Saqqannguaq Road, Narsaq, Greenland

FINN LARSEN

Changing Pathways

Expect changes and some surprises. These are the main conclusions from a review of the pathways by which contaminants are transported to, from, and within the Arctic and how these pathways might respond to shifts in climate.

During the 1990s, wind and weather patterns in the Arctic were quite different from the previous three decades. It is too early to say whether this is part of a natural, recurring change in climate regimes or the result of global warming. Nevertheless, the conditions provide some important indications about how pathways can change and potentially alter the load of contaminants to different parts of the Arctic. Despite the uncertainty, one truth still stands. When it comes to contaminants, the Arctic is not remote or isolated from the rest of the world. Human activities in industrial and densely populated areas will continue to influence what was once thought to be a pristine environment.

This chapter summarizes current knowledge on contaminant pathways and how they relate to climate change. It thereby provides further elaboration and discussion of some points raised in the chapters *Persistent Organic Pollutants*, *Heavy Metals*, and *Radioactivity*, especially looking at time trends and future perspectives. The chapter touches on the effects of long-term climate change in the Arctic. This topic will be treated in more depth in the forthcoming Arctic Climate Impact Assessment (ACIA), due in 2004.

European Route E4, Stockholm

POLFOTO / PELLE ERICHSSON

Climate change in the Arctic

The Arctic is subject to natural climate cycles. Some occur over time scales as short as a few years, while others may span decades, centuries, or even millennia. In addition to this natural variability, the Arctic will be affected by global climate changes related to increases in greenhouse gases.

The following is a short introduction to climate change and climate variability in the Arctic.

Global climate change will warm the Arctic

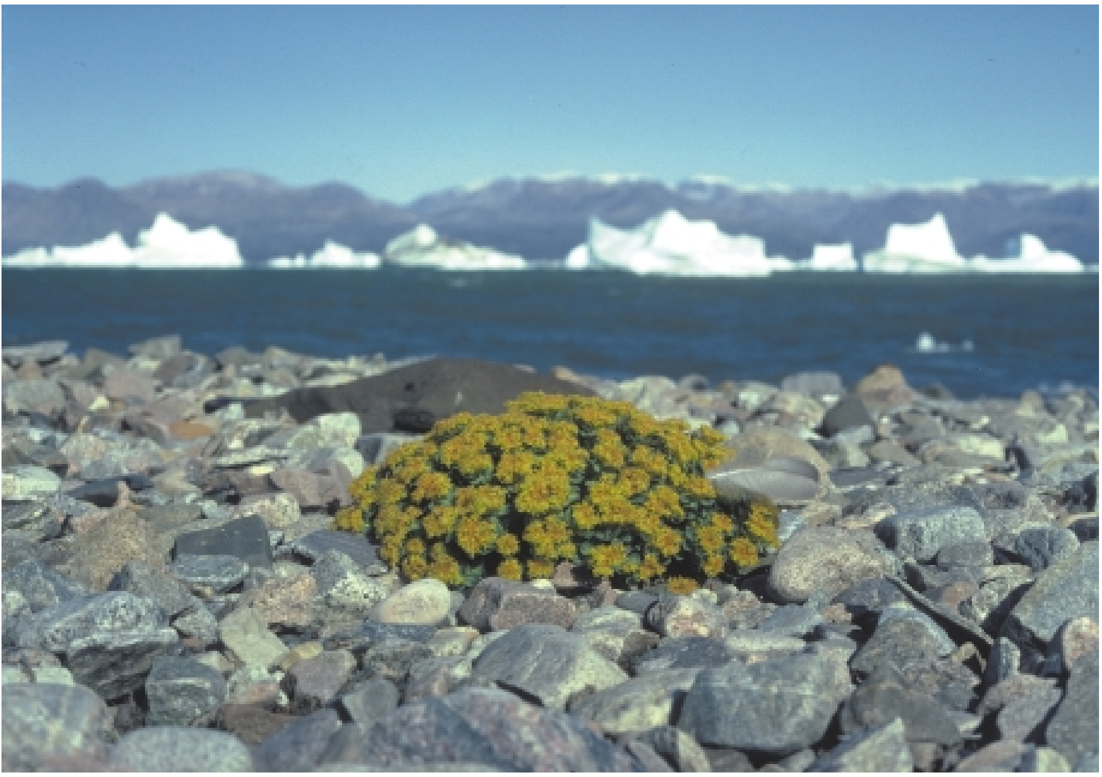
Human activities, such as the burning of fossil fuels, release greenhouse gases to the atmosphere. They affect the Earth's energy balance, which in turn has the potential to influence temperatures and weather patterns. Expert opinion, as expressed by the Intergovernmental Panel on Climate Change, is that some changes are already apparent. This conclusion is based on comparisons with past temperature records and indirect signs of climate variability during the past 1000 years. In the past century, the global mean air temperature has increased by 0.6 °C. Based on computer models of the effects of greenhouse gases on the global climate, the Earth's air temperature is expected to increase by an additional 1.4 to 5.8 °C over the next century. The range represents uncertainty about future emissions as well as an uncertainty about their effects. Climate models show that the warming will be especially pronounced in the Arctic. Excluding the more extreme predictions, the annual mean air temperature may still increase by 5 °C near the pole and by 2-3 °C around the margins of the Arctic Ocean. However, there are large regional variations, even including cooling in some areas.

Arctic Climate Impact Assessment

Climate change and variability, and, more recently, notable increases in ultraviolet radiation, have become important issues in the Arctic over the past few decades. Under the auspices of the Arctic Council, a program has been initiated to evaluate and synthesize knowledge about climate variability, climate change, and increased ultraviolet radiation and their consequences. This Arctic Climate Impact Assessment (ACIA) will also examine possible future impacts on the environment and its living resources, for example on human health, and on buildings, roads and other infrastructure.

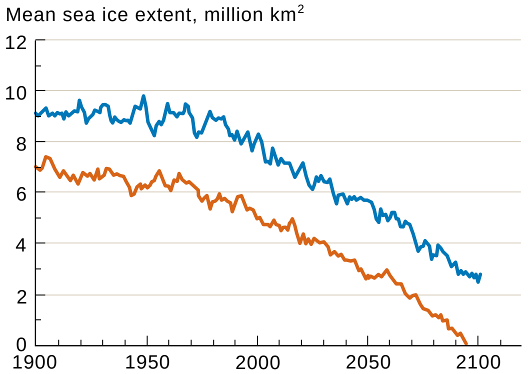
Three major documents will be completed by 2004. They are a peer-reviewed scientific report, a synthesis document summarizing results, and a policy document providing recommendations for coping with and adapting to change. The writing of the first two documents is guided by an Assessment Steering Committee with the lead authors, representatives from the Arctic Monitoring and Assessment Programme (AMAP), the Program for the Conservation of Arctic Flora and Fauna (CAFF), the International Arctic Science Committee (IASC), other international bodies, and persons representing the Arctic indigenous peoples.

The greatest warming will probably occur in winter. By the end of the 21st century, some



Large cluster of rose root on stony shore. Kangerterajiva, Greenland.

POLAR PHOTOS / HENNING THING



Model projections of change in sea ice cover for the Arctic Ocean. Annual mean sea ice extent is shown for the Northern Hemisphere as simulated by two different climate models, which differ in how they treat mixing of the water mass.

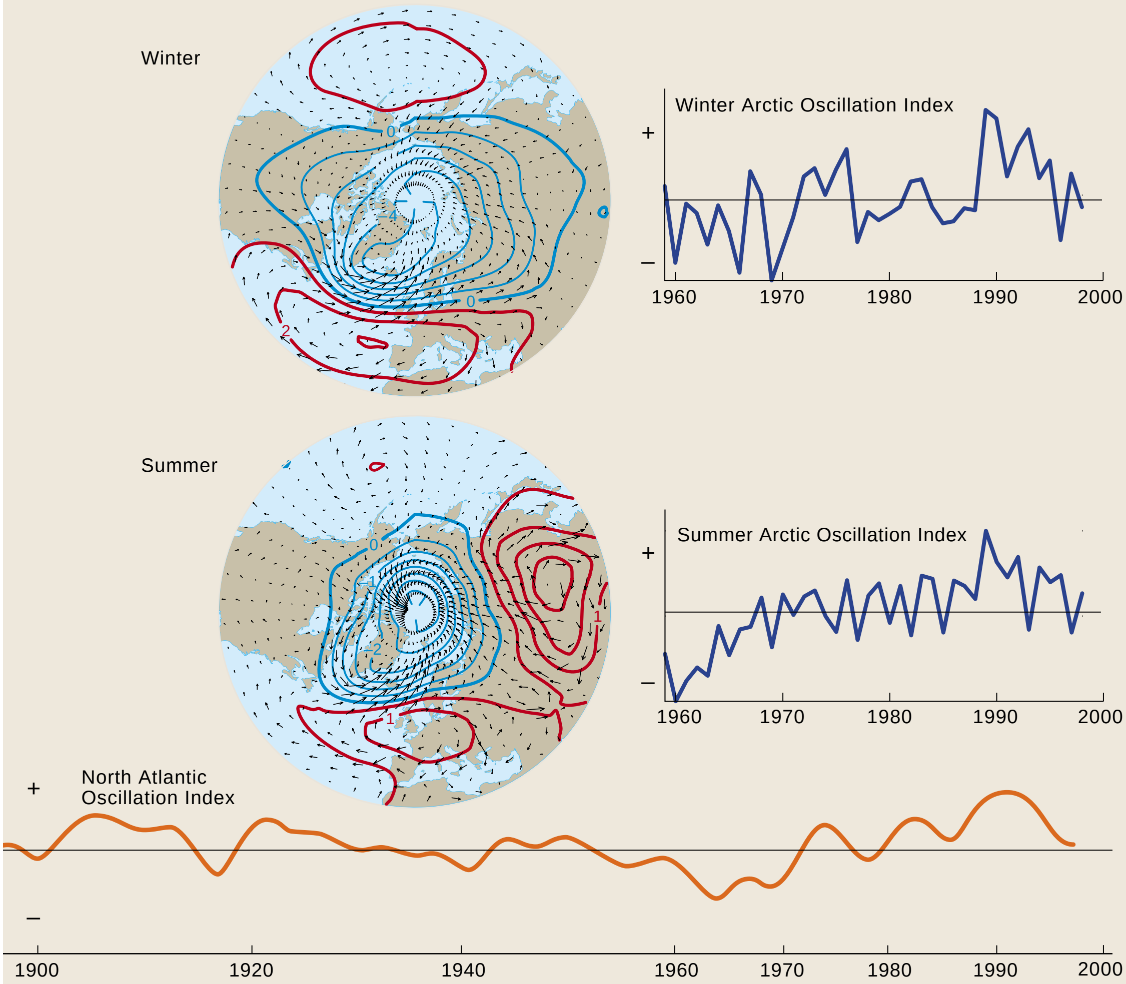
models predict that climate change caused by greenhouse gases might produce an Arctic Ocean that is free of sea ice in the summer.

It is not clear to what extent global climate change has already affected the Arctic. However, current models predict changes that are consistent with observations made during the 1990s.

Recent climate trends follow from Arctic Oscillation

It is well known that climate can oscillate between different climate regimes. El Niño/La Niña in the Pacific is one example outside the Arctic. In the Arctic, these climate regimes are characterized by a high or low Arctic Oscillation Index, which captures different regimes in atmospheric circulation (see box below). Wind and weather patterns affect ice drift and the distribution of water masses in the Arctic, which in turn can change the extent of ice cover. Changes in air circulation can thus influence the transport of contaminants into and within the Arctic in several ways.

Since the 1960s, there has been a change in the overall pressure pattern in the Arctic. The 1990s in particular have been characterized by lower than average atmospheric pressure over the pole. Expressed in a different way, a low

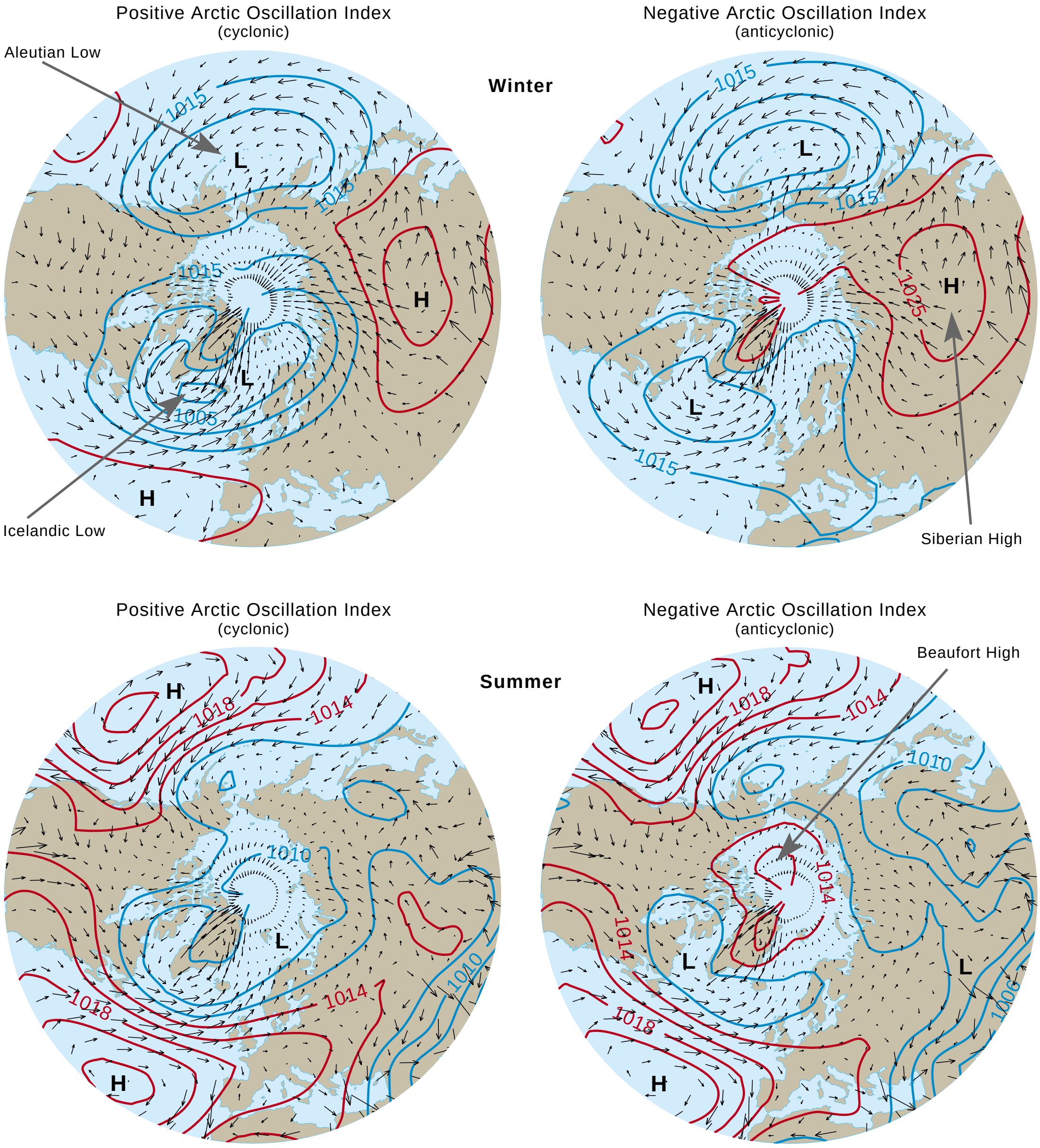


The Arctic Oscillation Index since 1960 and the North Atlantic Oscillation Index since 1900. The maps represent a combination of the Arctic Oscillation Index and atmospheric pressure fields during winter and summer.

The Arctic Oscillation and the North Atlantic Oscillation

A leading component of variation in the Arctic's climate is governed by the Arctic Oscillation, which captures different regimes in atmospheric circulation in the northern hemisphere. Atmospheric circulation patterns can be described by differences in sea-level air pressure, or the barometer reading in layman's terms. The Arctic Oscillation Index is a measure of sea surface air pressure patterns. Specifically, it captures winter pressure anomalies north of 20° North.

Strongly correlated with the Arctic Oscillation is the North Atlantic Oscillation, which is a measure of the surface air pressure difference between the Icelandic Low and the Azores High. This index is an indication of the main wind patterns over the North Atlantic.



Atmospheric pressure fields and wind patterns in winter and summer with the Arctic Oscillation Index strongly positive (left) or strongly negative (right).

Arctic Oscillation Index had been replaced by a high Arctic Oscillation Index. The cause for this shift is not completely understood. It could be the result of natural climate cycles, where short- and long-term patterns have coincided to produce a very high index in the 1990s. It could also be a sign of the Arctic responding to global climate change. Regardless of which explanation turns out to be correct, the changes observed in the early 1990s provide an example of how the Arctic might respond to global warming, including examples of how climate change may alter the transport of contaminants.

Winds, precipitation and temperature

The atmosphere provides an important pathway for contaminant transport. Winds carry contaminants from source regions, while precipitation promotes deposition to the land and the sea. Temperature plays a role in determining the relative distribution of contaminants between the air, land, and ocean. Changes in wind patterns, precipitation, or temperature can thus change the routes of entry of contaminants into the Arctic and the locations at which contaminants are deposited to surfaces or re-emitted to the air.

Wind patterns govern pollution transport

The Arctic is characterized by relatively predictable patterns of sea-level air pressure. Every winter, high-pressure areas form over the continents, while low pressure cells dominate the northern Pacific (the Aleutian Low) and the northern Atlantic (the Icelandic Low).

These low- and high-pressure areas produce wind patterns that pump airborne pollutants into the Arctic. The Icelandic Low produces westerly winds over the eastern North Atlantic and southerly winds over the Norwegian Sea, which can carry pollution rapidly from eastern North America and Europe into the High Arctic. Similarly, the Aleutian Low tends to steer air from Southeast Asia into the Bering Sea, Alaska, and the Yukon Territory. Here, however, the mountains along the west coast of North America obstruct the airflow, while intensive precipitation on their western flanks provides a mechanism to deposit contaminants to the surface.

In summer, the continental high-pressure cells disappear and the oceanic low-pressure cells are less intense. The result is much weaker transportation of air and pollutants into the Arctic from southern areas during summer.

With a high Arctic Oscillation Index, as in the 1990s, the Icelandic low deepens. Moreover, it extends farther into the Arctic, across the Barents Sea and into the Kara and Laptev Seas north of Russia. This increases wind transport eastward across the North Atlantic, across western and central Europe, and into the Norwegian Sea. Also, deep storms with strong winds become more frequent and extend farther into the Arctic.

The result of this shift in winter wind patterns is that the Arctic becomes more strongly connected to industrial regions of North America and Europe. The storms also carry rain or snow, which can wash contaminants from the air and deposit them on the ground, on ice, or in the water.

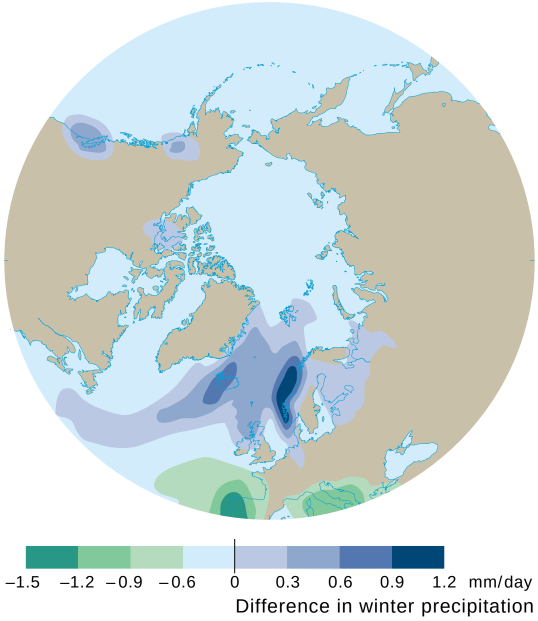
The wind patterns in the Pacific appear to change very little in a shift from a low to a high Arctic Oscillation Index.

Changes in wind patterns will affect all airborne contaminants. For example, spraying of pesticides in eastern North America and Europe is more likely to show up as peaks in Arctic air measurements during a high Arctic Oscillation Index. Similarly, re-emissions of previously deposited organic pollutants in the soil and water of North America and Europe will enter these same pathways and thus be transported more readily to the north. However, as we will see below, increased transport by air can be offset by other factors.

Precipitation transfers pollutants from the air to slower ocean currents

Air transport of particle-associated metals such as lead, cadmium, and zinc will be affected by changing wind patterns. However, these pollutants are scavenged inefficiently within the Arctic and thus tend to stay in the air rather than deposit to the surface. The actual load to land and sea surfaces in the Arctic depends strongly on the amount and kind of precipitation. Changes in snow and rain patterns thus have a much greater potential to alter loading than does a change in wind patterns.

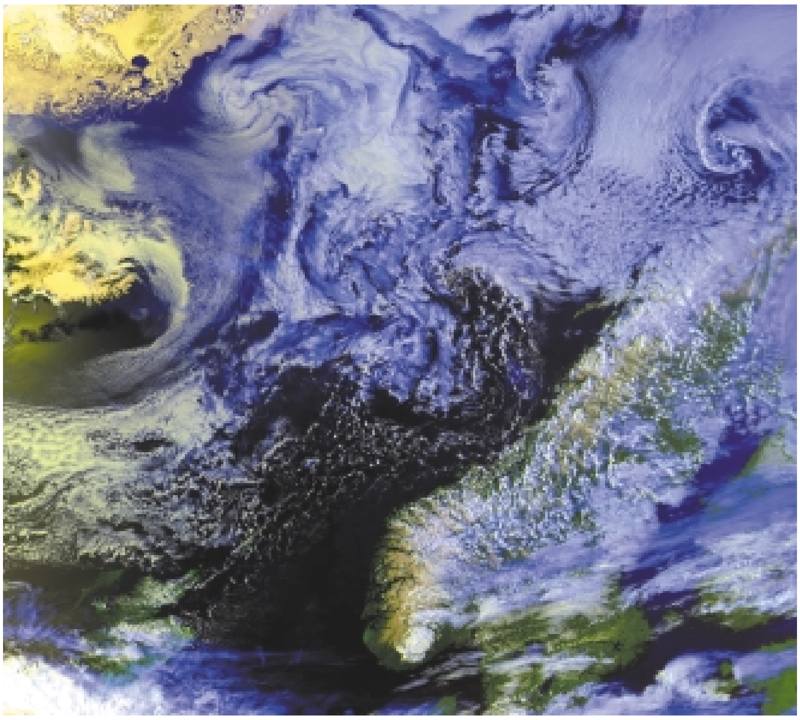
Particulate metals wash out in high precipitation areas. If this occurs over the sea, metals can then be carried by ocean currents. For example, lead from leaded gasoline, which is still used in many Russian and Eastern European cars, rains out in the Nordic Seas and in the southern portion of the Eurasian Basin. Ocean transport is much slower than air transport and the pollution signal to various parts of the Arctic can thus be delayed.



Difference in winter precipitation between low and high North Atlantic Oscillation Index.

The changes in winds and temperature that are associated with shifts in Arctic Oscillation are likely to affect precipitation. The network to monitor changes is sparse, however, and it is thus difficult to assess trends. Over a longer time span, the past 40 years, there are indications that precipitation has increased over Canada's North by about 20 percent. More moisture is probably also moving into the Barents, Kara, and Laptev Seas, carried by the strong southerly winds in the Norwegian Sea during autumn and winter. Models for long-term climate change predict that the Arctic will become a wetter place, and a greater fraction of

Storm over the Norwegian Sea. Satellite image.



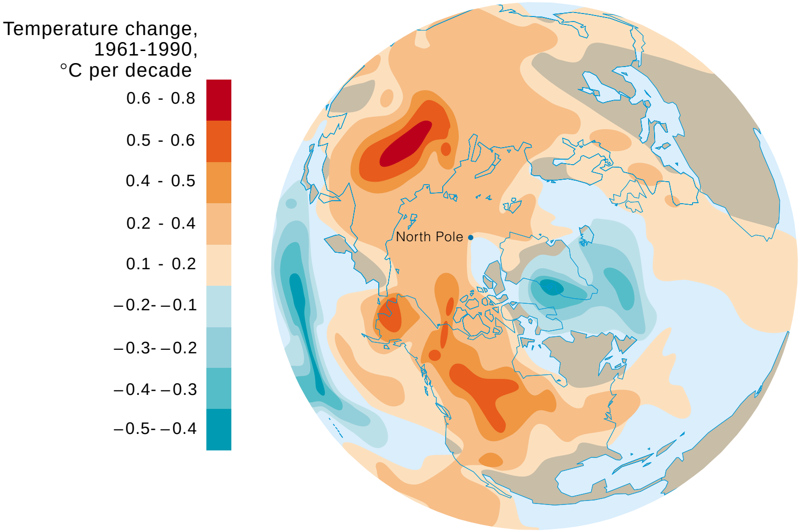
KONGSBERG SATELLITE SERVICES / NOAA

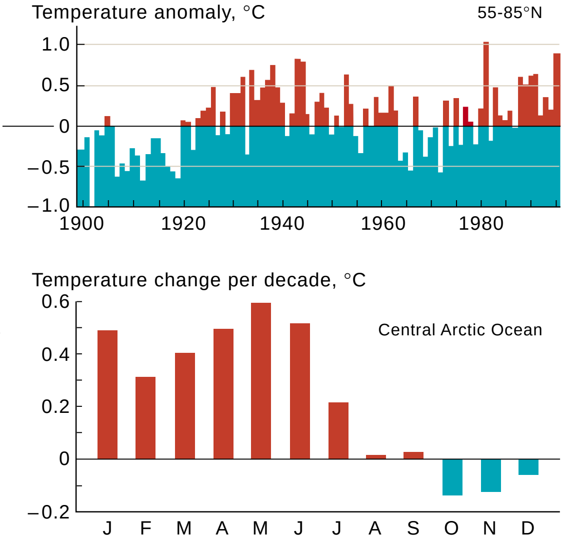
the atmospheric particles that enter the Arctic are thus likely to deposit there.

Snow and fog are far more efficient than rain in removing some contaminants from the air and depositing them to the surface. For metals, both a change in the amount of precipitation or in the relative amounts of rain and snow can thus have a large impact on transport.

In 1991, the Canadian air monitoring station at Alert recorded a marked dip in aerosol metal concentrations. It was noted that this decrease coincided with the economic collapse that followed the fall of the former Soviet Union, which significantly reduced emissions of some heavy metals in Russia. However, the air concentrations could also have been affected by the shift toward a high Arctic Oscillation Index that occurred at this time. It is difficult to determine the relative importance of the two explanations without data that both cover a wide range of sites and span several climate change cycles. Nevertheless, the Alert example illustrates that caution must be used in assigning causes for contaminants trends in relatively short time series.

Scavenging by rain and snow can also be important for particle-associated POPs, such as some PCBs, and for POPs that to some extent dissolve in water, such as HCHs and toxaphene. High precipitation in the Nordic Seas and southern Eurasian Basin would thus increase the role of ocean currents and ice as pathways. In the Bering Sea, rainout has selectively removed beta-HCH from the air, and switched the mode of delivery to the Arctic Ocean from transport by winds to transport by ocean currents. Beta-HCH, a component of the pesticide technical HCH, is especially likely to move from air to seawater.





Temperature trends for the Arctic showing the annual surface temperature trends over the Northern Hemisphere expressed as rates of change for the period 1961-90 (map), temperature anomalies (55-85° N) for 1900-1995 evaluated against the average for 1951-1980, and (lower panel) the trend by month in surface air temperature of the central Arctic Ocean for the period 1979-1995 showing the recent warming to be mainly a winter-spring phenomenon.

Most of the Arctic has become warmer

Parts of the Arctic have become warmer in the past 40 years. In spring, surface air temperatures in almost the entire High Arctic show a significant warming. In the Eurasian part of the Arctic Ocean, there is a trend toward a longer period of the year when the sea ice is melting. As an Arctic average, temperatures over land have increased by up to 2°C per decade during the winter and spring. However, there are significant regional variations. For example, on a yearly average basis, the western Greenland-Baffin Bay area has been cooling.

Changes in air temperature can have a direct physical effect on the transport of some contaminants. This is true for substances whose volatility, solubility, and adsorption to solids are sensitive to temperature, which is the case for most POPs. The previous AMAP assessment described how volatile contaminants can reach the Arctic from their source regions in the south by a series of ‘hops’. Higher temperatures in the Arctic would lead to an increased potential for atmospheric transport. Previously deposited organic pollutants would also be volatilized once again and move back into the atmosphere. On the other hand, if the temperature difference between the pole and equator decreases, as predicted by models, the global thermodynamic contrast that favors the Arctic as a final reservoir would weaken. Higher temperatures could also speed up some of the chemical reactions that remove pollutants from the atmosphere. Increases in ultraviolet radiation, which are connected to ozone depletion in the Arctic, also promote chemical reactions that destroy or change the form of contaminants.

Even more important than the effects on air chemistry might be that higher temperatures will lead to more efficient degradation of contaminants by aquatic microorganisms. For alpha-HCH, a simple calculation shows that a significant increase in temperature in the upper water layers of the Arctic Ocean could substantially reduce the environmental half-life of this substance. One model has tried to predict how an increase in temperature would change the health risk from hexachlorobenzene (HCB) to people in a temperate region. HCB poses a health risk partly because it biomagnifies in marine food webs and can reach people from traditional foods. The model implied a reduced exposure with increasing temperatures. The reason is that higher temperatures would enhance degradation and also force this pollutant from water into the air, reducing the water concentration and, therefore, reducing the amount of HCB entering the bottom of the food web.

Changing water flows in rivers

Changes in temperature and precipitation will affect runoff and flow in Arctic rivers. So far, changes in flow seem to be within normal year-to-year variability. With long-term climate changes, models suggest that the flow in the Yenisey, Lena, and Mackenzie Rivers is likely to increase. In other rivers, such as the Ob, it may decrease. For smaller rivers at high latitudes, the seasonal patterns of river flow are likely to change. It is projected that earlier snowmelt in spring would change the timing, amplitude, and duration of spring flow.

There are also some changes in where river water goes once it has entered the ocean. This is discussed in the section *New pathways in Arctic Ocean surface waters* on page 105.

Lakes, land, and glaciers

Ice can act as a physical barrier for contaminants and also, at times, as a reservoir. What happens when higher temperatures melt ice in lakes, in the ground, and in glaciers?

Lakes are sensitive to changes

Arctic lakes are sensitive to climate change, as temperatures directly affect the timing of freeze up in the fall and ice melt in spring. This, in turn, affects the flow of water to, within, and from the lake. There are no studies that show effects of changes in the Arctic Oscillation Index on Arctic lakes. In North America, long-term change has been observed, however. Over the past 100 years, there has been a delay of several days in freeze-up, while the spring break-up now comes almost a week earlier than it did a century ago. Changes in water flow through lakes can have a large impact on the transport of contaminants. Currently, Arctic lakes appear to retain only a small fraction of the contaminants they receive. The peak in runoff from the snowmelt in their catchment areas comes before the ice on the lake has melted or before the water in the lake has begun mixing from top to bottom, as it does when the lake warms up in summer. The runoff, which contains recently deposited contaminants, therefore traverses the lake just under the ice or above most of the water column, flowing out as quickly as it flows in.

With the reduced ice cover and loss of permafrost that is expected with climate change, Arctic lakes will probably become more like lakes farther south. Specifically, the water column will mix earlier, increasing the likelihood that contaminants will be retained in the lake. Moreover, the warmer water, along with wind mixing and more organic matter from the surrounding land, may influence primary production. A change in the amount or timing of primary production may increase the opportunity for contaminants to enter the food web directly. However, it could also lead to more sedimentation, which, at least temporarily, removes contaminants to the bottom sediments.

Permafrost changes may increase mercury cycling and natural radioactivity

In the Arctic, ice is a more or less permanent feature on land. The soil is typically gripped in permafrost, and only the relatively thin active layer on top thaws in the summer. This layer, which supports all biological processes and any vegetation, can be limited to the top meter or less. In the 1990s, permafrost degradation occurred in some parts of Alaska and Russia, but not in northeastern Canada. This matches the distribution of air temperature trends observed and predicted by climate models.

Permafrost melting will lead to more nutrients and sediments reaching lakes and rivers. The flow of organically bound carbon and mercury may also increase. Episodic, large-scale releases of organically bound mercury may become a dominant feature accompanying permafrost degradation. Clearly, Arctic lakes would be vulnerable, but increased input of carbon is also projected for Arctic seas, suggesting an increased load of mercury, which follows the carbon, in the marine environment. Hudson Bay may be especially vulnerable due to its large drainage basin and because permafrost melting is likely in the area. Mercury concentrations in snow have increased in this area, as have mercury fluxes to sediment.

Along the coasts, sea-level rise will promote erosion, which could disturb contaminated sites. It may also damage structures such as pipelines, thus releasing potentially contaminating substances to the environment.

MAGNUS ELANDER

Aerial view of polygon tundra, Lena Delta, Russia.

POLAR PHOTOS / HENNING THING

Glacier at Kangerlussuatsiaq, West Greenland. The light grey zones at each side of the glacier show the former extent.

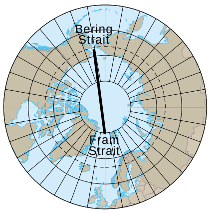
Change in permafrost also has an implication for radon that diffuses out of the ground. This radionuclide is not generally related to anthropogenic activities but comes from soils and bedrock. Radon is trapped in frozen ground in the Arctic, but with warmer temperatures, more radon will diffuse out of soils, increasing the dose of this element and its decay products to people.

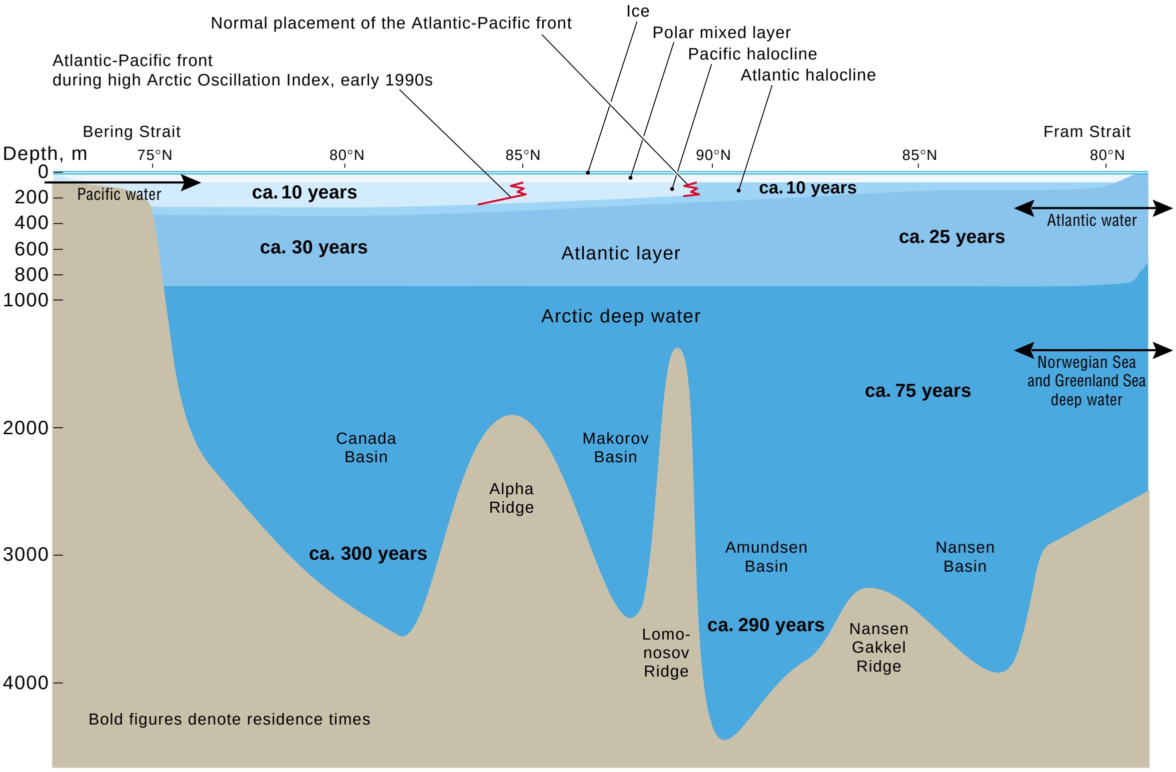
Glaciers could become sources of DDT

Glaciers have accumulated snow and ice over millennia. They also act as reservoirs for some airborne contaminants. When the glaciers melt, these contaminants can be re-emitted to the air or be released in the meltwater. In the Arctic, North American glaciers have been shrinking since the 1960s. In the Canadian Archipelago, the glacial melt was exceptionally strong in the 1990s, corresponding to the high Arctic Oscillation Index. In the European Arctic, the trend is not as clear. Scandinavian glaciers have grown during the 1990s, whereas most Svalbard glaciers continue to shrink at the same rate as they did throughout the 1900s. Russian glaciers may be retreating, but this is difficult to establish because of limited data. Measurements from the Agassiz Ice Cap in Canada give a hint of the size of glaciers as a potential source for contaminants. For DDT, glacial melt may provide an important climate-modulated source. For HCHs and PCBs, this source is small compared with the reservoir in the Arctic Ocean.

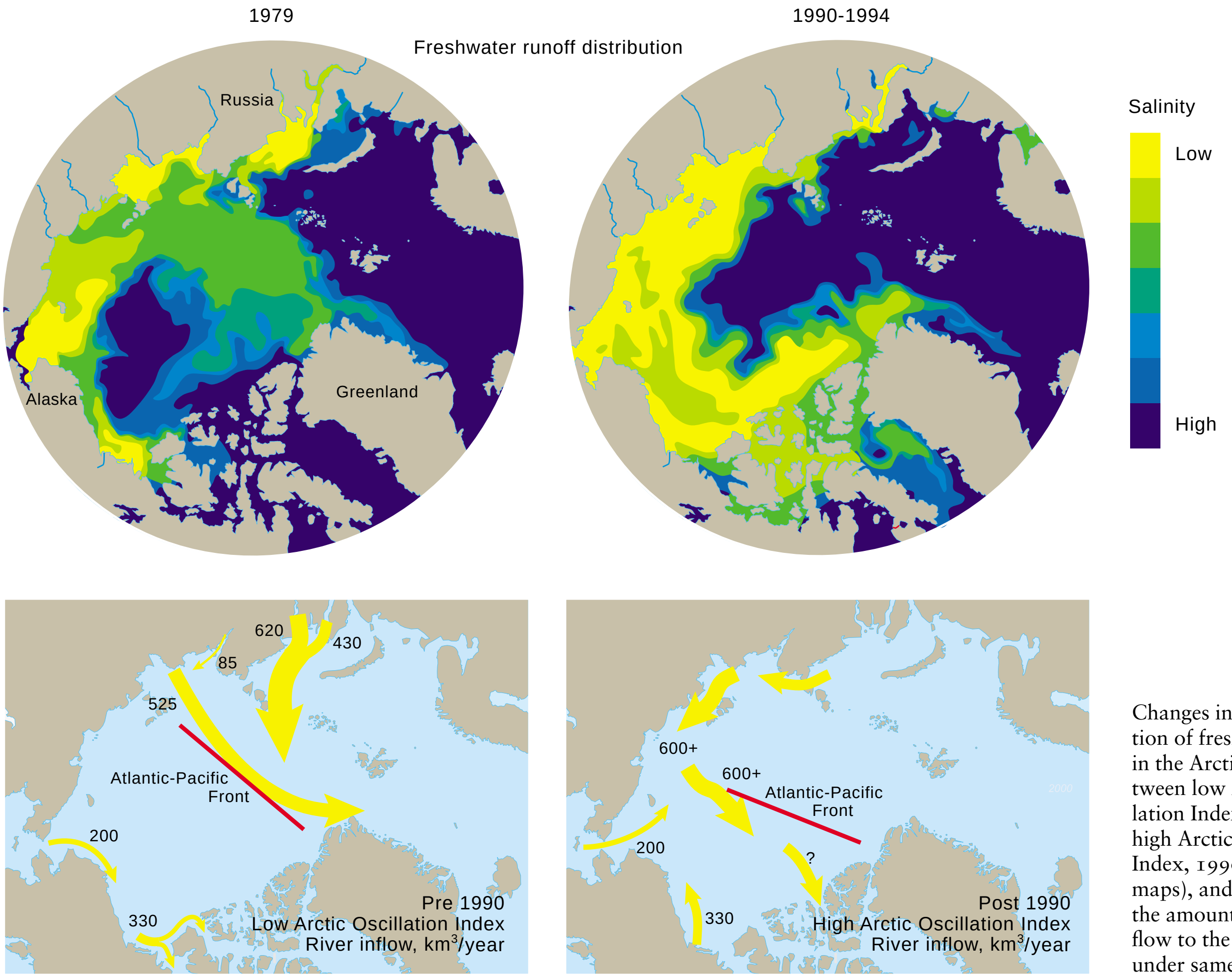
Ocean transport

The Arctic Ocean is divided into distinct layers. Below 800 meters is Arctic deep water, with a very long residence time. From 200 to about 800 meters is the Atlantic Layer. At the very top is the Arctic surface water, which is the most important for contaminant transport within the Arctic Basin. Between the surface water and the Atlantic layer is the halocline, a transition zone of increasing salinity. The significance of ocean transport for contaminants to, from, and within the Arctic has been increasingly recognized during the past few years. Currents are sluggish compared with winds, and oceans therefore become important later in a contaminant's history. However, the ocean may have a much larger capacity to carry contaminants than the air, allowing currents eventually to catch up with and surpass





The stratification of the Arctic Ocean. showing the polar mixed layer, the Pacific and Atlantic domains of influence and the haloclines. The red lines show the normal placement and the displacement of the Atlantic Pacific front during the high Arctic Oscillation Index of the early 1990s.



Changes in the distribution of freshwater runoff in the Arctic Ocean between low Arctic Oscillation Index, 1979, and high Arctic Oscillation Index, 1990-94 (upper maps), and changes in the amounts of river inflow to the Arctic Ocean under same conditions.

atmospheric transport in importance. Some of the ocean pathways have already exhibited changes clearly related to the Arctic Oscillation.

New pathways in the Arctic Ocean surface waters

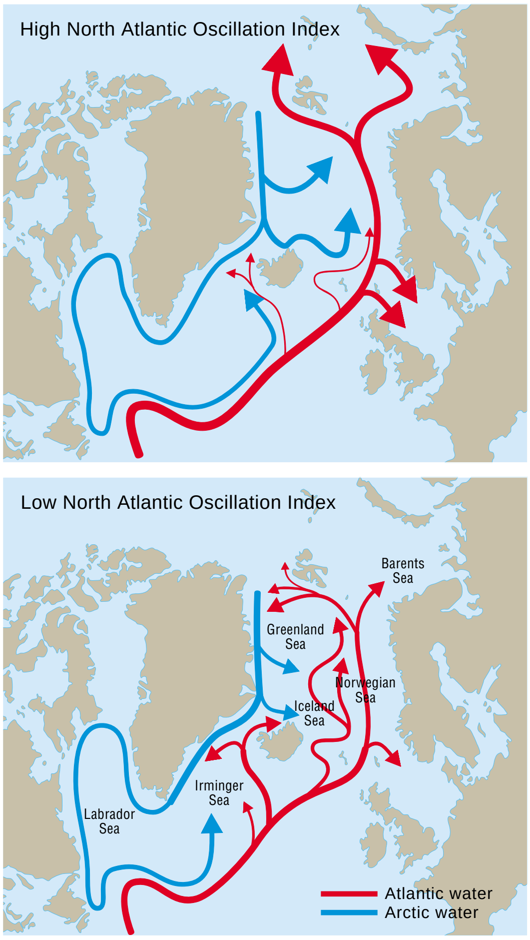
Surface ocean water pathways follow two basic trajectories: the Transpolar Drift that crosses the Eurasian Basin and exits through Fram Strait, and the circulating Beaufort Gyre on the North American side of the Arctic Ocean (see figure on page 3). With a high Arctic Oscillation Index, water in the Transpolar Drift moves closer to North America, while the Beaufort Gyre retreats into the Canadian Basin.

More important than changes in trajectories are the effects on the halocline. This is a transition zone of increasing salinity, which serves as a barrier for transfer of heat and contaminants from Arctic surface water to the Atlantic water below. In the 1990s, the halocline in the Eurasian Basin weakened. The most likely reason was that changes in wind patterns forced freshwater from the Russian rivers emptying into the Laptev and Kara Seas eastward, diverting their flow toward the East Siberian Shelf. The freshwater input to the Arctic Ocean is important for the development of stratification in the water column. A consequence of this diversion, therefore, would have been a reduction in stratification in the Eurasian Basin and increased stratification in the Canadian Basin.

The diversion of the Russian river outflow affects the transport of persistent organic pollutants both from the rivers and within the Arctic Ocean. Specifically, instead of entering the Transpolar Drift to exit the Arctic Ocean within about two years, the pollutants would enter the Canadian Basin, which has a ten-year residence time. Pollutants would thus stay in the Arctic Ocean much longer, especially increasing the load in the Canadian Basin. Furthermore, once in the Canadian Basin, pollutants from Russian rivers might then exit via the Canadian Archipelago instead of via the west side of Fram Strait. The increased residence time would lead to increased sedimentation, making it likely that more sediment-bound contaminants would remain in the Arctic.

Driftwood from Siberia found at Fleming Fjord, north of Ittoqqortoormiit, East Greenland.

POLAR PHOTOS / HENNING THING



Main features of ocean circulation in the North Atlantic and the Nordic Seas during high and low North Atlantic Oscillation Index.

The Atlantic's increased role leads to declines in cadmium

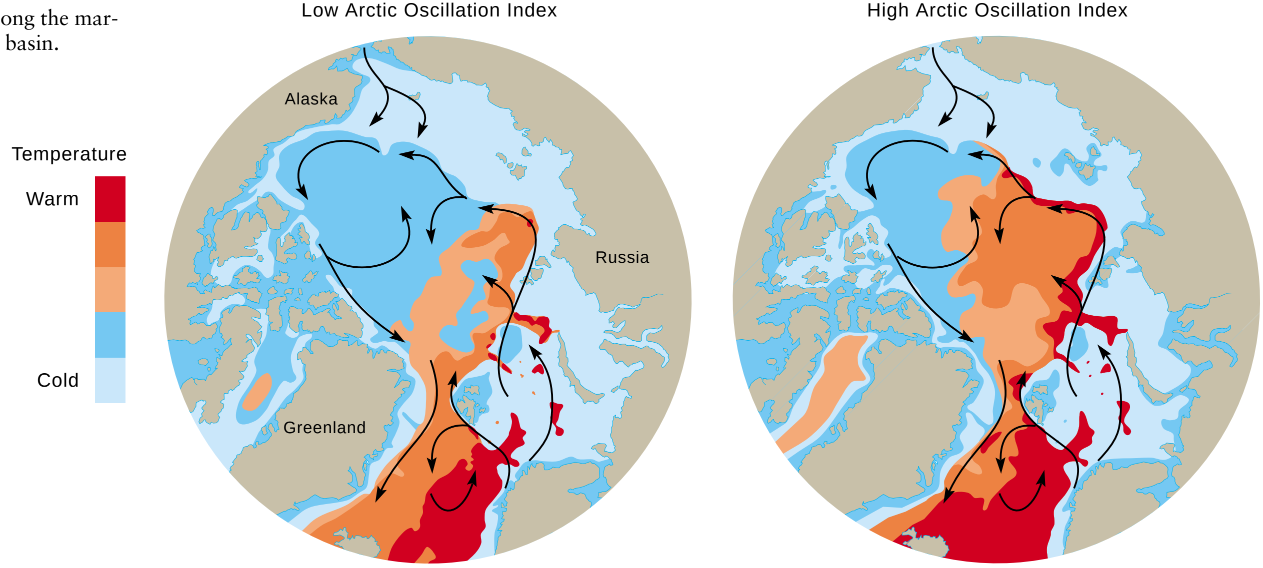
For the Atlantic Layer, the Arctic Oscillation influences the flow of water into and out of the Arctic Ocean. Communication with the Pacific is through Bering Strait, while communication with the Atlantic is through Fram Strait and through the Norwegian and Barents Sea. Important contaminants in the Atlantic inflow include radionuclides from European reprocessing plants, and any change in the flow of Atlantic water may thus affect concentrations and distribution of radionuclides in the Arctic marine environment. In the past few decades, the North Atlantic Oscillation Index has increased, causing changes in distribution of water masses in the Nordic Seas. This has brought contaminants from the reprocessing plants closer to the Norwegian coast and into the Barents Sea.

Traditionally, the Arctic Ocean has been thought of as a quiet, steady-state system characterized by several relatively stable layers. During the 1990s, there were some spectacular changes. The front between Atlantic and Pacific water was forced closer toward North America, which increased the Atlantic's area of influence in surface water by some 20 percent. Water in the Atlantic layer is both warmer and saltier than the Pacific water that it displaced.

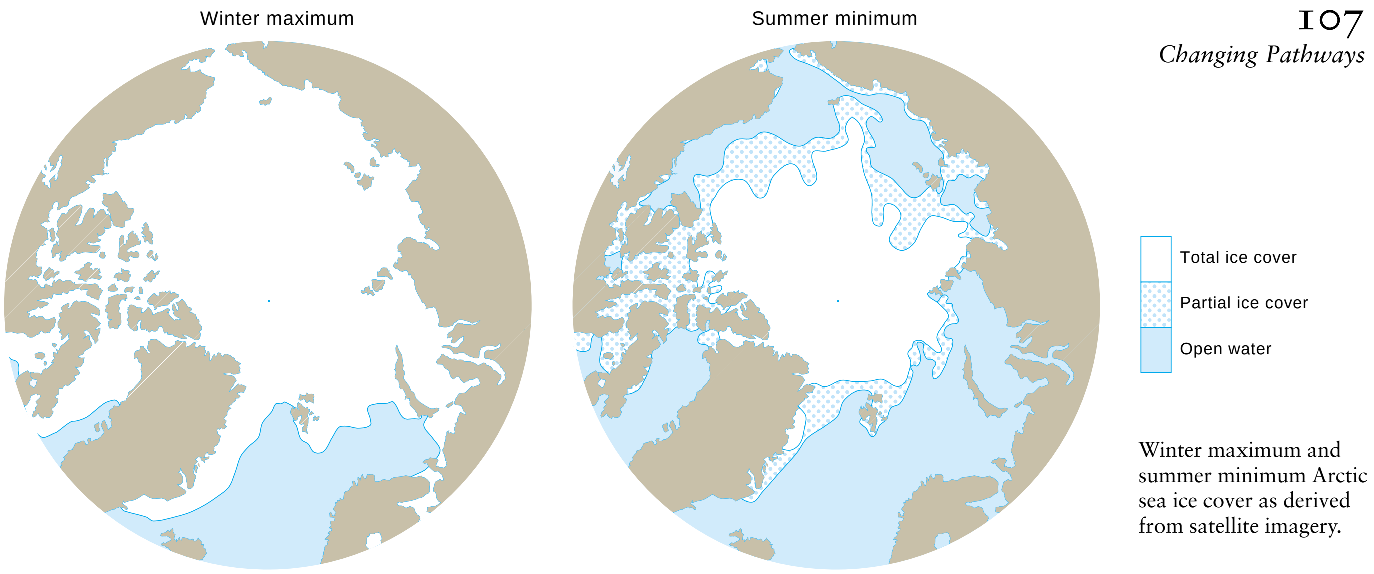
The declining role of Pacific water in the Arctic Ocean has implications for cadmium, a toxic metal that biomagnifies in the marine food web. In the ocean, the distribution of this metal is largely controlled by natural biogeochemical cycles, with the Pacific having higher natural concentrations than the Atlantic. Because the Pacific inflow through the Bering Strait is a dominant source to the surface waters of the Arctic, reduced Bering inflow since the 1940s has probably led to reduction in cadmium input. Furthermore, the encroachment of Atlantic water during the recent high Arctic Oscillation Index will have reduced the domain of Pacific water that is relatively enriched with cadmium within the Arctic. Changes in upwelling or mixing are also likely to affect the entry of cadmium into surface water from deeper layers.

Sea ice

One of the prominent features of the Arctic Ocean is its ice cover. Changes in ice cover have already occurred and the effects of this on persistent organic pollutants and mercury may become increasingly important.



An exceptionally strong shift to high Arctic and North Atlantic Oscillation Indices in about 1989 increased the influence of Atlantic water (red) in the Arctic basin. The Atlantic layer currents are relatively fast and move water at a rate of 300-1600 kilometers per year along the margins of the basin.

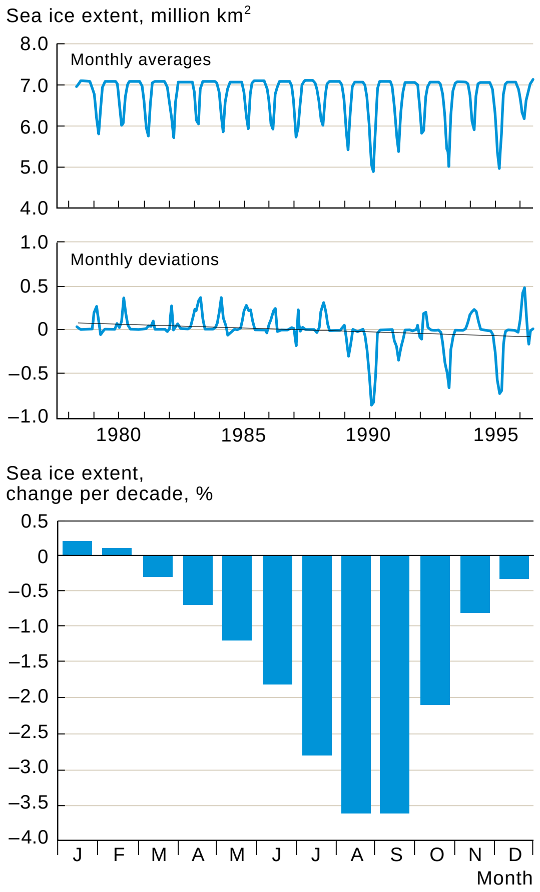


Winter maximum and summer minimum Arctic sea ice cover as derived from satellite imagery.

Less ice cover

During the 1990s, the scientific community recognized with some alarm that Arctic sea ice had retreated over the past three decades. The changes included a reduction in the area covered by sea ice, an increase in the length of the ice melt season, and a loss of multi-year ice. The rate of loss has been difficult to estimate but is approximately 3 percent per decade.

Most of the ice has been clearing during summer over the shelves of the Eastern Arctic, north of Russia. Multi-year ice has decreased even more rapidly and been partly replaced by first-year ice. First-year ice melts more easily than multi-year ice because it is thinner and saltier. In the East Siberian and Beaufort Seas, there were unusually large areas of open water in late summer at various times during the 1990s. It appears that the marginal seas are becoming only seasonally covered with ice, and that the extent of the permanent ice pack is decreasing.



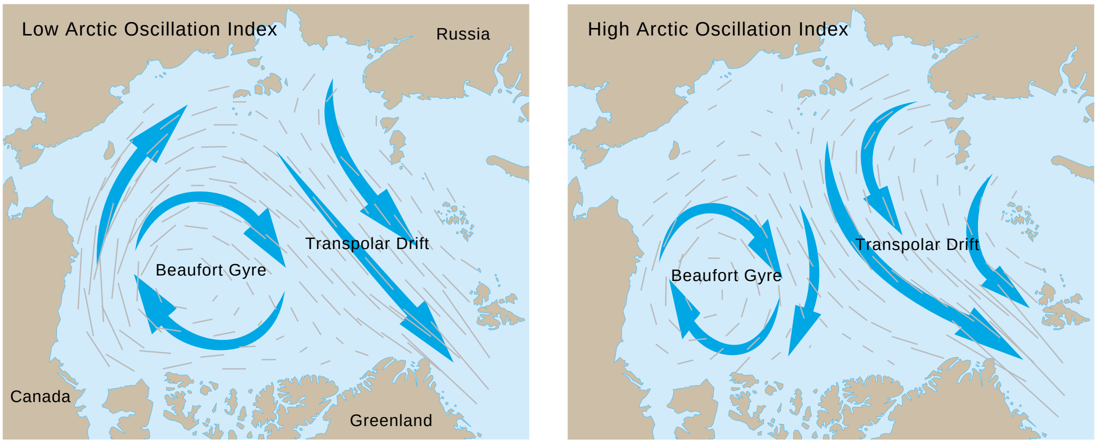
The change in Arctic Ocean sea ice extent from 1979 to 1995 showing the ice loss to be predominantly a late winter–summer phenomenon.

The loss of sea ice is consistent with what can be expected under a high Arctic Oscillation Index. Several factors are probably involved including more heat being transported to the pole by southerly winds. Even more important might be that winds cause changes in the distribution of ice. Ice-thickness measurements made from submarines indicate that the multi-year ice in the Central Arctic Ocean has been getting thinner. Most of the information has been gathered in the interior of the Arctic Ocean, and the decrease might be, at least in part, the product of a shift in the distribution of multi-year ice toward North America.

Sudden but temporary changes in ice cover have occurred earlier in Arctic history. Over a century ago, the whaling fleet experienced a dramatic decrease in ice cover in the North American Arctic. In the Barents Sea, about 15 percent of sea ice cover was lost around 1920.

Increased exchange of POPs between sea and air

Some persistent organic pollutants have accumulated in the Arctic Ocean surface waters. The low temperatures of the Arctic, which decreases their volatility in air and increases their tendency to dissolve in water, acts as a driving force in moving them from the air to the water. This pathway is especially important for compounds that prefer cold water, alpha-HCH being a prime example. Once these pollutants are in the water, they can become trapped under the ice and retained in the water masses, some of which have long residence times.



Ice drift patterns for years with low and high Arctic Oscillation Index.

For alpha-HCH, discontinued use of the pesticide technical HCH has led to a drastic reduction in air concentrations. As a consequence, the ice-covered areas of the Arctic Ocean became oversaturated relative to atmospheric levels. If the ice cover disappears, these areas will become a source to the atmosphere. Other contaminants, such as PCBs and toxaphene, are still loading into the Arctic Ocean from the air. The same loss of ice cover could thus lead to increased loading of these two contaminants into Arctic surface water.

Ice changes will affect mercury deposition in the Arctic

As described in the chapter *Heavy Metals*, mercury deposition in the Arctic increases dramatically at polar sunrise due to an extraordinary set of circumstances. The phenomenon is called mercury depletion. Although the mechanisms behind mercury depletion are not yet fully understood, results of investigations to date indicate that gaseous mercury in the air reacts with bromine compounds to form particulate and reactive mercury. The bromine compounds are formed when bromine, emitted from seawater and sea salts, reacts with ozone in the presence of ultraviolet light (hence the connection to the return of the sun). The reactive mercury that is produced is efficiently removed from the atmosphere and some of it remains in the snow. Some will eventually end up in meltwater and may thus enter aquatic ecosystems. The sensitivity of the Arctic to mercury probably lies in the fact that meltwater and runoff can drain into surfaces below the ice, where ice cover blocks the re-emission of mercury to the air.

Change in sea ice cover can affect this unique deposition mechanism if the availability of bromine is altered. Initially, it is likely that climate change will contribute to increasing the amount of first-year ice around the polar margins, leading to saltier ice and snow. It could thus enhance the emission of bromine and possibly extend the area of mercury depletion events.

With further climate change, parts of the Arctic will become more temperate. Mercury deposition would decrease, and at the same time more mercury could escape back to the atmosphere after being deposited. The end result would be less accumulation of mercury in marine and aquatic environments. It is harder to predict whether levels in biota would also change. Mercury biomagnifies and its levels depend on the structure of the food web. Changes in the food web structure could, therefore, be much more important than changes in physical pathways. Mercury levels may also be affected by changes in permafrost, and increase with an increased flux of organic carbon to both freshwater and marine environment. In summary, the complexity of mercury pathways combined with obvious sensitivities to climate change should alert us to the possibility of surprises in the future.

Shifting routes from drifting sea ice

The general patterns of ice drift have been recognized since the beginning of the 1900s, and follow the same trajectories as ocean surface water in the Transpolar Drift and the Beaufort Gyre. Only recently have these ice trajectories been mapped in detail. The new data suggest that there are two characteristic modes of ice motion, one during a low Arctic Oscillation Index and one during a high index. During a low index, which prevailed from the 1960s to the 1980s, the Transpolar Drift moves ice directly from the Laptev Sea across the Eurasian Basin and into the Greenland Sea. By contrast, during a high index, the prevailing situation for much of the 1990s, this ice transport route is diverted or splits. Some goes to the Greenland Sea and some moves across the Lomonosov Ridge and into the Canadian Basin. At the same time, the Beaufort Gyre shrinks back into the Beaufort Sea and becomes disconnected from the rest of the Arctic Ocean. This means that it exports less ice to the East Siberian Sea and only imports a little ice from north of the Canadian Archipelago.

The changes in ice-drift patterns have implications for the transport of sediment and any contaminants trapped in the ice. Specifically, when ice moves away from the East Siberian and Laptev Seas, new thin ice can form close to the coast, increasing the opportunity for sediments to be trapped. Moreover, less ice moves from the North American to the Eurasian part of the Arctic Ocean.

Biological impacts

Climate change will have impacts on plants and animals in the Arctic and thus on the biological pathways for contaminants. Although we can infer the types of changes that are likely to occur, we cannot predict their scope and timing. The following are examples of processes that should be examined further.

Changing plant cover will affect deposition

Vegetation provides surfaces onto which airborne contaminants can deposit when air masses pass over the land. Forests, for example, have a unique ability to take chemicals from the air via foliage and thence to a long-term reservoir in the soil.

Warmer winters will promote growth of woody shrubs and stimulate a northward migration of the treeline. So far, there is no evidence of large changes on the Arctic tundra. However, if permafrost melts and the water table changes, such changes could occur much more rapidly in the Arctic than in other regions of the world.

Aquatic ecosystems are sensitive to changes

Not only temperature but also changes in light and the flow of nutrients will affect freshwater ecosystems. For example, loss of permafrost will increase inputs of nutrients from the surrounding soil. Spring algae blooms will probably come earlier.

In the summer, increased water temperature will negatively affect fish species that are sensitive to temperature or have temperature thresholds during their spawning. Each species has to be evaluated separately, but trout and grayling are known to be sensitive. Increased winter temperatures will enhance microbial decomposition. Insects, phytoplankton, and zooplankton will also be affected, some positively and some adversely.

Along the North American Arctic coast, the loss of estuarine ice may displace cisco, which might be replaced by anadromous fish from the Pacific Ocean.

For marine fish, it is well known that changes in climate or ocean currents can affect the distribution of commercially important stocks, such as Atlantic cod and herring. Water temperatures are important, as are the distribution of prey and predators and the currents that determine the movement of larvae from spawning grounds to their nursery areas. Atlantic cod and its main food item capelin are likely to move northeastwards. Spring-spawning herring may return to the same migration route they followed in the mid-1960s, when the water temperature around Iceland was higher than today. Other more southerly species may become distributed farther north toward and into the Arctic. This will lead to the introduction of new species into the Arctic marine ecosystem. The consequences are difficult to predict but may include changes in the food web and thus in the load of contaminants in biota. Another possibility is changes in migratory routes and contaminants along the route.

Possible changes in the distribution of fish species if the seawater temperature increases 1-2 °C.

Changes in sea ice can alter marine ecosystems

In marine ecosystems, many contaminants are biomagnified in food webs, particularly those with many trophic levels. Therefore, any changes in food web structure can potentially have a large impact on contaminant burdens in top predators. The changes can be initiated at the bottom of the food web, for example if changes in light and nutrient cycles alter conditions for phytoplankton and zooplankton. Food-web changes can also be initiated at the top, by altering predation patterns, for example among bears and seals.

The amount of sea ice influences both light conditions and the distribution of nutrients in the water. Change in stratification of the water column is important in this respect and a decrease in mixing of water layers has already been noted in the Greenland Sea and in the Canadian Basin. The availability of nutrients influences the algae that are responsible for primary production at the bottom of the food web. This is true for the phytoplankton in the water column and also for the algae that grow on the bottom of the ice and support a unique ice-associated food web. Some of the algal production falls to the bottom of the ocean, where it supports the benthic food web. The distribution of sea ice thus has a major impact on the distribution of organic matter between the water column and the seabed.

The Beaufort and Chukchi Seas, crossed during the drift of the SHEBA (Surface Heat Budget of the Arctic Ocean) Project in 1997-98, provide a dramatic example of a large-scale bottom-up change in the marine food web. Compared with a study 20 years earlier, this new close look at life in the water revealed a marked decrease in large diatoms and large microfauna within the ice. The high Arctic Oscillation Index of the 1990s had diverted river water into this area, causing a strong stratification of the surface waters. The result was a decrease in the supply of nutrients from below, and a species composition that was more typical of freshwater ecosystems. The loss of large diatoms could potentially produce a shift toward smaller zooplankton grazers, perhaps then introducing an extra step at the bottom of the food web.

MAGNUS ELANDER

Walrus grazing on mussels. Most walrus feed low in the food web, for example by grazing on mussels. However, some individuals hunt seals, thus receiving higher contaminant intakes. If climate change were to cause a shift in feeding habits, it would thus have implications for contaminant levels in this species.

The Bering Sea provides another recent example of how bottom-up changes can permeate an entire ecosystem. In 1997-98, there were massive blooms of small phytoplankton. Because they were smaller than the diatoms that typically bloom in the Bering Sea, they were grazed on by copepods instead of euphausiids. The short-tailed shearwater normally feeds on the euphausiids, and the lack of food may have contributed to a large die-off of this bird species. The change in quantity of different zooplankton probably also decreased food availability for fish, whales, seals, and walrus, causing die-offs and long-distance displacements.

Loss of sea ice would lead to Arctic shelf seas looking more like temperate seas. The implications for food web structures are very difficult to predict and we should be prepared for surprises. One such warning sign was the massive blooms of jellyfish in the Bering Sea during the 1990s. Large-scale changes produced by the Arctic Oscillation have the potential to alter the balance between upwelling and downwelling along the coast, through changes in either the distribution of ice cover or in average wind speed and direction. Shifts in the Arctic Oscillation thus have the capacity to cause large-scale shifts in shelf ecosystems. In regions that are important for commercial fisheries, such changes can have major impacts on the regional economy.

Sea ice is also a crucial habitat for many species at the top of the food web. Ringed seals need landfast ice for pupping, which in turn influences the migration of polar bears that feed on the ringed seals. A decrease in suitable habitat for ringed seals to pup could lead to declines in their populations, with the possible consequence that polar bears could be forced to find other food sources or starve. Ringed seals feed on Arctic cod. If changes in the ice alter the balance between seals and polar bears, they would likely affect the Arctic cod as well.

Walrus provide an excellent example to challenge our predictive capability. Most walrus feed on bottom-dwelling organisms and are thus fairly low in the food web. Some walrus, however, are known to eat seals, and their higher position in the food web is reflected in higher contaminant levels. Many walrus use drifting ice for their haulouts because it provides good access to nearby feeding areas, reducing the amount of energy required to feed. If the summer ice edge retreats north of the relatively shallow areas where walrus can feed, as happened in the summer of 1998 in the Chukchi Sea, the walrus may be forced either to starve or to prey on seals. The latter adaptation would place walrus much higher in the food web.

Less sea ice could, however, benefit other species. Eiders, which also feed on the benthos, need open water in which they can dive. By benefiting some species and hindering others, the loss of sea ice is likely to cause major alterations in the marine food web. This is particularly true for changes caused in certain key species. Arctic cod, for example, plays a central role linking lower levels of the food web to seals, beluga, and many birds. Any changes to Arctic cod abundance or distribution could propagate both up and down the food web.

BRYAN & CHERRY ALEXANDER

Tourists visiting the North Pole on an ice-breaker cruise take the Polar Plunge.

Human activities will increase

Climate change will inevitably bring changes to human activities in the Arctic, with subsequent effects on contaminant loads and pathways.

For people, food habits have a great impact on exposure to contaminants. Changes in hunting opportunities because of changed animal distribution and availability or changed ability to travel over ice or land will thus have an impact. If a hunted animal is suddenly higher in the food web, its contaminant load could increase, thus increasing exposure even for people whose food habits remain the same.

A warmer Arctic with less sea ice will also encourage shipping, tourism, and oil exploitation, all of which increase the risk for contamination of new areas. More severe storms would further increase risks connected to shipping and other offshore activities. The expansion of commercial fisheries from the Arctic marginal seas into the Arctic Ocean would also likely affect food web structure and relative abundance of many species. Although the net effects of changes in human activities and behavior in the Arctic are impossible to predict with confidence, changes are certain to occur. They, in turn, will affect sources, pathways, and eventual fate of contaminants in the Arctic, including human exposure.

Summary

Long term-climate change and natural climate cycles affect the transport of contaminants to and within the Arctic. The 1990s provided an example of how widespread change can rapidly pervade much of the Arctic including winds, weather patterns, ocean currents, and sea ice. It is, however, difficult to predict whether long-term climate change will lead to a generally decreased or increased contaminant load.

Some pathway changes clearly lead to more efficient transport, one example being increased transport of airborne pollutants from eastern North America and Eurasia. Another example is Atlantic water carrying more radionuclides from European processing plants. Lead that has been deposited in the ocean to the west of Europe would also follow this pathway. A third example is the longer residence time in the Arctic Ocean for contaminants that are carried by ocean surface waters.

Long-term climate changes are likely to affect pathways that are influenced by sea ice. Such pathways will be important for many persistent organic pollutants that partially dissolve in water, some of which are currently trapped under the ice. Mercury is likewise trapped under ice. For mercury, changes in sea ice cover may also influence newly discovered physical pathways that enhance the deposition of mercury to surfaces.

Changes in lake ice and permafrost will affect lake hydrology, potentially increasing the input of contaminants into freshwater ecosystems and possibly releasing contaminants that have accumulated in soil or have been improperly disposed of in earlier times.

Many contaminants pose a problem in the Arctic because they biomagnify in food webs. Changes in food web structure, therefore, have a great potential to alter contaminant levels in top predators. However, the complexity of ecosystems and our incomplete understanding of the dependence of many species on habitats like sea ice make it especially difficult to predict change, and one should expect surprises.

A final conclusion is that the load of persistent organic pollutants, heavy metals, and radionuclides in the Arctic is dependent on many factors that operate after the contaminant has been released from its source. In the long run, anthropogenic emissions that affect the climate may become as important as the emissions of the contaminants themselves in determining the extent to which these contaminants reach and affect the Arctic.