071-2100, modeling suggests that river flows may increase by 25-50% over much of the region.

At the same time, the Arctic Ocean is getting warmer, under the influence of several factors. First, higher air temperatures warm the sea surface. Second, sea ice is declining, meaning that more solar energy reaches the ocean. Third, less sea ice also means that winds can mix surface layers with underlying waters; because deep water in the Arctic is warmer than surface waters, this brings heat up from lower depths.

As the Arctic warms, more of its freshwater

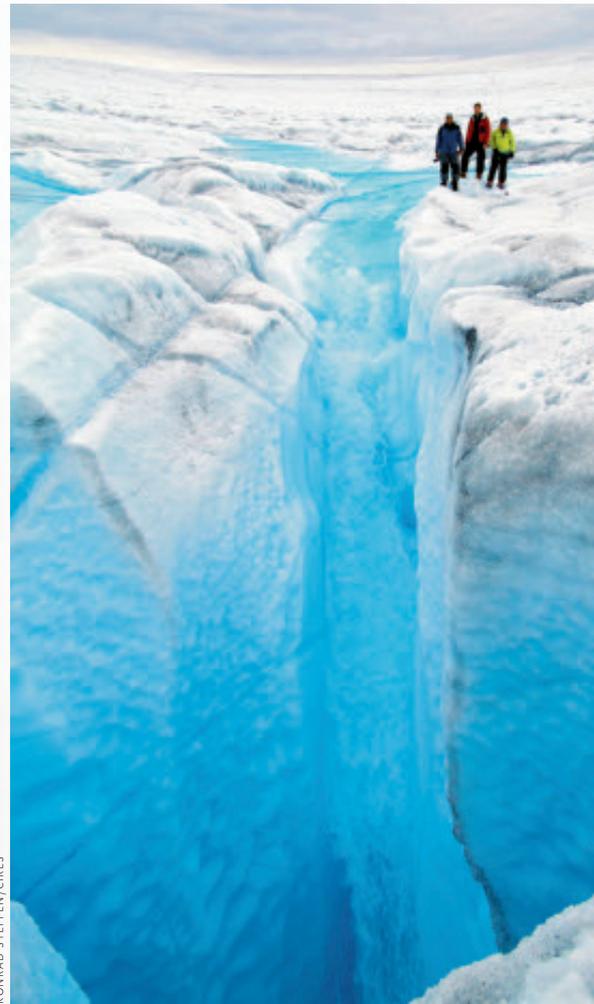


is in liquid as opposed to frozen form. In Arctic soils, this means that the area of permafrost (that is, ground that remains frozen all year round) is shrinking. Similarly, the area subject to seasonal snow and ice cover is also shrinking.

This reduction in snow and ice in the Arctic creates a feedback effect: snow and ice have a greater 'albedo' effect – that is, they reflect more solar radiation – than bare or vegetated ground. Reductions in snow and ice cover expose surfaces with a lower albedo, which absorb more heat, thus contributing to even more warming.

Less sea ice covering the ocean exposes more of its surface to solar radiation and wind, leading to increased evaporation. Higher temperatures also increase evaporation from the sea, rivers, lakes and soils, and lead to greater amounts of transpiration from plants. As the Arctic gets warmer and wetter, it is expected to support more plant growth, contributing to the so-called 'greening' of the Arctic region, as shrubs and trees replace tundra. Evapotranspiration from water, plants and soil is a major factor in the Arctic's changing water system. Models suggest that the rate of increase in evapotranspiration over the pan-Arctic basin in the period 1983-2005 is more than double that of 1950-99, and evapotranspiration is likely to continue to increase during the present century.

Together, these changes in the freshwater system are having a wide range of effects – on climate, ecosystems, landscapes, environmental systems and human society. The speed of these changes, and their linkages and feedbacks through different atmospheric, marine and terrestrial systems has



led to scientists introducing the term 'New Arctic' when they talk about the region. Some of these changes are well understood, most less so. While some projected changes are likely, particularly at larger scale, there is considerable uncertainty around changes at the local scale.

Modeling changes to the Arctic freshwater system

Understanding large-scale, complex systems such as the Earth's climate and oceans is extremely challenging. Physical measurements are limited – particularly for remote parts of the world, such as the Arctic – and may cover only certain parts of the year or relatively short time periods. It is impossible to test, through experiments, how changes to one or more variable are likely to affect the system as a whole.

Scientists therefore rely extensively on models to help them understand these systems, and how they may change in future. A model is a mathematical representation of a system, which can be used to fill gaps in observations, and to test how a system might change. They can be used to explore linkages and feedbacks within systems, and to forecast how systems might change over time. These models typically use some of the world's most powerful computers to analyze huge volumes of data.

Our ability to model the Arctic's freshwater system is improving, particularly by using a hierarchy of different modeling approaches. However, there are challenges to existing models, particularly around translating detailed models to large scales and, conversely, to add detail to models that cover large areas. Some models do not yet include important variables, such as ice sheets, glaciers, and human modifications of the water system.

Despite this progress, some limitations to modeling the water cycle are likely to remain. Water cycle variables, such as precipitation and river flows, are more unpredictable than air temperatures, for example, and uncertainties due to natural variability in the climate system are larger.

The changing Arctic atmosphere will have effects within and beyond the region

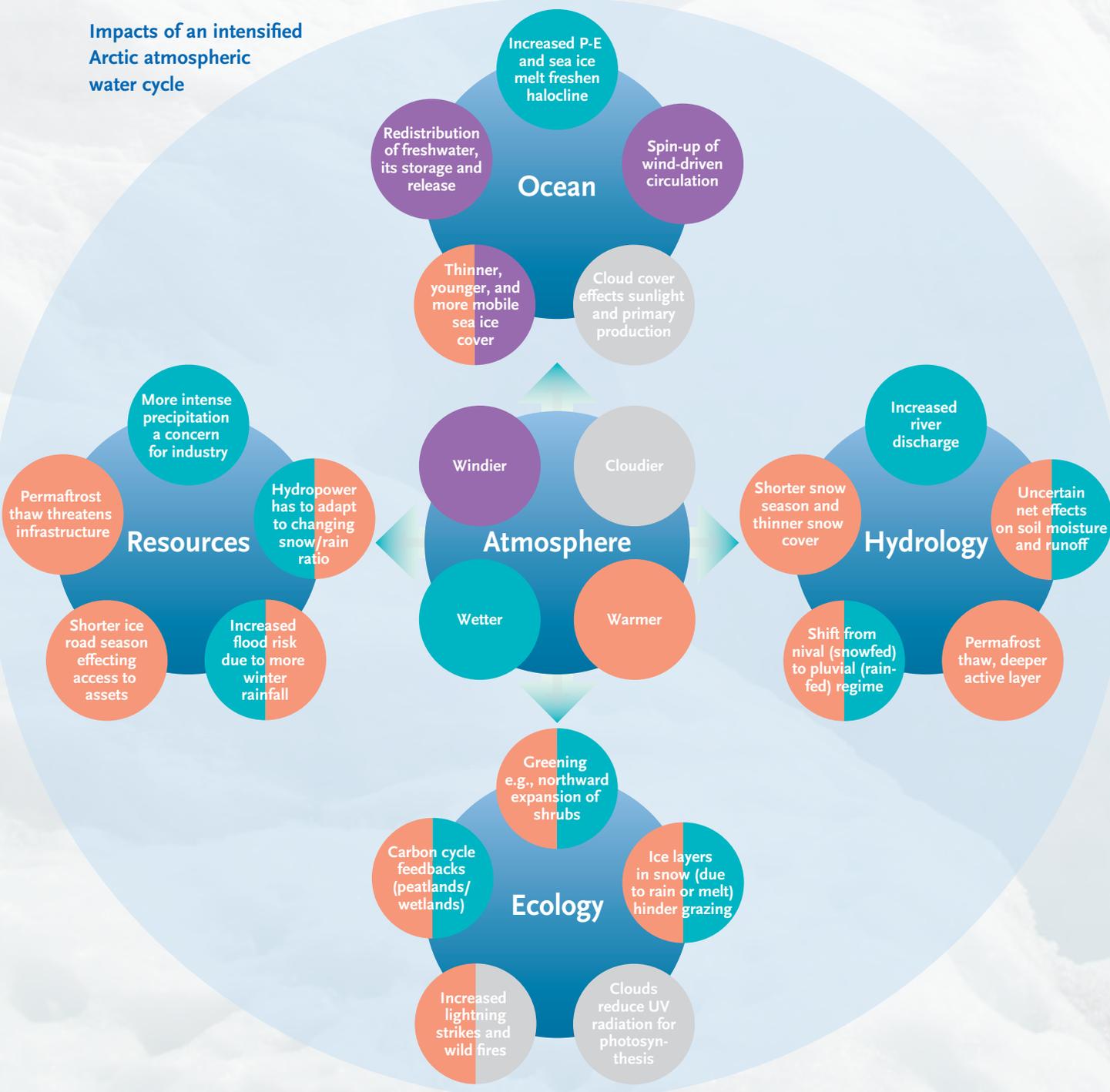
Patterns of precipitation are changing in the Arctic, with more rain and less snow. Reduced snow and ice cover and a warmer Arctic atmosphere is believed to be changing the weather further south.

Changes in the Arctic atmosphere are impacting Arctic ecosystems and weather, and also climate and oceans further afield. As water cycles through

the atmosphere, atmospheric moisture, clouds and precipitation simultaneously affect and are affected by the Arctic's rapidly changing climate. This makes monitoring and understanding the influence of the Arctic on weather patterns an important priority for both national and international bodies such as the World Meteorological Organization.

Rising temperatures in the Arctic, less ice, and

Impacts of an intensified Arctic atmospheric water cycle





SHUTTERSTOCK

more terrestrial plant life means more moisture evaporates from sea and land. A warmer atmosphere can hold more moisture. Water vapor is a greenhouse gas, therefore more water in the atmosphere also contributes to rising temperatures in the region, creating another warming feedback.

Changing patterns of precipitation affect the extent of sea ice and snow cover. If precipitation falls as rain rather than snow, it can have a dramatic effect on sea ice surface albedo, causing that ice to melt faster. While short-term trends in precipitation can vary substantially between years and in different areas of the Arctic, long-term climate trends are emerging. For example, summer snowfall is estimated to have decreased 40% over the Arctic Ocean between 1989 and 2009.

Some studies have shown that the number of cyclones (low pressure systems) entering the Arctic has increased in recent decades, leading to increases in net precipitation over northern continents. For land areas north of 55°N, the five wettest years since 1950 have all occurred after 2005. Climate models all point to further increases in precipitation, both in average precipitation and precipitation extremes.

Increased precipitation also contributes to the freshening of the Arctic Ocean, particularly from increased river flows. The ocean and atmosphere are interconnected and effects on one impact on the other: for example, fresher and therefore less dense water on the surface ocean prevents salt water mix-

ing up from the ocean depths. This affects ocean circulation and sea-surface temperatures – because, in the Arctic, water at lower depths is warmer than surface waters – thereby affecting the atmosphere.

Over land, whether precipitation falls as snow or rain affects both soil moisture and the timing and extent of spring run-off and flooding.

The effects of changes to the atmosphere in the Arctic are felt beyond the region – this is called ‘teleconnection’. Studies have found linkages between changes to weather in mid-latitudes, and reduced snow and ice cover in the Arctic and a warmer Arctic atmosphere. However, because many of these events are regional and occur irregularly, it is difficult to say whether changes in the Arctic are the main cause or just one of several factors.

Studies also suggest that the rapid warming in the Arctic may affect the jet stream – a high level airstream that circles the globe at mid-latitudes and affects the track of pressure systems and storms – causing it to become weaker and more meandering. The jet stream is driven by the difference in temperatures between cold Arctic air and warmer air from the south. Because this differential is getting smaller as the Arctic warms faster than low latitudes, these east-west winds are weakening. This is believed to have contributed to the recent mild winters in wet summers in Europe, and extreme snowfalls seen in the US East Coast in 2013-14 and 2014-15.

Changes to the water cycle are changing Arctic landscapes and ecosystems ...

Increasing precipitation and thawing permafrost are changing water courses and altering patterns of lakes and wetlands. Some species are thriving, others struggling, as the Arctic environment changes.

The Arctic is made up of a number of different ecoregions that support different communities of plants and animals. These include permanently frozen tundra, grasslands, wetlands, boreal forest, and glaciers and ice sheets. These biomes are characterized by a variety of freshwater ecosystems, ranging from shallow ponds that may exist for only a short period to large lakes, and from small intermittent streams to permanently flowing large rivers, as well as intricate wetland complexes of peat bogs and marshes.

As one travels from the subarctic boreal forest zone northward through tundra and on to the polar deserts of the High Arctic, the environment becomes progressively harsher. The dominant vegetation changes from trees and shrubs to specially adapted low-growing plants and mosses and lichens, and the diversity of vegetation decreases.

These biomes, and the living things they support, are often defined by how water moves through or is stored within them. As described on pages 6 and 7, patterns of precipitation, ice and snow cover, permafrost and river flow are changing in the Arctic as a result of climate change. As the Arctic water cycle changes, the biomes and their terrestrial and freshwater ecosystems are changing in nature and in the areas they cover.

Rising temperatures are reducing the permafrost area and, over large parts of the Arctic, the 'active layer' – the layer of soil above the permafrost that thaws in summer – is getting deeper. This is allowing shrubs and forests to encroach at the tundra's southern margins. On the other hand, it can also cause areas to experience perennially waterlogged conditions, suppressing forest growth.

As permafrost thaws, subsidence can create small lakes, whereas in other areas it is allowing water to drain away, causing existing ponds and lakes to dry out – both situations alter ecosystems.

Increased lake cover will lead to greater evapo-

ration, with effects on the amount of moisture in the atmosphere. This can affect local climate by increasing cloud cover and rainfall. Conversely, in areas where changes in hydrology and a warmer climate dries out soil and vegetation, leading to 'browning', or a reduction in plant growth, wildfires are likely to increase in frequency.

In river systems, warming can reduce the extent of the 'log-jam' resulting from the build-up of river ice, allowing wetlands in flood plains to drain, or to drain more evenly over the course of the year. This changes local ecosystems, and the species that can live there, potentially disrupting food webs.

As the Arctic warms, many plants will benefit from higher temperatures, a longer growing season and, in some places, more precipitation. Permafrost thaw allows plants to grow, and releases nutrients, contributing to the 'greening' of the Arctic. Nutrient release, and decreasing ice cover and thickness, which allows more photosynthesis, can increase productivity in freshwater ecosystems – although the release of dissolved organic matter into water can act to reduce photosynthesis, by coloring the water and decreasing light penetration. These factors change the types of plants in bodies of water, again altering food webs.

Changing landscapes and vegetation will also change the ranges of large mammals such as caribou, including the potential loss of unique species from certain areas of the Arctic. Meanwhile, the region is likely to see the arrival of new species from the south, either through the gradual expansion of their ranges as the Arctic warms, or as increased human activity in the Arctic brings invasive species, which can disrupt ecosystems by preying on or out-competing local species.

Gradual changes to the timing of the seasons can be particularly challenging for species to adapt to. For example, migratory birds time their arrival in Arctic breeding grounds so that their chicks hatch when there are large quantities of food available. But with the spring coming some two weeks earlier, a mismatch is emerging between the timing of migrations and food availability. Studies have found that the population of the East Atlantic light-bellied brent goose has declined as the species struggles to

reproduce at a level that sustains its population, and reduced growth rates have been reported for Baird's sandpiper in the Canadian Arctic as a consequence of such mismatches.

Similar challenges are faced by freshwater species. Higher water temperatures and longer ice-free periods shift the seasonal indicators that species rely upon. For example, warmer temperatures can cause larval insects to emerge earlier, before the fish

species that feed upon them have hatched. Equally, because these larvae have emerged earlier, they may be washed away by spring floods.

Overall, changes to the Arctic climate, water system and cryosphere, coupled with many ecological feedback processes, are likely to cause surprising and unexpected reorganizations of ecosystems in the region.



U.S. FISH AND WILDLIFE SERVICE

SELAWIK SLUMP

Thawing permafrost is changing the Arctic landscape, and threatening ecosystems on which local people rely. One of the most striking recent examples is the Selawik slump, where more than nine acres of land have collapsed, partially blocking Alaska's Selawik river and flooding it with sediment.

Such slumps occur when permafrost thaws sloped ground, which then collapses, exposing a new wall of permafrost. This in turn then thaws and collapses, continuing the cycle.

What is particularly concerning about the Selawik slump to biologists and local people is that it may disrupt the breeding patterns of sheefish, a long-lived species of fish and a food source for local indigenous communities. Biologists fear that sediment from the slump could be filling the nooks and crannies on the river bed in which sheefish lay their eggs.

... And are having profound effects on the coast and near-shore environments

The coastline has a particularly important role to play in the Arctic environment, but the effects of changes here – including less ice cover, higher water flows, and changing supplies of nutrients – are poorly understood.

Perhaps the most significant changes to the Arctic landscape are taking place in the coastal zone, where the land meets the sea and where the large amounts of freshwater and sediments carried by large rivers enter the Arctic Ocean.

The Arctic Ocean accounts for almost a quarter of the world's total coastline. The coastal zone is particularly important to humans in the Arctic as it is where they typically live, work and hunt. It is also changing rapidly as the Arctic warms, yet those changes, and their likely knock-on effects, are poorly understood.

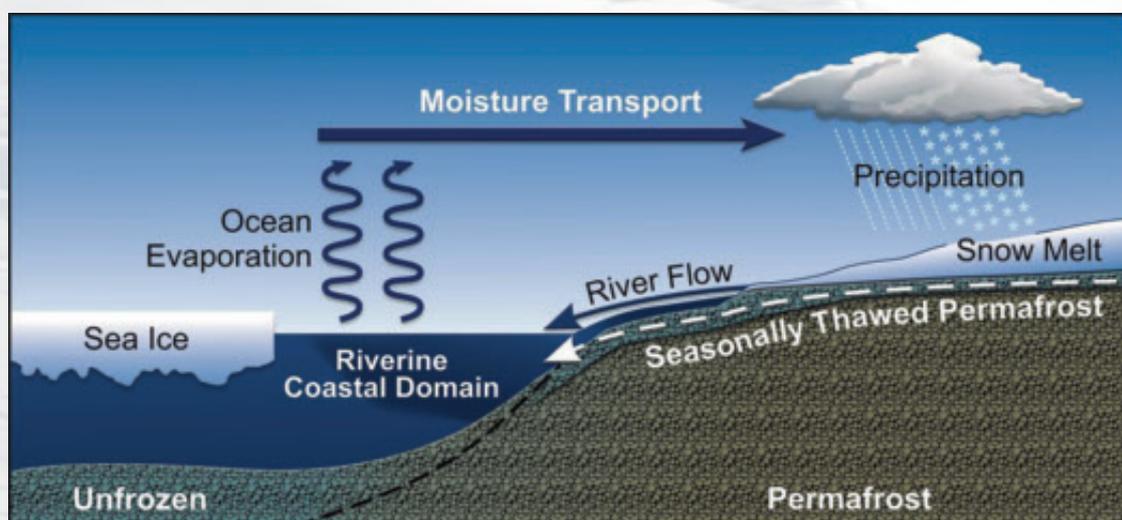
Connecting the terrestrial and marine ecosystems is a unique Arctic environment, known as the Riverine Coastal Domain. The Riverine Coastal Domain is a zone that extends offshore between 1 and 20 kilometers, and that is characterized by low salinity waters in the upper 10 to 20 meters. It provides a pathway along the coast for marine life to disperse and migrate. The nutrients, carbon and light available within it are heavily influenced by run-off from the land, so, as permafrost thaws and ice melts, and run-off increases, it is likely to see profound changes to the type of environment it provides, with less sea ice that is attached to land,

and more open water along the coast, for more of the year.

The role of the Riverine Coastal Domain in the onshore water cycle is also changing. On the Arctic tundra, 80% of the lowland area is within 100 km of the ocean. This area is strongly influenced by the climate along the coast, and how water moves through the atmosphere, land and ocean at the boundary of land and sea. For example, less ice along the coast will increase the amount of evaporation, leading to more precipitation inland, greater river flow, and thus further change to coastal environments and ecosystems.

The Riverine Coastal Domain has an important role in the flow of nutrients into the oceans, which in turn affects the type and range of life they support. Arctic rivers discharge enormous volumes of dissolved organic and inorganic matter onto the vast continental shelf, the shallow seas closest to land, where it is processed and cycled by organisms.

River-born sediments can both increase and suppress biological activity and the range of species present. On the one hand, additional flows of nutrients are expected to benefit plants and animals at the base of the food chain, as does reduced ice cover and higher temperatures. Conversely, large volumes of sediments and organic material make seawater cloudier, blocking light needed for photosynthesis and potentially clogging filter-feeding fauna such as shellfish. Brackish, or slightly salty, water typically supports fewer species than either





NASA/MODIS



LAWRENCE HISLOP

entirely freshwater or seawater, so it follows that increasing flows of freshwater may also reduce the range of animals and plants in the Riverine Coastal Domain.

These changes could have important ramifications for the success or otherwise of a large number of marine species, including commercially important fish species and marine animals – such as salmon and whitefish – that are important sources of food for indigenous communities in the Arctic.

Also, as discussed on pages 18 and 19, the role of the Arctic coastal domain in cycling carbon dioxide could be changing, with possible implications for the volume of greenhouse gases in the atmosphere, and hence our efforts to slow down climate change.

Despite the importance of the Riverine Coastal Domain to humans, our understanding of the processes at work in the estuaries, coasts and river deltas of the Arctic is far less developed than for those in other regions.

Changing freshwater flows into the oceans are affecting ocean currents and ocean biology

Increasing volumes of freshwater from the Arctic threaten to slow down crucial ocean currents, while also adding pressure on marine life.

The Arctic Ocean plays an important role in the circulation of the Earth's ocean currents. Warm water is carried by surface currents, such as the Gulf Stream, from the lower latitudes towards the poles. In the Northern Atlantic, it is cooled and then sinks below the relatively fresher water flowing outwards from the Arctic Ocean. This deeper current circulates within the Arctic marine system, and then flows southwards.

Some studies suggest that increased flows of freshwater, from the Arctic Ocean and aided by the melting Greenland ice sheet, could disrupt this mechanism, which is known as the Atlantic Meridional Overturning Circulation (AMOC), or the Atlantic Conveyor. By transporting heat from lower latitudes, the AMOC is thought to play a key role in global climate regulation.

Should the AMOC slow, as some models suggest,

a weakened Gulf Stream would carry less warmth to North-western Europe, leading to a substantial drop in average temperatures in that part of the world.

Increasing flows of freshwater into the Arctic Ocean will have a number of impacts on marine biology, both within the region and further afield. They are also expected to influence the process of ocean acidification, which poses a threat to important parts of marine food webs (see box).

As previously discussed, increasing volumes of freshwater entering the Arctic Ocean are expected to change the productivity of its coastal waters, through changes to the nutrients available, the cloudiness of water, and how larvae and fish move through coastal waters. Further offshore, the stratification caused by less-dense, fresher surface water also serves to suppress the upwelling of nutrients from the ocean depths. This lack of nutrients is likely to limit or offset the increased biological productivity caused by reduced sea ice and warmer temperatures.



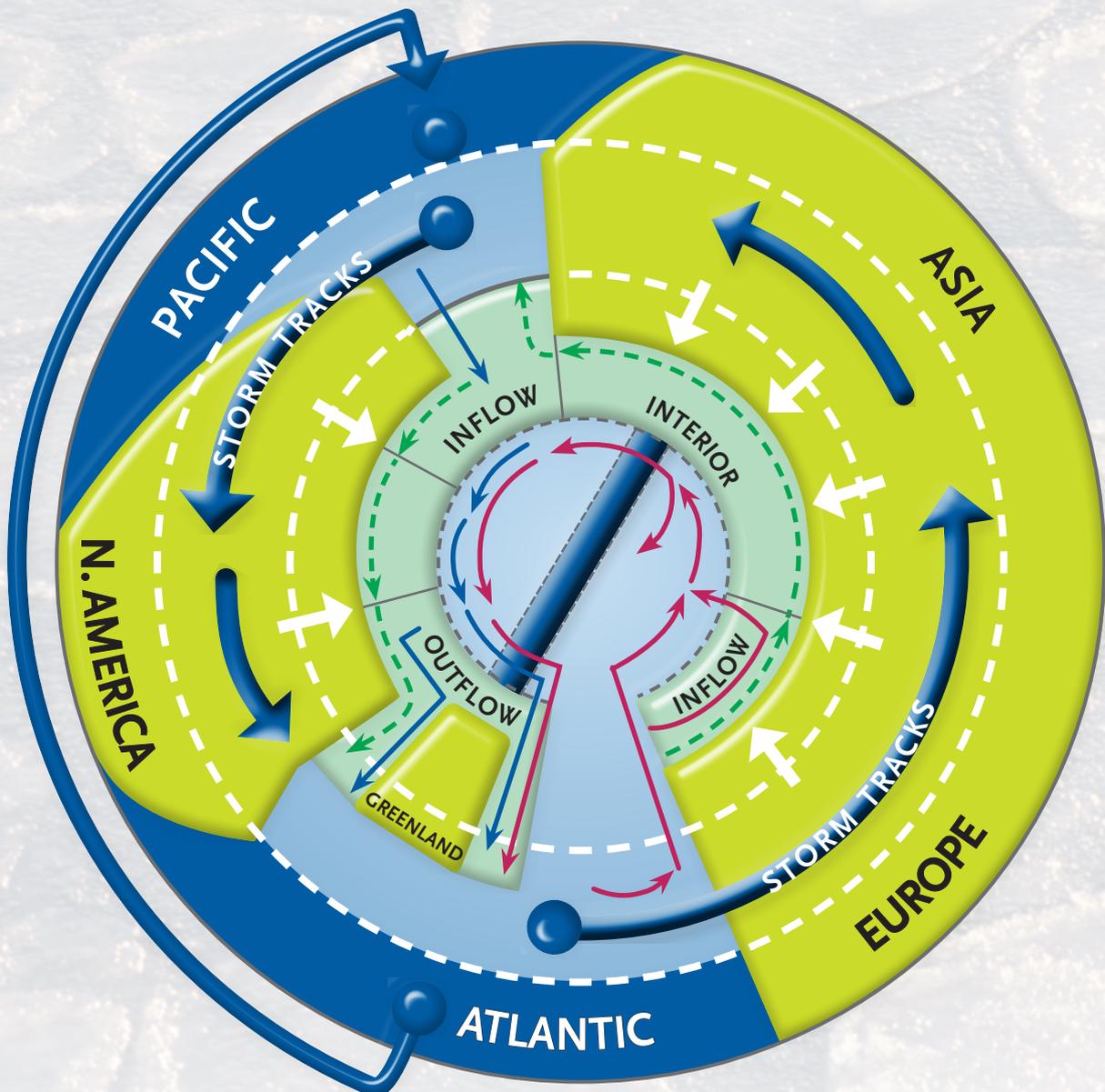
MARTIN FORTIER/ARCTICNET

Ocean acidification and Arctic freshwater

Ocean acidification is of growing concern to marine biologists. As they absorb CO_2 from the atmosphere, and as more organic matter is processed in coastal waters, the world's oceans are becoming more corrosive to certain species. This acidification has adverse impacts on many marine organisms, reducing their ability to form and maintain shells and skeletons. The effects on food webs, biodiversity and, ultimately, aquaculture and food security could be profound.

The input of freshwater into the Arctic makes it particularly vulnerable to ocean acidification. This freshwater – especially from melted sea ice – reduces both the alkalinity of Arctic surface waters and the concentrations of calcium ions, which are used to build shells and skeletons.

Freshwater from rivers and melting ice is therefore less effective at chemically neutralizing CO_2 's acidifying effects. Freshwater inputs also cause seawater to become stratified. Fresher, less dense water on the surface results in higher surface water temperatures and lower biological activity. Rivers and coastal erosion all supply organic material that bacteria can convert to carbon dioxide, thus exacerbating ocean acidification.



The ability of the Arctic to provide the ‘ecosystem services’ on which humans rely will be impacted

A healthy environment provides humans with vital services, such as food and water, and even pollution control. In the Arctic, permafrost helps people move around. Changes to the water system will threaten those services.

A more intense and altered Arctic freshwater system will, in tandem with other climate-related changes, have profound implications for the environmental services that humans rely on. These so-called ecosystem services include the provision of food and freshwater, relatively predictable weather patterns, and the breakdown of various types of waste and pollution.

The most obvious benefit that ecosystems provide to humans is the provision of food. Two of the world’s largest commercial fisheries are found in the Barents and Bering Seas. In addition, many indigenous people in the region rely upon traditional, wild-caught foods, including fish, waterfowl and mammals. Not only are these traditional foods important for nutritional reasons, especially in remote communities, they also have important social and cultural significance for indigenous peoples in the Arctic.

Changes to the ecosystems within which these fish and animals live will affect their numbers, ranges and, in extreme cases, species could become extinct in the wild. For example, increased inputs of nutrients caused by thawing permafrost and enhanced flows of water could lead to eutrophication in freshwater systems – leading to blooms of algae that reduce water quality and crowd out other species. This can alter local food webs and the range of wildlife supported by an ecosystem. Growth of shrubs as permafrost retreats reduces the availability of the lichen and grass habitats preferred by caribou.

The supply of clean water is also an important service provided by natural systems. Again, toxic algae blooms caused by excessive nutrient inputs can affect drinking water quality. Thawing permafrost and changes to the timing and extent of pre-

cipitation could damage the infrastructure on which Arctic communities rely for their supplies of water. They also often rely on permafrost to contain and isolate waste and wastewater, which could otherwise leach into ground or surface water. Healthy ecosystems help prevent problems caused by too much water. Wetlands prevent flooding, for example.

Another service provided by the environment is the capture and, in some cases, breakdown of pollutants and contaminants. A more intense hydrological cycle, however, will increase the rate at which contaminants such as mercury, persistent organic pollutants such as DDT, and radioactive particles move through the environment. For example, increasing temperatures could see contaminants that are currently captured in ice leach into wetlands or rivers. And changes to patterns of water flow can increase the volume of mercury found in water courses, as was shown by a study of the Mackenzie River in Canada.

The Arctic environment also provides a service not commonly found elsewhere: transport corridors on frozen rivers and permafrost. Ice roads provide an important means of supplying remote communities during the winter months, and are often essential for economic activity that relies on heavy machinery (see page 20). Indigenous people also rely on ice to move around and reach remote hunting grounds. Declines in permafrost and shorter periods of winter ice reduce the amount of time these transport routes can be used, and in some cases threaten their existence entirely. They may be replaced with all-weather roads, but these are expensive and only likely to be constructed where there is a significant need.

The unique Arctic environment is also attractive to tourists. Ecotourism in the region has grown rapidly in recent years, and is expected to continue to do so, partly as a result of reduced summer sea-ice offering easier access for cruise ships. This benefit may, however, be partly offset by possible declines in the populations of species that ecotourists come to see.

ICE ROADS

The winter ice roads that many Arctic inhabitants rely upon are becoming increasingly unpredictable as a result of rising air temperatures and earlier snow-melt. Scenes like these – at the Kwethluk River in March 2015 – are becoming more common, as ice roads thaw earlier in the spring than in the past.

The Arctic Daily News reported that two pick-ups used by construction crews sank through slushy ice which had been passable two days prior. A bulldozer sent to recover the vehicles also sank through the ice. All those in the vehicles managed to escape.

Not all are so lucky. The previous December, three people died when the four-wheeler they were travelling in broke through ice on Kuskokuak Slough, near Kwethluk, the report added.

Such effects will be felt across the Arctic. Rising temperatures will prevent up to 400,000 square miles, or 13% of land suitable for ice roads, from freezing sufficiently by mid-century, according to a 2011 study by the University of California, Los Angeles.

The researchers estimate that the Tibbitt to Contwoyto winter road, the longest winter road in the Northwest Territories, will lose 17% of its operating season between 2008 and 2020. It connects four diamond mines in the Northwest Territories and Nunavut.

Journeys will also take longer: the study predicted that it will take 6.5 days to travel from Yellowknife to Bathurst Inlet, Nunavut by 2050, compared with 3.8 days now, due to deterioration of winter roads.



WILLIAM C. PETERSON III



LOREN HOLMES/ADN

But permanent roads are also vulnerable. Increasing precipitation and changing patterns of ice melt increase the likelihood of such roads being flooded. The photograph shows the Dalton Highway – the main supply route for the Prudhoe Bay oil fields – overflowed by the Sag River, in May 2015.

The changing hydrological cycle will influence the role of the Arctic as a store of carbon

Huge volumes of greenhouse gases are stored in permafrost and are absorbed in the Arctic Ocean. Changes to the freshwater system could lead to much of those eventually being released.

Arctic seas, soils and vegetation perform another vital ecosystem service: regulation of the climate. By absorbing carbon dioxide from the atmosphere, and subsequently storing it, plants and marine life help to prevent atmospheric greenhouse gas concentrations, and average temperatures, from rising too high. Changes to the Arctic freshwater system, and to the landscape, could therefore see large volumes of stored carbon being released into rivers, the oceans or the atmosphere.

The terrestrial Arctic has become a significant store of carbon. The layer of permafrost contains remnants of plants and animals accumulated over thousands of years; by some estimates, it contains twice as much carbon as there is currently in the Earth's entire atmosphere. The thawing of this permafrost allows microbes to break down this organic matter, producing greenhouse gases.

Although the permafrost contains sufficient amounts of carbon to dangerously disrupt the climate if it were to be rapidly released, it is likely that the carbon will instead enter the atmosphere gradually, over decades to come – and at smaller volumes compared with emissions caused by human use of fossil fuels. Scientists estimate that, given likely



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temperature rises, carbon from permafrost would likely be equal to about 10% of manmade emissions, though higher values cannot be ruled out.

In addition to permafrost carbon, peat lands and the edges of lakes contain very large carbon stocks; if these dry out, this carbon will be lost to the atmosphere or surface water. Also, the loss of ice cover over Arctic lakes, and the associated warming of those lakes, can greatly increase the production of methane, another greenhouse gas, over vast wetlands across northern latitudes.

An additional factor is the degree to which thawing permafrost and rising temperatures lead to the production of methane. Microbes breaking down organic matter in wetlands, lakes or waterlogged soil, where there is no oxygen, produce methane rather than carbon dioxide. Methane is a more potent greenhouse gas than carbon dioxide, but

it stays in the atmosphere for a shorter period of time.

Some studies suggest that changes to the Arctic freshwater system may, conversely, help to store carbon. For example, as permafrost degrades, subsidence causes small lakes to form, helping to protect wetlands. Also, an increased hydrological cycle will carry dissolved organic carbon into the sea, where it is likely to be deposited as sediment and therefore kept out of the atmosphere.

Other natural processes will add to carbon stored in the Arctic. As temperatures rise, the process of 'Arctic greening' will see shrubs and trees advance northwards. These plants will capture carbon from the atmosphere as they grow. On balance, however, changes in the Arctic are likely to add to the concentrations of greenhouse gases in the atmosphere, and therefore add to rising temperatures.

Changes to the Arctic Freshwater System will have important positive and negative implications for the economy in the Arctic

Water is not only important for environmental reasons – it is essential for human societies and economies. The Arctic region is already home to some 4 million people. As the Arctic warms, more people are likely to live and work in the region as it becomes easier to exploit its natural resources. However, changes to Arctic freshwater systems will also pose threats and challenges to the Arctic economy.

Water infrastructure

A reliable water supply is a necessity for any human community. Water is generally plentiful in the Arctic, and is likely to become increasingly so as a consequence of climate change. However, the infrastructure that communities rely upon to store, clean and supply that water could become more vulnerable.

Higher air temperatures and the increase in the active layer of permafrost may heighten the risk that freshwater sources become contaminated by municipal and industrial waste water. Subsidence caused by thawing permafrost could damage water and wastewater facilities. Extreme weather, such as flooding, could also damage water infrastructure.

On the other hand, wastewater treatment processes may be more efficient as a result of higher water temperatures.

Transport in the Arctic

In much of the Arctic, transport infrastructure is very limited. Communities, especially in remote areas, often rely on ice roads in the winter, and rivers in the summer, for transport.

Ice roads require temperatures to drop for sufficient ice to form; a warmer Arctic means these roads will be open for shorter periods. Conversely, however, higher air and water temperatures mean that rivers will be navigable for more of the year. Meanwhile, higher temperatures mean that all-weather roads and railways built on permafrost are at risk from subsidence as that permafrost thaws.

Mining, oil and gas

There is increasing interest in the enormous mineral wealth that is believed to be present in the Arctic. Alaska and Arctic Russia are already important sources of oil and gas. Greenland contains substantial deposits of uranium and other minerals.



B&C ALEXANDER/ARCTICPHOTO



MARKKU HEIKKILA

In some respects, the warming of the Arctic will make it easier to extract these resources. Many of the processes involved use large amounts of water, and it is likely that more water will be available. It may also be easier to access mineral deposits, due to less sea ice.

However, a warming Arctic also creates challenges. Some industrial activity in remote parts of

the Arctic relies on ice-roads to transport heavy machinery. If these roads are only usable for shorter periods of the year, the costs of remote plants will rise. Also, some activities rely on permafrost – either on which to build pipelines to transport oil and gas, or to contain waste material. As permafrost thaws, it may be necessary to build new transport infrastructure and facilities to store waste.



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IVAR SILIUS/TUSAGASSIVIK

Hydroelectric power

Almost all of Norway's electricity, more than half of Canada's, and nearly half of Sweden's, is produced by hydroelectric power stations. Some of these plants are in the Arctic; most of the rest are within the Arctic hydrological system.

The intensification of Arctic freshwater systems will make more water available for hydropower.

This could create an economic opportunity for the region. However, changes to precipitation and snowmelt may alter the availability of water for some existing plants. Flooding and dam 'overtopping' can damage hydroelectric plants. It is important that changes to water flows in the region are better understood to help protect existing plants, and guide investments in new ones.



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The Arctic as a source of water?

While most experts believe climate change will make the Arctic wetter, it is also likely to make other parts of the world drier. Parts of the US, for example, are experiencing droughts that are expected to become more common, while demand for water – for domestic, industrial and agricultural use – is projected to increase. The Arctic could, potentially, be viewed as a source of water for drier regions to the south.

Transporting water great distances from the Arctic to southern regions would be challenging. Plans by the Soviet Union to reverse the flow of rivers, by building a series of giant canals, to direct water from the north to the south of the country were abandoned. A similar proposal in the US, the North American Water and Power Alliance Plan, was developed in the 1960s but was also ultimately rejected. However, China's South-North Water Transfer Project has, at least in its own terms, been more successful in diverting water over great distances, using canals, tunnels, pumping stations, aqueducts and reservoirs.

Nonetheless, the obstacles – and costs – would be significant. Aside from the engineering challenges involved, such a scheme would raise concerns about invasive species, ecosystem destruction and the effects upon ice formation in the Arctic.



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Conclusions

Knowledge gaps

Across all aspects of the Arctic Freshwater System, there is a need for more extensive and accurate observations. This need is greatest over the oceans, but problems remain over land areas, with a limited network of stations.

Specifically, knowledge of water and waterborne material flows are restricted by limited surface water monitoring. While large Arctic rivers are monitored, the discharges from the huge number of smaller Arctic rivers are poorly understood.

More research is needed into the loss of lake and river ice, and its effects on local evaporation. These effects could be significant, given that the area covered by ponds and lakes in the mid- to high-latitudes is comparable to the area of sea-ice loss in recent decades.

Climate modeling is improving, but there is a great need for more accurate representation of land surface effects, such as vegetation, lakes and human interventions, in climate models.

There is a need for developing an improved understanding of interactions among and between ecosystems, along with improved predictive models of ecosystem responses to alterations in water-, snow and ice-, and atmosphere-related drivers. Consideration should be given to the use of the catchment scale as an ecological unit of study.

In terms of resources, there is insufficient water-related information on consumption, irrigation, flow rates and the impact of climate change on water resources. The knowledge of impacts and of climate change on water quality and ground water are insufficient for adequate water resource management.

Recommendations for policymakers

The Arctic Freshwater system is undergoing profound change, with significant impacts already observed within and beyond the Arctic. These impacts will become more pronounced over the coming decades. Given the importance of the Arctic Freshwater System to people living in the region, the Arctic Monitoring and Assessment Programme,

the International Arctic Science Committee, and the World Climate Research Programme's Climate and Cryosphere Project recommend that policymakers should consider:

- Supporting the efforts of the research community in improving the observation of key processes that affect the hydrological cycle in the Arctic and sub-Arctic regions.
- Promoting the understanding of the interlinkages between key processes, such as the effects of changing freshwater fluxes into Arctic oceans on currents and climate, and the effects of reduced river and lake ice on atmospheric and ecological processes.
- Facilitating deeper understanding of the physical, biological, ecological and climatic consequences, over the short, medium and long terms, of a more intense freshwater cycle.
- Working to better understand the likely key socioeconomic consequences of changes to the Arctic freshwater system, with particular regard to how the ecosystem services it provides are likely to be affected, and to the development of tools for stakeholders to use to adapt to these changes, especially when planning and managing infrastructure in the region.
- Assessing the potential for some parts of the Arctic to become a future source of freshwater for water-poor regions to the south, with particular regard for the environmental and socio-cultural consequences of any large-scale transfer of water from the Arctic.
- Providing additional resources to improve access to safe drinking water and waste treatment facilities for smaller communities in the Arctic.
- Continuing to support outreach and education about the state of the Arctic environment, its effects on people living within the region, and its importance to the climate and oceans much further afield. It is particularly important to support and encourage the next generation of Arctic researchers – especially those who grew up in the region.

The content of this report is based on the views of the authors of the Arctic Freshwater Synthesis scientific report and does not necessarily represent the views of the organizations that coordinated this work or their members.



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