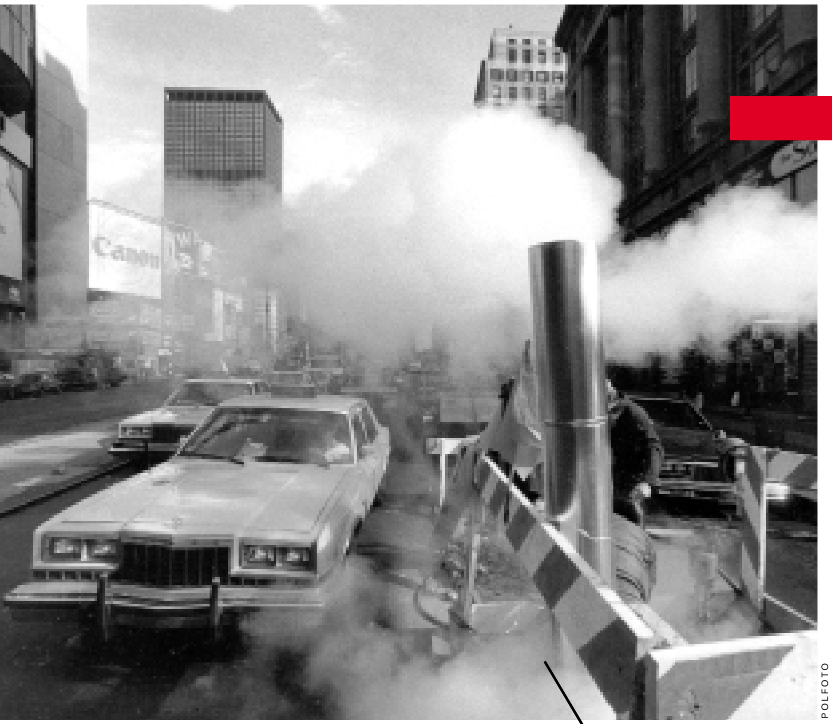
Physical path



hways of contaminant transport


STAFFAN WIDSTRAND

In the mid-1950s, airplane pilots flying in the North American Arctic saw a strange, discolored haze on the horizon. It was thick enough to obscure visibility and different than any flying conditions they had come across before. In the 1980s, the haze was identified as aerosols of sulfate and soot, along with some soil particles, which were carried by winds from heavily industrialized areas in Europe.

This Arctic haze was the first sign that the northern polar environment is closely connected to activities in other parts of the world. Other observations have added to this insight. Around Svalbard, Norway, and in Canada, measurements of toxic organic compounds in polar bears have shown unexpectedly high levels. Svalbard had been chosen as a background station for environmental monitoring and was thought to be an example of a clean, undisturbed environment. Where did the pollution come from? Local sources could not explain the high levels.

A third example made the issue of long-range transport of contaminants into the Arctic even more acute. A study of traditional foods from the sea showed that some people in native communities in Canada ingested high levels of the environmental contaminant PCB in their diet. Could the nourishing food, so essential for health and culture, also be a threat? Again, local sources of PCB could not explain the high levels. It must have been transported from regions outside the Arctic.

High levels of contaminants in Arctic environments that had been thought pristine led to intensified research into the pathways by which pollutants reach the Arctic – the air and water that enter the region from industrialized areas of the world. As it turns out, its geographical characteristics and cold climate make the Arctic a sink for many contaminants that are spread around the globe.

This chapter describes the pathways involved in transferring contaminants from one place to another and the physical processes that determine their fate in the Arctic.

The atmosphere

The atmosphere contains relatively small amounts of contaminants compared with the total load in polar soil, sediments, and water. However, the rapid movement of air makes it an important pathway for delivering contaminants to the Arctic. Any chemically stable, wind-borne material will follow winds and weather patterns into and within the Arctic region. The atmosphere is the fastest and most direct route from the source of pollution: transport from the sources to the Arctic occurs in a matter of days or weeks.

Winter and spring winds carry dirty air

Air-transport patterns are highly dependent on season and on the position of major weather systems. In winter and spring, an intense high-pressure system over Siberia pushes the Arctic front far to the south, so that important polluted areas of Eurasia are actually within the Arctic air mass, the lower one-to-two kilometers of which can move contaminants across the pole. Winds that can carry contaminants to the Arctic are therefore more frequent in winter and spring than in summer and autumn.

The transport of contaminants during the Arctic winter is made even more effective by the lack of clouds and precipitation over the areas dominated by high-pressure systems. Low wind speeds and temperature inversions, caused by the cold winter weather, allow contaminants to accumulate in the atmosphere. Rather than falling to the ground in the vicinity of the source, they follow the large-scale patterns of atmospheric circulation. This, together with the lack of light, which would help break down some contaminants, explains why sulfates and soot from Eurasia can contribute to haze throughout the lower layer of the Arctic atmosphere in winter and spring. It takes 13 to 16 days for contaminants in the lower atmosphere to travel from Europe to Alaska during the winter.

North America and East Asia only rarely contribute to Arctic haze since air masses from these areas move over huge ocean distances before reaching the Arctic, where low pressure systems give rain and snow a chance to clean the air. They may, however, be important source areas for occasional bursts of high levels of contaminants that are not efficiently removed by rain and snow.

In summer, the continental high-pressure systems break up, and the low-pressure systems over the oceans become weaker. Therefore, the transport of air and contaminants from mid-latitudes becomes much less important in summer than in winter. Summer is also warmer, allowing for cloud formation and for drizzling rain that can remove contaminants from the air before they are carried far. Moreover, sunlight during the summer months allows for photochemical degradation of some contaminants.

The position of the Arctic front influences contaminant transport in the atmosphere. The figure shows the mean position of Arctic air mass in January and July and the winter and summer frequencies of winds driving the major south-to-north transport routes.

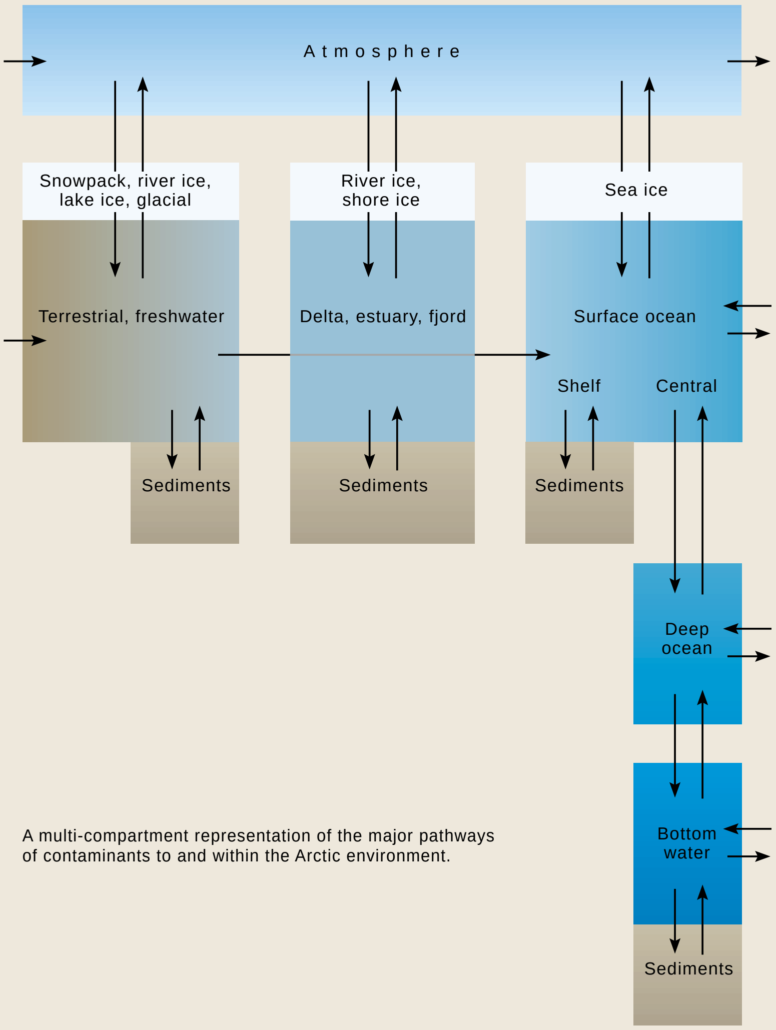
Particles take one hop from source to site

Contaminants that are in the form of minute particles, or aerosols, are relatively easy to track. This is also true for gases that transform into particles, such as sulfur dioxide. These contaminants start their journey with a ride on northflowing winds from the source. Once they land, they usually stay on the ground. They are often labeled one-hop contaminants. Acids carried as sulfates, non-volatile metals, and radionuclides are some examples. Non-volatile organic compounds behave the same way. One-hop contaminants follow the same route as Arctic haze, from mid-latitude sources, mainly in Eurasia, to the Arctic.

The distances over which one-hop contaminants travel is determined by the location of their sources in relation to the Arctic airmass, precipitation patterns, and how far the airmass moves during the atmospheric lifetime of the particles. In the Arctic winter, particles can stay in the air as long as 20 to 30 days, creating conditions for long-range transport and accumulation of contaminants in the polar region. In summer, the contaminants usually stay in the air for only 2 to 5 days.

Volatile substances gain global distribution

Some contaminants are transported as gases. This is true for volatile and semi-volatile organic compounds. Their behavior is different from particle-bound contaminants and aerosols in that their journey consists of sev-



A multi-compartment representation of the major pathways of contaminants to and within the Arctic environment.

Modeling the fate of contaminants

Where do contaminants come from? How do they get from one point to the other? Much of what is known about contaminant transport comes from computer models that mathematically simulate pathways. The input to the models are data on emissions, information about meteorological conditions such as winds and precipitation, and equations describing processes that change the chemical and physical characteristics of the compounds or that remove them from the air.

Single-hop compounds, such as radionuclides and sulfate aerosols, can be modeled in the same way as weather parameters in computer-based weather forecasts. Winds, precipitation, temperature, humidity, clouds, and deposition to Earth's surface are the major factors that determine the pathway from source to deposition site. Such models have been used to describe the fallout from Chernobyl, the fate of pollution from the Kuwaiti oil fires, and the impact of acid rain in Europe, eastern North America, and southeast Asia.

Models for multi-hop compounds are much more complex. In addition to the meteorology, a model has to describe how the contaminant moves between different environmental compartments, such as the atmosphere, the land, and the ocean. To get a more accurate picture, the compartments are often subdivided: Will the contaminant enter the surface of the ocean and remain there or will it also reach the deep layers? Will it adhere to particles and end up in soil or sediments, or will it dissolve in water and follow land runoff to a river? Often, the same contaminant will be present in several compartments, and there is an exchange between them that depends on the temperature and on the total mass of the compound present in each compartment. The model should, for example, be able to describe how a decrease in the load of contaminants in the atmosphere can turn a sink, such as the oceans, into a source. Similar models exist for marine environments. An illustrative example of this phenomenon is how the pesticide hexachlorocyclohexane spreads around the globe by moving in and out of the ocean.

eral hops. The compounds are first picked up by the winds as gases. They can then land on the ground, on ice, or in the oceans by adhering to particles or organic films, as well as by dissolving in water. But this is not necessarily the end of their journey. When summer brings higher temperatures, the compounds can volatilize again, re-enter the atmosphere, and continue their journey as gases. If the contaminants do not break down, as is the case for persistent organic pollutants and mercury, and if the temperature conditions are right, the process can repeat itself a number of times. Eventually, the compounds might break down to less harmful chemicals or be deposited in bottom sediment in oceans and lakes.

Multi-hop compounds can travel great distances and become truly global in distribution. At some point in their journey, the winds are likely to carry them into the Arctic, which explains why chemicals that have never been used in the Arctic can still be found in the tissues of people and wildlife in the region.

For some compounds, the levels are higher in the Arctic than one would expect, even taking transport into account. Why? One explanation lies in the cold climate. As the temperature drops, the compounds condense out of the gas phase onto particles or snowflakes in the air, which eventually land on the ground. They can also condense directly onto the Earth's surface. At the low temperatures typical of the Arctic, they are not as likely to revolatilize as in warmer climates. Another explanation is that gases dissolve in water more readily at low Arctic temperatures than in warmer environments.

The breathing oceans

For multi-hop contaminants, it is difficult to pinpoint the sources of the high levels that have been detected in the Arctic. Some of these contaminants have been used for decades, during which time a portion of the chemicals has ended up in the world's oceans or in soils. For some compounds, the concentration in the oceans can be thousands of times higher than in the air. This capacity to hold on to contaminants is especially pronounced when the water is cold, as it is in the Arctic Ocean. When the temperature increases, the capacity of the water to retain the contaminants decreases, and the oceans 'breathe out'. Because the mass of contaminants is higher in the water than in the air, the ocean can be expected to have 'bad breath' for a long time, at least ten years for the Arctic Ocean. For contaminants that adhere to particles, soil can serve as a similar reservoir.

To understand the levels of multi-hop contaminants in the air, one has to know the conditions under which the oceans and the land breathe out. First, there is a seasonal pattern. For example, an increase in water temperature may lead to a release of contaminants. The breakup of ice in spring and the fall breakdown of water stratification can also turn the ocean into an important seasonal source to the air. Contaminants captured in snow or soil behave in a similar manner and can also be released to the atmosphere when temperatures rise in summer.

Over the long term, the concentration of contaminants in the air will determine the role of oceans and soils as sources. If air concentrations drop, as they would if we were to place restrictions on use, the oceans and the land may release more of their loads.

Rain, snow, fog, and rime clean the air

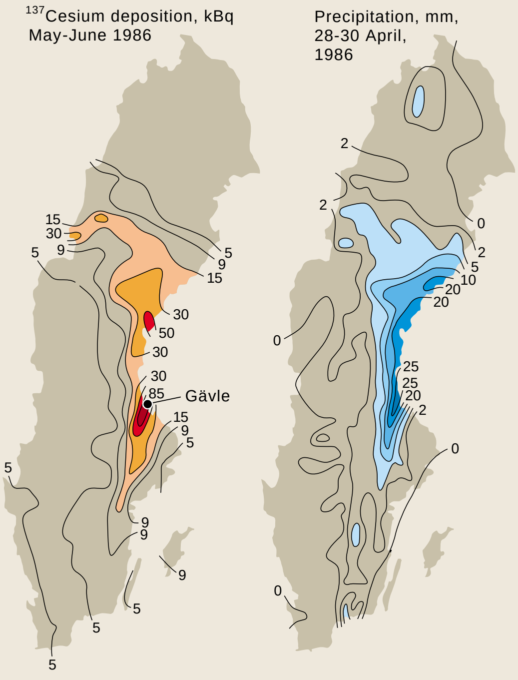
Contaminants are cleaned out from the air by several processes. They can be caught when raindrops or snow crystals form in a cloud or when the rain or snow is actually falling. Fog can scavenge contaminants and deposit them when it condenses onto surfaces. Rime ice, which forms when supercooled cloud droplets freeze on contact with snow crystals or surfaces, is also an important scavenger of contaminants from the air. In Greenland, rime ice has been estimated to contribute about 5 percent of the annual snow load, while accounting for approximately 30 percent of the annual deposition of contaminants.

An additional route from the air is dry deposition. Particles can land by themselves and semi-volatile, gaseous contaminants can condense on the cold ground where they adhere to soil particles or plants. For many contaminants in the Arctic, wet and dry deposition from the atmosphere is the major pollution source.

Radioactive rain

Precipitation was important in washing wind-borne radionuclides from the Chernobyl accident out of the air and onto the ground.

In Scandinavia, the deposition of radionuclides was very similar to the pattern of local rain showers. The areas that had rain the days after the accident were those with the highest levels of cesium-137 in the ground. For example, the city of Gävle, where it rained the day after the accident, received substantial deposition, as did the reindeer herding grounds in the middle parts of northern Sweden. The Saami reindeer herders farther north were much less affected by the fall-out.



The land and rivers

The Arctic landmass receives contaminants from the atmosphere. Contaminants are also transported to the Arctic by large rivers that can move material from polluted areas farther south along the river. Mines, metal processing facilities, factories, oil and gas drilling, waste dumps, and settlements can add to the local load. The diagram opposite gives a conceptual picture of some different pathways.

The fate of contaminants in the terrestrial environment depends on the landscape as well as on the physical and chemical characteristics of each compound. Water-soluble compounds will be carried by snow-melt, surface water, groundwater, and rivers. Unless they degrade, they tend eventually to end up in the ocean. Contaminants with low water solubility normally adsorb onto particles in the soil or sediment. Their fates depend on whether erosion will wash the soil into waterways and, if so, on what happens to the particles during a river's journey to the ocean.

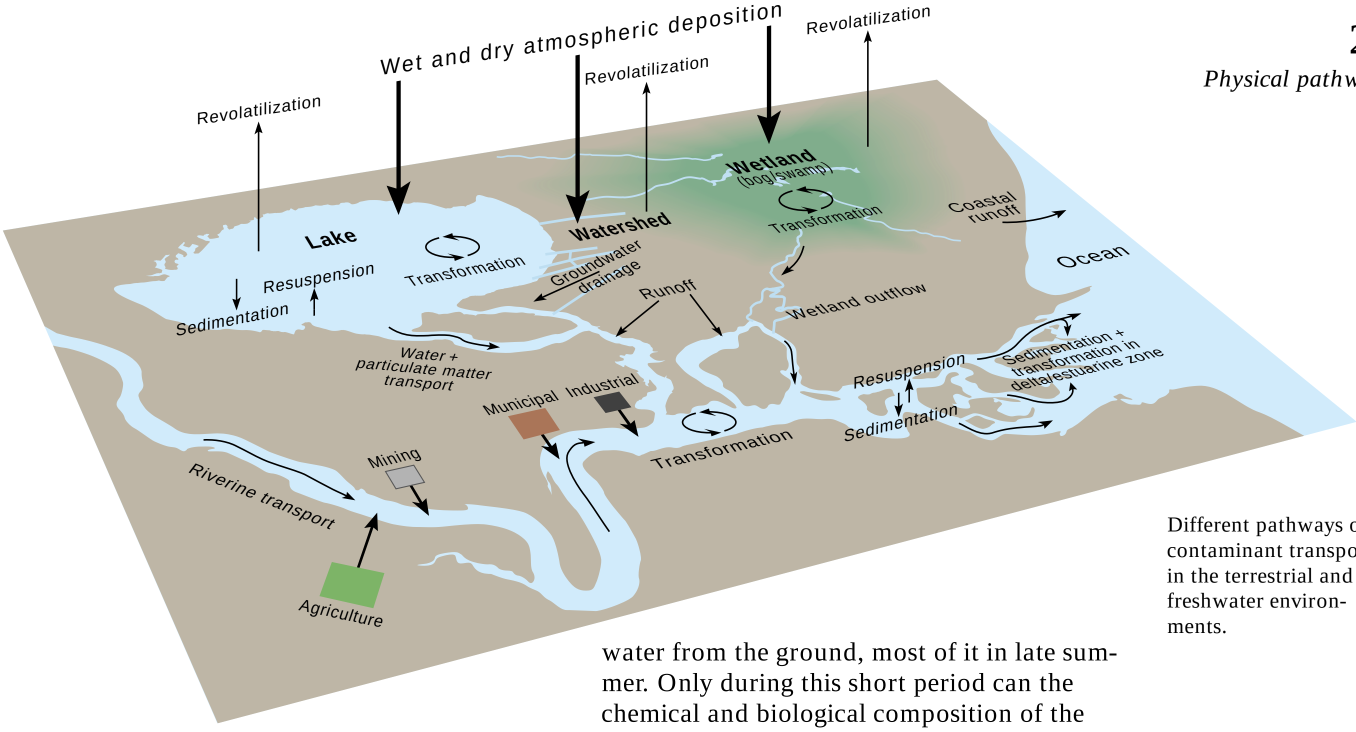
Snowmelt creates a chemical surge

Melting snow plays an important role in transporting contaminants in the terrestrial environment. By spring, the snow has had a whole winter to accumulate contaminants from the air. A deep snow pack can even retain volatile contaminants, which shallow snow packs would release back to the air.

When the temperature rises, water-soluble chemicals concentrate in the melt-water, and the initial 20 to 30 percent of the meltwater can remove 40 to 80 percent of the total mass of pre-melt contaminants. Most of the meltwater flows over frozen ground directly into streams and lakes. The chapter on acidification provides an example of the effect this chemical surge can have on the water quality of small streams.

Meltwater can also be a powerful erosive force. In areas where the ground cover has been disturbed, the rushing water easily forms erosion gullies and washes away soil. Overgrazing, seen in Scandinavia, Russia, and North America, can thus affect water quality. Construction work is another potentially damaging activity, especially if the permafrost is disturbed.

Erosion also introduces suspended particles, which provide surfaces to which contaminants can attach. Therefore, erosion can increase contaminant transport in a river.



Different pathways of contaminant transport in the terrestrial and freshwater environments.

Permafrost makes surface water vulnerable

Even when the ground is not completely frozen, the shallow active layer of Arctic soils makes patterns of water transport over and through the ground very different than in warmer areas. Specifically, there is a greater risk of surface water contamination, whereas the groundwater is relatively more protected. For example, a small lake in a permafrost area might only receive slightly more than half its water from the ground, most of it in late summer. Only during this short period can the chemical and biological composition of the active layer affect the contaminant load brought by precipitation. In spring and early summer, the lake gets its water directly from surface runoff, and the active layer plays no role. Farther south, groundwater becomes progressively more important as the active layer becomes thicker.

Rivers are key pathways

Rivers are central to many Arctic settlements, providing drinking water and fish for food.

Tundra with River. Drawing: Ruth Qualluaryuk.

They are also important pathways for contaminants.

Rivers are also key pathways for long-range transport. They can gather water and particulate matter from huge catchment areas and transport them over long distances. The major inflow of freshwater to the Arctic Ocean comes from rivers that originate outside the Arctic.

The catchment areas of large rivers often include many diffuse sources of contaminants, such as agricultural runoff loaded with pesticides. Discharges of municipal and industrial sewage from heavily populated and industrialized areas south of the Arctic also contribute to the contaminant load. Other polluting activities are mining and oil and gas exploitation. In Russia, some rivers are used as roads and for dumping dirty snow in winter. Contaminants from vehicles and from materials gathered in the snow will also be carried by the water or by the ice during spring melt.

Some of the Arctic rivers have polluting activities in their catchment areas. The major Russian rivers, in particular the Yenisey and the Ob, have their upstream basins in heavily developed areas with industries, urban centers, and intensive agriculture. However, very little is known about what these rivers actually transport. In North America, the Nelson River system, which empties into Hudson Bay, flows through areas with intensive agriculture in mid-west Canada. The same is true, though to a lesser extent, for the Mackenzie River.

The large rivers in the Arctic and in the subarctic receive most of their water during spring snowmelt, and in most areas the melted snow is also the most important source of contamination. In highly urbanized regions, such as the large industrial cities of the Russian Arctic, direct discharges of wastewater are equally important.

In Russia, large volumes of industrial and municipal waste water are not treated. For example, in 1994 less than 5 percent of the waste water produced in the Murmansk region of the Kola Peninsula was treated according to specified purification standards. In general, however, the main watersheds in both Russia and North America are relatively clean, and they have many lakes and reservoirs that act as traps for contaminated sediment.

Dirty river ice, Lena delta.

HEIDI KASSENS

Early summer brings peak input and floods

The flow in Arctic rivers is highly seasonal, especially in those unregulated by dams and reservoirs; see the graphs opposite. In winter, water flow is very low, and some rivers even freeze to the bottom. Peak flow usually comes in June and July, and this is when one would expect the largest input of contaminants to the Arctic Ocean.

The peak flow in the rivers coincides with the greatest transport of river ice, and in some rivers the combination of high flow and ice jams leads to flooding. If the landscape is flat, as is the case in many parts of the Russian tundra, the water can cover vast areas. Floods can leave contaminant-laden sediments on the flood plain, temporarily removing them from the riverine pathway. However, in years where flooding is extreme, the water may pick up previously deposited material, and the load of contaminants will then reflect inputs from several years.

Slower-flowing rivers with well-developed flood plains usually do not rise until the rivers are clear of ice and might thus be more efficient in moving contaminants to the coast.

In summer, heavy rains or periods of dry weather control river flow. In small waterways, the water level can change dramatically depending on the weather. Nonetheless, most sediment transport occurs during the spring flood.

River ice gathers contaminants

River ice has a special role in the transport of contaminants. The ice gathers material from the atmosphere and from the river itself as the water freezes. The incorporation of particle-borne contaminants from the water can continue throughout the winter as the ice grows.

When the water freezes all the way to the bottom of a river, material from the river bottom gets caught in the ice. Also, if the entire water column in the river is supercooled, i.e. has a water temperature below freezing, a sudden change in temperature or turbulence can lead to ice formation around rocks and sediment on the bottom of the river. Known as anchor ice, these formations can lift rocks as heavy as 30 kilograms. Supercooled water is also involved in formation of frazil ice, which collects small particles in the water and incorporates them into the ice cover. As a result, river ice can contain large amounts of sediments.

The sediments and any contaminants in the ice itself are released to the river water during the spring melt, when the biological productivity of the water is at its peak. The seasonal freeze-thaw cycle thus creates conditions in which the contaminant load built up in winter can be effectively incorporated into animals.

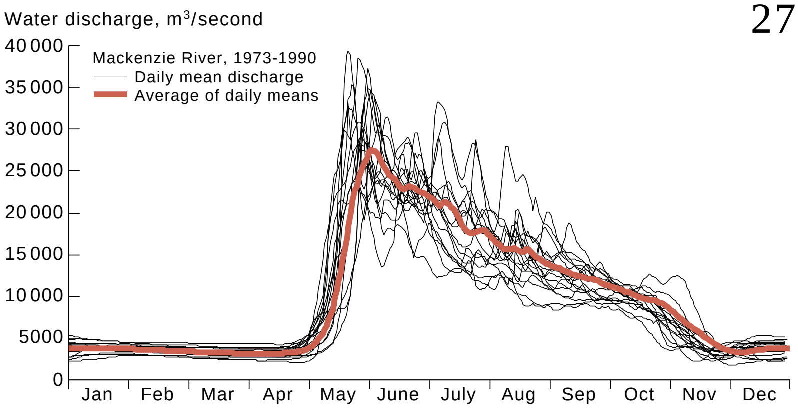
Lakes and dams trap sediment

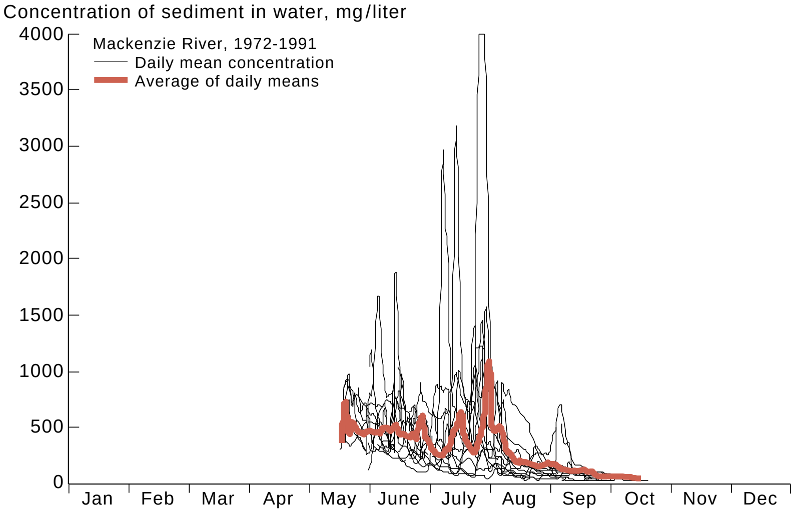
The landscape through which a river flows plays an active role in the fate of contaminants. Many contaminants are bound to particles, and sedimentation and resuspension processes will determine whether the contaminants reach the Arctic Ocean or are deposited along the way. When a river flows slowly, particles usually settle, and bottom sediments can become enriched in metals, persistent organic pollutants, and hydrocarbons. However, the river bottom is usually only a temporary trap since turbulent flow can lead to the resuspension of particles. Large lakes, on the other hand, can serve as permanent traps for contaminants. Great Slave Lake on the Mackenzie River system, for example, blocks much poleward transport of contaminants, particularly those bound to particles.

Man-made lakes are no less important. Dams constructed along the Yenisey River in the 1960s and 1970s illustrate the role of man-made lakes as particle traps. Eight reservoirs, controlling about one-fourth of the river flow, caused a three-fold reduction in the amount of sediment that reached the mouth of the river. These sediments were deposited in the reservoirs. Dams can also change the seasonal pattern of the flow, distributing it more evenly throughout the year.

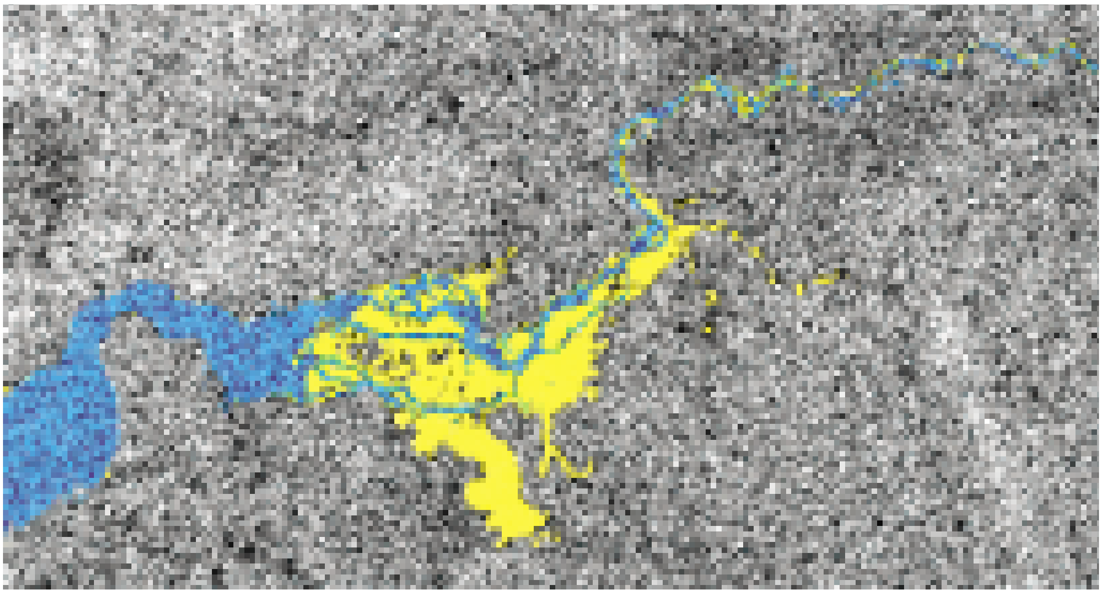
The fate of specific contaminants is determined by how well they adhere to particles and by the type of particles in the water. The smallest particles often have the highest concentrations of contaminants due to their larger relative surface area, and these settle less quickly than coarser material. There is thus a potential for transport over long distances even when contaminants are adsorbed to particles. Through resuspension of bottom sediments, these fine clay particles also gather metals and hydrocarbons originating from natural weathering processes.

Living organisms help the sedimentation process in lakes, just as they do in deltas and estuaries. Phytoplankton extract material that is dissolved in the water, and many zooplankton and larger filter feeders gather suspended matter, effectively packaging small particles into larger ones. The material is deposited on the bottom, which becomes a mixture of inorganic sediment, shells, and excrement.





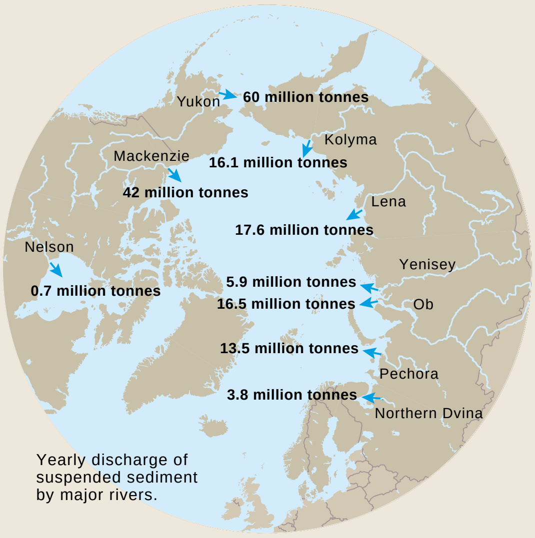
Top: Variation in discharge of water in the Mackenzie River over the year.
Bottom: Variation in concentration of sediment in the water of the Mackenzie River over the year.



Flooding of Yenisey River shown in yellow on satellite image.

Rivers carry fresh water and sediment to the Arctic seas

In total, Arctic rivers carry about 4200 cubic kilometers of water per year into Arctic seas, along with about 221 million tonnes of sediment per year. The landscape determines the role of each particular river. Those crossing flat, frozen tundra generally carry relatively small amounts of sediment. The Mackenzie River, on the other hand, flows through a much steeper landscape, with less permafrost and with abundant surficial material that can be eroded. Consequently, it carries larger amounts of sediment.



Lakes do not control the transport of waterborne contaminants as much as they do for particle-bound substances. Often, snowmelt flows through small Arctic lakes without mixing. Therefore, at least for headwater lakes, most of what comes in also flows out. The load of contaminants in lakewater is therefore more likely to reflect input from rain and ground runoff during summer.

Wetlands can be contaminant sources

Through snow, rain, and dry deposition, the vast wetland areas in the Arctic, with numerous shallow lakes, swamps, marshes, and bogs, gather contaminants from the air. Water in wetlands naturally contains much organic matter, such as humic substances from peat. Hydrophobic contaminants tend to bind to organic matter, in both soil and water. Some of these bound contaminants remain in the ground but some will enter waterways.

Local sources add to the load. For example, oil and gas exploitation in northwest Siberia releases untreated waste water as well as oil to depressions in the landscape. The cold weather does not allow for much decay of the organic pollutants, which are likely to stay for a long time in the flat landscape. During spring melt, they will follow the runoff and end up in rivers. Wetlands are thus important secondary sources of pollution to surface rivers in this region and are likely to remain so for a long time.

Another example where wetlands act as secondary sources is in areas with intensive metal industries, such as the Kola Peninsula, where metals are likely to leach into waterways even after emissions decrease.

Mackenzie River delta.

STAFFAN WIDSTRAND

Where the river meets the sea

Rivers enter the ocean through estuaries and deltas along the coastal zone. The physical and biological processes in these environments have a major impact on the fate of contaminants carried by river water and river ice.

Deltas and estuaries serve as particle traps

In the context of contaminant transport, the major physical role of deltas and estuaries is as particle traps for particulate matter in river water. Rivers flow more slowly and with less turbulence when they reach the coast, allowing particles to settle. The containment of particles is enhanced when sediments that settle farther out are transported back toward the river mouth by inflowing seawater. The sediment is thus advected back upstream before it finally deposits. The settling process is enhanced by the mixing of fresh water and sea water, which makes fine colloidal particles stick together and become large enough to settle.

Some water-soluble substances can also be caught in deltas and estuaries. The main mechanism for this is flocculation, in which dissolved organic and mineral substances are gathered into suspended particles. The process is driven by changes in acidity and salt concentration. Living organisms also help the sedimentation process.

The efficiency of coastal sediment traps depends to a large extent on whether a delta is formed, i.e. a depositional plain where the sediments build up new land into the sea; or if tides and waves eventually carry most sediments away from the river mouth. The largest deltas are created by major rivers draining large areas and carrying abundant sediment. If the continental shelf is shallow, the delta plain can continue far out to sea, beneath the ocean surface. Two examples of huge deltas are those of the Lena River in Russia and the Mackenzie River in Canada. The Mackenzie Delta accumulates several centimeters of overbank sediment every year. This can be compared with accumulation rates of 10-100 centimeters in 1000 years in estuaries, or 1-3 millimeters per 1000 years for ocean sedimentation.

Large amounts of the suspended matter in rivers can thus be deposited and excluded from further transport to the open ocean. Along the Russian Arctic coast, only 10 to 20 percent of the particulate matter in the Ob and Yenisey Rivers travels farther than the borders of the deltas and the Kara Sea shelf.

Landfast ice keeps sediments close to shore

Many Arctic rivers discharge into areas with extensive ice cover. Maximum river flow occurs at the time that the landfast ice in the shelf seas is about to break up. If the early, sediment-laden river water flows on top of the ice, the heavy load of dark particles will speed up the melt, and the sediments will settle to the bottom along the coast. If the near-shore ice cover is anchored to shallow off-shore banks, it can form a barrier to offshore transport of any floating material such as dirty river ice. In both cases, the sedimentary material will most likely be deposited near the shore.

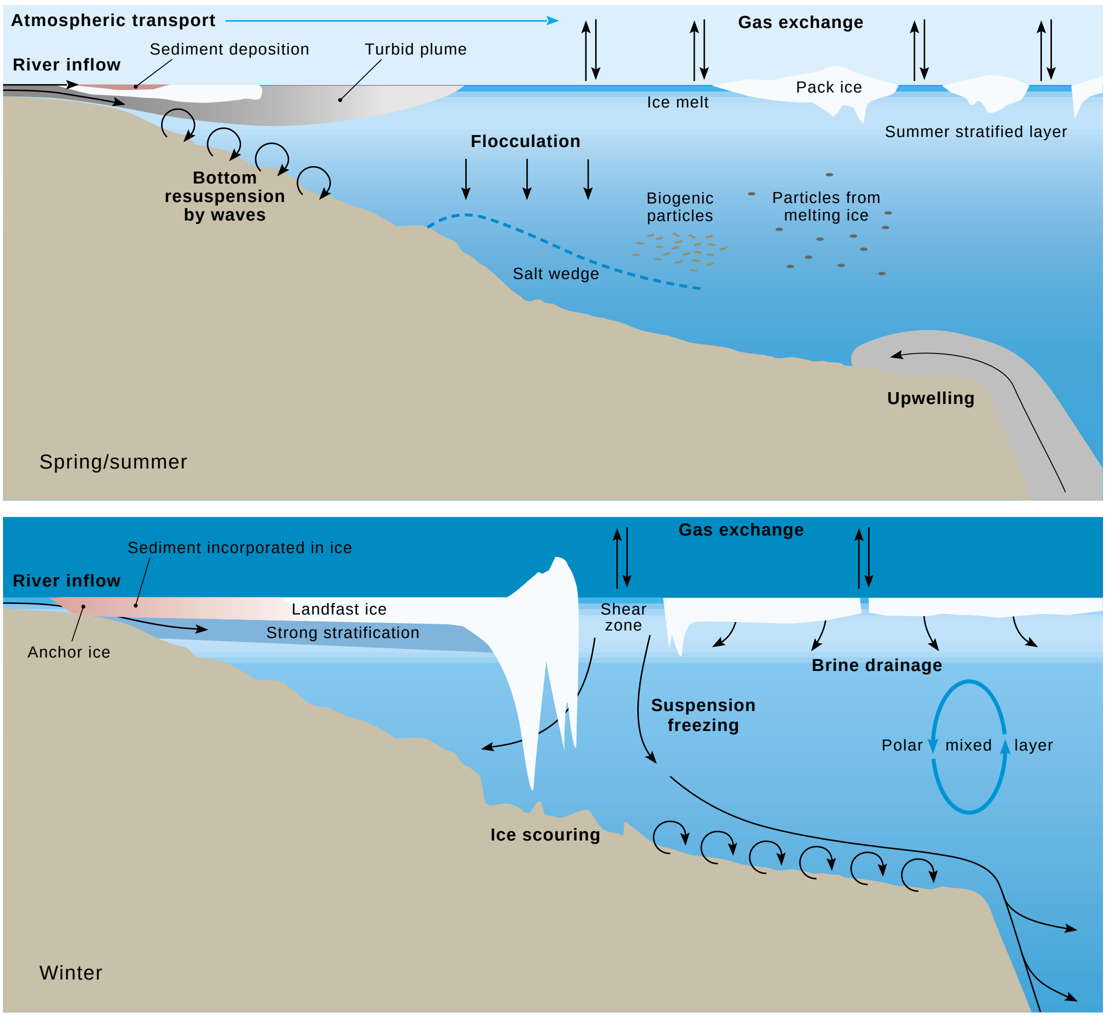
The continental shelves

The shallow continental shelves surrounding the Arctic Ocean are important for the transport of contaminants within the Arctic for three reasons: they are the primary areas of ice formation and ice melt; they have open water during part of the year, which allows for the exchange of contaminants between water and air; and they have high biological productivity, which provides a route for contaminants into the food web. The diagrams below summarize the major processes for redistribution of contaminants in the coastal zone.

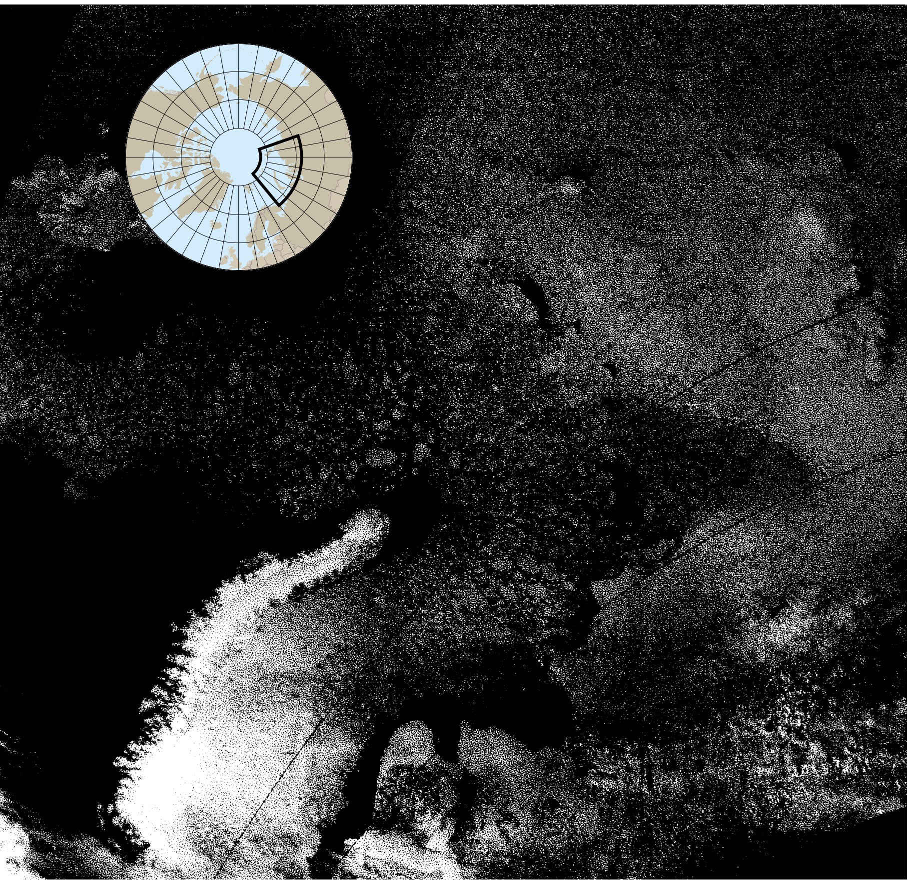
Sea ice may gather and transport contaminants

In recent years, sea ice has become a focus of research concerning contaminant pathways in the Arctic. The picture is just emerging, but some hypotheses are interesting to consider. There are two major ways in which sea ice gathers contaminants: from the atmosphere, where its large surface area makes it an efficient trap for air-transported contaminants, and from the water during ice formation. Sea ice can incorporate sediments in much the same way as river ice: frazil and anchor ice formation capture material from the sea bottom. This incorporation of particles in ice is especially effective for silt-size or smaller particles. Because many contaminants are preferentially associated with these fine-grained particles, the ice can become more contaminated with these substances than the water.

When ice formed in the shelf seas becomes part of the pack ice, associated contaminants



Summary of different processes determining the fate of contaminants along the coast and in the shelf seas in spring/summer and in winter.



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Satellite image of sea ice in the Barents and Kara Seas. The large white area is snow-cover on Novaya Zemlya, Russia.

are carried away by the drifting ice. Much of the ice in the Arctic Ocean circulates for one to seven years before it leaves the basin and melts. The map on page 32 shows the major circulation patterns.

Ice is not a passive vessel for contaminants. Melting at the surface, drainage, and refreezing from the bottom will redistribute the material carried by the ice. Most of it will appear at the surface after a few years. The dispersed, contaminant-laden particles often form pools of dirt on the surface, so called cryoconites. Once at the surface, any semi-volatile material can interact with the atmosphere. Other materials will be released when the ice melts.

Sediment traps along the Fram Strait show that most of the ice-carried debris will be released in the marginal ice zone. The timing and location of the ice melt coincide with the bloom of biological activity, and thus provides an opportunity for contaminants to enter the food chain. Many small plants and animals live at the ice-water interface (the epontic zone), and can be exposed to much higher levels of contaminants than would be expected from the contaminant load of the water. Similar processes also occur under the ice in the central Arctic Ocean, but are less well understood.

If the sediments have aggregated into pellets, they will sink to the ocean floor much faster than fine particles. If the ocean is deep enough, contaminants in these pellets are less likely to be taken up in the food chain.

Water-soluble contaminants follow the brine

Water-soluble substances behave differently than those that adhere to sediments, but sea-ice formation can still provide a route for long range-transport. The mechanism is quite different. When sea water freezes, brine (a concentrated salt solution) is expelled into the water, and water-soluble compounds follow along. If the water is not stratified, the brine mixes with the surrounding water and can penetrate into the deep parts of the ocean. In the absence of particles, even contaminants

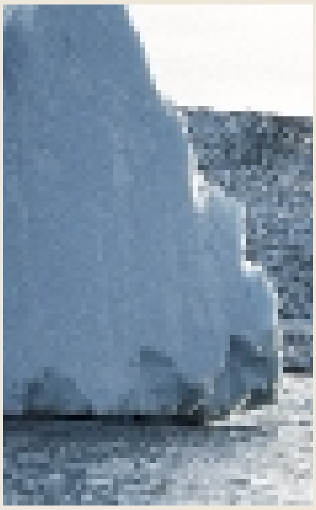
Ice can scour the sea floor

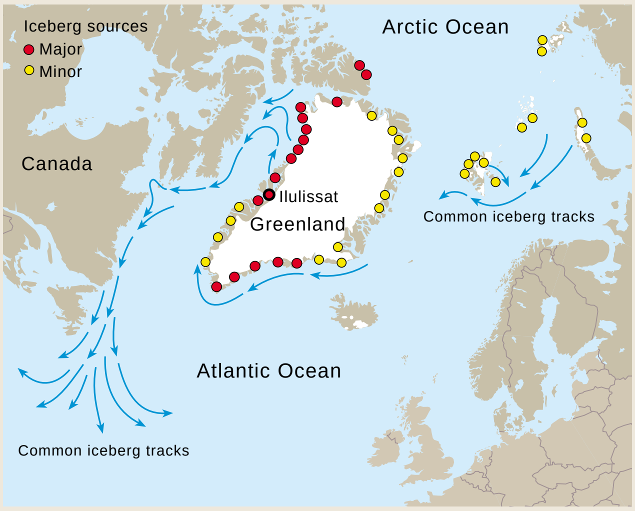
Icebergs are a spectacular feature of Arctic ice. They are pieces of glaciers that have broken off and floated away in the sea. Calving glaciers cover much of Greenland, Svalbard, Franz Josef Land, Severnaya Zemlya, and the northern island of Novaya Zemlya. The photos show icebergs near the Jakobshavn Icebrae, Ilulissat.

Beneath the surface, icebergs can reach depths of more than 100 meters, and can scour the bottom in shallow areas. Such scouring marks can be several meters deep and tens of meters wide. Icebergs are not important for transporting contaminants but might disrupt waste containers that have been dumped on the sea floor.

Sea ice can also disturb the bottom, especially along shallow shores and when it is compressed into thick pressure ridges. The ridges can scour the bottom and stir up contaminant-laden sediment, making it available to biota and to further transport by water currents.

Left: HENNING SLOTH PETERSEN; right: ANNIKA NILSSON





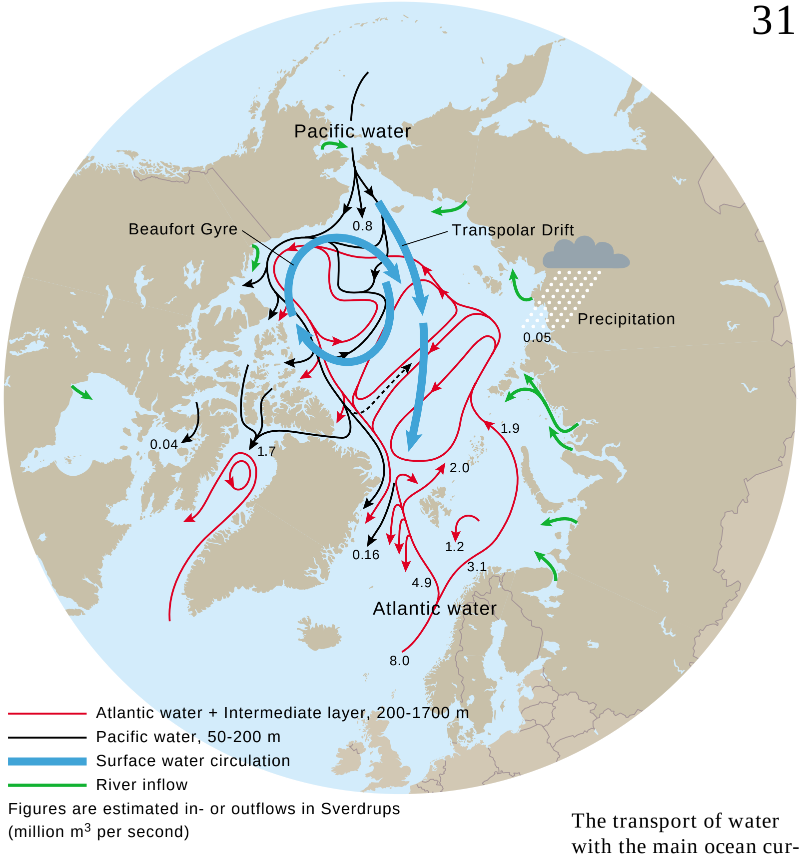
that normally adhere to particles, such as radiocesium, follow the brine.

Open water allows for atmospheric exchange

In summer, the shelf seas are relatively free of ice, while in winter, ice covers the areas closest to the coast. Farther out, between the landfast ice and the permanent pack ice, offshore winds often form areas of open water. These flaw leads, also called coastal polynyas, can extend over thousands of square kilometers.

Flaw leads along the coast are important areas for the interchange of semi-volatile contaminants between water and air. For example, soluble, gaseous pollutants that make their way to the Arctic can dissolve in the cold Arctic waters.

Moreover, the leads typically form the locus of ice break-up from late April to mid May and thus are a gathering place for many marine animals. As is the case along the marginal ice zone, the high primary productivity and rich wildlife of these areas provide a route for contaminants to enter biological pathways, as is further discussed in the chapter *Arctic Ecology.*



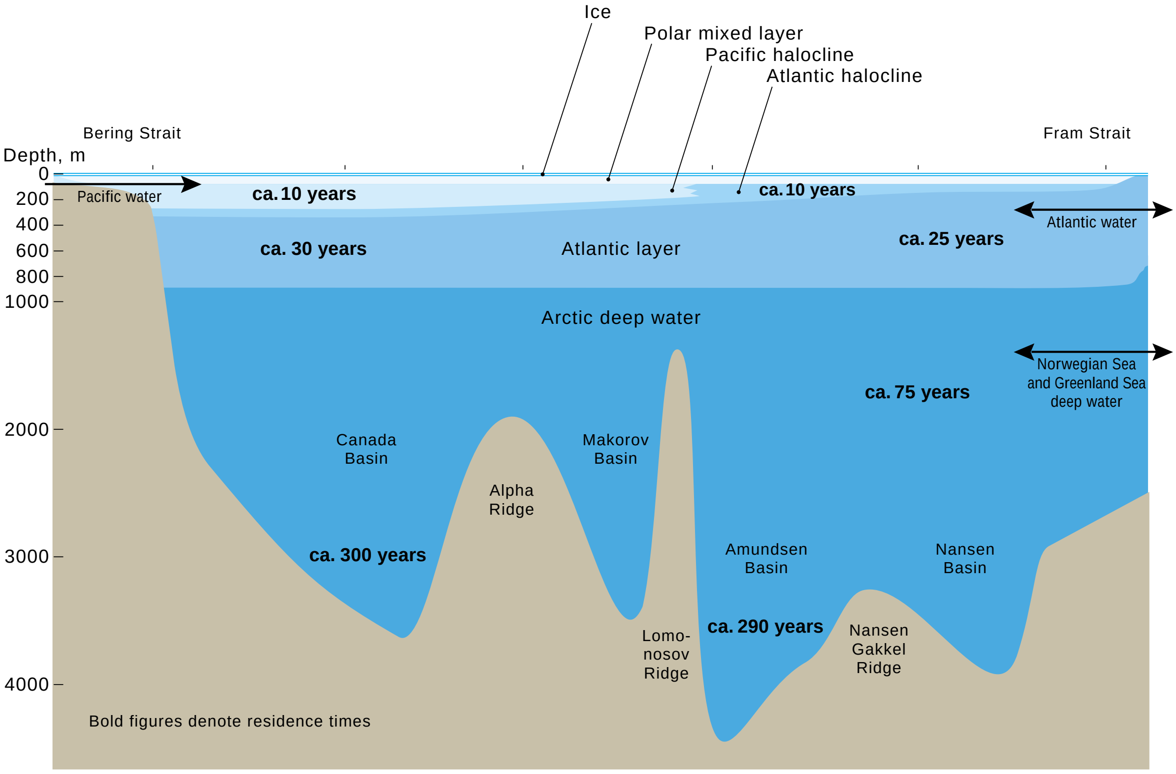
The transport of water with the main ocean current systems in the Arctic. The Atlantic-layer water mass originates from the surface of the North Atlantic Ocean and descends below less-dense Arctic Ocean surface water, which is affected by freshwater from rivers. The Pacific water mass is produced by modification of water entering the Bering Strait on the broad Chukchi Shelf and occurs in the Canada Basin.

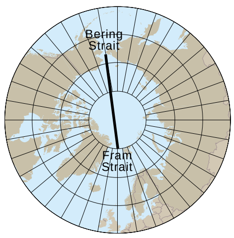
The Arctic Ocean

The Arctic Ocean and the surrounding seas receive contaminants from air, other oceans, rivers, and from direct discharges. The fate of these substances is determined both by Arctic Ocean circulation patterns and by the stratification of the ocean waters.

Geographically, the Arctic Ocean is often described as a 'mediterranean' sea because it is surrounded by land, communicating with other oceans only through restricted passages. The major inflow of ocean water passes from the North Atlantic through Fram Strait and the Barents Sea. There is also some inflow from the North Pacific through the Bering Strait. The ocean transport of pollutants is slow, taking years to decades to transport water from industrialized, temperate coastal regions to the Arctic Ocean.

The movement of water and pollutants in the Arctic Basin is best understood by viewing





Vertical section of the Arctic Ocean and the different water masses with their approximate residence times. The vertical scale is exaggerated compared to the horizontal scale.

Sea-ice extent in September and March and the major surface currents governing the transport of sea ice. The numbered lines show the expected time in years for the ice at that location to exit the Arctic Ocean through the Fram Strait.

the ocean as a layered system; see the diagram below.

Arctic surface water has a mixed layer and a halocline

The Arctic surface water extends to a depth of approximately 200 meters. This water can be further subdivided into the polar mixed layer (0 to 50 meters depth) and the halocline (50 to 200 meters depth). The water comes from rivers, the shelves, and from the Atlantic Ocean through the Fram Strait. One of the most important routes is via the North Atlantic Current.

The polar mixed layer is formed in winter when the ice freezes and excludes brine, and in summer by melting sea ice and river runoff along the coast. It is the only water within the Arctic that has direct contact with the atmosphere and consequently the only water that can exchange semi-volatile contaminants with the air.

The halocline is a structurally complex region with water of increasing density. It is crucial to the transport of contaminants. Over the shelves, it transports water laterally, away from the coast, as heavy, saline water sinks along the bottom.

Away from the shallow coast, the role of the halocline depends on the season. In spring and summer, it provides a barrier between the surface water and any deeper waters, effectively blocking vertical mixing of contaminants. It also limits the exchange of volatile contaminants between deeper layers of the ocean and the atmosphere. One important transport process thus takes place when the halocline breaks up and allows surface waters to sink and deep water to rise to the surface. This happens every fall and winter when the water cools and when ice starts to build, expelling brine. This vertical mixing allows both nutrients and contaminants from deeper layers to reach the surface in the shelf seas and Nordic Seas.

Two main features characterize the circulation of the surface water: the Beaufort Gyre and the Transpolar Drift; see map left. The Beaufort Gyre is a large clockwise gyre extending over the entire Canadian Basin. It circulates slowly between the pole and the Canadian Archipelago. In this way, water is exported both to Baffin Bay through the Canadian Archipelago and to the Transpolar Drift.

The Transpolar Drift runs east to west across the Eurasian Basin from the Siberian coast out through the western Fram Strait. Tracer studies show that about 10 percent of the water in this current comes from rivers, making it a conveyer belt for any contaminants that reach the open ocean through estuaries and deltas. The rest of the water comes from the Bering Strait and from the shelf seas. The transport takes only five years from the continental shelves to Fram Strait.

Atlantic layer circulation has been traced with radionuclides

Immediately below the Arctic surface layer is the Atlantic layer. This water enters the Arctic Ocean at the surface through Fram Strait and the Barents Sea, submerges, circulates around the Arctic Basin, and exits back through the Fram Strait, still submerged.

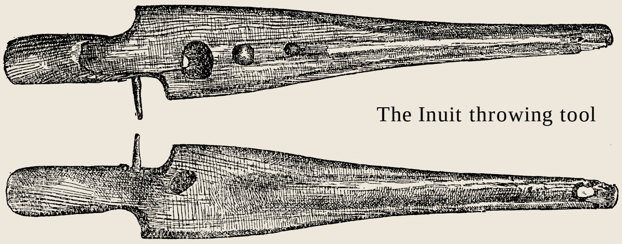
Radionuclides from Sellafield, a nuclear reprocessing plant on the northwestern coast of England, give a tell-tale sign of water currents. The North Atlantic Current (an extension of the Gulf Stream) transports large quantities of warm water from the Gulf of Mexico via the European coast to the Arctic. Any contaminants entering the current from rivers, ocean dumping, or the atmosphere will be carried along. Radiocesium from the Sellafield

Time taken for radiocesium released from Sellafield to be transported to the Arctic Ocean. Bold figures represent relative concentrations at different points.

Fridtjof Nansen counted on the Transpolar Drift

'Everywhere, the ice has stopped people in their quest to reach the North. Only in two cases have the ships drifted northward once they were stuck in the ice . . . By reading the history of Arctic research, it became clear to me that it would be difficult to capture the secrets of the unknown widths of ice by the routes that have been tried. But where did the road go?'

The transpolar drift was documented in the 19th century by the Norwegian polar explorer Fridtjof Nansen with his ship *Fram*. Three observations gave him the idea that water and ice moved according to a particular pattern. He had found trees from Siberian forests as driftwood on the eastern coast of Greenland. He had also found a throwing tool for bird hunting that was typical



The Inuit throwing tool

of Alaskan Inuit on the Greenland shore. But most important, pieces from the American ship *Jeanette* had been found on the drift ice south of Greenland. *Jeanette* had been lost in the ice near the New Siberian Islands on her way north from the Bering Strait. Nothing but drifting ice could have carried this material over such long distances. There had to be a current from east to west, and Fridtjof Nansen was determined to take advantage of this in his quest to cross the unexplored polar sea. He built a ship that would survive the crushing forces of the ice and set out on his journey in the summer of 1893. By mid fall, the ship was securely lodged in the pack ice north of the New Siberian Islands, just as predicted, and it was only a matter of time and patience to let the currents do their job. The journey was slow and trusting his theory was not always easy. Every sign of progress was noted in his diary:

'Friday February 16. Hurrah! Our meridian observation this morning gave 80°1'N. We have come a few minutes northward since last Friday, even though the wind has been blowing constantly from the north since Monday. It is very strange. Could it be, as I have thought myself, observing the skies and the misty air, that it has been a southerly wind further south, which stops the drift of the ice in that direction? Or have we finally come within an area where a current acts?'

Time proved that Fridtjof Nansen was right, that there is an east-to-west current. After three years, in August 1896, *Fram* was released from the ice as the Transpolar Drift reached Spitsbergen.

nuclear reprocessing plant can, for example, be detected all along the Norwegian coast as well as in the Arctic Ocean. Some of the north-flowing water is returned to the North Atlantic in a subsurface flow along the eastern coast of Greenland, but a substantial part of this historical discharge now resides in the Arctic Ocean.

Arctic deep water has extremely long residence time

Arctic deep water extends from 800 meters downward and is divided into the Canadian Basin deep water and the Eurasian Basin deep water. The only inflow is through Fram Strait and the Barents Sea as the Bering Strait is too shallow. The water moves counter-clockwise.

Contaminants enter Arctic deep water mainly by flow of dense water off the shelves. Once there, they can be transported long distances. One example is the anomalously high ratio of cesium-137 to strontium-90, which in 1979 was observed at the Eurasian Basin flank of the Lomonosov Ridge. It represents a signal from the Sellafield nuclear reprocessing plant on the Irish Sea. The signal was carried either from Spitsbergen or from the continental slope off the Barents Sea to the North Pole and then around the perimeter of the Eurasian Basin in about 3 years.

The Arctic deep water has an extremely long residence time, and any contaminants entering this layer might stay in the Arctic for up to 300 years.

Summary

Air, water, and ice can carry contaminants over great distances.

In winter, industrial areas of Eurasia are within the Arctic air mass, which provides for efficient air transport of particle-bound contaminants across the pole. Semi-volatile compounds are carried to the Arctic by cycles of evaporation, transport, and condensation in a multi-hop process. The cold climate traps them more effectively here than anywhere else on the globe.

Snow, rime ice, rain, and dry deposition cleanse the air and contaminate the surfaces on which they land. The contaminants often end up in meltwater that feeds both rivers and the ocean surface layer.

Rivers process contaminants along their routes by sedimentation and resuspension of particles. Lakes, estuaries, and deltas serve as sediment traps and sinks for contaminants.

Ice forming in the shelf seas can pick up contaminants from the coastal shelves, and can travel far in the Beaufort Gyre and Transpolar Drift. The ice may release its load of contaminants in the biologically productive shelf seas and in the North Atlantic, where they can be taken up into the food chain.

Another important pathway is via ocean currents. They act slowly compared with the atmosphere, but take water with water-soluble and particle-adsorbed contaminants from distant industrialized coasts into the Arctic within a few years, and out again through the East Greenland Current and the Canadian Archipelago. The sea is the final resting place for most contaminants.

Modeling is a useful tool for understanding contaminant transport. Its importance will grow as the basic processes become better understood and the models improve.