



Spring sun, 78°N

SIEBA PROJECT OFFICE

Heavy Metals

The rise of the sun after the polar winter is a time of celebration in the Arctic. The lengthening days herald warmer weather and the return of migratory animals. But the recent discovery that the Arctic may be an important global sink for atmospheric mercury casts a shadow over polar sunrise.

Each spring, a substantial amount of airborne mercury is deposited on Arctic snow and ice as a result of reactions spurred by sunlight. Once in the snow, some of the mercury is present in reactive, biologically available forms. As the snow melts, some of the mercury can enter the food web just as the burst of spring productivity begins, a time when life in the region is vulnerable.

This chapter examines heavy metals in the Arctic, focusing on mercury, lead, and cadmium. Mercury pollution is an increasing concern because levels in the Arctic are already high, and are not declining despite significant emissions reductions in Europe and North America.

Lead, on the other hand, clearly demonstrates the effectiveness of actions to reduce

pollution. Overall, lead levels in the atmosphere have gone down considerably, mainly thanks to restrictions on leaded gasoline. In some local areas within the Arctic, however, the use of lead shot for hunting has left particles of this metal on the ground or at the bottom of ponds, a source of exposure for many birds.

Cadmium remains an enigma. Its sources, levels, and biological effects are still not sufficiently well documented to assess the environmental impact cadmium has in the Arctic.

In parts of Russia, around the large smelter complexes in Norilsk and on the Kola Peninsula, emissions that include metals and sulfur dioxide have destroyed all nearby vegetation. This chapter also provides updated information from these areas.

In addition to sources, pathways, and levels of heavy metals, this chapter discusses effects of metals on vegetation and wildlife. Effects on people are covered in the chapter *Human Health*, which shows that mercury, in particular, is a serious health concern for some Arctic people.



Coal-burning power plant, 40°N

POLEFO / T.C. MALHOTRA

Introduction

Metals are naturally occurring elements. They are found in elemental form and in a variety of other chemical compounds. Each form or compound has different properties, which affect how the metal is transported, what happens to it in the food web, and how toxic it is. Some metals are vital nutrients in low concentrations.

The previous AMAP report assessed a wide range of metals and concluded that the ones raising most concern about effects in the Arctic are mercury and cadmium. They have no known biological function but bioaccumulate (see table), can be toxic in small quantities, and are present at high levels for a region remote from most anthropogenic sources. For both metals, a primary emphasis was on increased understanding of the possible biological effects of the levels that have been doc-

Parts of the mercury belt, the geological areas naturally rich in mercury, lie within the Arctic.

Metal	Organism	Uptake efficiency (how much of available metal is taken up in the indicated tissue)	Half-life (time it takes for the tissue concentration to be reduced by half)
Lead	Mammals	5-10% via intestines 30-50% via the lungs	40 days in soft tissues 20 years in bone
Cadmium	Fish	1% via intestines 0.1% via gills	24-63 days
	Mammals	1-7% via intestines 7-50% via lungs	10-50% of life span in liver 10-30 years in kidney
Mercury	Fish	depends on chemical form, water temperature, and water hardness	323 days for organic mercury from diet 45-61 days for inorganic mercury from water or diet
	Mammals	>95% for organic mercury via intestines >15% for inorganic mercury	500-1000 days in seals and dolphins for methylmercury, 52-93 days for methylmercury and 40 days for inorganic mercury in whole body of humans.

umented in Arctic animals. A third metal of concern was lead. Lead is also toxic, but environmental levels of lead appeared to be decreasing as a result of the change to unleaded gasoline in most countries. Other metals, such as nickel and copper, were of local concern, especially near large smelting operations.

Mercury: sources and pathways

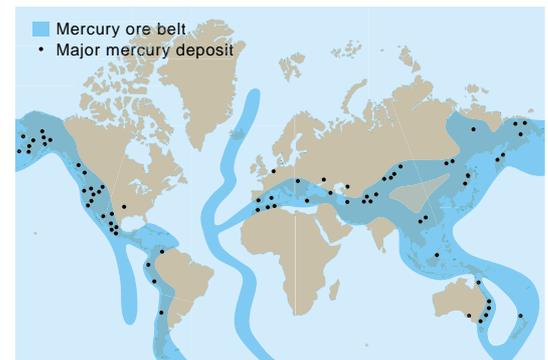
Coal burning, waste incineration, and industrial processes around the world emit mercury to the atmosphere, where natural processes transport the metal. The Arctic is vulnerable because unique pathways appear to concentrate mercury in forms that are available to the food web. Environmental changes may have made these pathways more efficient in recent years.

Global emissions of mercury to the air in 1995 from major anthropogenic sources. Estimated emissions from natural sources are roughly the same as total anthropogenic emissions.

Technological advances have reduced emissions in some industrial areas, but these reductions have been offset by increases in other regions. Many sources are still poorly documented.

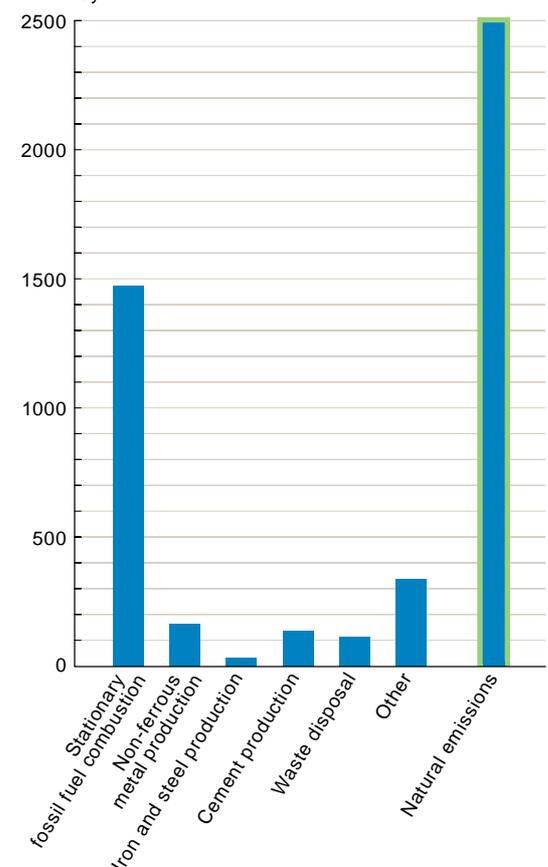
Human activities release mercury

Mercury is a relatively common metal, found in rocks, sediments, and organic matter throughout the world. Typically, naturally occurring mercury is strongly bound in these media and not readily available to the food web.



Human activities can mobilize mercury, either through mining and subsequent use of mercury in a range of products, or by burning fossil fuels. In 1995, the most recent year for which global emission figures are available, some 2240 tonnes of mercury were released into the air as a result of the burning of fossil fuels, the production of metals and cement, the disposal of waste in landfills and incineration plants, and other industrial activities. Fossil fuel combustion, particularly burning coal to generate electricity and heat, was

Worldwide mercury emissions, tonnes/year



Current international actions on metals

In addition to national regulations concerning emissions and use of heavy metals, some significant steps have recently been taken internationally to address the heavy metals.

The United Nations Economic Commission for Europe (UN ECE) Convention on Long-Range Transboundary Air Pollution adopted a Protocol on Heavy Metals in 1998. The protocol targets mercury, lead, and cadmium. Countries that are party to the protocol will have to reduce total annual emissions to below the levels they emitted in 1990.

As of June 15th, 2002, there were 36 signatories to the protocol, including all the Arctic countries except Russia. Of these, 10 had ratified it, including Canada, Denmark, Finland, Norway, Sweden, and the United States. For the protocol to enter into force, sixteen countries must ratify it.

At its meeting in 2000, the Arctic Council called on the United Nations Environment Programme (UNEP) to initiate a global assessment of mercury that could form the basis for appropriate international action. This request was based on the findings of AMAP's first assessment. In 2001, the UNEP Governing Council agreed to undertake such a study. At the same time, UNEP agreed to tackle the issue of lead in gasoline.

The study on mercury will summarize available information on the health and environmental impacts of mercury, and compile information about prevention and control technologies and practices and their associated costs and effectiveness. In addition, the UNEP Governing Council requested, for consideration at its next session in February 2003, an outline of options to address any significant global adverse impacts of mercury. These options may include reducing and or eliminating the use, emissions, discharges, and losses of mercury and its compounds; improving international cooperation; and enhancing risk communication.

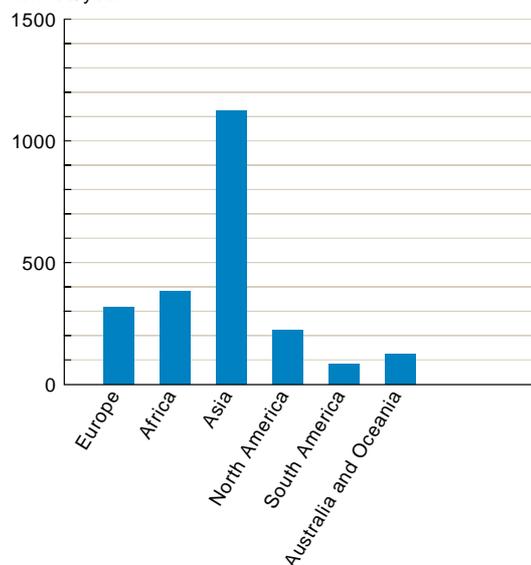
responsible for about two-thirds of these emissions.

Recent conversions to cleaner-burning power plants and the use of fuels other than coal reduced emissions significantly in Western Europe and North America during the 1980s. Industrial coal combustion now produces only half the mercury that it did at the beginning of the 1980s. There is evidence, however, that global emissions may now actually be increasing. The recent reductions have been offset by rising emissions in some parts of the world, particularly Asia, which now produces half the world's mercury emissions.

The main source of Asian emissions is coal combustion to produce electricity and heat, particularly in China. Chinese emissions from sources such as small industrial and commercial furnaces, residential coal burning, and power plants are responsible for about half the Asian total, or one-quarter of global emissions.

Re-emissions of mercury that has already been deposited can be a significant source,

Anthropogenic mercury emissions, tonnes/year



especially as human activity has increased the total amount of mercury available in the environment. Natural sources, such as volcanoes, add to the total mercury in the Arctic environment. It is very difficult to quantify and distinguish the contributions of re-emitted mercury and natural sources. For example, a natural event such as a forest fire can release mercury that had been deposited after initial emission from a coal-burning power plant.

However, the contribution of natural sources is believed to be comparable, on a global scale, to emissions from human activities. Locally, the contributions of re-emissions vary greatly. About three-quarters of the mercury emitted to the atmosphere is gaseous elemental mercury, or mercury vapor. About one-fifth of the mercury is reactive mercury, and the remainder is mercury bound to aerosol particles such as soot.

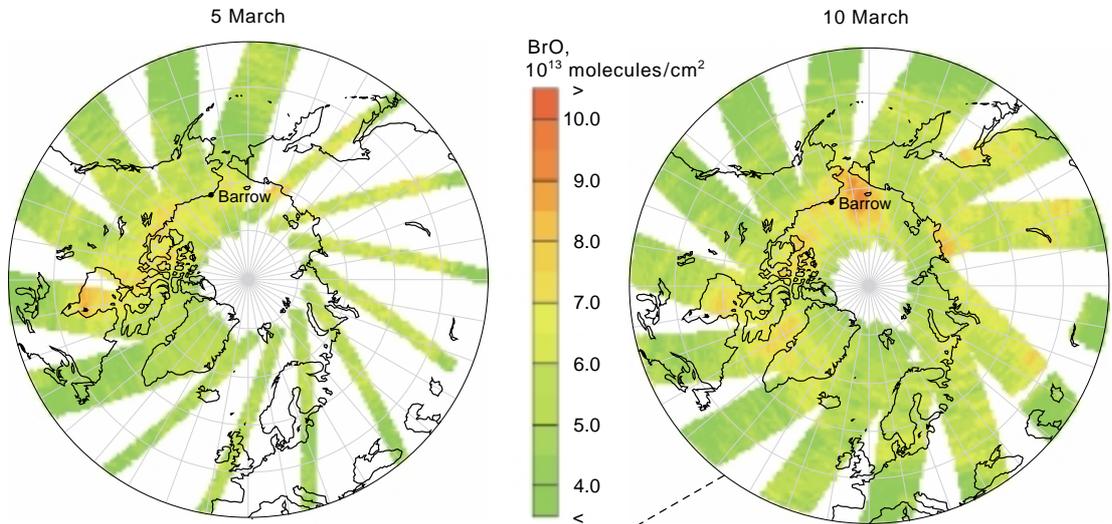
Volatility ensures global distribution

Atmospheric transport is the most important pathway of mercury to the Arctic. Globally, an estimated 5000 tonnes of mercury are present in the air at any given time. At present, combustion, particularly of coal in Asia and Europe, is the most significant source of anthropogenic mercury in Arctic air.

Mercury can appear as a vapor, which means that it can be re-emitted after it has been deposited on land or in water. Long residence time in the atmosphere, 1-2 years, helps it spread around the northern hemisphere.

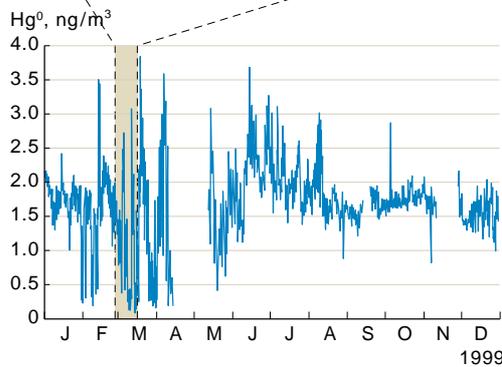
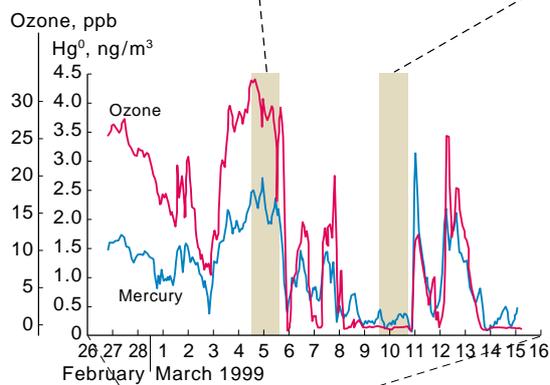
The presence of mercury does not by itself explain how it enters the food web. Elemental mercury in the air must be transformed into bioavailable mercury. One mechanism by which this can occur has been recently discovered, and appears to be unique to the Arctic.

◀ Global anthropogenic emissions of mercury to the air in 1995 from different continents.



Mercury depletion in spring 1999 at Barrow, Alaska, one of the sites where these events have been measured.

Lower panel: onset of the main mercury depletion in March.
Center panel: Similarity between gaseous elemental mercury and ozone depletion patterns.
Upper panel: the strong mercury depletion on 10 March coincides with high bromine levels near Barrow, which were not present a few days earlier.



Polar sunrise leads to mercury depletion in air

At the monitoring station in Alert, in the Canadian High Arctic, the concentration of gaseous elemental mercury levels drops sharply each spring. Researchers first noticed this phenomenon in 1995, and initially thought that their instruments were malfunctioning. The phenomenon occurred again the next spring, however, and similar observations were made at other air monitoring stations around the Arctic.

The drop in mercury is not a one-time event, but a series that begins shortly after the first sunrise of spring, and continues until snow-melt (see graph to the left). Depletions are highest at midday, when sunlight is strongest, and are closely correlated with a depletion of ozone in surface air. Although further research is needed to determine exactly what is occurring each spring, a likely explanation is a series of chemical reactions in the air. The catalyst for these reactions appears to be bromine, which is emitted from the ocean to the surface layer of the atmosphere. Spurred by sunlight, the bromine reacts with ozone to create compounds that in turn may react with elemental mercury (see diagram on top of opposite page).

The net result is that elemental mercury is oxidized to some form of reactive gaseous mercury, while ozone is destroyed. Thus, gaseous elemental mercury and ozone show a sharp decline together. The mercury and ozone required for these reactions are replenished from air above the surface layer. The gaseous bromine, on the other hand, is returned to its original form by the sequence of reactions, ready to act as a catalyst again.

Part of the evidence for the role of bromine in mercury depletion events is that mercury in snow and lichen is higher nearer the coast than inland. This pattern is the same for sea-salt aerosols, which are one source of the bromine necessary for the reactions. Another key

Mercury can take many forms

Mercury exists in many forms in the environment, each of which has different properties affecting distribution, uptake, and toxicity. These forms include:

Elemental mercury – mercury atoms that have not lost electrons. At room temperature, elemental mercury is a liquid, but it produces mercury vapor (also called gaseous elemental mercury, Hg^0), which can be transported by air. Elemental mercury is not particularly toxic, but is readily taken up by air-breathing organisms.

Reactive mercury – mercury that reacts readily with other molecules, and deposits very quickly from the air.

Methylmercury and related compounds – mercury joined to methyl groups to form new molecules. Some microorganisms can turn inorganic mercury into methylmercury, a highly toxic form that is bioaccumulated and biomagnified.

Particulate mercury – mercury atoms bound to soil, sediment, or aerosol particles. Particulate mercury is generally not very bioavailable.

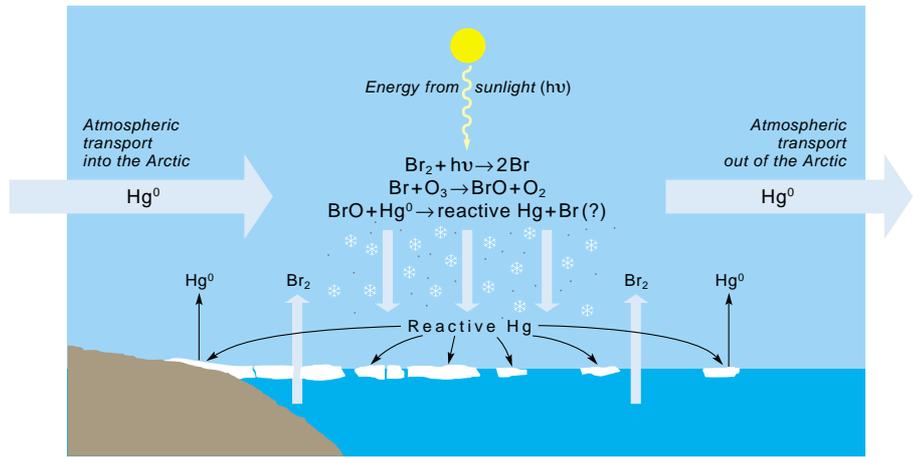
piece of evidence is the finding that mercury in snowfall on the Arctic Ocean increases dramatically after polar sunrise.

Recent mercury transport models have incorporated the mechanisms thought to be responsible for mercury depletion events. These models and other calculations indicate that the amount of mercury deposited in the Arctic may be considerably higher than previously realized. Estimates of annual deposition in the Arctic range from 150 to 300 tonnes, or more than twice the estimates made without including the springtime depletion events.

Mercury enters the food web

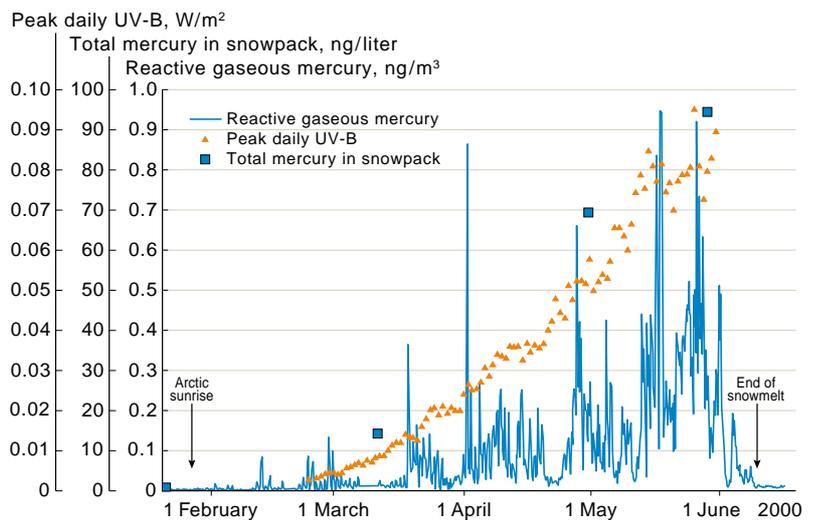
Reactive gaseous mercury, unlike elemental mercury, deposits quickly on whatever surface it touches. During the Arctic spring, this is most likely to be snow. Once in the snow, much of the mercury is returned to the elemental form and is re-emitted to the atmosphere. However, a significant amount of the mercury remains in reactive form in the snow (see figure to the right), where other processes convert some of it to a bioavailable form. The bioavailable mercury is likely transformed to highly toxic methylmercury by microbial action. Bioavailable mercury is negligible in the snow prior to polar sunrise, but levels increase after the mercury depletion events start, reaching a maximum just before snowmelt.

Snowmelt is the time when Arctic plants and animals become active and productive. Snowmelt is also the main source of freshwater to most Arctic landscapes. Though further study is needed to determine the fate of the reactive mercury, the release of bioavailable mercury into terrestrial and aquatic ecosystems may be the chief mechanism for transferring atmospheric mercury to Arctic foodwebs.



Because the mercury depletion events have only recently been discovered, it is not clear whether they have always taken place. Changes in Arctic climatic regimes or the levels of anthropogenic pollutants may influence the scale of mercury depletion. The chapter *Changing Pathways* explores the potential role of climate change on mercury transport and deposition.

Reactions involving sunlight and bromine remove gaseous elemental mercury from the atmosphere (mercury depletion) and transfer it to the surface as reactive mercury. Part of the reactive mercury may reach the food web; part is re-emitted as Hg⁰.



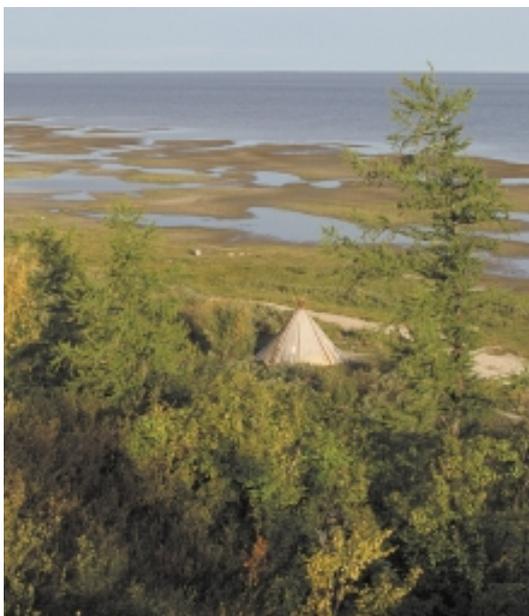
Rivers and biological pathways can be locally important

Even if most mercury reaches the Arctic through the air, there are some additional pathways. Russian rivers carry mercury released by industrial activities upstream. Although their mercury concentrations are much lower than mean global values, the great volume of water in the Ob, Yenisey, and Lena rivers make them significant regional pathways. Together, the Eurasian rivers transport 10 tonnes of mercury each year to coastal estuaries and the Arctic Ocean, most of it in particulate form.

Biological pathways can also be important locally. For example, salmon migrating from the ocean to spawn deliver mercury to lakes and rivers when they die. One study in Alaska estimated that, over the past twenty years, a total of some 15 kilograms of methylmercury

Production of reactive gaseous mercury at Barrow starts as UV-radiation increases following polar sunrise, and ends at snowmelt. Total mercury in the surface snowpack also increases over this period.

Ob Estuary. Eurasian rivers transport mercury to coastal estuaries.



BRYAN & CHERRY ALEXANDER



BIOFOTO / ADI

Migrating salmon can serve as a biological pathway for mercury.

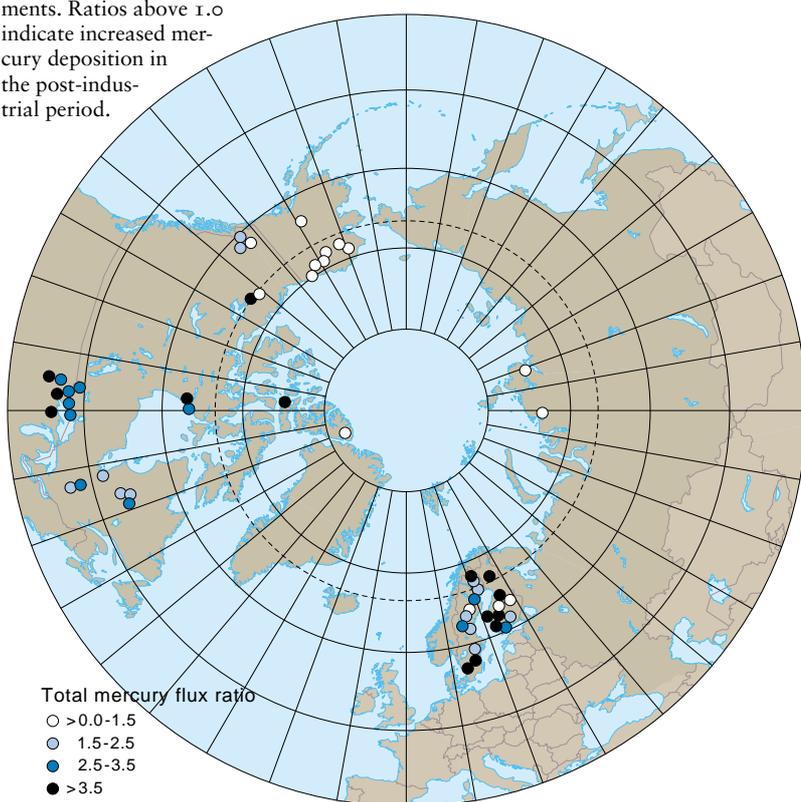
has been transported by Pacific salmon to the lakes and streams of the eastern Bering Sea coast.

While riverine inputs and biological transport can be locally significant, analysis of mercury and other compounds in sediments confirms that, across the Arctic, deposition from the atmosphere is the main source of mercury from human activities.

Ocean pathways are not well understood

Atmospheric deposition, including mercury depletion events, and river inputs supply mercury to the ocean. Mercury is removed from the upper layers of the ocean by settling of particles or by emission of gaseous mercury to the air. The cycling of mercury and its eventual fate in the ocean, however, are poorly

The ratio of post-industrial to pre-industrial flux of mercury to lake sediments. Ratios above 1.0 indicate increased mercury deposition in the post-industrial period.



understood, especially for the Arctic. Some mercury enters the food web and some is buried in sediments, but the linkages between mercury depletion events and mercury concentrations in marine biota have not been determined. It seems likely that the mercury exchange between atmosphere and ocean in the Arctic differs significantly from other oceans simply because of ice cover. Sea ice forms a barrier to the gaseous emission of mercury accumulated in the upper ocean layer, but the potential of this barrier to enhance mercury concentrations in the marine environment has not been evaluated.

Mercury time trends

Mercury has always been present in the Arctic, but levels in many areas of the Arctic are considerably higher now than they were before the beginning of the industrial era. Recent trends vary geographically and levels do not seem to be dropping as would be expected from regional emission reductions in Europe and North America. In some areas they are clearly increasing.

Diagenesis may affect metals profiles in sediments and peat bogs

Mercury in sediments and peat bogs may move after it is deposited, a process known as diagenesis. This movement can alter the profile of mercury in the sediment or peat layers, confounding trend analyses. Although there are still questions relating to diagenesis in lake sediments and peat bogs, a number of studies appear to provide good evidence that mercury deposition in the Arctic has increased considerably since the industrial era began.

Mercury levels are higher than in pre-industrial times

Lake sediments in Greenland show that mercury increases started by the late 19th century, and perhaps as early as the 17th century. Recent concentrations are on average three times higher than in pre-industrial times. Similar results have been found across Eurasia, with increases highest in the west and at lower latitudes, closer to the industrial areas of central Europe. Lakes in the Taymir Peninsula in northern Russia, for example, showed a much smaller increase than lakes in northern Scandinavia (see map).

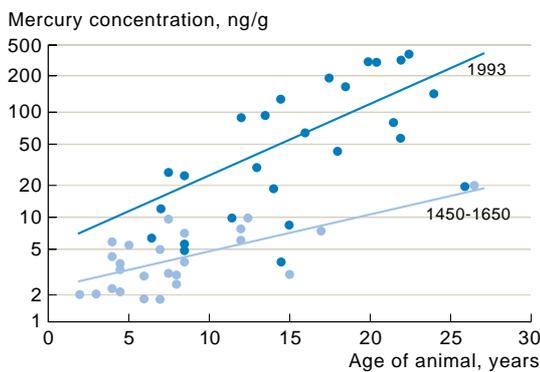
In North America, similar geographic patterns emerged, with higher increases in southeastern lakes near mercury sources in eastern North America. By contrast, no increase has been seen in the sediment in some lakes remote from source regions. This includes YaYa Lake in the Yukon Territory, Lake Hazen

on Ellesmere Island in the Canadian High Arctic, and lakes on the Arctic coastal plain of Alaska.

Peat bogs in Arctic Canada, Greenland, and the Faroe Islands provide evidence supporting the trends found in lake sediments. Mercury concentrations in cores from these bogs were seven to seventeen times higher after the industrial revolution than before. More information about the behavior of mercury in peat bogs is needed to interpret the differences between the peat and lake sediments.

Long-term time trend data for biota are relatively scarce, but the existing records show an increase in most parts of the Arctic. In Greenland, mercury in human and seal hair shows a three-fold increase since the 15th century. These data are discussed further in the chapter *Human Health*. In Norway, mercury in human teeth (without modern mercury amalgam fillings) was thirteen times higher in the 1970s than in the 12th century, although levels appear to have declined substantially since the 1970s.

Concentrations in beluga whale teeth from the Beaufort Sea showed an increase of four to seventeen times between the 16th century and the 1990s. The data suggest that industrial mercury accounts for more than 80% of total mercury in this species.

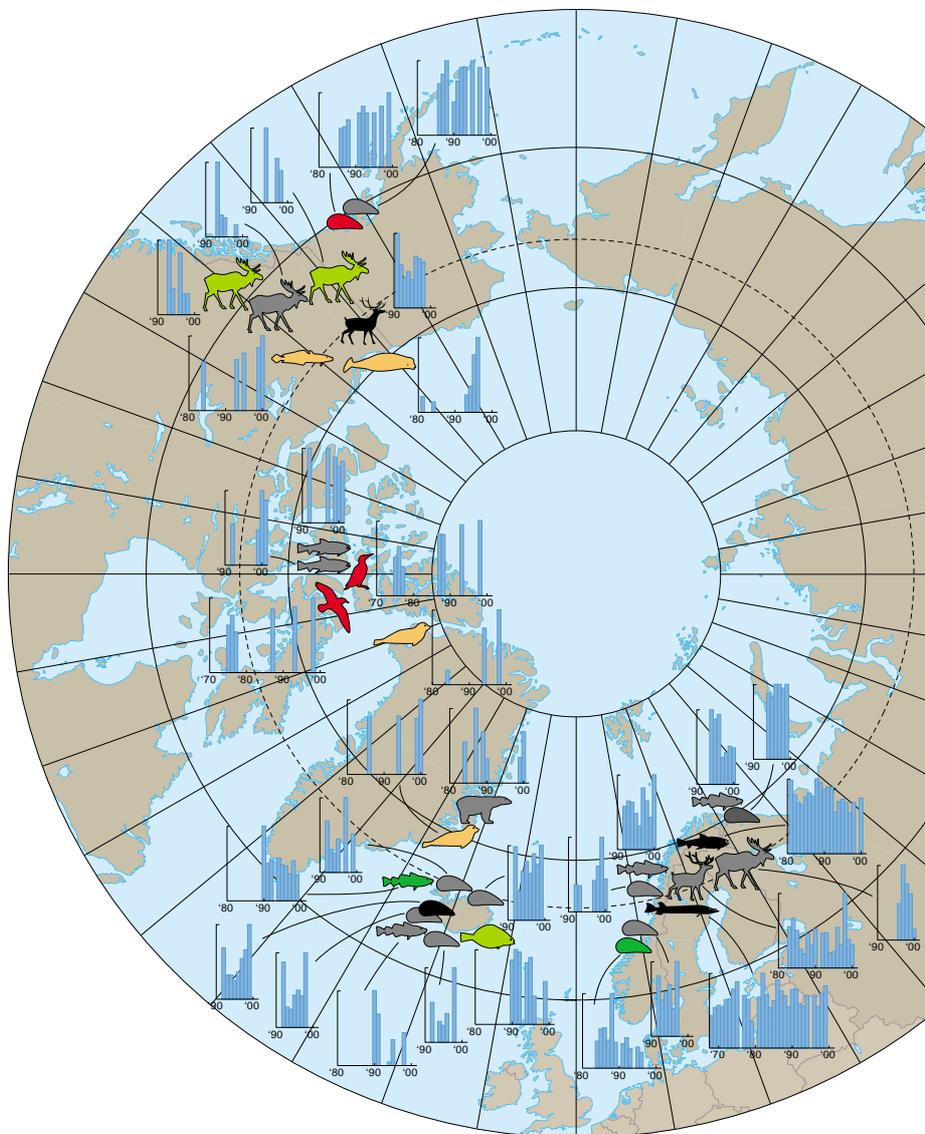


Mercury in teeth of Beaufort Sea beluga collected in 1993, compared with 300-500 year old teeth.

Mollusk shells in Hudson Bay indicate a doubling of mercury concentrations in seawater since the pre-industrial age. By contrast, mollusk shells and walrus teeth from the Canadian High Arctic show no change in mercury from the 16th century to the present, perhaps reflecting their greater distance from industrial sources.

Recent trends vary

Where available, trends data from the past few decades indicate that mercury levels are increasing in some Arctic biota, specifically in marine birds and mammals from some areas in the Canadian Arctic, and some species in West Greenland. By contrast, in lower-order marine biota samples from the European Arctic, mercury levels are stable or declining. However, most time trend studies have been

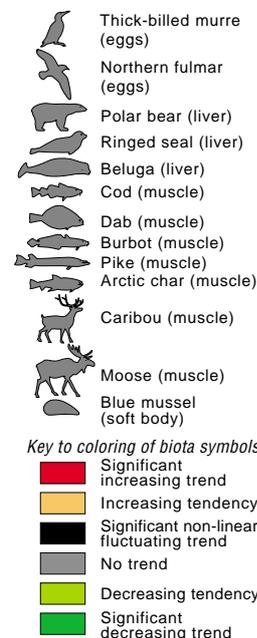


of too short duration to provide evidence of definitive recent trends.

In the eggs of thick-billed murres collected from Prince Leopold Island, Canada, the mercury concentration almost doubled between 1975 and 1998. In northern fulmars, the increase was 50% over the same period. The trend does not appear to be the result of changes in feeding patterns or the food web. Mercury levels in kittiwakes showed no significant change, even though these birds migrate to more polluted areas at lower latitudes.

Mercury in the liver and kidneys of ringed seal, beluga, and narwhal across Canada appears to have increased by a factor of two or three over the past twenty years, though annual variations are high. In the late 1990s, there was an increase in mercury in beluga from the Beaufort Sea in the western Canadian Arctic, but no consistent pattern in the eastern Canadian Arctic. Mercury in ringed seal liver from West Greenland is higher now than in the mid-1980s, but in ringed seal from East Greenland, no change has been seen over the same period. In polar bear muscle from East Greenland, mercury is higher now than in the mid-1980s, but no change was found in polar bear liver, kidney, or hair.

Marine fish and invertebrates show differing trends. In Greenland, mercury in short-



Trends in mercury levels have been measured over the past 10-30 years in various Arctic species. Selected time series are shown, with animal symbols colored to indicate the trend. Increasing trends are apparent in some marine animals, especially in the Canadian Arctic.

horn sculpin increased from the mid-1980s to the mid-1990s. In Arctic cod over the same period, mercury decreased. Recent collections of sculpins from Greenland show no clear trend. Cod sampled around the coasts of northern Norway showed no change in the 1990s. In northwest Iceland, levels in both cod and dab declined. In blue mussels, levels remained stable at most sites in Norway, Iceland, and Greenland. Two sites were sampled in Prince William Sound, Alaska, one of which showed no change and the other a significant increase. In Qeqertarsuaq, Greenland, mercury declined in larger mussels from 1994 to 1999.

In the terrestrial environment, changes appear to be occurring in some cases. Moose in parts of the Yukon Territory may have declining levels of mercury, as measured from 1993 to 1998. Mercury in reindeer livers in Isortoq, Greenland declined from 1994 to 1999. Mercury levels in American peregrine falcon in Alaska may have increased from the period 1988-90 to 1991-95. Longer-term monitoring is required to confirm these findings.



Measuring a burbot – mercury levels in fish are related to the size and age of the individual.

In freshwater environments, the picture is similarly varied. The only recorded increase is in male burbot from the Mackenzie River, Canada. At Fort Good Hope, Northwest Territories, mercury levels in burbot muscle increased by 36% between 1985 and 2000. In other areas where monitoring has occurred, mercury appears to have declined or remained stable. Lake trout from Lake Laberge in the Yukon Territory showed a 30% decline in mercury in muscle from 1993 to 1996, but no change from 1996 to 1998. Also in the Yukon, lake trout in Quiet Lake showed no change from 1992 to 1999. Arctic char in Resolute Lake in the Canadian Arctic show no changes from 1992 to 2000. In northern Sweden, Arctic char and pike showed no trends over the past twenty and thirty years, respectively, although levels fluctuated considerably within that period. In Greenland, no trend was found in Arctic char over the period 1994-1999.

Levels in freshwater environments may not respond immediately to declines in emissions because previous deposition in the catchment area can make the surrounding soils a continuing source.

A need for further studies

The increases in mercury since the start of the industrial age are clear evidence of the role of human activities. Drawing firm conclusions about changes in the role of anthropogenic emissions in a shorter time period is not as easy.

The decline in some areas probably reflects decreases in emissions. In Canada, mercury levels in sediments have decreased in southern lakes, following emissions reductions at nearby sources. However, there is no clear explanation for the increases in marine birds and mammals from some areas in the Canadian Arctic and West Greenland or why the time trends should be different for Canada/Greenland and the European Arctic. The Canadian belugas that showed the greatest increase in uptake in the 1990s were collected in areas with large freshwater drainage, suggesting that the change could be more related to freshwater input than direct deposition from the air.

There is a need to better understand pathways and processes influencing mercury distribution. Such studies should include the possible influence of climate change, which is discussed further in the chapter *Changing Pathways*.

Mercury levels and effects

Mercury levels in the environment reflect a combination of different factors, including pathways and proximity to natural sources. Moreover, mercury-rich rocks in some areas



lead to locally higher background levels. Once mercury enters the food web, differences in food web structure can greatly affect levels of mercury, even in the same species in different locations. In the Arctic, the potential for bio-magnification is generally greatest in aquatic food webs, where levels are high enough in some species to raise concern about toxic effects.

Mercury ore (cinnabar).

Mercury can have a variety of toxic effects

The toxicity of mercury to individual plants and animals is well known through laboratory studies and through examining accidents where mercury was released into the environment or introduced into food items.

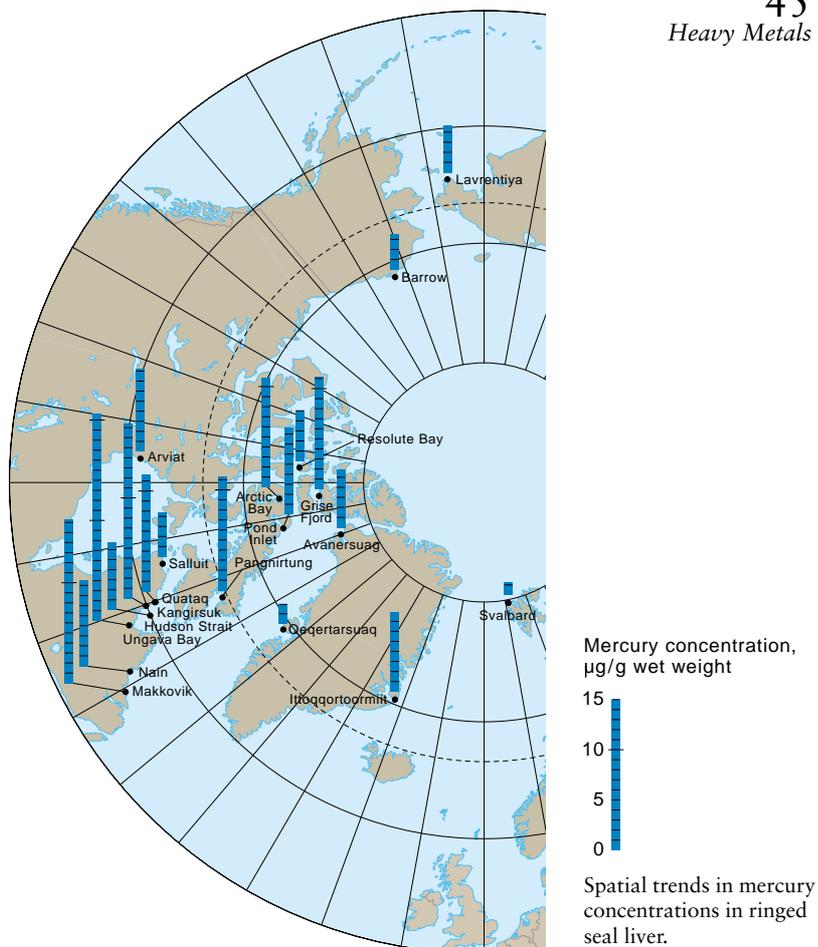
In mammals, mercury causes nerve and brain damage, especially in fetuses and the very young. It can also interfere with the production of sperm. In birds, high levels of mercury can cause erratic behavior, appetite suppression, and weight loss. At lower levels, egg production and viability are reduced, and embryo and chick survival are lower. Outside the Arctic, some seabirds show signs of cellular-level kidney damage from accumulated mercury. Fish exposed to high mercury levels suffer from damage to their gills and sense of smell, from blindness, and from a reduced ability to absorb nutrients through the intestine. Plants with high concentrations of mercury show reduced growth.

Mercury is significant in the marine environment

The major focus for mercury research has been on the marine environment. Blue mussels and shorthorn sculpins, two species that have been studied around the Arctic, show no clear spatial trends.

Seabirds, on the other hand, had in general lower levels in the Barents Sea than in Greenland, Canada, and northeastern Siberia. Fulmars and black guillemots show comparable levels between the Faroe Islands and Arctic Canada, though Faroese levels may be closer to the high end of the range for Canadian samples. The Canadian Arctic seabird data show an increase in mercury as latitude increases.

For migratory species, the winter range may be a critical factor in mercury levels. Birds in northeast Siberia, which winter in eastern Asia, show higher levels of mercury than birds in other regions. Moreover, feeding habits and food web structure likely play a role in spatial differences. Birds of the same species may eat invertebrates in one region and fish in another, with correspondingly different exposures to contaminants. Regional geology and the effects of temperature on



growth processes are other factors that could play a role in regional differences.

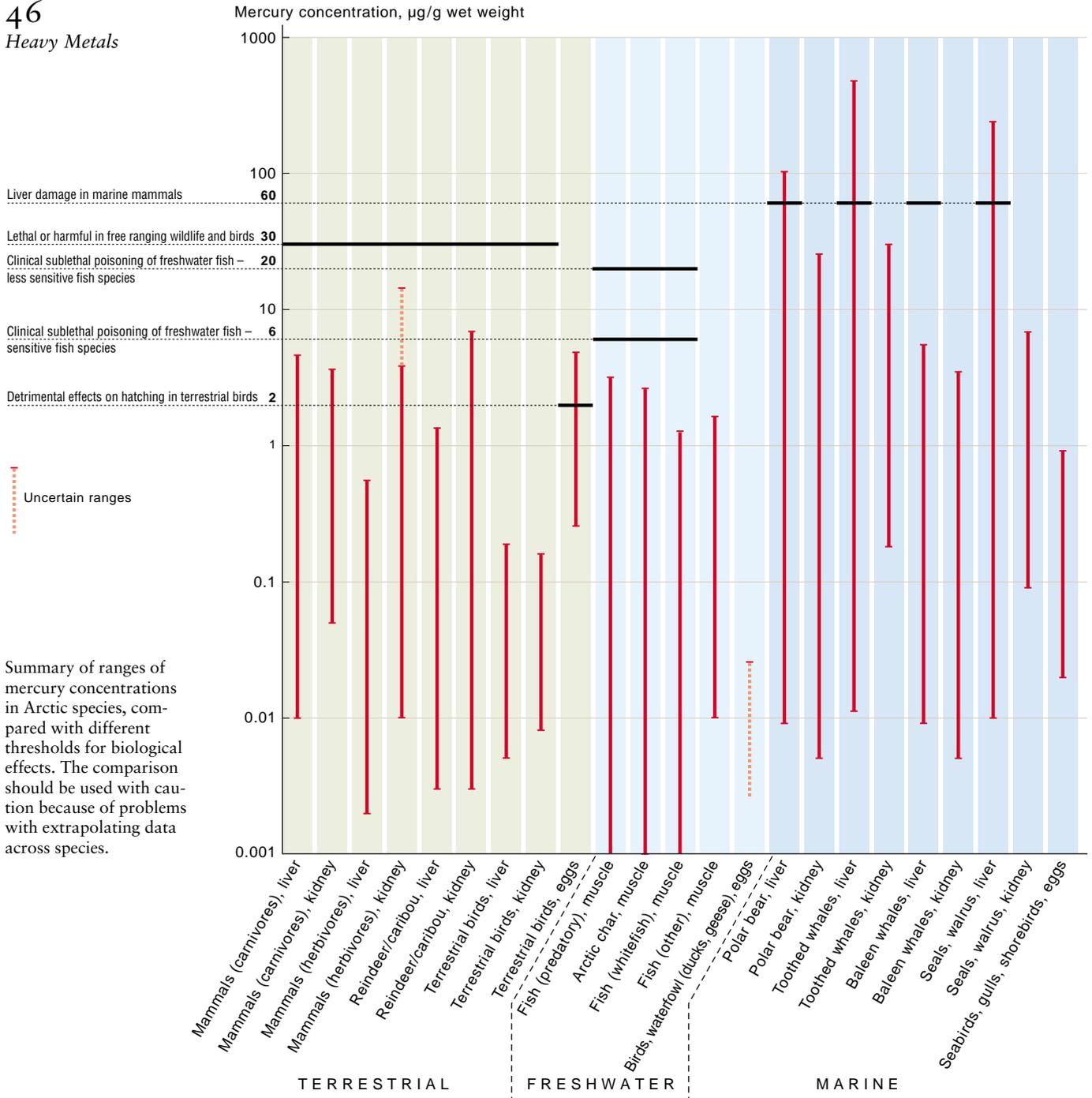
There is some evidence that, as one moves westward across the Canadian Arctic, mercury levels in beluga whales and ringed seals increase. In the North Atlantic, mercury levels in minke whales were found to be higher around Jan Mayen and the North Sea than around Svalbard or West Greenland. In gray seals from the Faroe Islands, mercury levels are similar to those found in the same species at Sable Island, eastern Canada, but higher than gray seals from Jarfjord, Norway. In polar bears, mercury levels are higher in the northwestern Canadian Arctic than in southern, northeastern, and eastern Greenland.

Seabirds and some whales may be vulnerable

Documenting mercury levels is an important step, but these levels do not by themselves tell us what effects mercury may have on the individual animals or on wildlife populations. The natural environment is a complex system, and different species and even different individuals can respond in very different ways to mercury and other contaminants. In most marine animals, mercury concentrations are highest in liver, followed by kidney and then muscle. Polar bears and terrestrial animals have the highest levels in the kidney.

◀ Ringed seal – a key species in circumpolar Arctic monitoring.





Bowhead whales, beluga, and seals harvested in northern Alaska have concentrations of mercury and other metals that are high compared with normal ranges found in livestock. Nonetheless, they appear to be in good body condition, with no lesions that would indicate effects of heavy metals. In fact, the levels found in bowhead whales are comparable to the levels found in most other baleen whales around the world.

Some birds and marine mammals have mercury levels that are a cause for concern. Studies of some seabirds show that higher mercury levels were associated with lower body weight and lower amounts of abdominal fat. Selenium, however, may help protect these animals from the effects of mercury exposure. Seabirds are also able to tolerate higher mercury exposure than non-marine birds.

Less is known about freshwater and terrestrial environments

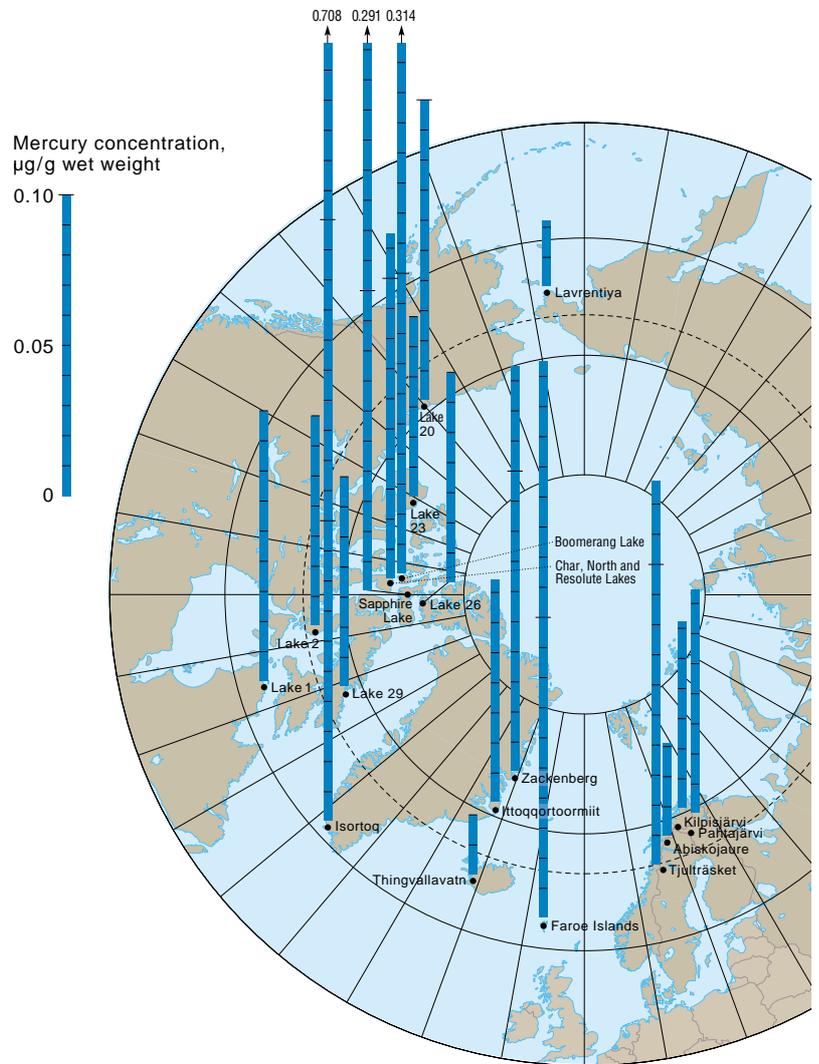
Although there are some spatial differences in mercury in the freshwater and terrestrial environments, most levels are low. The differences may reflect local sources, including geology of the local bedrock. In the terrestrial environment, there is evidence that mercury accumulates as it progresses up the food web, and that eating lichen is the primary means by which caribou and reindeer are exposed to mercury.

There are large variations in mercury concentrations in Arctic char in the AMAP area. Overall, the levels are below the Canadian subsistence food guideline of 0.2 micrograms per kilogram. However, there are areas such as southwestern Greenland, lakes near Qaus-

uittuq in Arctic Canada, and the Faroe Islands, where levels exceed the Canadian subsistence food guideline. The variability can be seen even in limited geographical regions. For example, in Sweden, levels in the lake Tjulträsket were four times higher than in the lake Abiskojaure (Åbeskojávri), without any obvious explanation.

Arctic char can inhabit different trophic levels, even within the same lake. The position of an individual fish in the food web can also change over time. Because freshwater fish at higher trophic levels have higher mercury concentrations in their tissues, the position of a given char at a given time is a critical factor in determining its mercury load. Thus, comparisons are difficult to make. Furthermore, char that spend time in the ocean appear to have generally lower mercury levels than land-locked char.

Fish that eat other fish have higher mercury levels, and are thus the main concern in relation to human exposure. These predatory species include walleye pike, lake trout, and northern pike. In the western Northwest Territories, Canada, mercury levels in these species are typically above Canadian consumption guidelines, regardless of size or age.



affect mercury availability and uptake. Acidification, for example, can greatly enhance the process of methylation, producing a higher proportion of bioavailable methylmercury.

Spatial trends in mercury concentrations in land-locked Arctic char muscle.

Evidence of effects in peregrine falcons and grayling

In some birds of prey and in some fish, there is evidence of biological effects from mercury exposure. In American and Arctic peregrine falcons, mercury levels in eggs in one study in Alaska exceeded the critical threshold for reproductive effects in up to 30% of eggs, depending on year and sub-species. American peregrines, which are also exposed to high POP levels, have suffered from reduced productivity.

Experimental research with freshwater fish has shown that grayling embryos exposed to mercury may suffer reduced growth if the levels are high enough. Later in life, grayling exposed even to moderate concentrations of methylmercury are likely to be poorer at catching prey. This result suggests that mercury levels documented in the environment may lower the ecological fitness of grayling, with the potential to affect the population of grayling in Arctic waters. Similar results have been found for juvenile walleye pike exposed to low levels of methylmercury in the diet.

Ice fishing for Arctic char, Igloodik, Nunavut.



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Other factors affect mercury in freshwater biota. As discussed above, the presence of selenium may alter the effects of mercury within an organism, or lower the uptake of mercury. This effect could explain a lack of correlation between mercury levels in fish and in sediments in some lakes. Water chemistry, especially acidity, and food web structure also

Is it time for global action?

Temporal trends show a clear rise in mercury contamination since the beginning of the industrial age. Moreover, in some areas, particularly in North America and West Greenland for marine birds and mammals, mercury levels are still increasing. As discussed in the chapter *Human Health*, mercury exposure is a significant health risk for some Arctic people.

Documenting the circulation of mercury in the environment and its uptake into the food web will take more research, and it is vital to understand how these processes work. Although it may not be possible to counteract the toxicity of mercury directly, knowing which species or areas are most at risk will allow us to take other measures to protect them from additional stresses. It will also help identify species of concern for human consumption.

Despite the uncertainties, some things are clear. Humans contribute a significant portion of the mercury found in the Arctic. The levels now found in many Arctic animals are cause for concern, even if ecological complexity makes mercury's effects difficult to isolate. The problem of mercury will not diminish without global action. A first step in this direction is the UNEP study currently underway, as described earlier.

Lead – success for political action

Lead is a dense, soft metal with many uses. Lead is also toxic. Altered behavior resulting from lead affecting brain and nerve tissue is the most widely recognized effect of lead poisoning. Lead also interferes with many enzymes, most notably those associated with the production of hemoglobin and cytochromes. Other effects include kidney damage and dysfunction, anemia, intestinal dysfunction, and reproductive problems including abnormal growth and development.

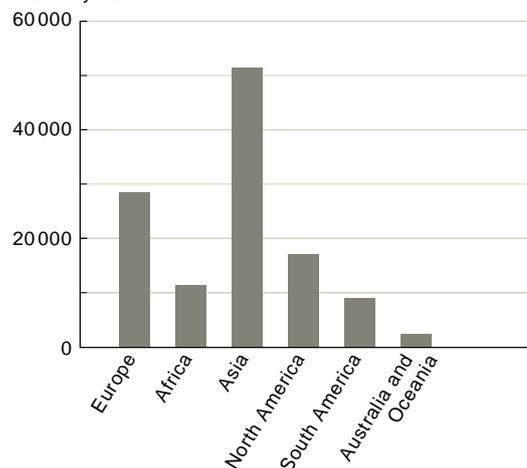
Found throughout the world, most lead in the environment does not enter the food web, but is adsorbed onto soil and sediment particles. Some lead, however, is taken up by plants and animals. It remains a concern in some areas of the Arctic, but bans on the use of lead, especially in gasoline, have greatly reduced emissions and thus global environmental levels.

Eurasia is the major source region

Europe and the Asian part of Russia contribute all but a few percent of the airborne lead reaching the Arctic. Models show that the main atmospheric pathways are across the North Atlantic, from Europe, and from Siberia. Even in the Canadian High Arctic, analysis confirms that Eurasia is the main source.

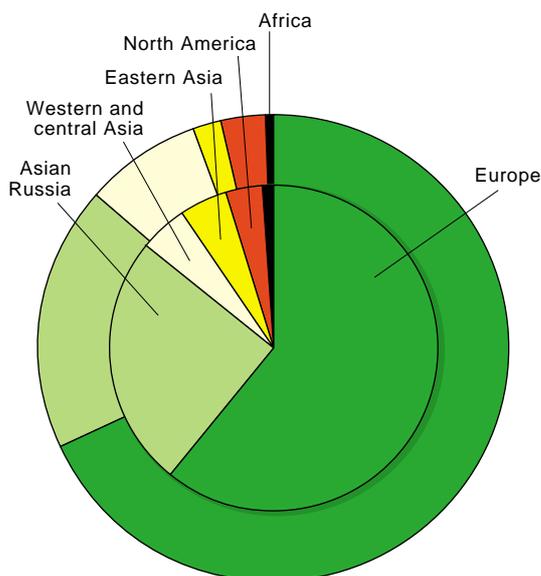
The transport of lead follows seasonal patterns. Lead levels in airborne particles are lowest in early fall, and at this time of the year lead reaching the Canadian Arctic comes mostly from natural sources in the Canadian Arctic Archipelago and West Greenland. In late fall and winter, airborne lead comes primarily from industrial sources in Europe. By late spring and into summer, lead from Asian industrial sources can be detected.

Anthropogenic lead emissions, tonnes/year



Eurasian rivers are also a significant source of lead delivered to coastal estuaries and the Arctic Ocean, comparable to the amount of lead delivered via atmospheric transport. Together, these rivers carry some 2450 tonnes of lead each year, most of it in the form of suspended particles.

Ocean currents may be more important in transporting lead to and within the Arctic than previously recognized. While atmospheric deposition is the initial pathway from anthropogenic sources to the environment, most of the lead found in the Arctic Ocean is likely transported by currents from the North Atlantic and the Laptev Sea. The circulation



Inner pie: MSC-E model – Total deposition: 3.5 ktonnes/year
Outer pie: DEHM model – Total deposition: 6.1 ktonnes/year

► Global anthropogenic emissions of lead to the air in 1995 from different continents.

► Different air transport models give different estimates for total lead deposition in the Arctic in 1990, but agree well on the source regions for the lead.

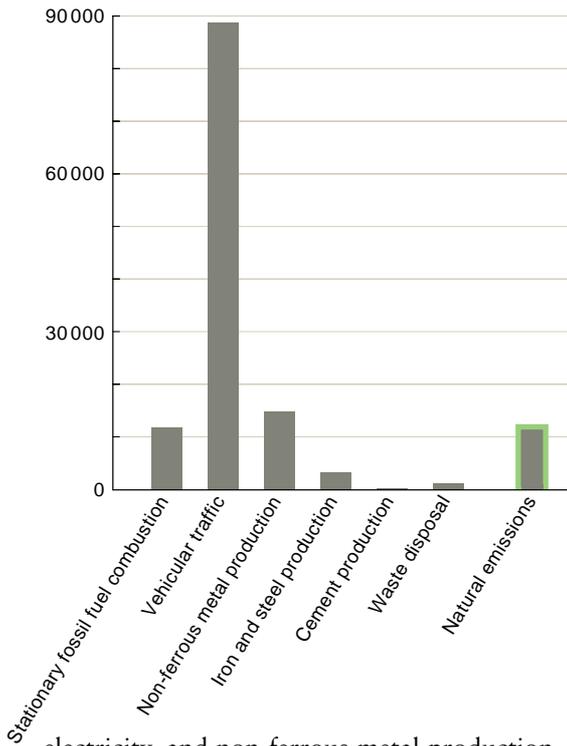
patterns of water and sea ice within the Arctic Ocean have resulted in most anthropogenic lead being deposited in sediments in the Eurasian Basin. Recent changes in Arctic Ocean circulation patterns suggest that this pattern of deposition may also have changed.

Leaded gasoline has been the most important source

Historically, leaded gasoline has been by far the most important source of lead to the Arctic. However, most countries in source regions to the Arctic have now stopped using leaded gasoline. This has greatly reduced emissions to the atmosphere. However, leaded gasoline is still used in a number of countries, including Russia, though its use is declining.

A summary of worldwide anthropogenic sources of heavy metals to the atmosphere showed that in 1995, vehicle traffic emitted nearly 90 000 tonnes of lead to the atmosphere, almost three-fourths of the total. Stationary burning of fossil fuels, to generate heat and

Worldwide lead emissions, tonnes/year



electricity, and non-ferrous metal production accounted for another 25 000 tonnes. Data on sources are likely to underestimate emissions from waste incineration, and so must be regarded as conservative. The total atmospheric emissions in 1995, however, were almost two thirds lower than emissions in 1983.

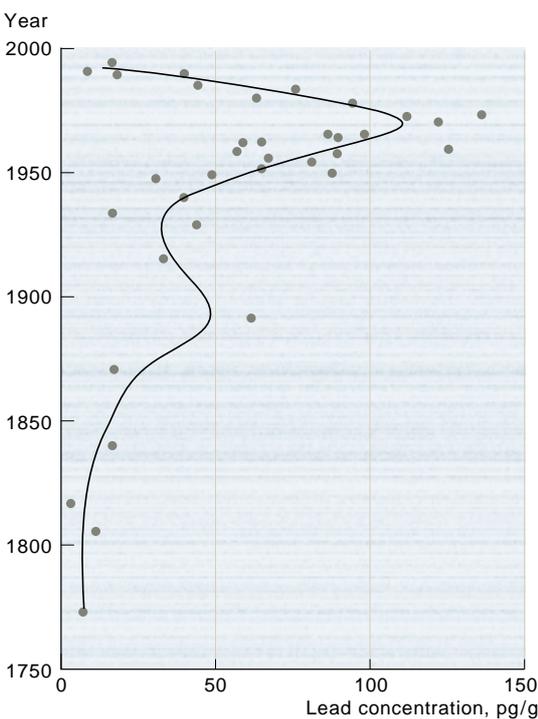
Lead is declining in the abiotic environment

Lead deposition patterns across the Arctic are in some ways similar to the patterns seen in mercury. In the Canadian High Arctic, in the



Yukon Territory, and in northern Alaska, recent lead levels in lake sediments are similar to those from pre-industrial times. West Greenland and Hudson Bay region lake sediments, on the other hand, show increasing lead concentrations beginning in the 18th and 19th centuries.

Ice core data from Greenland indicate that, along with most other heavy metals, lead levels increased significantly following the Industrial Revolution. By 1970, lead levels were twelve times what they had been less than two centuries earlier. Proto-industrial activities had been releasing lead before the industrial era, and the highest modern levels may be as many as 200 times higher than background levels. Between the early 1970s, when unleaded gasoline was introduced in North America, and the early 1990s, lead deposition on the Greenland Ice Sheet dropped by a factor of 6.5.



Unleaded gasoline is now available in much of the Arctic – here at Nuuk, Greenland.

Global emissions of lead to the air in 1995 from major anthropogenic sources are about ten times those from natural sources.

Lead concentrations in a Greenland ice core show increases during the industrial period, but decreases since the early 1970s when unleaded gasoline was introduced in North America.

Air samples taken at Alert on Ellesmere Island confirm decreases in lead over the past three decades. Mosses in northern Sweden show either stable or declining levels of lead. Forest mosses in Finland showed declines in lead levels from the late 1980s to the mid-1990s, corresponding to declines in bulk deposition. These declines are almost certainly a result of the reduced use of leaded gasoline.

Lake sediments in Sweden show declines in lead over the past two decades, but also reveal that low levels of lead from remote sources have long been deposited from the atmosphere.

... but levels in many biota are stable

In some areas, lead levels in biota have been stable in recent years. Lead levels in moose in the Yukon Territory showed no change from 1993 to 1998. In Swedish reindeer, lead declined significantly in liver, but remained unchanged in muscle from 1983 to 2000. Other trends in terrestrial animals are unclear, largely because monitoring studies have been of too short duration.

Levels in northern pike in Lake Storvindeln and Arctic char in Abiskojaure in northern Sweden show no significant trend in lead from 1968 to 1999 and 1981 to 1999, respectively. One possible explanation for the lack of decline is that this area has received relatively little lead pollution, and thus has not been affected by decreases in lead emissions.

▶ Even after closure, mines such as Nanisivik, shown here, can be a source for contaminants. Here tailings are experimentally capped with a thick layer of gravel so that they are fixed in the permafrost layer.

and Nanisivik Mines in the Canadian Arctic, and the now-closed Black Angel Mine in West Greenland. The high levels of lead in the rocks at these sites means that levels in nearby streams and lakes were already high before the mining began. But mining activities in many cases greatly increased releases to the surrounding waters.

Caribou near the Red Dog Mine in northwestern Alaska have elevated levels of lead in liver and feces, as might be expected in a min-



BO EILBERLING



BIOFOTO / SVEN HALLING

Reindeer are used to monitor temporal trends in metals in Sweden.

Walrus at Igloolik in Foxe Basin showed no evidence of increased lead in the industrial era, consistent with findings from lake sediments and mollusks elsewhere in the Canadian High Arctic. Levels in blue mussels sampled in Alaska and Norway have remained stable for the period 1986 to 1999 and 1992 to 1999, respectively.

Local lead levels connected to ores and mining

Some of the richest deposits of lead ore are found in the Arctic, for example at the Red Dog Mine in northwestern Alaska, the Polaris

eral-rich area. The observed levels, however, are not high enough to cause concern for toxic effects.

Industrial facilities such as the smelter complexes at Norilsk and on the Kola Peninsula also release considerable amounts of metals, including lead to their surrounding areas. The effects of this pollution are discussed later in the chapter.

Lead shot creates problems for birds

While lead from industry and vehicles has declined, local contamination from lead shot has started to receive attention. Although now banned in most Arctic countries, the use of lead shot for hunting waterfowl introduced large quantities of lead pellets into the environment. These pellets were, and are, eaten by birds, and the lead is taken up through the digestive system.

Steller's eiders in Alaska have levels of lead in their blood that are above avian toxicity thresholds for lead poisoning. These birds have suffered from reduced breeding success. Analyses of livers and kidneys from the eiders show that some levels are high enough to cause concern about toxic effects. The levels appear to increase over the summer, indicating local sources, such as the ingestion of lead shot found in tundra ponds. These findings, although preliminary, suggest that lead shot

may be a significant problem for breeding Steller's eiders in Alaska.

In an ongoing study in Greenland, there are no indications of a similar threat from lead shot to the common eider. White-tailed eagles, on the other hand, may be poisoned by lead because they feed on seabirds hunted with lead shot. In Greenland, lead shot in birds also appears to be the most important source for human dietary exposure.

Notes of caution and possible new threats

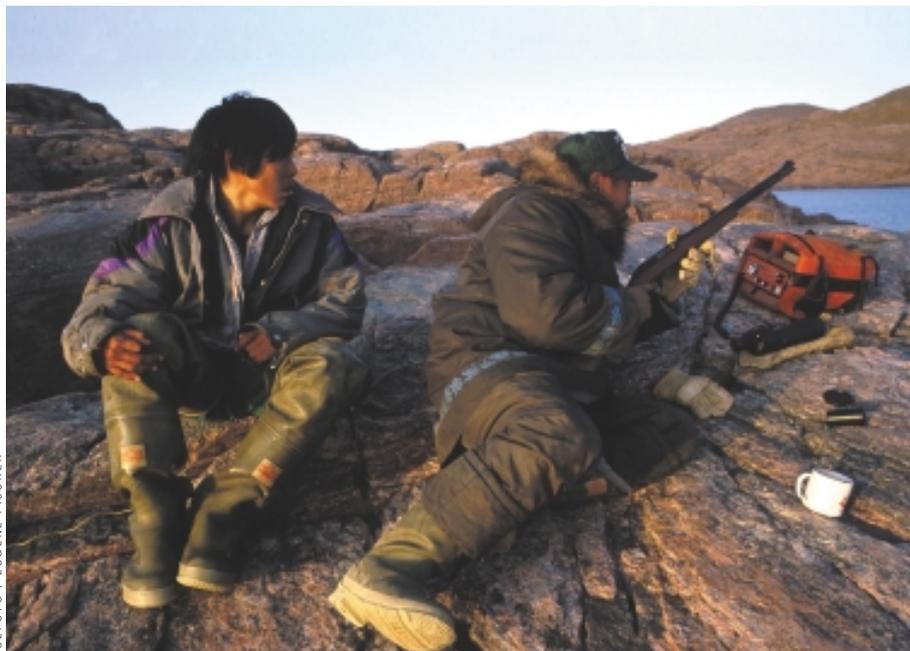
Globally, lead emissions have declined sharply following the introduction of unleaded gasoline. But not all sources of lead are well documented, and levels in some parts of the Arctic do not appear to follow the declining trend. Furthermore, local natural and man-made sources such as mines, mineral outcrops, and



STAFFAN WIDSTRAND

lead shot may have a significant impact on local plants and animals. In cases such as the Steller's eider, which is endangered in the United States, effects on an already limited breeding area may have a major impact on the population.

An additional note of caution is sounded by recent analyses of platinum, palladium, and rhodium in Greenland snow and ice. These metals are used in the catalytic converters placed in automobiles to reduce hydrocarbon emissions. Their levels in recent snow are low but still vastly higher than in ice from thousands of years ago, showing that human activity is responsible for almost all of the current deposition in the Arctic. Little is known about the toxicity and bioaccumulation potential of these elements. Further study is thus needed to determine the significance of these results, and to assess whether the benefits of decreased lead are to some extent offset by the introduction of these other metals.



POLFO / EUGENE FISCHER

Cadmium – still largely unknown

Like other metals, cadmium occurs naturally and is also released by human activity. It can be taken up directly from air and water, and accumulates in living organisms. Mushrooms can be particularly high in cadmium. It can reduce the growth and reproduction of invertebrates, and interfere with calcium metabolism in fishes. Mammals can tolerate low levels of cadmium exposure by binding the metal to a special protein that renders it harmless. In this form, the cadmium accumulates in the kidney and liver. Higher levels of exposure, however, lead to kidney damage, disturbed calcium and vitamin D metabolism, and bone loss. The body takes decades to remove cadmium from its tissues and organs.

Hunters, Nunavut – lead shot in the environment is a threat to wildlife and humans.

◀ Steller's eider. In Alaska this species has high lead levels, probably from ingesting lead shot.

Assorted mushrooms being dried for storage at a hunting camp. Preserving mushrooms by drying, pickling or canning is an important seasonal subsistence activity in many areas. In Chukotka, throughout the year, no holiday table is complete without mushrooms.



SVETA YAMIN

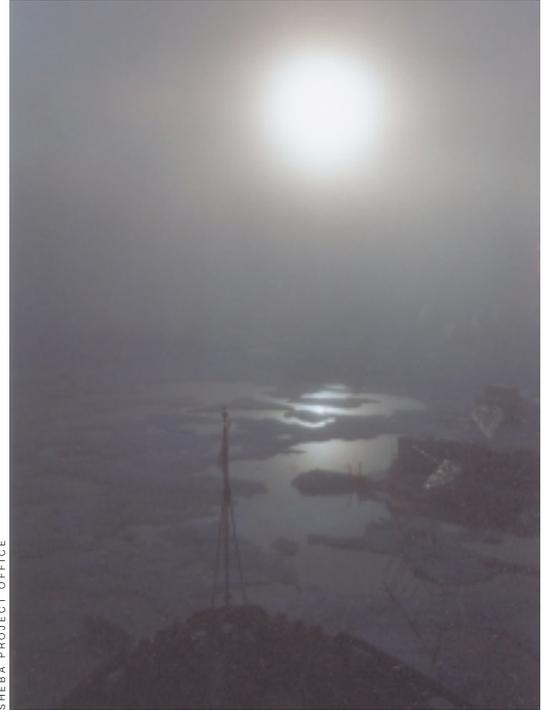
Cadmium is widespread with localized hot spots

Cadmium is found throughout the Arctic, but levels vary widely. Arctic char in northern Canada have ten times the cadmium of char in northern Sweden. Moose and caribou in the Yukon Territory have high levels, most likely due to local geology. Around Disko Island in West Greenland, locally high levels of cadmium have been found in blue mussels, shorthorn sculpin, and the livers of ringed seals. In spring, deposition of cadmium from the atmosphere can occur on particles which adhere to fog droplets and sea-salt aerosols. It is thus concentrated downwind from open leads and polynyas.

Broad geographic trends have been found for cadmium. In Scandinavia, moose in Sweden and a variety of mammals and birds in Norway show a declining cadmium trend south to north. The distribution patterns follow those of deposition and of accumulation in forest soils, indicating that long-range transport is the source of this contamination. In far northern areas, the observed levels are very close to background levels.

Levels of cadmium in ringed seals are highest in northeastern Canada and northwestern Greenland, lower at Barrow, Alaska, and lowest in Labrador. In Quebec and Labrador, there is some indication that cadmium in ringed seals increases to the north. Beluga

▶ Sundisk through fog over meltponds, 78°N. Airborne cadmium adheres to fog droplets and deposits downwind from open waters.

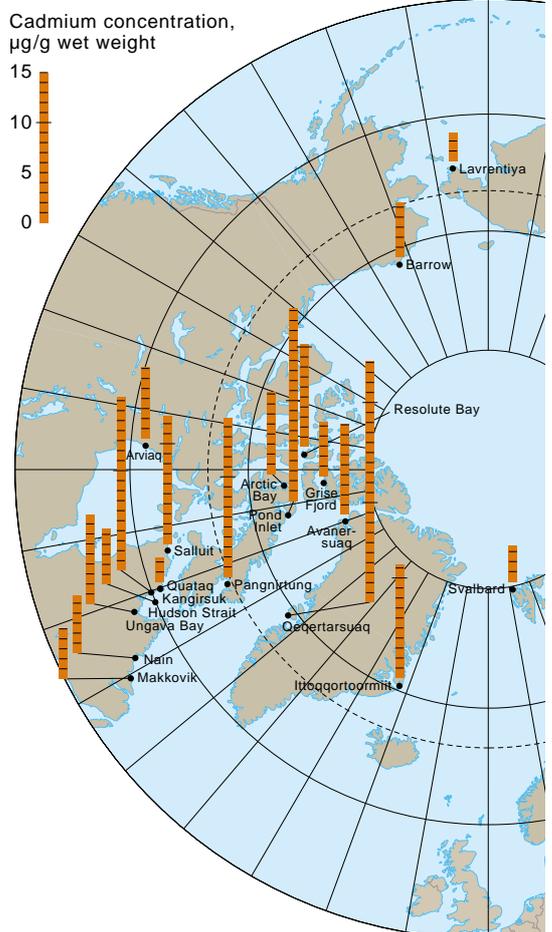
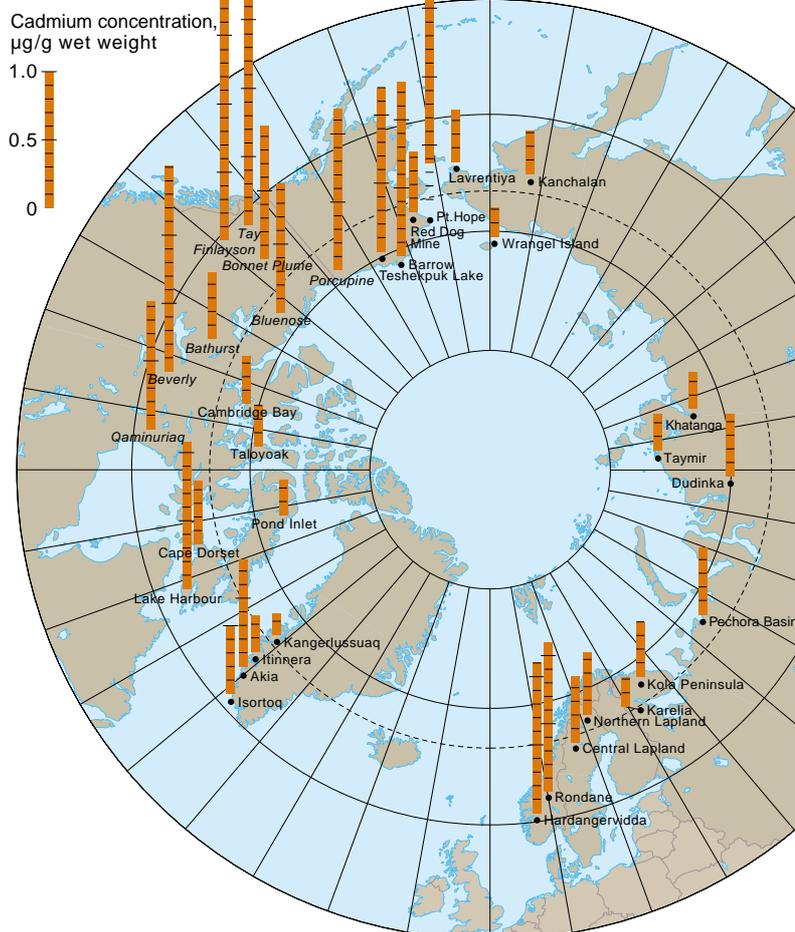


SHEBA PROJECT OFFICE

whales show an increase from west to east across Alaska and Canada. Narwhals appear to have lower levels in West Greenland than in the eastern Canadian Arctic, and females have higher levels than males. Levels in polar bear are highest in eastern Canada and northwestern Greenland.

Other regional patterns have been found, too. Walrus in Alaska have high levels of cad-

Spatial trends in cadmium concentrations in caribou/reindeer liver – italics indicate herds (left) and ringed seal liver (right).



mium, indicating local sources or particular food web pathways. In Faroe Islands gray seals, females have higher liver concentrations of cadmium than males and other seal species. The reason for this difference is not known.

Seabirds provide a circumpolar comparison. The highest levels are found in northeastern Canada and northwestern Greenland. Birds in northeastern Siberia have relatively high levels of cadmium, but may be exposed in wintering grounds in eastern Asia as well as in the Arctic. In the Barents Sea, cadmium concentrations in seabirds are in general lower than in Greenland, Canada, and northeastern Siberia. For fulmar and black guillemot, cadmium levels in the Faroe Islands are similar to those observed in Canada, Greenland, and the Barents Sea. Eiders in Alaska have levels comparable to Greenland, but higher than in Norway.

Mussels give a different picture. Cadmium in mussels is highest in Greenland, due probably to local geological sources. Alaska has the next highest levels – which may explain the high levels in Alaskan walrus – followed by Labrador and Norway. Mussels from Iceland and the Faroes have the lowest levels in the Arctic.

Human activities are a major source

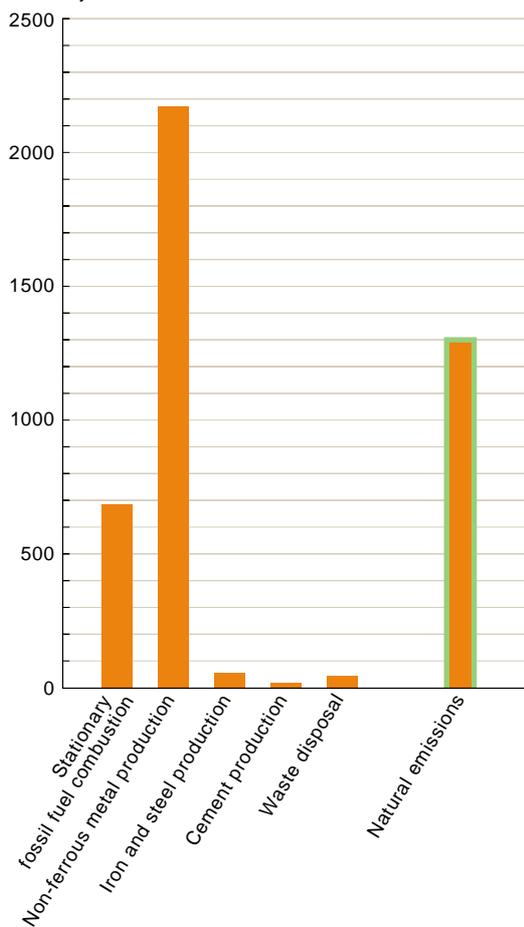
The processing of zinc ore is the major source of cadmium emissions to the atmosphere. Non-ferrous metal production accounts for nearly three-quarters of global anthropogenic cadmium emissions to the atmosphere. Burning of coal accounts for most of the remainder, with some contributions from other activities, such as iron production, cement production, and waste disposal.

Estimates of a total anthropogenic release of about 3000 tonnes in 1995 must be treated with caution. Emissions from waste incineration and the disposal of municipal waste such as sewage are largely underreported. Total releases may be substantially higher. According to one estimate, natural sources of cadmium account for only one-quarter to one-third of total atmospheric releases.

The global significance of human releases can be seen in the ice core records from the Greenland Ice Sheet. Cadmium deposition in the 1960s and 1970s was eight times higher than in pre-industrial times. Since the 1970s, however, deposition has declined steadily. Emissions from non-ferrous metal processing, in particular, declined by a factor of two or three between the 1980s and 1990s. This is chiefly the result of pollution-control improvements in major smelters in Europe and North America.

River transport of cadmium to the Arctic is comparable to the amount transported by the atmosphere. As with lead, most of the cadmium is in the form of suspended particles.

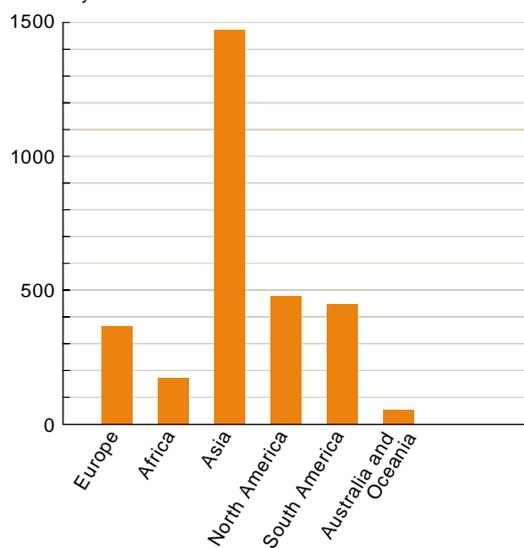
Worldwide cadmium emissions, tonnes/year



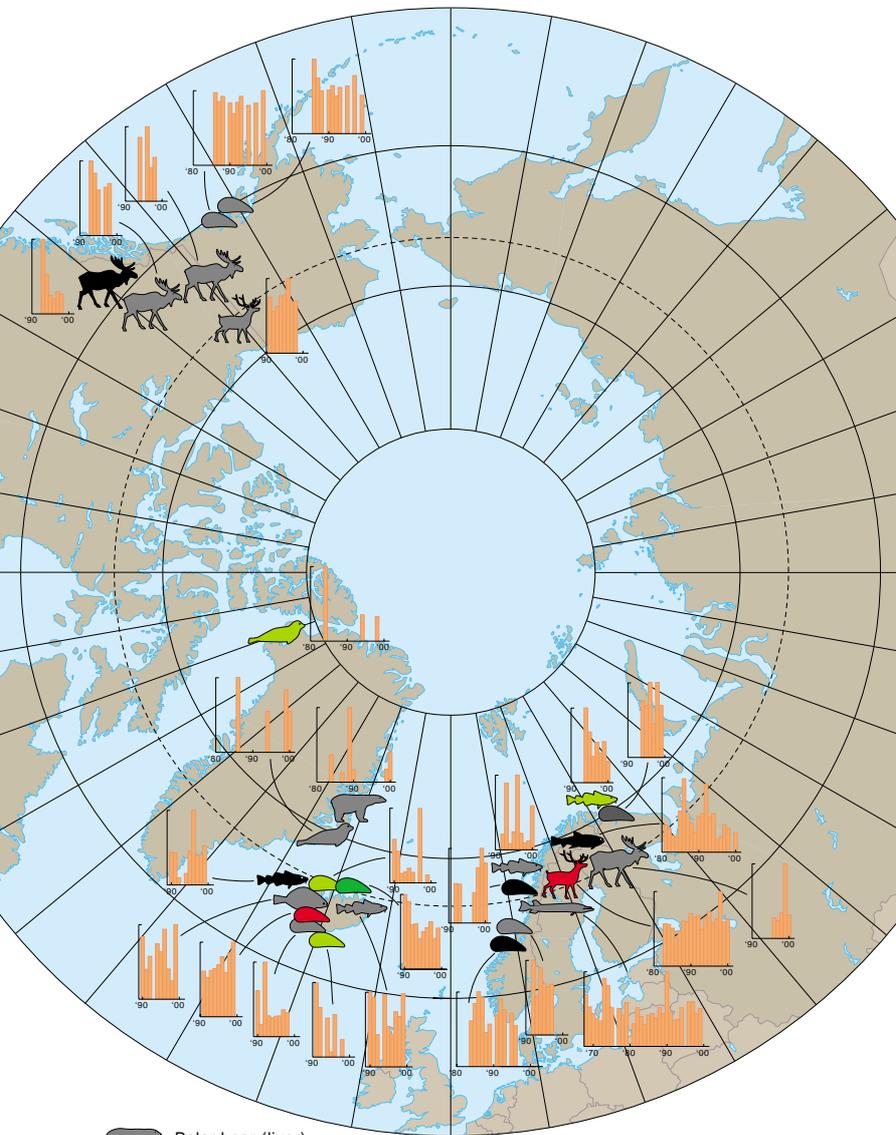
Global emissions of cadmium to the air in 1995 from major anthropogenic sources. Anthropogenic emissions are about two to three times those from natural sources.

In the ocean, natural cycling of cadmium is the most important process for moving the metal. Cadmium is removed from surface waters during primary production of plankton, and is subsequently returned to deeper waters where biotic material decays. This pattern correlates strongly with the ocean's phosphorus cycle. The Pacific Ocean, which supplies nutrient-rich water to the Arctic through the Bering Strait, therefore also supplies a substantial amount of cadmium to the upper layers of the Arctic Ocean. Although industrial activities may be locally important sources of

Anthropogenic cadmium emissions, tonnes/year



Global anthropogenic emissions of cadmium to the air in 1995 from different continents.



-  Polar bear (liver)
-  Ringed seal (liver)
-  Cod (muscle)
-  Dab (muscle)
-  Pike (muscle)
-  Arctic char (muscle)
-  Caribou (muscle)
-  Moose (muscle)
-  Blue mussel (soft body)

- Key to coloring of biota symbols**
-  Significant increasing trend
 -  Significant non-linear/fluctuating trend
 -  No trend
 -  Decreasing tendency
 -  Significant decreasing trend

Trends in cadmium levels have been measured over the past 10–30 years in various Arctic species. Selected time series are shown, with animal symbols colored to indicate the trend.

cadmium to the ocean, natural processes such as mixing of water masses, coastal upwelling, and primary production are far more important in determining the marine distribution of cadmium.

Recent cadmium time trends vary

As with mercury and lead, industrial age increases in cadmium are not found everywhere in the Arctic. Sediments from lakes in the Arctic coastal plain of Alaska and from YaYa Lake in the Yukon Territory show no differences between the pre-industrial age and today. Walrus from Igloodik in Foxe Basin and beluga from the Beaufort Sea, similarly, show no change in cadmium levels over the past few centuries, consistent with results from sediment and mollusks in the Canadian Arctic.

In recent years, trends across the Arctic vary. Mosses in northern Sweden show stable or declining levels of cadmium. By contrast, cadmium in liver of reindeer from northern Sweden increased significantly between 1983 and 2000, though it remained the same in muscle. Moose kidneys in the same region, however, showed no significant change in

cadmium levels from 1996 to 2000. The same is true for moose in the Yukon Territory from 1993 to 1998. Other studies of terrestrial animals have not gone on long enough to produce evidence of changes.

In northern pike from Lake Storvindeln and Arctic char from Abiskojaure in northern Sweden, cadmium levels remained the same from 1968 to 1999 and from 1981 to 1999, respectively.

Over the past two decades, no trends have been found in cadmium levels in the kidney and liver of beluga and narwhal in the Canadian Arctic. The same is true for mussels in Alaska, Greenland, Iceland, and Norway. Cadmium in livers of shorthorn sculpins in Uummannaq, Greenland may be declining, as measured from 1980–1993, but the trend was not significant. No change was found in cod and dab in Iceland. Similar consistency has been found in the muscle of long-finned pilot whales in the Faroe Islands, though there is some recent evidence of possible increases.

In ringed seals in Greenland, cadmium levels increased from the mid-1970s to the mid-1980s, then decreased by the mid-1990s, after which they have been stable. Changes in feeding have been suggested as the likely explanation. Cadmium may have increased in minke whales in the North Atlantic in recent years, but further monitoring is needed to confirm the trend.

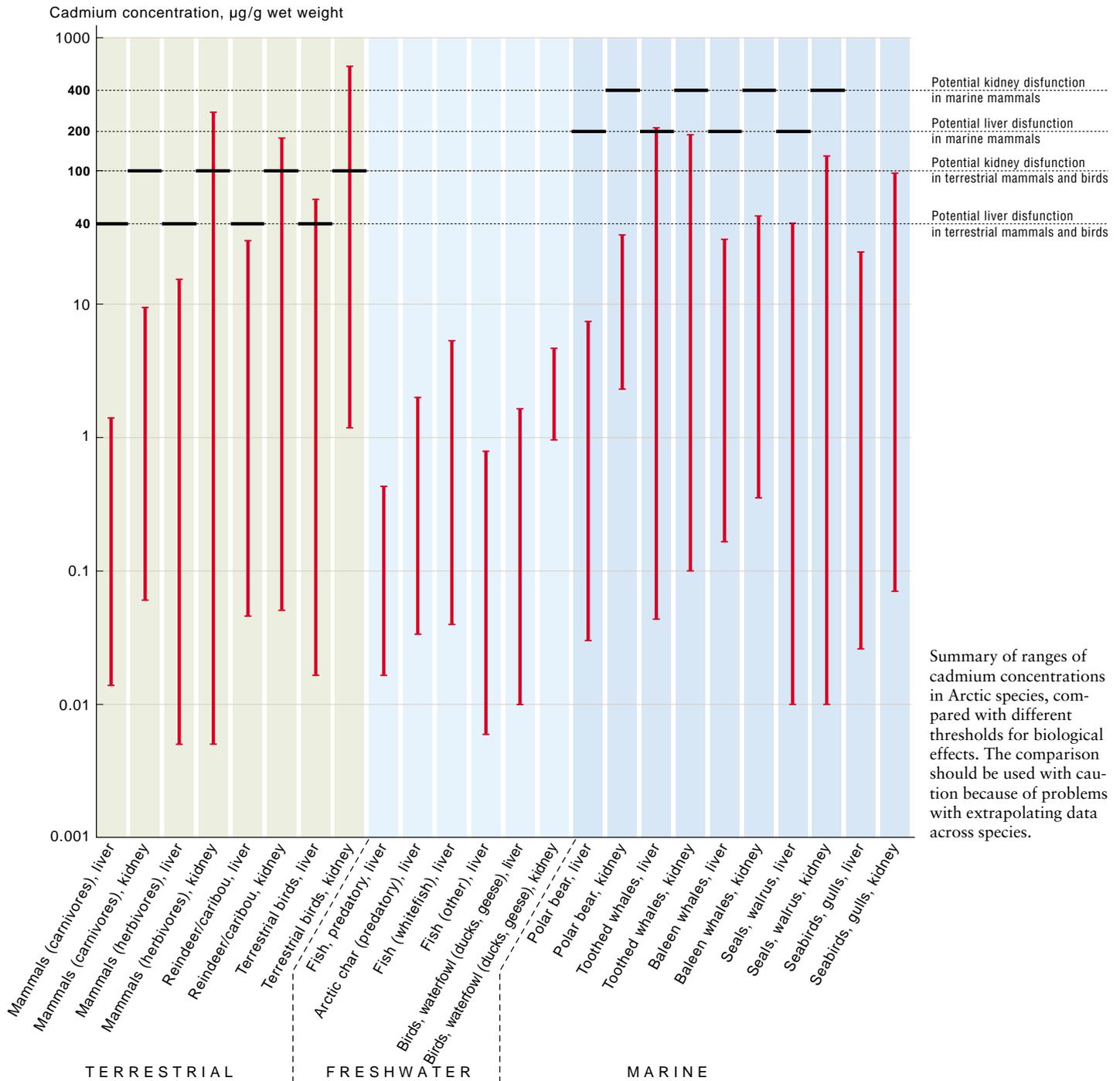
Cadmium accumulates in birds and mammals

In animals, cadmium concentrates in the internal organs rather than in muscle or fat. It is typically higher in kidney than in liver, and higher in liver than in muscle. Cadmium levels usually increase with age. Kidney levels of cadmium in caribou in northwestern Alaska, for example, showed a marked increase with age. This is potentially a concern for those who eat Arctic animals, particularly if they favor older adult animals.

Bowhead whales in Alaska have non-essential element levels comparable to those of most other baleen whales around the world. Cadmium concentrations in liver, however, appear higher, perhaps due to the large proportion of invertebrates in the bowhead diet.

Among birds, there are differences among species, likely reflecting diet and physiology. In the Barents Sea region, the highest concentrations of cadmium were found in fulmar, kittiwake, Arctic tern, and common eider. Common guillemot had the lowest levels.

In freshwater fish, in contrast to most species, cadmium may actually decrease with age, reflecting changes in predation as the fish grows. Young fish tend to eat invertebrates, which have high cadmium levels, whereas older fish often eat other fish, which have lower levels of cadmium.



Some levels indicate possible effects

Seabirds in general are known to accumulate high levels of cadmium. One difficulty in monitoring cadmium in birds, however, is that the metal does not accumulate in feathers or eggs. Cadmium levels thus cannot be determined accurately without killing the bird.

Based on effect thresholds in domesticated birds, observed levels in seabirds are in some cases high enough to cause concern for kidney damage. However, this does not necessarily indicate a problem as seabirds may have adapted to the higher levels of cadmium found in seawater and thus have higher thresholds for effects. Seabirds and marine mammals in Greenland have high levels of cadmium, but researchers have found no evi-

dence of effects in a study of selected ringed seal specimens with very high cadmium levels in their kidneys.

In the Yukon Territory, which has high levels of naturally occurring cadmium, levels in some caribou, moose, and ptarmigan are high enough to cause concern for kidney damage, though effects have not been documented.

One indication of cadmium exposure in an animal is the presence of metallothionein, a protein that has a physiological role in protecting an animal from the toxic effects of metals. This protein is also produced in response to some other metals, such as copper and zinc. In Norway, metallothionein levels were correlated with cadmium levels in ptarmigan, following exposure to naturally high levels of the metal. There is no evidence, how-

ever, that the cadmium concentrations were above levels that the birds could tolerate.

One laboratory study found that cadmium-contaminated sediments from the Mackenzie River Delta in Canada caused some effects on algae and phytoplankton. However, the levels at which the effects occur and their impacts on primary production and the ecosystem as a whole are not known.

In studies of lake trout exposed to different levels of cadmium, researchers found that cadmium affected foraging behavior, resulting in lower success at catching prey. Decreased thyroid function as a result of cadmium exposure has also been documented. Both responses indicate a low response threshold for cadmium-caused behavioral changes.

Other studies with rainbow trout indicated an ability of that species to acclimate to relatively high levels of cadmium. Arctic char are able to produce metallothionein, which sequesters cadmium.

Uncertainty remains

Although cadmium levels have been documented in a number of species, there is still a great deal that remains unknown about this metal. Anthropogenic emissions are a major source of atmospheric cadmium. The role of underlying geology, however, is not clear, particularly for freshwater and marine pathways. Geographic trends reflect patterns of air circulation and local deposits, but the relationship between these pathways and observed trends is not well understood.

There is also much to learn about what happens to cadmium once it enters the body and how sensitivity to cadmium may vary among species. Effects on individuals and populations have not been well studied. The overall importance of cadmium as a contaminant in the Arctic cannot yet be assessed with confidence.

▶ Smelters, here at Norilsk, are major sources of metal pollution within the Arctic.

Damaged forest around Monchegorsk.



PHOTO / PETER JANSSON



BRYAN & CHERRY ALEXANDER

Severe local pollution around smelters

The highest concentrations of heavy metals in the Arctic occur near the copper-nickel smelters at Nikel and Monchegorsk on the Kola Peninsula and at Norilsk in Siberia. Air pollution around the Kola Peninsula facilities is comparable with the most polluted regions of Europe and North America. Together, these sources contribute 10% of the world's copper emissions to the atmosphere, and 3% of the world's nickel emissions.

The effects of heavy metals around the smelters appear to be devastating, but are often difficult to separate from the effects of sulfur dioxide, which is also emitted in huge quantities and has devastating and documented impacts on vegetation. Nickel and copper are the main pollutants from the smelters, but cobalt and vanadium are among other metals emitted in large quantities.

Most heavy metals emitted from the smelters appear to stay within about 200 kilometers of the source. Five to ten percent, however, are estimated to be deposited across the High Arctic. To the north of Norilsk, elevated levels of heavy metals do not appear to extend more than 100 km from the smelter sites. However, the area affected by metals may be expanding. The accumulations of heavy metals are a significant problem, and their presence is likely to remain a barrier to recovery even if inputs from smelter emissions cease.



The accumulations are also a large potential source of metals to nearby surface water and groundwater.

Damage surrounds the smelters

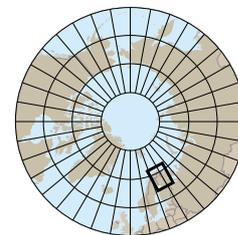
The damaged areas surrounding the smelters can be divided into three zones. Weather patterns and local topography determine the shape of each zone. First, the forest-death zone extends for up to 15-20 kilometers around Nickel and Monchegorsk, and up to 80 kilometers downwind at Norilsk. In this zone, vegetation is dead, vertebrates and invertebrates are almost entirely absent, soil microbial activity is minimal, and the organic layer of soil is often absent due to fire or erosion.

Beyond the forest-death zone lies the visible-damage zone, which extends up to about 50 kilometers at Nickel and Monchegorsk and up to about 200 kilometers at Norilsk. In this zone, trees suffer defoliation, reduced growth, death of needle tips, and other problems. Lichens growing on the trees are absent. Species composition and the chemical and microbiological properties of the soil have been altered. The cumulative effect of these impacts, on the trees and on the ecosystem, is not fully understood.

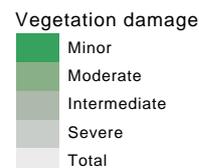
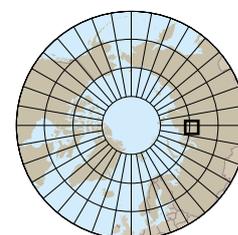
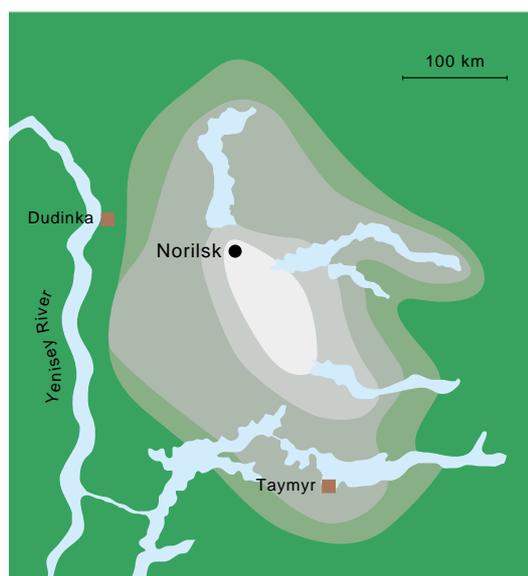
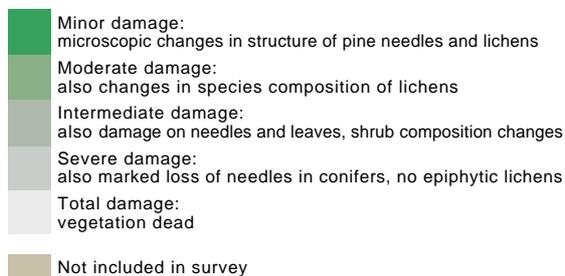
At Nickel and Monchegorsk, a non-visible damage zone extends up to about 150 kilometers. In this zone, the effects of emissions are primarily changes in the physiological functioning and microscopic structure of plant tissues.

Ecological impacts are extensive

One response of trees and shrubs to high concentrations of heavy metals in soils is to extend roots to deeper, less-contaminated levels of soil. The lower soil layers may offer fewer nutrients, however. Plants in areas of high heavy metal loads showed depleted levels of essential nutrients such as phosphorus,



Extent of vegetation damage on the Kola Peninsula due to the combined effects of metal and acidifying substances.



Extent of vegetation damage around Norilsk due to the combined effects of metal and acidifying substances.



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Conifer and peregrine falcon – two sensitive species.

magnesium, manganese, and zinc. Depletions of this kind are often an indicator of poor ecosystem health.

Conifers are the most sensitive trees to sulfur dioxide and heavy metal exposure. Deciduous trees, including the larch, can withstand higher levels, with birch and willows usually the last to disappear. Reproduction is affected by heavy metals, as is regenerative capacity. Older trees, with higher concentrations, may be unable to reproduce.

For birds and mammals, avoiding the damage zone is one clear response, made more likely by the lack of food in the forest-death zone. In the visible-damage zone, the animals may survive but their heavy metal levels will increase over time, possibly leading to toxic effects.

Summary

The Arctic may act as a global sink for atmospheric mercury. This recent discovery, related to mercury depletion events observed each spring, emphasizes the global nature of mercury pollution. Although mercury is a naturally occurring element, and as such will always be present in the environment, human activities worldwide have led to several-fold

increased levels in the Arctic environment compared with pre-industrial times.

In some areas, mercury levels in the environment continue to increase. It may already be affecting the reproduction of peregrine falcons, and impacts are suspected in fish, birds, and marine mammals. The chapter *Human Health* demonstrates that some Arctic people may ingest enough mercury in their diet to harm children's development.

Current mercury emissions have decreased in Europe and North America, but these declines have been offset by increases in East Asia. Further reductions in global emissions will require global action.

Lead provides an example of the effectiveness of reducing emissions. The introduction of unleaded gasoline has greatly reduced emissions in Europe and North America, and environmental levels are decreasing as well. In Arctic plants and animals, the trend is not as pronounced, reflecting continued uptake of previously deposited lead.

Local problems with lead still exist, particularly in areas where lead shot was or still is widely used for hunting. Lead pellets will continue to be eaten by birds as long as they remain in the environment. Effects of lead poisoning are apparent in some birds, such as the endangered Steller's eider in Alaska.

The implications of cadmium levels in the Arctic environment remain unclear. There are indications of levels high enough to threaten fish, birds, and mammals, but actual effects have not been documented. Increasing levels in some areas show the need for continued monitoring as well as further investigation of effects.

Platinum, palladium, and rhodium have recently been found in ice and snow samples from Greenland. They are used in catalytic converters in automobiles, which have become increasingly common. The levels of these metals are still low, but many times higher than they were a few decades ago. The environmental and human health effects of these metals are unknown.

Recent time trends for most metals, particularly in biota, are often uncertain and more work is needed to substantiate current findings and their underlying causes.

Around the large smelters in Russia, the damage from pollution is clear with forest death and effects on soil nutrient cycling. Elsewhere, the impacts of heavy metals are less obvious.

Much has been learned about heavy metals in the Arctic, though many gaps remain to be filled. Of particular concern are the rising emissions of mercury in Asia and the discovery of mercury depletion events in the Arctic. Recent increases in mercury levels in some Arctic animals indicate that the risk posed by mercury to Arctic ecosystems and people may be increasing.