Arctic Pollution 2011

Arctic Monitoring and Assessment Programme (AMAP)

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Contents

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Preface

The Arctic Monitoring and Assessment Programme (AMAP) is a Working Group of the Arctic Council. The Arctic Council Ministers have requested AMAP to:

- produce integrated assessment reports on the status and trends of the conditions of the Arctic ecosystems, including humans;
- identify possible causes for the changing conditions;
- detect emerging problems, their possible causes, and the potential risk to Arctic ecosystems including indigenous peoples and other Arctic residents; and to
- recommend actions required to reduce risks to Arctic ecosystems.

These assessments are delivered to Ministers at appropriate intervals in the form of 'State of the Arctic Environment Reports' on pollution and climate related issues.
These reports are intended to be readable and readily comprehensible, and do not contain extensive background data or references to the scientific literature. The complete scientific documentation, including sources for all figures reproduced in this report, is contained in a related report – AMAP Assessment 2011: Mercury in the Arctic – which is peer reviewed and fully referenced. For readers interested in the scientific background to the information presented in this report, we recommend that you refer to the AMAP Assessment 2011 report.

This report is the seventh 'State of the Arctic Environment Report' that has been prepared by AMAP in accordance with its mandate. It presents the results of work conducted during AMAP's fourth phase (2008-2011) in relation to the priority issue of mercury in the Arctic. The assessment described in this report builds upon the previous AMAP assessments of this issue that were presented in 1997 and 2002. It updates information presented in the previous assessment reports and addresses new issues that were not covered in the earlier assessments.

A large number of experts from the Arctic countries (Canada, Denmark/Greenland/Faroe Islands, Finland, Iceland, Norway, Russia, Sweden, and the United States), from indigenous peoples' organizations, from other organizations, and countries with an interest in Arctic monitoring, have participated in the preparation of this assessment.

AMAP would like to express its appreciation to all of these experts, who have contributed their time, effort, and data; especially those who continue to be involved in the further development and implementation of the AMAP Trends and Effects Monitoring Programme, and related research. A list of the main contributors is included in the acknowledgements on the previous page of this report. The list is based on identified individual contributors to the AMAP scientific assessment, and is not comprehensive. Specifically, it does not include the many national institutes, laboratories and organizations, and their staff, which have been involved in the various countries. Apologies, and no lesser thanks, are given to any individuals unintentionally omitted from the list. Special thanks are due to the lead authors responsible for the preparation of the scientific assessment that provides the basis for this report. Special thanks are also due to the author of this report, Kate Ravilious. The author worked in close cooperation with the scientific experts and the AMAP Secretariat to accomplish the difficult task of distilling the essential messages from a wealth of complex scientific information, and communicating this in an easily understandable way.

The support of the Arctic countries is vital to the success of AMAP. AMAP monitoring work is essentially based on ongoing activities within the Arctic countries, and the countries also provide the necessary support for most of the experts involved in the preparation of the assessments, including the participation of indigenous peoples' organizations in the work of AMAP. Canada and Denmark acted as the (co-)lead countries for this assessment. Furthermore, this assessment could not have been delivered without the additional financial support received from Canada, Denmark, Norway and Sweden; and from the Nordic Council of Ministers.

The AMAP Working Group, who are responsible for the delivery and content of the AMAP State of the Arctic Environment Reports, are pleased to present this State of the Arctic Environment Report, the seventh in the series, for the consideration by governments of the Arctic countries. This report is prepared in English, which constitutes the official version.

Oslo, May 2011

Russel Shearer
AMAP Chair

Lars-Otto Reiersen
AMAP Executive Secretary

Executive Summary and Key Recommendations

Previous AMAP assessments of mercury in the Arctic published in 1997 and 2002, reported that a substantial amount of the mercury in the Arctic arrives via long-range transport from human sources at lower latitudes and that, owing to their traditional diet some Arctic populations receive high dietary exposure to mercury, raising concern for human health. This situation prompted calls by the Arctic Council for global action to reduce mercury emissions.

The previous AMAP assessments also identified fundamental questions regarding what controls mercury levels in the Arctic, and how (and when) these levels are likely to fall in response to controls on emissions. The cycling of methylmercury (one of the most toxic forms of mercury) is paramount in this respect. The likely impact of future climate change in altering mercury delivery and fate in the Arctic is also extremely important. The effects of mercury on biota may be particularly relevant for species at the limits of their tolerance to other stressors. The overarching goal of this assessment was therefore to update information relevant to answering the question: *What controls mercury levels in the Arctic and what are the effects on Arctic biota?*

Mercury continues to present risks to Arctic wildlife and human populations. Despite many remaining gaps in knowledge, this assessment confirms the need for concerted international action if mercury levels in the Arctic (and in the rest of the world) are to be reduced. It is of particular concern that mercury levels are continuing to rise in some Arctic species in large areas of the Arctic, despite reductions in emissions from human activities over the past 30 years in some parts of the world.

The human health components of this assessment reflect information on mercury and human health that was presented in the 2009 AMAP Assessment of human health in the Arctic. Risk communication and dietary advice have been used to reduce human mercury exposure in some regions of the Arctic; however, solutions that are more effective over the longer term still need to be found. Reducing human and environmental exposure to mercury in the Arctic will ultimately depend on global action to reduce the quantities of mercury entering the 'environmental reservoirs', in which mercury has already been accumulating as a result of human activities for several hundred years. It is therefore important that the momentum for global action is maintained.

Policy-relevant science recommendations

On supporting international processes

- *A legally-binding global agreement to control mercury emissions must be established to complement national and regional efforts to reduce environmental mercury concentrations and to lower human exposures to mercury in the Arctic. The Arctic Council should continue to support the ongoing intergovernmental negotiations under UNEP to develop a comprehensive, legally-binding global instrument that will significantly reduce global mercury use and releases.*
- *Existing international agreements such as those under the UN ECE LRTAP Convention, should continue to receive the support of the Arctic Council to ensure that the best-available scientific information from Arctic studies is made available to these processes.*

On reducing human exposure in the Arctic

- *Health authorities should collaborate with communities to develop effective, culturally appropriate communication strategies concerning contaminants and human health. Any advice to Arctic residents should include both the benefits of traditional/local food consumption and the results of risk assessments concerning contaminants, including mercury.*
- *Health authorities should work with relevant food agencies to promote the availability and consumption of imported food items with high nutritional value and to promote consumption of traditional/local foods such as fish and terrestrial mammals that have lower levels of mercury and high nutrient value.*

On reducing emissions from human activities

- *Support efforts by those countries where mercury emissions are increasing or have been identified as major global sources, to adopt measures and technologies that can reduce their mercury emissions. The support could include the transfer and sharing of knowledge on pre-treatment of raw materials and mercury capture technology, which have already been successfully implemented in a number of countries.*
- *Reduce human-induced re-emissions (e.g., by avoiding intentional burning and forest clearance) to slow re-emission of mercury to the global environment.*
- *Take advantage of co-benefits of reducing mercury emissions and other contaminants, including greenhouse gas and soot emissions to reduce global warming and related impacts.*

Where does mercury in the Arctic environment come from, and how does it get there?

Mercury enters the global environment from natural sources (such as volcanoes and weathering of rock that is naturally enriched in mercury) and from human activities (that either extract mercury for intentional uses or release mercury that is present as a natural impurity in fuels and other raw materials used for industrial processes). Coal burning is the main source of human emissions. Once released, naturally emitted mercury is indistinguishable from mercury from human sources. Humans have been mining and using mercury for thousands of years, however emissions from human activities have increased dramatically during the past 150 years due to industrialization. The total amount released to the air each year from present-day human sources is estimated at about 2000 tonnes. A further 3000 to 4000 tonnes are released to the air either from natural sources, or as a result of re-emission of mercury that has previously been deposited to surfaces, back into the air. It is important to recognize that much of the re-emitted mercury was originally released by human activities. Climate warming is likely to promote re-emission.

Mercury is transported to the Arctic by air currents (within a matter of days) and ocean currents (that may take decades) and by rivers. The form in which mercury is released and processes that transform mercury between its various chemical forms are key in determining how mercury is transported to the Arctic and what happens to it when it gets there.

It has been estimated that about 100 tonnes of mercury are delivered to the Arctic Ocean from the air each year, with about the same amount in inflow from the Atlantic and Pacific Oceans, rivers and coastal erosion. Recent budget calculations suggest that Arctic Ocean seawater accumulates about 25 tonnes of mercury each year.

***In order to** improve validation of atmospheric modeling estimates, to constrain Arctic Ocean models and to improve Arctic mercury budgets, **it is recommended** to implement monitoring of mercury in air and mercury deposition at additional Arctic sites and to extend mercury measurements in the central basins of the Arctic Ocean.*

What is the fate of mercury entering the Arctic environment?

Mercury is mostly deposited from the air in inorganic forms. The pathways and chemical transformations of inorganic mercury in aquatic and terrestrial ecosystems are to a large extent influenced by organic carbon. Methylmercury is an organic form of mercury that bioaccumulates more readily than inorganic forms; it is also one of the most toxic forms of mercury. Sediments and wetlands in which oxygen levels are very low are the main sites of methylmercury formation in Arctic lakes and terrestrial environments. In the marine environment, methylmercury is formed in seabed sediments, and possibly by bacteria in the mid-water column of the Arctic Ocean.

The rate of methylmercury production (and destruction) in the physical environment, and its transfer within food webs, governs mercury accumulation in Arctic biota. Methylmercury biomagnifies through food chains and dietary intake is the main source of mercury exposure in top predators. Atmospheric mercury depletion events enhance deposition of mercury from the air to snow and ice surfaces, however it is now understood that a large fraction of this deposited mercury is re-emitted from the snowpack within a few days. The role of these events as a source of mercury to Arctic food webs remains unclear.

Less is known about mercury dynamics and pathways in the ocean than the atmosphere. There are virtually no time-series datasets with which to evaluate what is happening in ocean pathways, but budget calculations suggest that at present about 75 to 90 tonnes of mercury are exported from the Arctic Ocean in ocean outflow each year and that about 110 tonnes are deposited in Arctic Ocean shelf and deep ocean sediments.

How does climate change influence Arctic mercury?

Climate change (and its associated impacts on the environment) is already having discernable effects on some aspects of the transport pathways and behavior of mercury within the Arctic, and may further increase Arctic ecosystem and human exposure to mercury. The potential for future profound effects is large. For example, warmer and longer ice-free seasons could promote the production of methylmercury, one of the most toxic forms of mercury to biota. At the same time a loss of sea ice may reduce the mercury burden of the Arctic Ocean, by providing more water surface area for gaseous mercury to escape or by reducing release of bromine that is believed to promote atmospheric mercury deposition in the Arctic. Large quantities of mercury, accumulated during previous millennia and including recent emissions from human activities, are currently stored in permafrost, soils, sediments and glaciers. A portion of this mercury could be remobilized if these stores are disrupted by climate change.

Are mercury levels in Arctic biota increasing or decreasing, and why?

Studies suggest that there has been a ten-fold increase in mercury levels in upper trophic level marine animals (beluga, ringed seal, polar bear, birds of prey) over the past roughly 150 years. Over 90% of the present-day mercury in these animals, and possibly some Arctic human populations, is therefore believed to have originated from human sources. The average rate of increase in wildlife species over the past 150 years is 1% to 4% per year.

Most of the time-series datasets showing increasing trends in recent decades are for marine species, followed by predatory freshwater fish species. No significant recent increases were found for terrestrial animals. The fact that trends are increasing in some marine species in Canada and West Greenland despite reductions in North American emissions is a particular cause for concern, as these include species used for food. Increasing trends are less apparent in northern Europe, and trends are mostly downward in this area, possibly reflecting their closer proximity to areas where emissions are declining.

Several factors, including factors influenced by climate change, can affect mercury accumulation in biota, particularly in species at the tops of food chains. The extent to which mercury concentrations in Arctic animals are being affected by regional shifts in emissions of mercury, from source regions in Europe and North America to those in Asia, is currently not clear.

***In order to** monitor the impacts of climate change, human emissions and the effectiveness of mitigation strategies for mercury, **it is recommended** to continue monitoring of temporal trends of mercury in air, humans and wildlife, and extend coverage of such monitoring in particular in Alaska and the Russian Arctic.*

What are the toxicological effects of mercury in Arctic biota?

Arctic biota, especially higher trophic level predators are mainly exposed to mercury (mostly as methylmercury) through their diet. The presence or absence of other contaminants and nutrients (such as selenium) is believed to affect the toxicity of mercury and its impact in some Arctic species, including humans. For example, there is some evidence that selenium, if present in large enough quantities, can act as an antioxidant, providing wildlife and humans with some protection from methylmercury.

Some Arctic species, in particular marine top predators, exhibit levels of mercury in their tissues and organs that are believed to exceed thresholds for biological effects. In the past, these thresholds have been largely derived from laboratory studies on non-Arctic species, but in recent years knowledge arising from studies of Arctic species has increased.

Those species where thresholds are exceeded include a number of species of toothed whale, polar bears and some bird species. Polar bears and marine birds can excrete mercury through replacement of hair and feathers. Toothed whales appear to be one of the most vulnerable groups, with high concentrations of mercury recorded in brain tissue and associated signs of neurochemical effects. Evidence of increasing trends in mercury in some biota in Arctic Canada and Greenland is therefore a concern with respect to human and ecosystem health.

What are the likely changes in mercury concentration in the Arctic atmosphere and ocean under future emissions scenarios?

Global mercury emissions to air have been fairly constant since around 1990, but with emissions decreasing in Europe and North America and increasing in Asia. East Asia currently contributes about 50% of global mercury emissions to air from human sources. There are indications that, after decreasing from a peak in the 1970s, global emissions from human sources may be starting to increase again. If measures are not taken to reduce emissions, models suggest that global emissions could increase by 25% by 2020.

Models suggest that East Asia may now be responsible for much of the present-day mercury deposition in the Arctic. However, emissions scenarios project that if currently available emission reduction measures are implemented globally, then mercury deposition in the Arctic might be expected to decrease by as much as 20% by 2020 (relative to 2005 levels). There are no reliable global estimates of mercury released to the marine and freshwater environments.

Control technologies installed at industrial facilities remove mercury that would otherwise be emitted to air. There is little information about the ultimate fate of the mercury removed in this way and about how the mercury-containing wastes are subsequently disposed of. However, it can be assumed that these technologies will reduce the amount of mercury that is transported to the Arctic, by concentrating it, at least temporarily, in material that is disposed of in the source regions.

The atmosphere responds relatively quickly to changes in mercury emissions, but the large reservoirs of mercury in soils and ocean waters mean that there may be a long lag time (of the order of tens of decades) before changes in mercury inputs are reflected in the concentrations in these media, and thus in wildlife taking up mercury from them.

What is the impact of mercury contamination on human health in the Arctic?

Some Arctic human populations, especially some indigenous communities that consume large quantities of certain species of freshwater fish or marine mammal tissues for their traditional/local food, receive high dietary exposure to mercury. This raises concerns about human health effects, such as effects on brain development, and effects on the reproductive, immune and cardiovascular systems.

Exposure at current levels in the Arctic can have adverse impacts on human health, particularly for the developing fetus and children. Pregnant women, mothers and children are critical groups for monitoring and measures to reduce dietary exposure. There has been an overall decline in the proportion of Arctic people that exceed (U.S. and Canadian) blood mercury guidelines, but a significant proportion of people including women of child-bearing age from communities in the eastern Canadian Arctic and Greenland still exceed these guidelines. Dietary advice has been effective in reducing mercury exposure in some critical groups, but such advice needs to be carefully formulated to balance risks and benefits of traditional/local food consumption. The general dietary transition from traditional/local to more 'western' diets is also reducing mercury exposure, but at the same time is raising risks of other conditions or diseases associated with a western diet and lifestyle (such as obesity, diabetes, and heart disease). Since traditional/local foods low in mercury are not always available to Arctic indigenous people, the achievement of declining mercury levels in the environment is imperative to allow for the safe promotion of traditional/local food consumption.

Gaps in knowledge remain

The scientific background document to this assessment details recommendations to address this issue. Some of the main areas identified include:

- Further improving understanding of atmospheric mercury depletion events, with a particular focus on understanding how much of the deposited mercury is readily available to biota.
- Investigating further the fate of mercury entering marine systems.
- Ascertaining how methylmercury enters Arctic food webs and better understanding the Arctic marine methylmercury cycle.
- Developing a more detailed understanding of the impact of climate change on mercury.
- Undertaking further wildlife studies to measure mercury levels in different tissues and organs to assess mercury-induced health effects.
- Exploring the effects of multiple stressors (both chemical and environmental) and nutritional factors on the toxicity of mercury in biota.
- Addressing key knowledge gaps to reduce uncertainty in mercury models.
- Gathering more accurate information on worldwide economic and social variables, to improve future emissions scenarios.
- Studying the health impacts of mercury in human populations and determinants of food choice and availability.

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▶Mercury has been used by humans for thousands of years. Contamination of the environment is not new. In 1724, the *Conde de Tolosa* left Cadiz, Spain with a cargo of 150 tonnes of mercury destined for use in silver and gold mines of the Spanish Empire in Mexico. Caught in a hurricane, the vessel sank near Samaná Bay, Dominican Republic.

Introduction

Mercury is a naturally occurring element found throughout the global environment. In pre-industrial times, the natural release of mercury was roughly in balance with the natural processes leading to its removal. Over time, and particularly since the Industrial Revolution, however, human activities have mobilized vast quantities of mercury from the Earth's crust and redistributed this throughout the surface soils, air, snow/ice, lakes, rivers, and oceans. The much greater quantities of mercury now circulating within the global environment have significantly increased the exposure of biological systems to mercury, which has in turn increased the risk to ecological and human health.

Although the Arctic is a remote region far from the major sources of mercury release, concentrations within the Arctic environment can still reach levels of concern, particularly in the animals at the top of the Arctic's aquatic food webs. This is an issue for Arctic indigenous peoples that rely on subsistence hunting and fishing for their nutritional, social and cultural well-being. Their traditional diet, which is based on marine mammals and some species of seabird and freshwater fish, can expose these Arctic residents to high levels of mercury. Although dietary changes following information programs are helping to reduce mercury exposure in some high-risk Arctic residents, this is only a short-term solution. The longer-term solution is to reduce mercury concentrations in the environment and in species of importance to the traditional diet.

Reducing mercury concentrations in the environment is not simple. The way in which mercury moves through the environment is complex. Many of the environmental reservoirs in which mercury is temporarily stored (soils, ice, ocean water) are slow to load and slow to unload their mercury, leading to a considerable lag time between changes in emissions and levels recorded in the environment and biota. For example, it cannot simply be expected that halving emissions will result in an instantaneous halving of mercury concentrations in Arctic biota. Many of the processes driving the global mercury cycle are also likely to be significantly affected by the impacts of climate change; especially as Arctic ice and snow cover reduce and permafrost thaws.

The purpose of this third AMAP assessment of mercury in the Arctic has been to update the findings reported in 1997[1] and 2002[2] and increase understanding of the sources, pathways, processes and effects of mercury in the Arctic, including the uptake and accumulation of mercury within the Arctic food web and the associated ecological and human health risks. The report also examines the potential for climate change to significantly alter mercury pathways and fate in the Arctic. A better understanding of the factors controlling mercury levels in the Arctic environment, and a better understanding of the effects of this mercury on the Arctic biota and the potential impacts of climate change, will lead to improved policies on mercury emissions that should eventually lead to a decrease in mercury levels observed in the Arctic.

1 AMAP, 1997. Arctic Pollution Issues: A State of the Arctic Environment Report. Arctic Monitoring and Assessment Programme (AMAP). xii+188 pp.

2 AMAP, 2002. Arctic Pollution 2002: Persistent Organic Pollutants, Heavy Metals, Radioactivity, Human Health, Changing Pathways. Arctic Monitoring and Assessment Programme (AMAP). xii+112 pp.

Why is mercury a concern in the Arctic?

The quantities of mercury released from human activities have been increasing over the past 150 years (since the Industrial Revolution) and this mercury has now been distributed all over the world. Even regions that are remote from most anthropogenic sources, such as the Arctic, have accumulated high levels of mercury. This mercury exists in the environment in various chemical forms, and some of these can be toxic even in very small quantities. Globally, soils and ocean waters are the main 'environmental reservoirs' for mercury, in which mercury cycles through the system until it is finally removed by burial in deep sediments or soil layers.

Increased levels of mercury in the Arctic environment are of particular ecological concern because of mercury's known ability to **bioaccumulate** and **biomagnify** in food webs. Living organisms readily take up mercury from their surrounding environment (either directly from the surrounding air or water or by eating food containing mercury), with levels generally increasing with each step up the food chain. The high mercury levels resulting in some tissues of upper food chain species, especially those feeding in aquatic systems such as polar bear, toothed whales, seals and some predatory fish, may have serious health consequences for those Arctic indigenous peoples that rely on subsistence hunting and fishing and who consume significant amounts of these species.

Bioaccumulation refers to the increase in concentration of a substance (including contaminants) in the body of an animal over time. Contaminants that bioaccumulate tend to remain in a form that cannot easily be eliminated.

Biomagnification refers to processes whereby the tissue concentrations of a contaminant increase at successive levels in a food chain, generally through a series of predator-prey relationships.

Mercury – a well-known poison

In animals and humans, elevated levels of mercury have the potential to cause adverse effects on the reproductive, immune, cardiovascular and neurological systems. In the industrialized world, workplace exposure to mercury was common in the 19th century and many people died early as a result of the poisoning they received. More recently, accidental mercury poisoning events such as that at Minamata in Japan (where a toxic form of mercury released in industrial wastewater accumulated in fish and shellfish that were subsequently eaten by the local population) have increased awareness of mercury as an environmental toxin. Despite this, people around the world continue to be poisoned by mercury. This often includes people living at the margins of society, such as some artisanal gold miners (who use mercury to extract the gold from the ore).

The 'Arctic Dilemma'

Owing to their traditional lifestyle and dependence on foods obtained by hunting and fishing, indigenous peoples are especially vulnerable to mercury present in the Arctic environment. Commonly consumed traditional/local foods, such as those derived from marine mammals and some fish species, can contain high levels of mercury. At the same time these foods are rich sources of essential nutrients and vitamins. The need to balance the risks associated with consuming these mercury-contaminated foods with the many associated benefits they confer has led to what


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▲ ▶The Arctic Dilemma: The change from traditional diets to greater reliance on imported store-bought food may reduce mercury intake, but it also has negative impacts on health.


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has been termed the 'Arctic Dilemma'. To reduce their mercury exposure indigenous people would have to replace many traditional/local foods with imported foods or restrict their consumption of traditional/local food items to those with low mercury levels. Due to a complex mixture of socio-economic and environmental factors, a switch to imported foods is already being observed as part of a general trend in indigenous communities; but because the healthy food choices in local stores are quite expensive, if available at all, it is often the more affordable but less nutritious processed foods that are chosen. Combined with a more sedentary lifestyle (i.e., one that is no longer focused on hunting and fishing), this new diet increases the risks of developing obesity-related diseases, such as diabetes and coronary heart disease. Foregoing traditional/local foods also has negative consequences for the social and cultural well-being of communities, since for many indigenous peoples participation in the harvesting and sharing of traditional/local foods is an important part of their cultural and spiritual identity.

Where does the mercury come from?

Mercury exists naturally in the Earth's crust, most commonly as the mineral cinnabar (mercury sulfide). Volcanic and geothermal activities, along with the natural weathering of rocks, release this mercury into the environment where it is then cycled through the various components of the system. The total quantity of mercury emitted to the air each year through natural processes is roughly the same as the amount emitted to the air from present-day human activities (at around 2000 tonnes for each). However, the situation is complicated by the continual re-emission into air and re-deposition of historical mercury, of both natural and human origin, that had previously been emitted and deposited onto the land and sea.

In terms of emissions to air from human activities, coal burning is by far the largest source; emitting just under half of the total global emissions in 2005. Mercury is present in coal as a natural impurity that is released to the air when the coal is burned. It is also present in the ores used to produce ferrous and non-ferrous metals and so the metal production and smelting industries are another major source of mercury to the air. These emissions can be reduced by pre-treating the coal and metal ores to remove

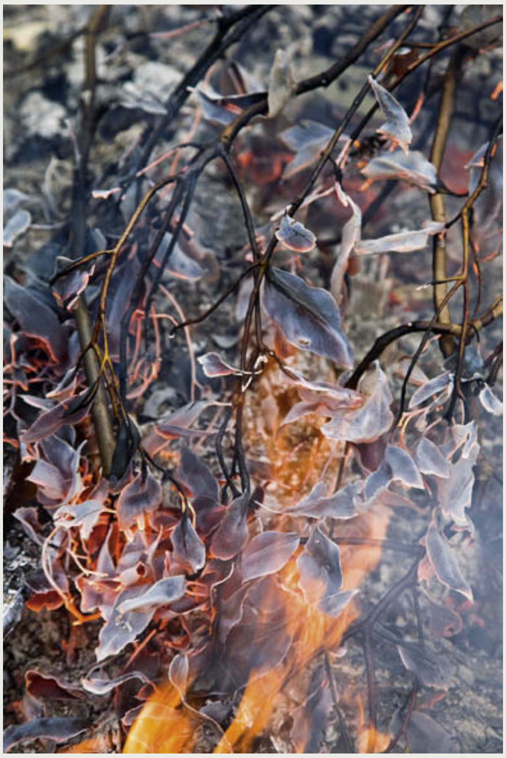
Mercury re-emission

In pre-industrial times, natural mercury emissions and mercury re-emitted from environmental reservoirs such as soil, vegetation and ocean surfaces were together roughly in balance with the permanent burial of mercury in deep sediments or soil layers. The present-day increase in emissions due to human activities, however, has upset this balance and the system is no longer in equilibrium.

It is difficult to establish the amount of mercury in air that is due to re-emission. Most estimates are derived from models that attempt to reproduce the measured mercury concentrations in different environmental compartments (water, soil, etc.), taking into account the estimated quantities of mercury in each compartment and the physical and chemical processes that move mercury between them, as well as estimates of mercury inputs from human activities.

Despite a significant proportion of the re-emitted mercury in air having originated from human activities, estimates of re-emissions are typically included under natural emissions.

Wildfires, for example, are sources of largely re-emitted mercury. Although accidental wildfires are hard to avoid and may increase due to climate change, intentional burning and forest clearance are not. Reducing the global extent of human influenced re-emissions would slow this re-cycling of mercury through the environment.



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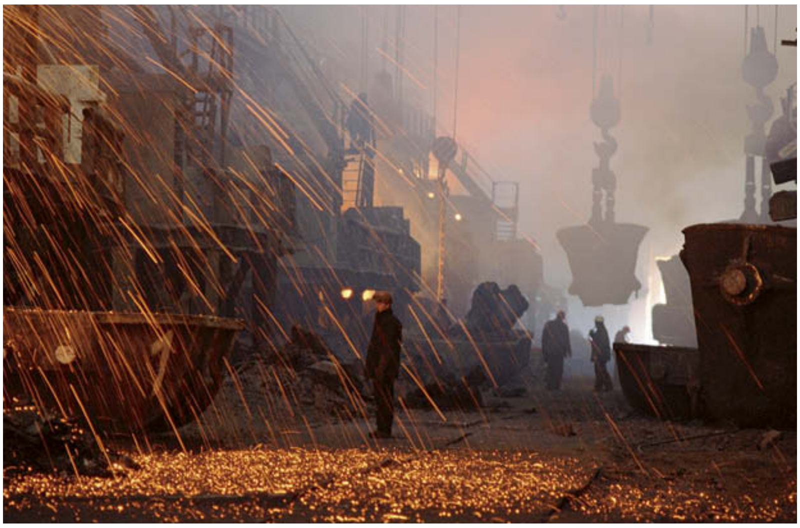

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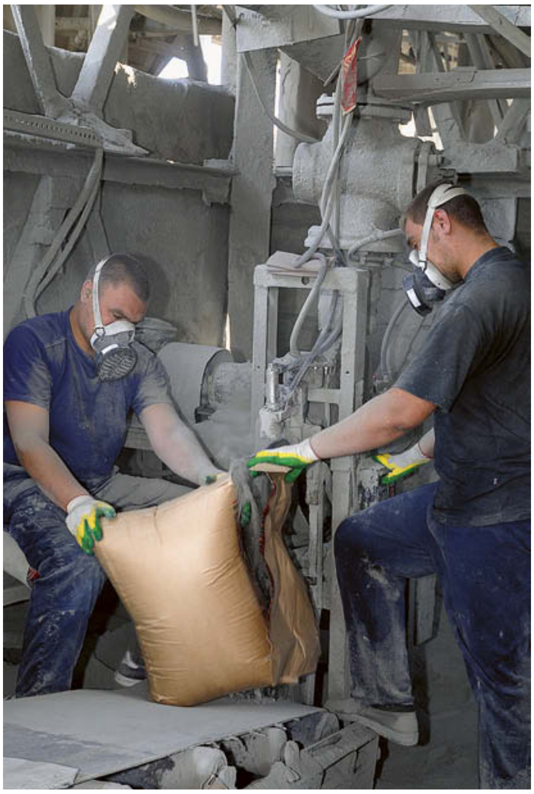

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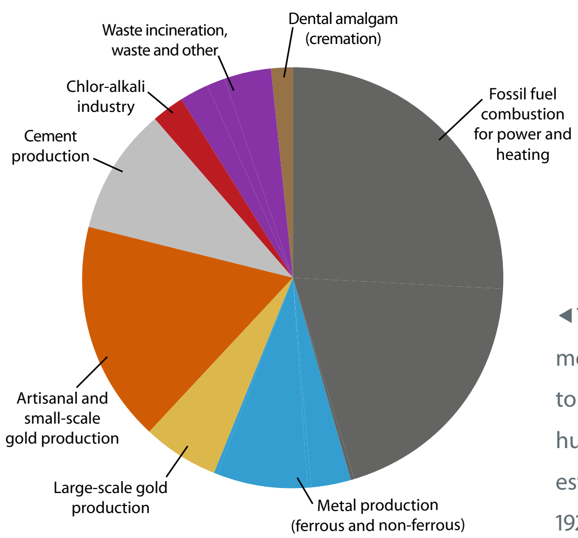
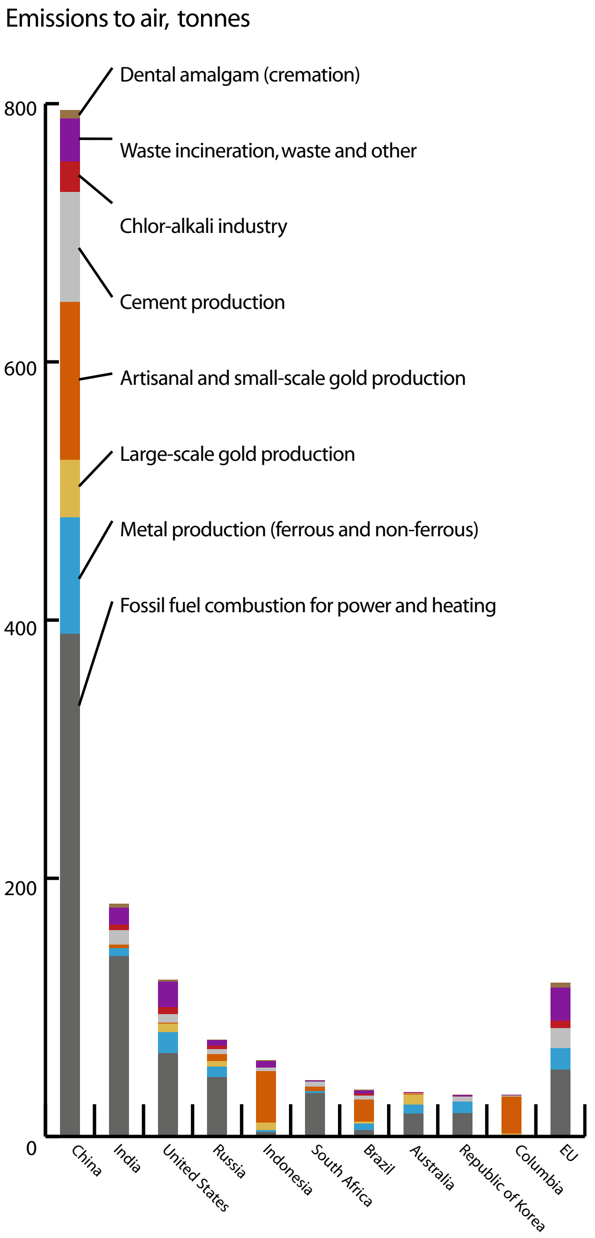
◄▲ Coal burning is the largest human source of mercury emissions to air. Other sources include (clockwise from top right) non-ferrous metal production, cement manufacture, intentional use in consumer products such as lamps, and artisanal and small-scale gold production.

mercury before they are used or by 'capturing' the mercury at the end of the process before it is released. Various types of control technology (see box on page 7) installed at large power plants to reduce dust and sulfur dioxide emissions are effective at capturing mercury. However, new technologies are currently being developed and introduced that specifically target mercury emissions. Other human sources include cement production, gold production, waste incineration, and, in some countries, human cremation (from the use of mercury in dental fillings).



◄Total global mercury emissions to air in 2005 from human activities are estimated at about 1920 tonnes.

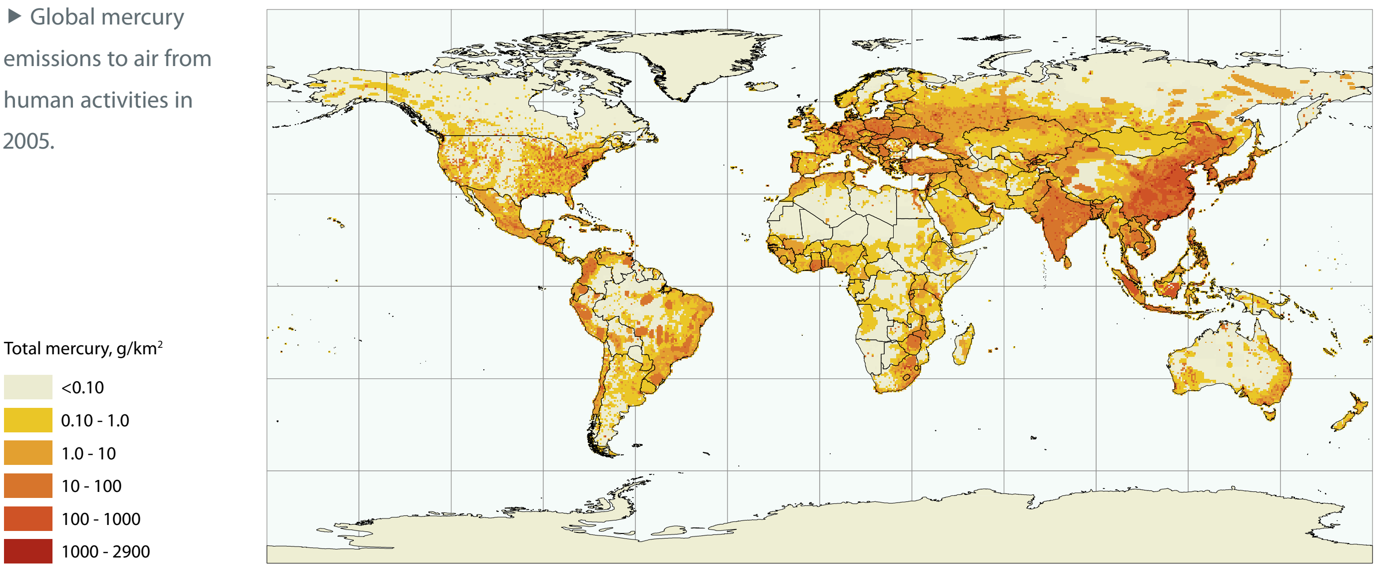


▶ In 2005, estimated mercury emissions to air from human activities were at least four times greater from China than from any other country.

Asia is currently the largest global source of mercury emissions from human activities; responsible for an estimated 65% of emissions in 2005. China, with its rapidly expanding economy, is responsible for a large proportion of these emissions. The second biggest global emitter of mercury is India, followed by the United States and Russia. Fossil fuel combustion for power and heating is the main source of emissions in all four countries.

Most of the human-derived mercury found in the Arctic today is thought to have originated from sources outside the region. This has been shown using air transport models including 'back trajectory' models – models which use past meteorological data to work backwards in time to estimate the most likely path taken by mercury-containing air masses arriving in the Arctic. Such models consistently indicate that most of the mercury carried into the Arctic today is coming from sources in the Northern Hemisphere, particularly those in East Asia. Previously, North America and Eurasia were the dominant sources of mercury transported to the Arctic.

▶ Global mercury emissions to air from human activities in 2005.



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Capturing mercury

Mercury emissions from industrial processes can be reduced in three main ways: by selecting raw materials with low mercury contents or pre-treating the raw materials, by capturing and cleaning the emissions at source, and by removing the mercury from waste products. Often the treatments used have the added benefit of also reducing other pollutants. Some of the commonly used treatments are outlined below.

- For coal-based power generation, pre-treatment of coal via coal washing can partially reduce mercury emissions. Other pre-treatments include the introduction of additives such as bromine salts which increase the efficiency of mercury removal in control equipment for other gases and particles.
- Capturing mercury from power station flue (stack) gases can also be achieved using technologies developed for other air pollutants. Electrostatic precipitators and fabric filters are commonly used for particle removal and can also capture some of the mercury (depending on, for example, the properties of the coal and use of additives). Combined with wet scrubbers, the capture efficiency of electrostatic precipitators and fabric filters generally increases. If in addition to the above, selective catalytic reduction for NO_X (nitrogen oxides) removal is installed, the removal efficiency for mercury can be further increased.
- Measures specifically designed to remove mercury, such as chemically treated activated carbon injection in combination with particle removal, can achieve significant mercury emission reductions (more than 90%).
- For metal production, the most effective way of reducing mercury emissions is to use ores or scrap metal with low mercury contents. Emission controls similar to those used at coal-fired power plants as well as mercury removal techniques specifically designed for metal production can also be used to remove mercury from flue gases.
- The best way to reduce mercury emissions from cement production is to use raw materials (limestone and coal) that are low in mercury, although technical emission control options are also available.
- Mercury emissions from waste and process by-products can be reduced by introducing stricter regulations on the separation, cleaning and storage of waste products (such as ash).

There is little information about the ultimate fate of mercury captured through the various types of control technology and about how the mercury-containing wastes are subsequently disposed of. However, it can be assumed that these technologies will reduce the amount of mercury that is transported to the Arctic, by concentrating it, at least temporarily, in material that is disposed of in the source regions.

▶ Reducing mercury emissions to air by capturing ash and particulates from power plant stack gases requires the disposal of potentially hazardous waste.

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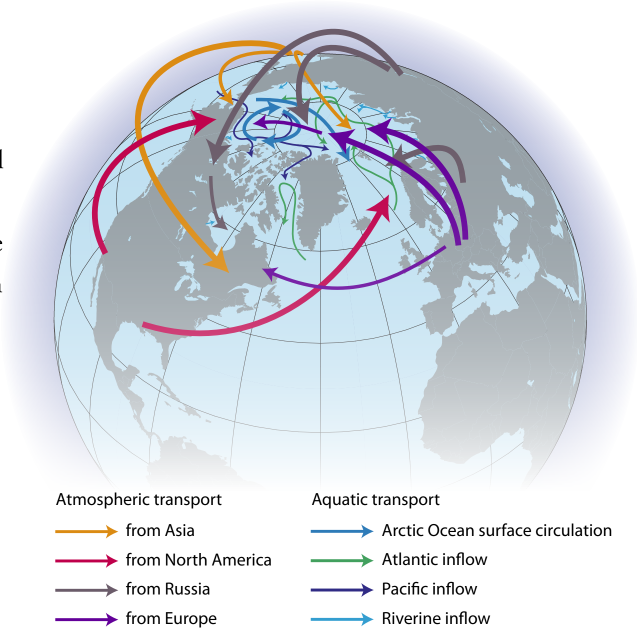
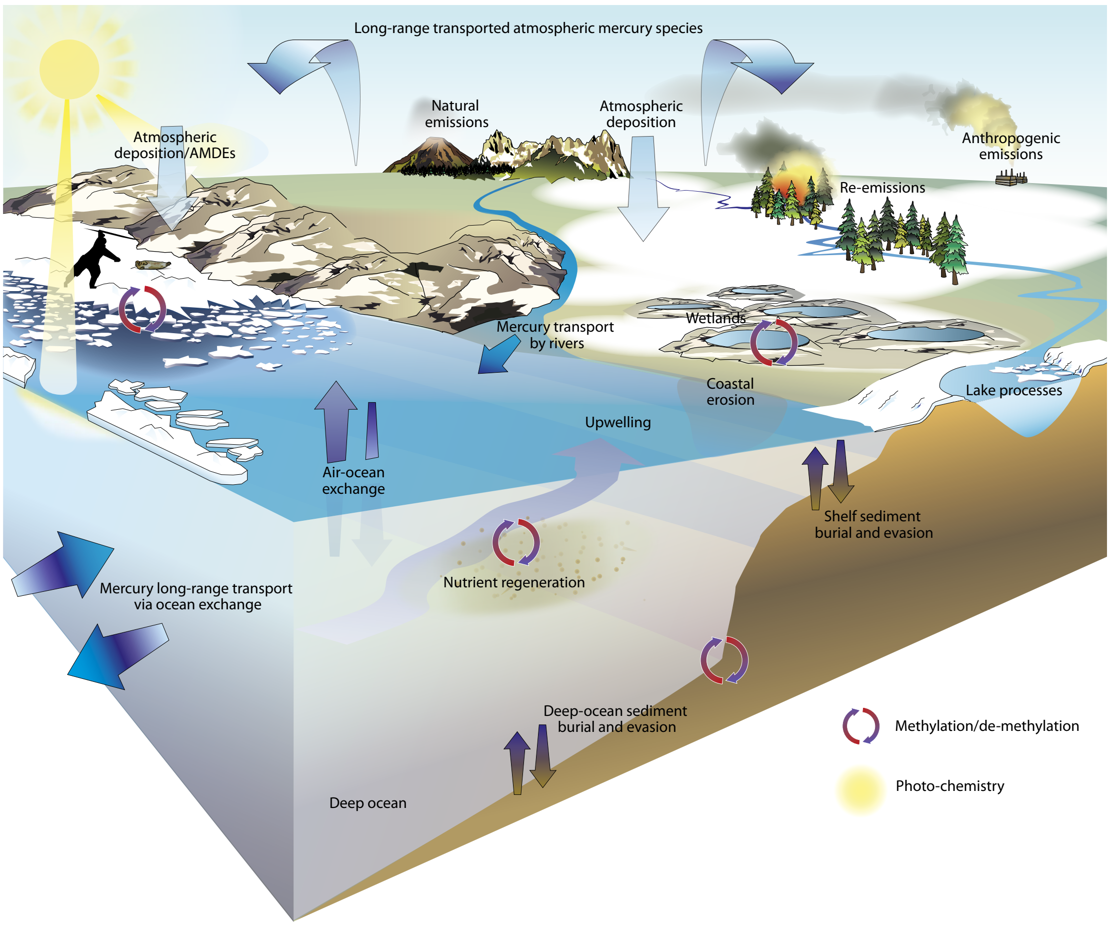
How does mercury get to the Arctic?

▶ Mercury from the major source regions in the northern mid-latitudes is mostly carried into the Arctic by the prevailing winds and ocean currents.

Most of the mercury arriving in the Arctic is carried in by the prevailing winds, ocean currents and rivers. Airborne mercury can travel from a power station chimney in a mid-latitude industrial area to the High Arctic in a matter of days to weeks. Gaseous elemental mercury can exist in the atmosphere for several months, easily long enough to be transported around the entire Northern Hemisphere, if not the globe. Other forms of mercury are removed from the air more rapidly and tend to be deposited closer to their sources (i.e., outside the Arctic).

Ocean currents can transport significant quantities of mercury into the Arctic, particularly those flowing in from the Atlantic Ocean. But





▶ Mercury exists in a range of chemical forms as it cycles through the Arctic environment.

unlike the prevailing winds, ocean currents travel far more slowly and it may take years or even decades for mercury to be carried from the mid-latitudes to the Arctic Ocean. Nevertheless, because mercury is capable of residing in the upper ocean for very long periods (decades), and because the total amount of mercury contained in the oceans is orders of magnitude greater than in the atmosphere, ocean currents do represent a significant long-distance transport pathway. Sediment from Arctic rivers and coastal erosion can also be a significant source of mercury in some coastal areas.

© Peter Outridge

◄The bottom sediments of the Arctic Ocean continental shelves are a biologically active zone which is the ultimate repository of much of the mercury entering the Arctic.

Once the mercury reaches the Arctic, it spreads throughout the physical and biological systems that make up the Arctic environment. The rate and extent to which this happens is dependent on the different chemical forms in which the mercury exists (see box), the physical and chemical processes involving mercury that dominate each system, and a wide range of climatic, geochemical, biological and environmental factors.

Mercury exists in different chemical forms

Mercury exists in a number of different chemical forms, each having particular properties that affect its distribution, uptake and toxicity within the Arctic environment.

Elemental mercury refers to mercury atoms in their pure metal form. Elemental mercury can exist as both a gas and a liquid at room temperature. The vapor form ('gaseous elemental mercury') is the most common form in air. Once mercury enters the air it remains there for periods of around a year. Elemental mercury is not particularly toxic when ingested, but through inhalation gaseous elemental mercury (at far higher concentrations than are found in Arctic air) can be toxic to air-breathing animals. Gaseous elemental mercury exchanges rapidly with water, where it is referred to as 'dissolved gaseous mercury'.

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Inorganic mercury includes elemental mercury and mercury compounds that do not contain carbon. Inorganic mercury compounds are formed when mercury atoms bond with other atoms or molecules found in soil, sediment or small atmospheric particles. Although the most common form of mercury in the environment, inorganic mercury is not as easily taken up by living organisms as other forms such as methylmercury (see below).

Reactive mercury is a term used to describe various inorganic mercury compounds. Some of these are formed by sunlight-induced reactions that convert gaseous elemental mercury to 'reactive gaseous mercury' in the air. Once formed, this reacts readily with other molecules and is rapidly deposited onto surfaces where it becomes available for uptake by organisms.

Methylmercury is the predominant form of organic mercury and is one of the most toxic forms to living organisms. It comprises mercury attached to a carbon-hydrogen group and is easily absorbed by living organisms. Methylmercury tends to biomagnify as it passes up the food chain – with levels in tissues and organs of species at the top of the food chain up to a million times higher than in species at the bottom of the food chain. Methylmercury is formed primarily in the environment by biological processes, such as microbial activities.

Mercury pathways

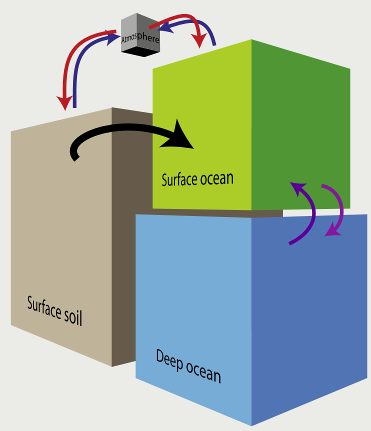
Most of the mercury released to the environment is cycled within and between three main 'environmental reservoirs' – surface soils, oceans and air – before it is removed from the system by deep burial in soils and ocean or lake sediments (see box). Globally, by far the largest amount of mercury is stored in surface soils, followed by surface and deep ocean waters. The atmosphere stores a much smaller quantity of mercury. The ways in which mercury moves between these reservoirs depends mainly on the pathways and processes that connect them, and less on the amounts of mercury that they contain. Mercury transfers in and out of soils and oceans relatively slowly, while the atmosphere is able to respond much faster to changes in mercury emissions and provides a significant pathway for fast mercury transport into the Arctic.

Some of the mercury arriving in the Arctic as gaseous elemental mercury is transformed into other more reactive forms, which are then deposited onto land and sea surfaces and become available for uptake by organisms. One important transformation mechanism in the polar region is known as an 'atmospheric mercury depletion event' (see box on facing page). Atmospheric mercury depletion events occur in spring when polar sunrise initiates a range of chemical reactions in the lower atmosphere, which result in a rapid deposition of mercury, and are associated with elevated mercury concentrations in surface snow and ice. The processes and pathways affecting the mercury after its release into meltwater are unclear, and the proportion of mercury from a depletion event going on to enter the ocean and other aquatic ecosystems is not known because about three-quarters of the deposited mercury is believed to be re-emitted to air within two days of a depletion event.

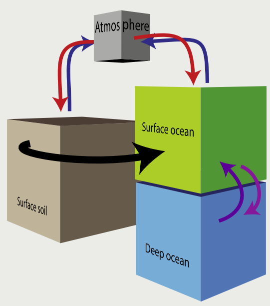
Environmental reservoirs

In pre-industrial times, most environmental mercury was from natural sources with the quantities of mercury cycling between the atmosphere, surface soils and ocean waters more or less in equilibrium. Mercury that has entered the environment in the post-industrial period is also accumulating in the atmosphere, surface soils and ocean waters, but the system is no longer in equilibrium. The time taken for the different reservoirs to respond to changes in inputs reflects the 'lifetime' of mercury in that reservoir. The atmosphere (lifetime of elemental mercury ~ 1 year) can be expected to respond relatively quickly to changing (atmospheric) emissions. Surface oceans respond more slowly, and deep oceans and surface soils more slowly still.

Pre-industrial



Post-industrial
contaminant mercury



The relative size of the boxes in this illustration reflects the amounts of mercury 'stored' in the reservoirs.

Atmospheric Mercury Depletion Events

Every spring, air monitoring stations around the coastal regions of the Arctic record sharp drops in the concentration of gaseous elemental mercury in the lower atmosphere. These phenomena, known as mercury depletion events, start shortly after polar sunrise – the first sunrise marking the end of the long cold winter of 24-hour darkness. Depletion events occur during a period of just a few weeks, ending when the snow melts. Depletions are greatest at midday, when the sun is at its strongest, and correlate closely with a drop in ozone levels in surface air.

Scientists have shown that these mercury depletion events are caused by sunlight-induced chemical reactions that require the presence of bromine (emitted from the ocean surface in sea spray) and some other gases. Spurred on by the first rays of sunlight in spring, the bromine reacts with ozone to create compounds that react with gaseous elemental mercury. During this process, ozone is destroyed and gaseous elemental mercury is converted to reactive gaseous mercury. The reactive mercury deposits quickly onto any surface – in this case the Arctic snowpack or sea ice. Measurements suggest that mercury levels in snow can be up to 100 times higher after a mercury depletion event.

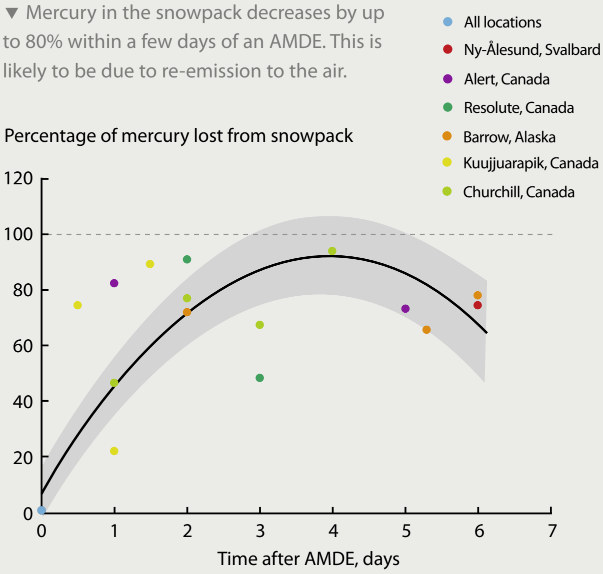
Once in the snowpack about three-quarters of this mercury may be rapidly converted back to an elemental form and then re-emitted to the atmosphere. However, a significant amount of the mercury deposited is thought to remain in the snowpack where other processes may convert it into bioavailable forms. Some microorganisms in the snow are thought to be able to convert inorganic forms of mercury into the more toxic methylmercury form. A small increase in methylmercury has been measured in the snowpack, just before the spring snowmelt. But it is not clear how much of this is produced within the snowpack and how much falls with the snow.

The precise geographical extent of areas affected by mercury inputs from atmospheric depletion events is unclear. This is one of the reasons why it is not yet possible to determine how significant mercury depletion events are as a pathway for mercury to enter the Arctic food web.

If global warming causes more sea ice to melt, greater quantities of bromine could become available (via increased levels of sea spray), possibly leading to greater mercury deposition through atmospheric mercury depletion events. Plus, more of the mercury would deposit directly into ocean water, helping its entry into the marine food web. On the other hand, warmer temperatures could shorten the season in which atmospheric mercury depletion events can occur, leading to decreased mercury deposition.

▼ ▶ Frost flowers grow on the surface of newly formed sea ice and are thought to play a significant role in the complex chemistry of atmospheric mercury depletion events.

▼ Mercury in the snowpack decreases by up to 80% within a few days of an AMDE. This is likely to be due to re-emission to the air.

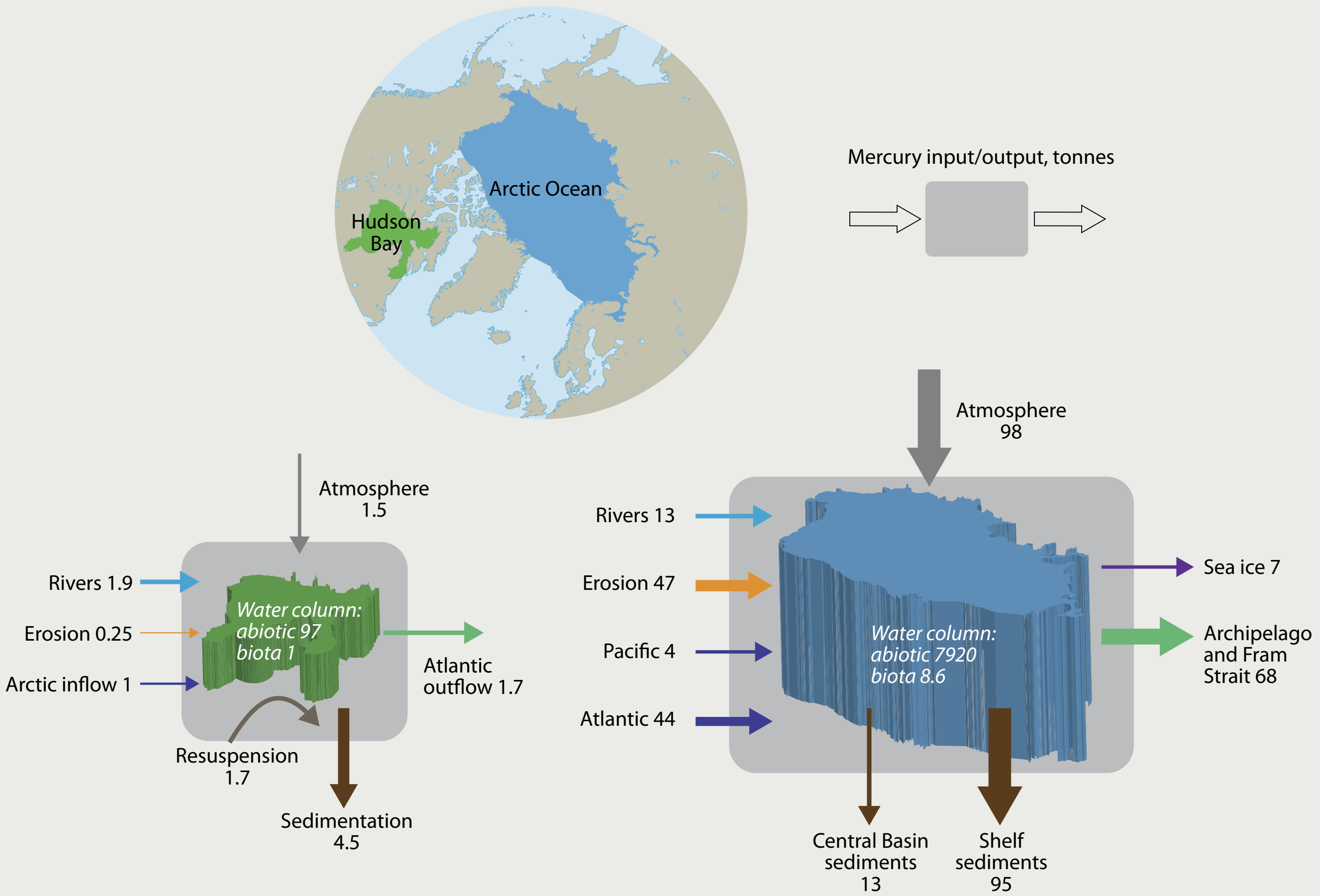


Because most of the human exposure to mercury in Arctic traditional/local foods comes from marine foods, particular attention has been directed in this assessment towards mercury transport within the Arctic Ocean. Measurements and modeling have helped to improve our understanding of the different transport pathways involved (see box). Mercury enters ocean surface waters via deposition from the air, from snow and ice melt, in runoff from rivers, via soil erosion at coastal margins, by transport in ocean currents from other oceans, and through upwelling of deep Arctic Ocean waters to the surface. Once in the upper ocean waters, mercury is subject to a number of processes and transformations. In highly productive marine areas (such as upwelling regions) mercury may be taken up by phytoplankton, ultimately ending up in benthic (seabed) and pelagic (water column) food webs or in sediments. The heavy 'rain' of dead organic matter – to which mercury readily attaches – from surface waters downwards is a particularly important route by which mercury may be transported into sediments. Some microorganisms

Mercury budgets

Mass balance studies help to indicate the relative importance of inputs and outputs. Models have been developed to estimate the annual total mercury budget for the semi-enclosed Arctic Ocean and Hudson Bay water bodies.

For the Arctic Ocean, inflows from the Atlantic and Pacific oceans and coastal erosion are significant sources. The largest single source is the atmosphere, which contributes about half the total input with around 50% of this deposited in spring. The large atmospheric input (the net input minus re-emission) reflects the enormous ocean surface area available. In contrast, rivers are the most important source of mercury to Hudson Bay, followed by the atmosphere and ocean inflow. The difference in the relative importance of rivers is in part due to the 'edge effect' – meaning that river inputs are relatively larger for smaller, semi-enclosed bodies of water. In terms of mercury export, sedimentation was important for both systems, as well as ocean outflow and, to a lesser extent, gaseous release back to the air.



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◄ Automated mercury monitoring equipment is deployed at several locations around the Arctic. It can also be installed in an air monitoring laboratory container for deployment on scientific cruises.

(such as those present on sea ice) may convert inorganic mercury into methylmercury, which is subsequently taken up by the oceanic food chain and biomagnified into the high mercury levels observed in upper food chain species such as polar bears. Inorganic mercury in surface waters may also be converted back to elemental mercury, and then re-emitted to the air. All of these processes are heavily influenced by the prevailing environmental conditions. In the polar oceans, sunlight and the organic carbon cycle are key factors controlling mercury cycling, as is the presence of sea ice because this limits gas exchanges between air and sea, and restricts the amount of sunlight reaching the upper ocean, thus affecting primary productivity and processes like the sunlight-induced breakdown of methylmercury. The periodic switch from 24 hours of darkness in winter to 24 hours of sunlight in summer is therefore important.

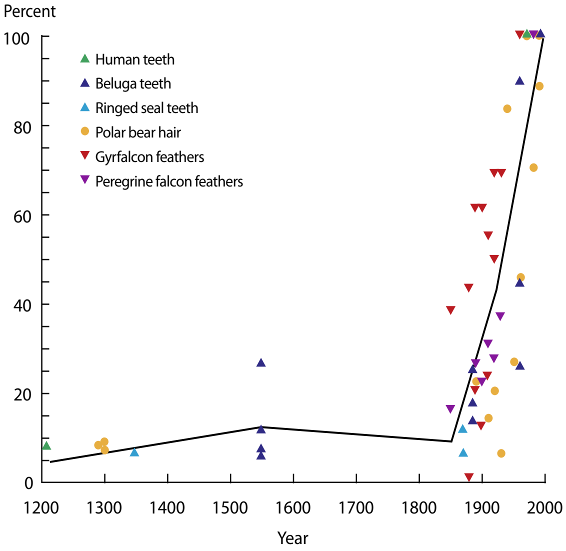
Freshwater rivers and lakes are also sites of mercury accumulation in the Arctic. The way in which mercury is deposited in lakes varies according to local conditions. Studies in the Canadian High Arctic have shown that snowmelt is an important source of mercury, delivering a pulse of inorganic mercury to lakes during June and July each year. Whether the mercury is retained in the lakes may depend on their productivity levels and organic matter content. This is because some scientists believe that material suspended in the water provides surfaces onto which the mercury can attach and then be carried down to the sediments – a process known as 'scavenging'. In general, High Arctic lakes have low levels of biological production, which would reduce their ability to retain mercury. Nevertheless, much of the mercury deposited in lakes is thought to be re-emitted to the air, via a sunlight-induced reduction to its elemental state.

The rise in mercury since pre-industrial times

Mercury was present in the Arctic in pre-industrial times, but in far smaller quantities than today. Trends in mercury concentration over time vary from region to region and from one type of environmental system to another. In lake sediments, for example, mercury concentrations are on average two to three times higher than in pre-industrial times. In top predators such as beluga, seals, polar bear and birds of prey, mercury concentrations are now about ten times higher than in pre-industrial times, meaning that over 90% of the mercury currently present in their tissues is thought to have originated from sources associated with human activities. In recent years, mercury emissions in Europe and North America have been falling, and while this seems to be reflected in decreasing mercury levels in the High Arctic atmosphere, this has not yet led to corresponding declines in mercury levels in Arctic lake sediments or in most animals.

The rise in mercury levels in the Arctic has been documented by studying tissues from Arctic animals, such as teeth, hair and feathers, dating back as much as 800 years. In general, mercury

▶Museum collections provide a source of artefacts that can be used to find out about mercury levels in historical times. Primary feathers from gyrfalcons and polar bear hair from clothing have been used to monitor trends in mercury in central West Greenland.



▶Mercury concentrations in the hard tissues of different Arctic biota expressed as a percentage of present-day concentrations, show the sharp increase in Arctic mercury levels following the Industrial Revolution.

levels in these hard tissues (obtained from museum collections and archeological sites) reflect the levels in the diet of the animal when it was alive, making them a good proxy for the increase in environmental mercury concentrations over time. Mercury levels in archeological samples of human teeth from northern Norway have also been studied and indicate similar increases since pre-industrial times.

A scarcity of data from before 1850 makes it hard to determine exactly when mercury levels in the Arctic really started to rise, but it is clear that levels accelerated rapidly after 1900, when the Industrial Revolution in Europe and North America was well underway.

Some species appear to have experienced the increase in mercury levels earlier and more quickly than others. In particular, birds of prey from Greenland dating back to the 1850s, show an earlier and more rapid increase in mercury concentration than animals such as beluga (where levels in teeth only began to increase in the early 20th century) and polar bear from Greenland (where levels in hair only really increased after 1950). One explanation could be the different food sources exploited by these species. While the birds of prey had a mixed diet based on prey from both the land and the sea, the diet of polar bears and beluga was exclusively marine. Given that mercury is transported more rapidly through the atmosphere than the ocean, high tissue concentrations due to mercury arriving in the Arctic from human activities at lower latitudes are likely to appear in terrestrial food webs (due to mercury deposited from the air on to vegetation and soils) long before they are seen in marine systems. This finding may also give a clue as to how rapidly mercury levels in different types of animal may respond to future reductions in global emissions. Uptake of mercury from more contaminated areas during migration, or feeding on prey that have acquired mercury in this way is also a factor.

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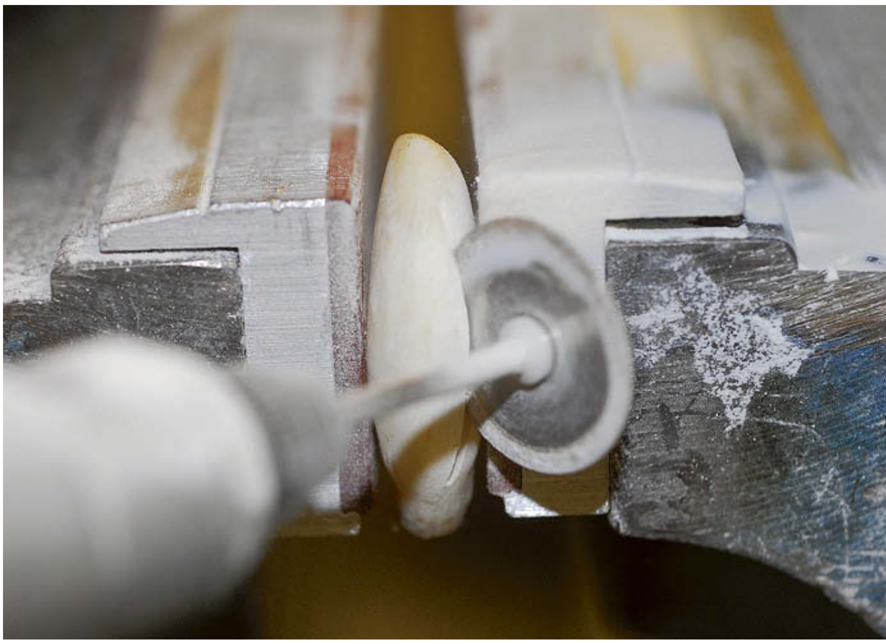

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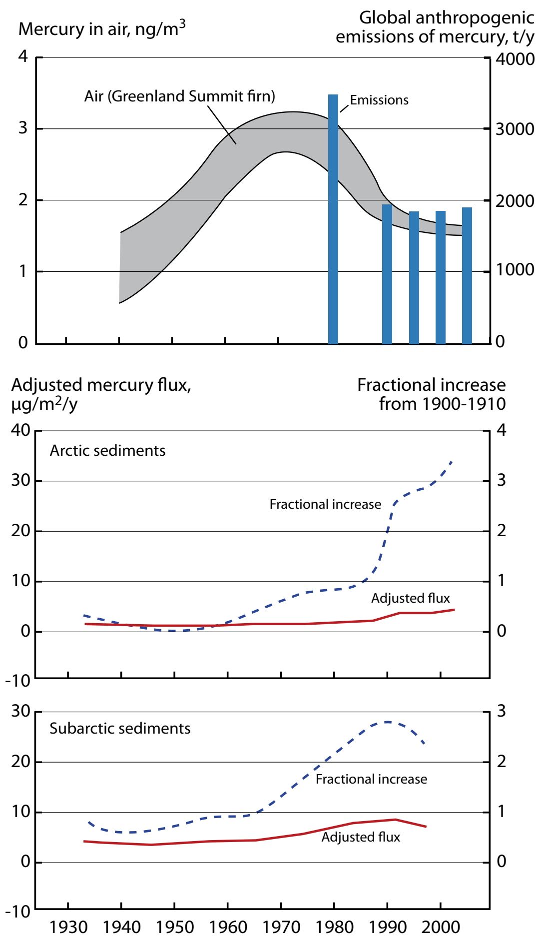
▶ Mercury has been measured in teeth extracted from beluga skulls.

▶ Mercury measurements in ice from the Greenland ice sheet indicate that contamination peaked in the 1970s. Canadian lake sediments have also been used to track trends in mercury deposition in the Arctic.



Ice, sediments and peat also log the rise in mercury in the Arctic environment since pre-industrial times. However, these records are not always simple to interpret, owing to the many processes (see box on facing page) that can affect the way in which mercury is incorporated into these environmental 'archives'.

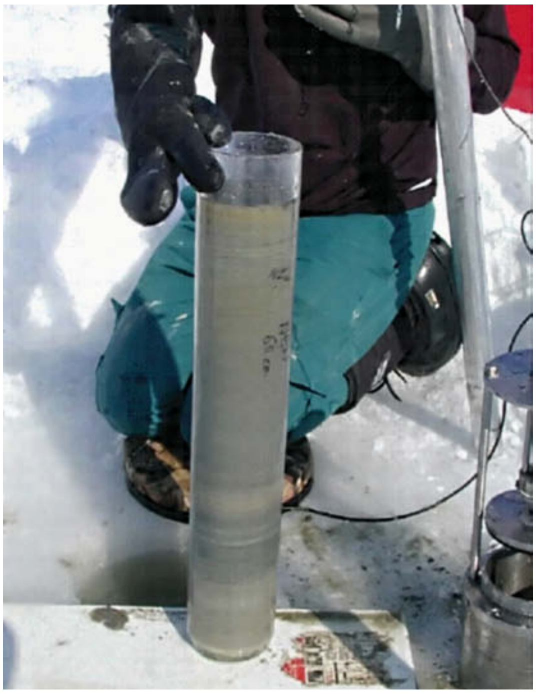
Air trapped in compacted snow and ice layers on Greenland (which reflect the composition of the atmosphere at the time the snow fell) reveal a rapid rise in gaseous elemental mercury after the Second World War, which peaked around 1970 and then declined sharply after the widespread introduction of 'clean air' policies, particularly in relation to coal-fired power plants. The measurements show levels to have been relatively stable since around the mid-1990s.

Meanwhile lake sediments in Canada have shown a three-fold increase in mercury concentration over the course of the 20th century, with the increase more pronounced at lower latitudes (closer to the major emission sources). Similar increases have also been seen in lake

▼ Air trapped in compacted snow and ice has been analysed to provide information about past levels of mercury in the atmosphere.

sediments across Eurasia and North America. However, changes in sedimentation rates and levels of lake productivity (as outlined in the box) may result in lake sediments providing a less accurate and less precise record of the rise in Arctic mercury levels since pre-industrial times.

Peat bogs in Greenland and the Faroe Islands appear to show an even greater degree of variation in their accumulation of mercury; with concentrations increasing seven- to 17-fold since pre-industrial times. Similarly for lake sediments, these findings need to be treated with caution.



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◀ Studies of varved (layered) sediment cores indicate that factors related to climate change may be responsible for some observed mercury trends.

A Muddled Record

It is tempting to interpret the profile of contaminants in environmental archives such as ice, lake sediments and peat cores as a simple reflection of changes in deposition from the air over time. However, this picture is complicated by various factors that need to be taken into account if such records are to be interpreted in a valid manner.

Mercury in sediments and soils (such as peat bogs) may move or alter after it has been deposited. For example, animals may burrow through the sediment and mix up the layers, or changes in sediment conditions (temperature, acidity, oxygen or sulfide content) may favor conversion to mobile forms of mercury which then relocate within the sediments.

Year-to-year variations in weather patterns and environmental influences (e.g., deforestation or high rainfall years) can alter the amount of erosion and runoff of soil from the land. As a result, the amount of sediment deposited at the bottom of lakes or oceans varies from year to year, with some years 'drawing down' proportionally more mercury from the air than others.

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Warming is altering the movement of mercury through the Arctic environment. For example, pulses of mercury are released from thawing permafrost and peatlands into adjacent water bodies as surface soil temperatures increase.

Changes in algal productivity at the base of food chains ('primary productivity') in northern lakes in response to a warmer climate appear to be altering the rate at which mercury is transferred into sediments.

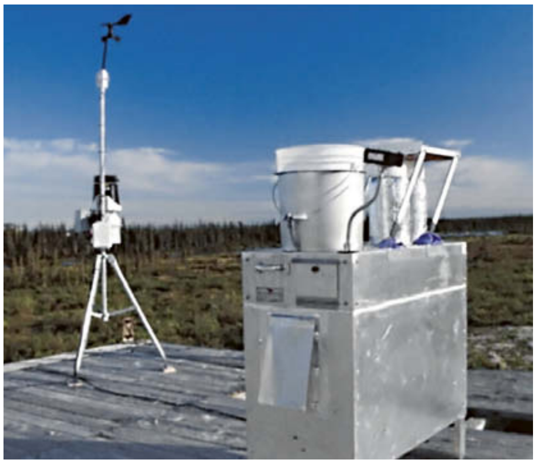
Mercury in the Arctic today

Mercury in the air

▶Data on mercury in rain and snow from the Arctic can only be reliably collected using cold-adapted precipitation collectors.

Taking into account uncertainties in the models, the best estimates of the net amount of mercury added to the Arctic environment each year (i.e., the amount arriving adjusted to take account of the amount leaving) are currently between about 80 and 140 tonnes.

The results generated by the models have been validated using actual mercury concentration data measured at six atmospheric mercury monitoring stations in the Arctic. But the observational data are still extremely sparse. Some recent models are now beginning to include processes specific to the Arctic, such as atmospheric mercury depletion events and the 'fast' re-emission of mercury from the snowpack. As a result, although confidence in the actual numbers produced by the models is still limited, the models are considered to be good indicators of the broad geographical patterns in atmospheric mercury concentration within the Arctic and the general trends in mercury concentration over time. The models are also considered to be reasonably good at reproducing the seasonal cycles in atmospheric mercury levels observed within the Arctic.



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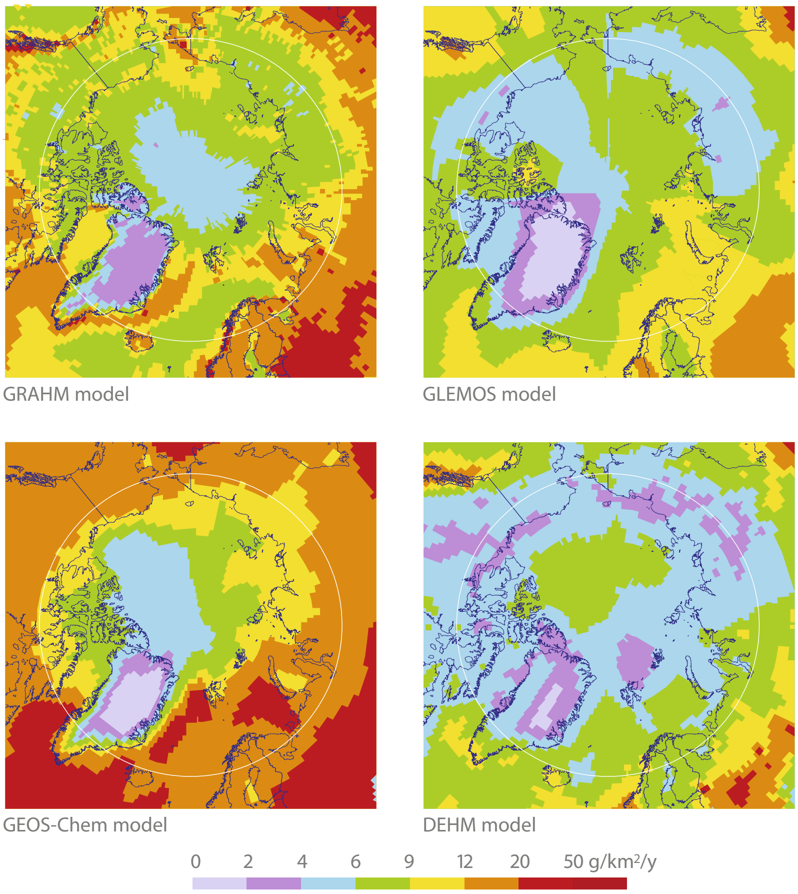
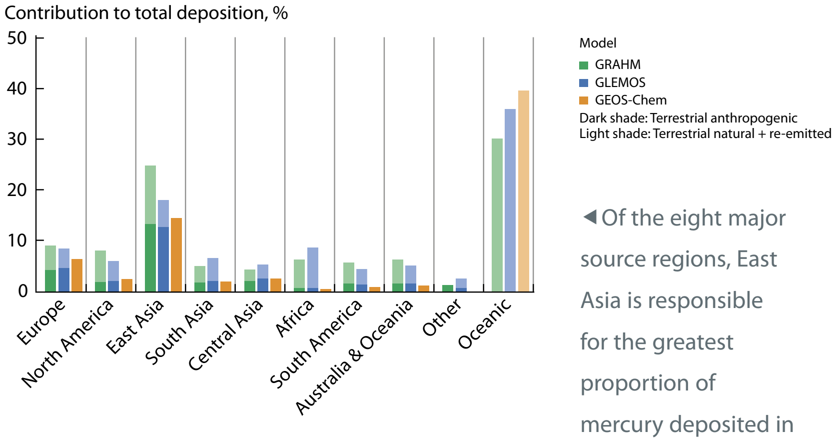
▼Model results for mercury deposition across the Arctic in 2005 show the same broad trends.



As part of this assessment, a number of different models were used to simulate the atmospheric transport of mercury to the Arctic, and the air concentrations and deposition of mercury to the Arctic in 2005. Although estimates of the absolute amount of mercury deposited in the Arctic differ from model to model, there is broad agreement between the models in terms of the geographical distribution and temporal trends over the course of a year. The models suggest that air concentrations and deposition are lowest over Greenland and highest over the Greenland Sea and Barents Sea regions. Deposition appears to decrease with increasing latitude, as might be expected given that the higher latitudes tend to be further from the major emission areas and to have lower precipitation rates (which is important in controlling how much mercury falls with rain and snow). Increased mercury deposition in coastal areas is predicted as a result of mercury depletion events.

The models were also used to investigate the relative contributions from the different source regions, particularly those having the greatest impact on the Arctic (Europe, North America, East Asia, South Asia). Such studies show that the North American and East Asian impact is slightly greater in the western Arctic, whereas the South Asian impact, although delivering much less mercury, is highest over Greenland and the adjacent oceans. European sources are closer to the Arctic, and their influence is correspondingly greatest over the European Arctic. Studies like this make it possible to examine the likely impacts of changing emissions in the source regions. For example, models suggest that an increase in mercury emissions in East Asia could potentially result in an increase in mercury deposition in the Canadian Arctic, perhaps offsetting any decrease due to reduced North American emissions. Models also indicate that decreased European emissions could decrease deposition in the European Arctic, regardless of any change in East Asian emissions.

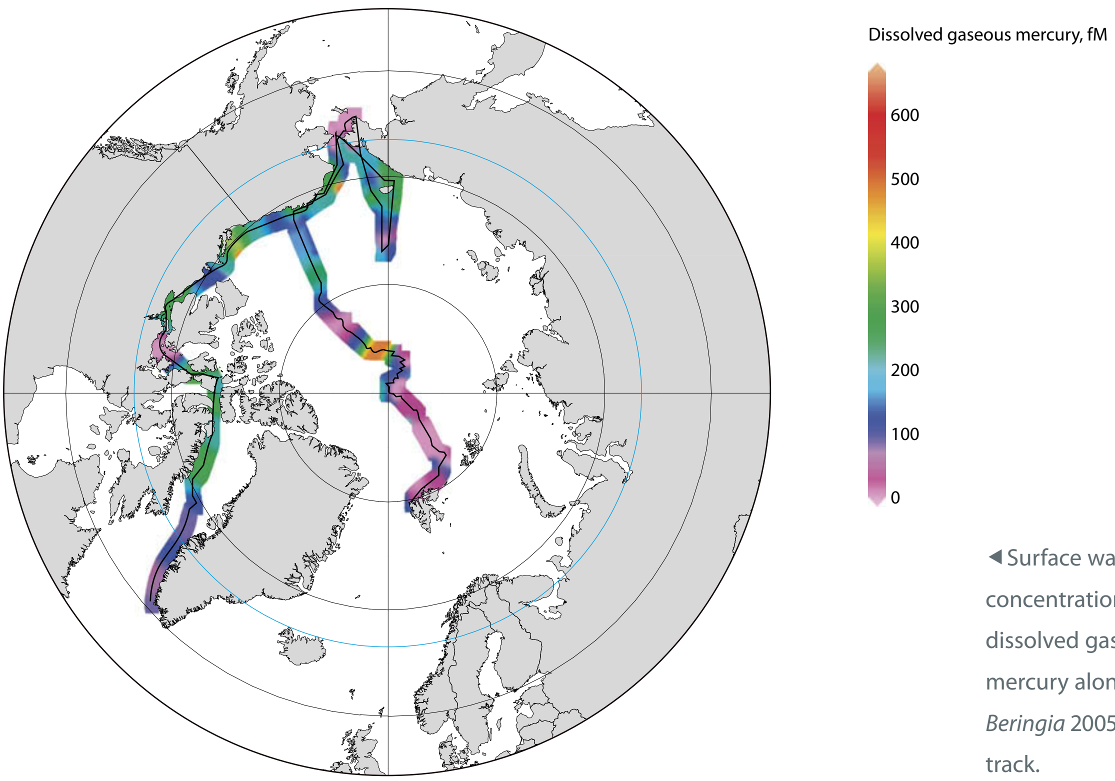
Models are currently being used to investigate the likely effects of different mercury emission scenarios (and climate change scenarios) on future mercury deposition in the Arctic (see also page 35). Although still at an early stage of development, such studies are extremely useful for providing the information needed for making informed policy decisions on emissions.



◀ Of the eight major source regions, East Asia is responsible for the greatest proportion of mercury deposited in the Arctic from land-based sources.

Mercury in the ocean

Data for mercury in oceans are derived from scientific cruises that vary in the routes they take, their frequency, and their scientific objectives, thus time-series datasets with which to evaluate what is happening in ocean pathways are almost non-existent. As a consequence, the budgets on page 12 necessarily involve many assumptions and so should be regarded as snap-shots in time which will need to be updated with information arising from future sampling programs, particularly in relation to mercury concentrations in seawater.



◀ Surface water concentrations of dissolved gaseous mercury along the *Beringia* 2005 cruise track.

Mercury in ecosystems

The **Arctic food web** refers to the network of interconnected food chains within the Arctic environment.

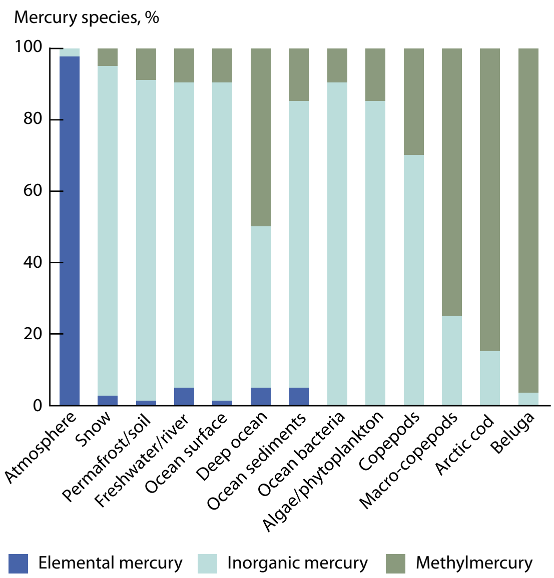
A **food chain** is the sequence of organisms at successive trophic levels within a community.

A substance is **bioavailable** if it can be taken up by living organisms.

To enter the **Arctic food web** mercury needs to be in a form that can be readily taken up by organisms. Although organisms at the base of the food web (algae and a range of microscopic organisms such as bacteria) can take up inorganic mercury and methylmercury, it is the uptake (and production) of methylmercury that poses the greatest ecological risk – owing to its toxicity and because this is the form that is most easily taken up by animals and so drives biomagnification through food chains. Typically, methylmercury levels are two to seven times higher at each successive step (trophic level) in a food chain, i.e., moving from prey to predator. And, the longer the **food chain**, the more pronounced the biomagnification effect becomes with methylmercury levels in the highest predators up to a million times higher than those in organisms at the base.

Entry into food chains

The fate of the (predominantly inorganic) mercury deposited in the Arctic depends on a range of physical and chemical processes, but scientists now believe that microbial processes may play a major role in determining whether or not this mercury enters the food chains. Studies have shown that sulfate-using bacteria in Arctic environments with low oxygen levels (such as marine sediments and wetlands) can convert inorganic mercury to methylmercury and there is good evidence that various types of bacteria are living at subzero temperatures in the Arctic snow and ice. The extent to which these snow and ice bacteria are converting inorganic mercury to methylmercury is still unknown, but one study found that during atmospheric mercury depletion events up to 13% of the mercury present in the snow was present in a **bioavailable** form. Studies have found that bacteria within ocean waters are also producing methylmercury, especially in water layers with elevated nutrient concentrations. The significance of these microbial processes for methylmercury production within the Arctic is an area that requires more study.

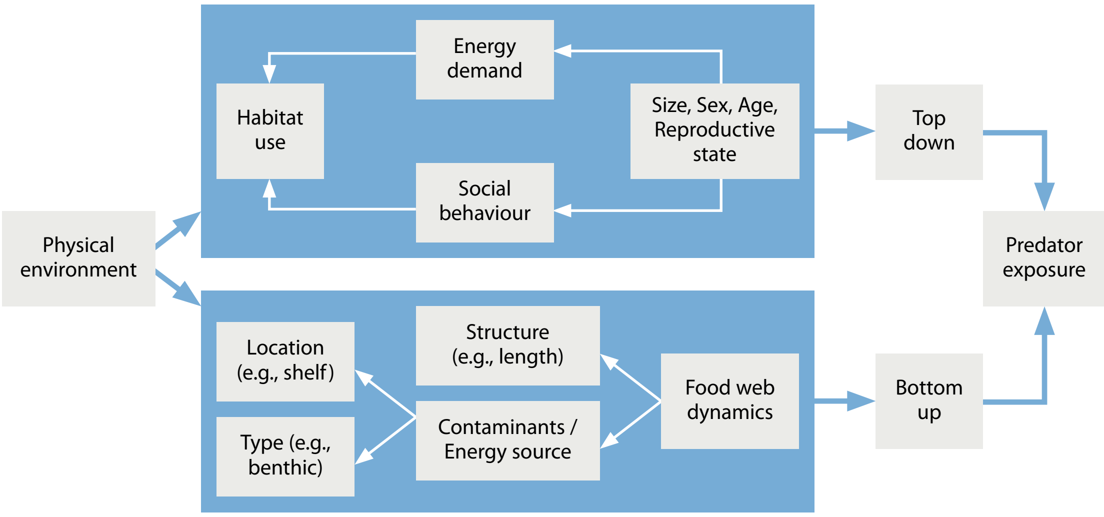


▸The proportion of methylmercury increases through the food chain. In top predators such as beluga, the mercury is almost entirely present as methylmercury.

Levels in higher predators

Methylmercury levels in top predators such as polar bear and beluga reflect the combined effects of a range of 'top-down' and 'bottom-up' trophic processes. Top-down processes include the feeding ecology and dietary preferences of the animals (see the box for a case study on beluga), while bottom-up processes concern the factors that influence the extent to which methylmercury concentrates at successive tropic levels of the food chain. The initial methylmercury concentration at the base of the food chain, the bioavailability of this mercury, and the seasonality and location of organisms at the base of the food chain are very important to bottom-up processes.

Bottom-up processes play a particularly important role in controlling mercury levels in Arctic freshwater food webs. Methylmercury production by bacteria in sediments is thought to be a key process. Freshwater fish feeding at or near the tops of food chains in lakes in Alaska,



◄ Mercury levels in Arctic biota reflect the combined effects of a range of top-down and bottom-up processes, many of which are sensitive to the influence of climate change.

Canada and Greenland often contain high levels of mercury. These species include lake trout, northern pike and land-locked Arctic char.

The Arctic marine ecosystem has four major elements: sea-ice food webs, pelagic (open-water) food webs, estuarine/nearshore food webs, and benthic (seabed) food webs. How the methylmercury deposited in (and generated within) the marine environment enters these food webs, and the pathways via which it is subsequently transported into the higher predators, is determined by a wide range of bottom-up processes. Coupling between these food webs increases the difficulty of establishing the exact processes by which the mercury is transferred from the main 'environmental reservoirs' (air, sediments, water) into the species selected by predators as prey, and ultimately those marine mammals, seabirds and predatory fish forming the basis of the indigenous peoples' traditional diet.

Case study: Eastern Beaufort Sea beluga

The Eastern Beaufort Sea beluga population divides into three separate groups during summer: one moves to shallow open water near the mainland and feeds on the estuarine/nearshore food web, the second moves to areas near the sea ice and feeds on the open-water food web, while the third moves further offshore and feeds on the bottom-associated food web. Mercury concentrations in the three groups differ, with high levels in the beluga feeding on the open-water and bottom-associated food webs and much lower levels in the beluga feeding on the estuarine/nearshore food web. The diet is dominated by Arctic cod in all three groups.

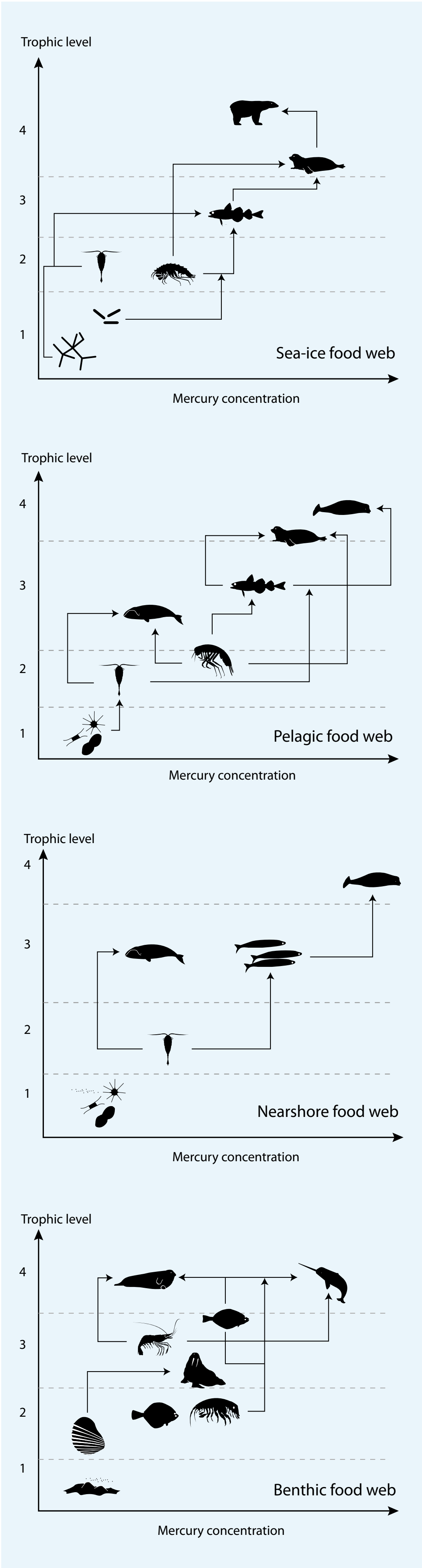

© W. Lynch / ArcticPhoto

Mercury levels in the beluga are driven by the location of the fish they consume, with concentrations highest in the offshore fish and lowest in the nearshore fish. This example illustrates the importance of dietary preference (a 'top-down' process) in controlling mercury levels in animals at the top of the food chain.

Recent trends in exposure

As part of this assessment, information on changes in wildlife mercury concentration over the past 20 to 40 years was examined in more than 80 datasets for Arctic species in Alaska, Canada, Greenland, Iceland, the Faroe Islands, Norway and Sweden. The review included data on marine mammals, marine fish, marine invertebrates, seabirds, freshwater fish, and land mammals. Many of these time series are now long enough and powerful enough to reliably detect a trend if one exists, and increasing the time period covered by the datasets and adding new time series covering other parts of the Arctic will further improve this capability. The results of the review showed that trends in concentration varied depending on the type of animal and its geographical location.

Overall, mercury concentrations showed a recent increase in 16% of datasets, a recent decrease in 5% of datasets, and no change or fluctuating trends in the remaining 79% of datasets. Most of the recent increasing trends were found in marine animals, especially marine mammals and seabirds (there were no recent decreasing trends in the seabird and marine mammal datasets). Mercury concentrations in land animals tended to show either no trend or a recent decreasing trend. There was a clear west-to-east gradient in recent increasing trends, with more recent increasing trends in Canada and West Greenland than in regions further east. These results suggest that different factors are controlling mercury concentrations in different species in different areas. The decreasing trends in land animals in areas closer to source areas in North America and Europe may reflect decreasing atmospheric emissions. In marine species, however, in particular those in the more remote Arctic areas, the recent increasing trends may reflect the slower response of the marine system to changes in emissions, coupled with oceanic system changes



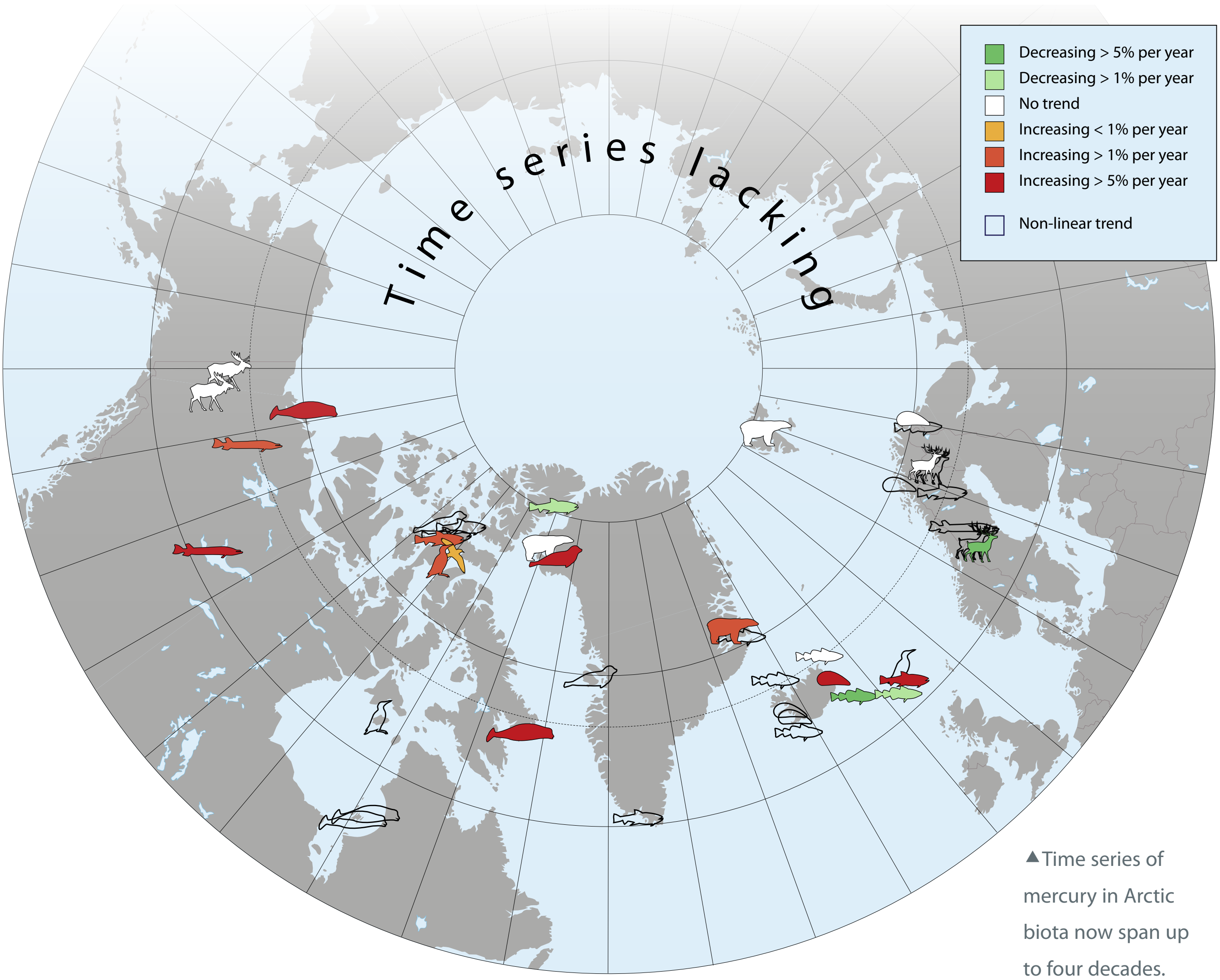
▶ Sea-ice food webs begin with algae growing on sea ice and end with marine mammals and birds feeding on species like Arctic cod. Mercury arrives primarily from the air.

▶ Pelagic food webs begin with algal blooms and end with marine mammals and birds feeding on Polar and Arctic cod. Mercury enters from the surrounding ocean water.

▶ Estuarine/ nearshore food webs begin with algae and end with marine mammals and birds. Mercury enters mostly from the adjacent rivers.

▶ Benthic food webs start with invertebrates and end with walrus and bearded seal feeding on benthic bivalves. Mercury enters mainly from the sediment.

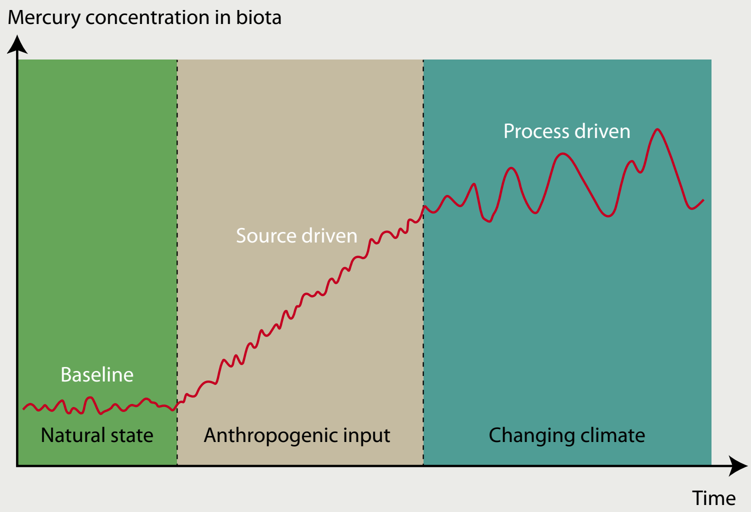
◀ Mercury flow through marine food webs in the Beaufort Sea, northern Canada (seabirds and humans not included).



▲Time series of mercury in Arctic biota now span up to four decades. Statistically significant trends show apparent differences in the trend patterns to the east and west of Greenland.

in mercury dynamics that are possibly related to climate warming. The recent increasing mercury trends in marine species are a matter of particular concern as they include species used as food by humans. Increasing trends also imply increasing potential for biological effects in animals. The only way to reduce mercury exposure in wildlife is to reduce levels of environmental contamination.

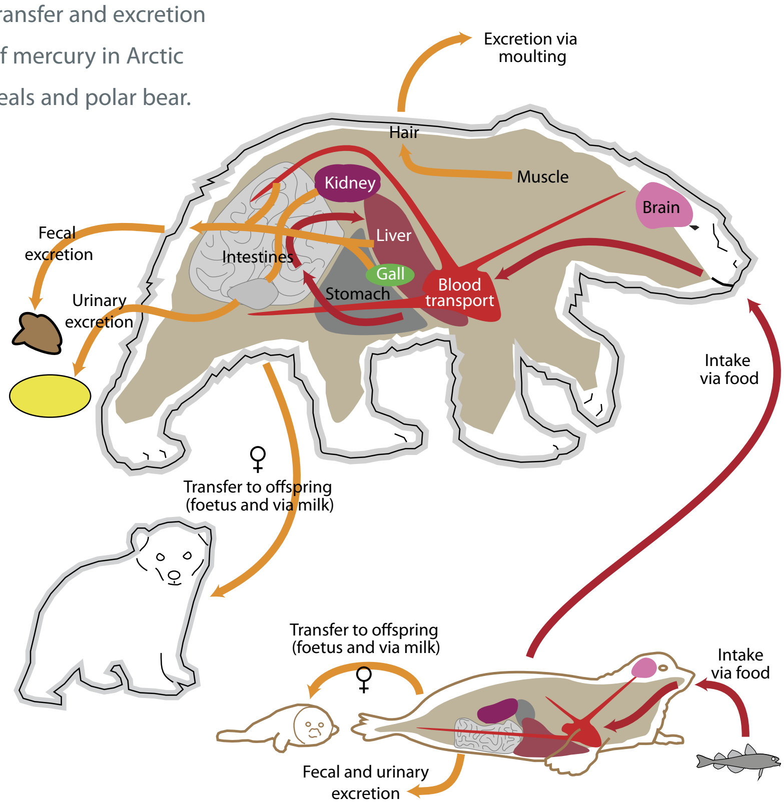
Mercury trends in Arctic marine biota reflect changes in emissions and in processes that lead to uptake of mercury in animals. In recent decades, and increasingly in the future as climate change influences come into play, process-driven variability in concentrations may be large enough to obscure source-driven trends, at least at the decadal scale.



Toxic effects of mercury in Arctic biota

Because the highest mercury levels are found in animals at the top of the Arctic food web, studies looking at the toxicological effects of mercury in Arctic animals have mainly been carried out on higher predators. Recent evidence suggests that mercury concentrations in these top predators have increased over the past 150 years, resulting on average in more than 90% of the mercury body burden having come from human activities. As concentrations in some Arctic animals (including top predators) are still increasing, Arctic species are not only exposed to far higher mercury levels today than they were in the past but some are also likely to be exposed to increasing concentrations of mercury for some time to come. This is due to the lag time between lower emissions and lower environmental levels (or due to climate-related processes).

▼Routes of uptake, transfer and excretion of mercury in Arctic seals and polar bear.



Estimating toxicological risk

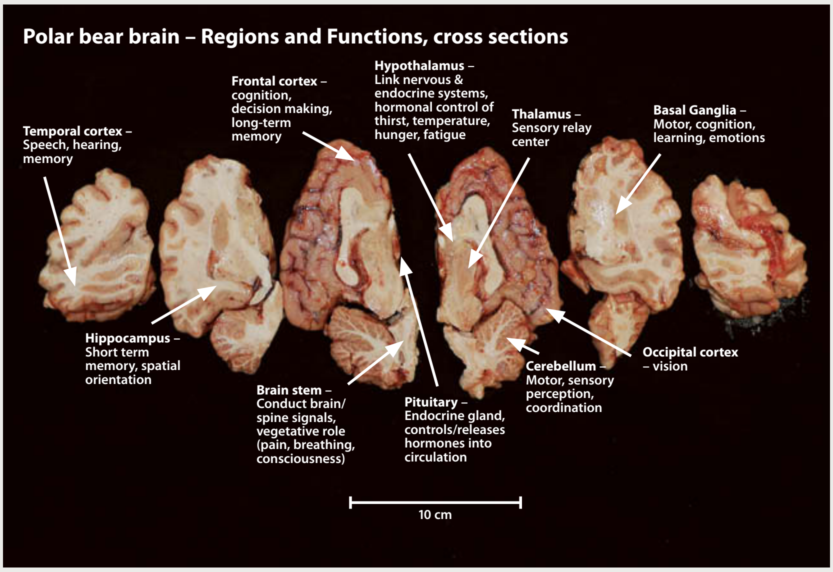
Two main approaches are used to identify and estimate the risk of toxicological effects of mercury in Arctic species. In the first, mercury concentrations in certain tissues are compared against particular levels ('thresholds') known to cause harm. These thresholds are often based on data from laboratory studies and it is difficult to know how representative these levels are for free-ranging Arctic species living under the extreme environmental conditions imposed by the polar climate. This assessment has focused on recent (post-2000) concentration data, especially those datasets from areas where mercury concentrations in top predators are known to be high or clearly rising. The second approach is to examine the animals for mercury 'biomarkers' – responses in the animals known to be associated specifically with mercury (see box on facing page). Because Arctic animals are exposed to a whole range of pollutants, not just mercury, and because mercury can interact with these other pollutants (as well as other chemicals such as selenium) in ways that both increase and decrease its toxicity, the levels of mercury in the environment do not alone reflect the potential health risks involved.

Uptake and excretion

Once ingested, methylmercury is readily absorbed into the circulatory system and transported around the body in blood, bringing all tissues into contact with the mercury. Concentrations in top predators vary from tissue to tissue. The main organ where methylmercury is stored (and broken down) is the liver in marine mammals and birds, and the kidney in land mammals, including polar bear. Methylmercury is also excreted. As well as excretion in feces and urine, polar bears can excrete large amounts of methylmercury into

A biomarker for mercury stress?

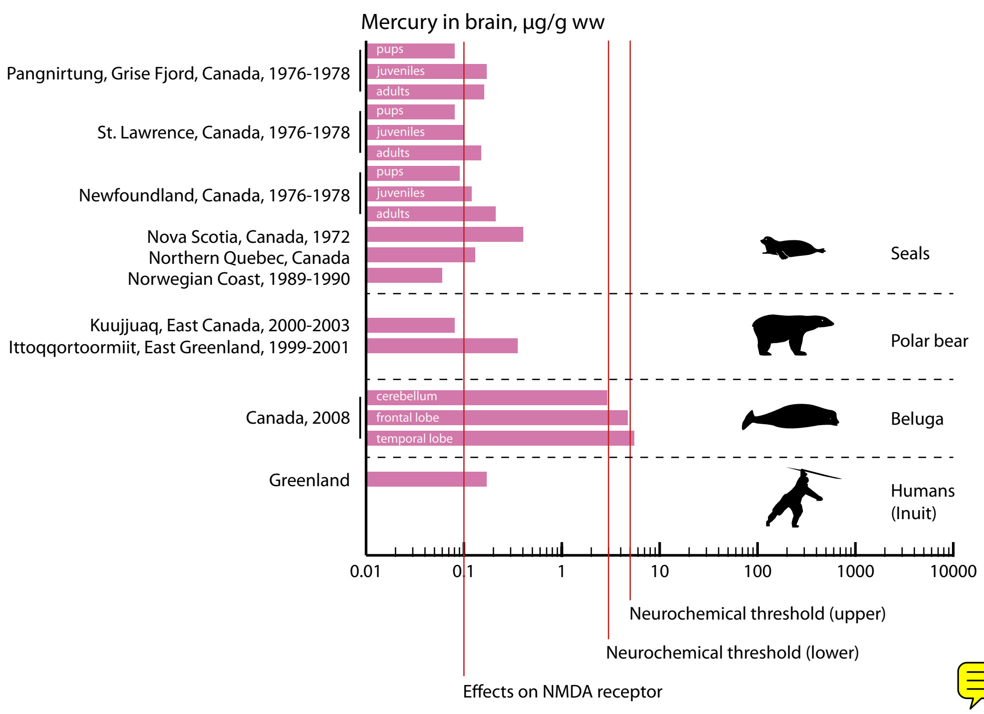
For polar bears, there is a strong negative relationship between mercury concentration in the brain stem and the level of a chemical responsible for around 40% of all brain activity. This chemical (known as NMDA) controls all aspects of the animal's behavior, survival and reproduction and changes in the levels of this chemical may be one of the earliest signs of mercury stress. Analyses concerning other regions of the brain are now underway, and it seems that mercury concentrations in some of these may be up to six times higher than in the brain stem.



growing hair and birds can excrete it via feathers. Toothed whales (beluga, narwhal, pilot whale) are not able to excrete methylmercury in this way and this might explain the higher mercury concentrations in their muscle and brain tissue. Mercury concentrations in blood appear closely linked to recent food consumption and so are a good measure of recent dietary exposure.

Toxicological effects

One of the reasons why methylmercury is so toxic is that it can cross the blood-brain barrier and disrupt the central nervous system, causing problems such as numbness, tingling, lack of coordination and memory loss. This transfer from blood to brain gives a potential for neurotoxicity, which may have implications for the Arctic biota with high methylmercury tissue levels, and also



◀ Some studies have found high mercury levels in brain tissue from toothed whales, such as beluga, within the range associated with neurochemical effects.

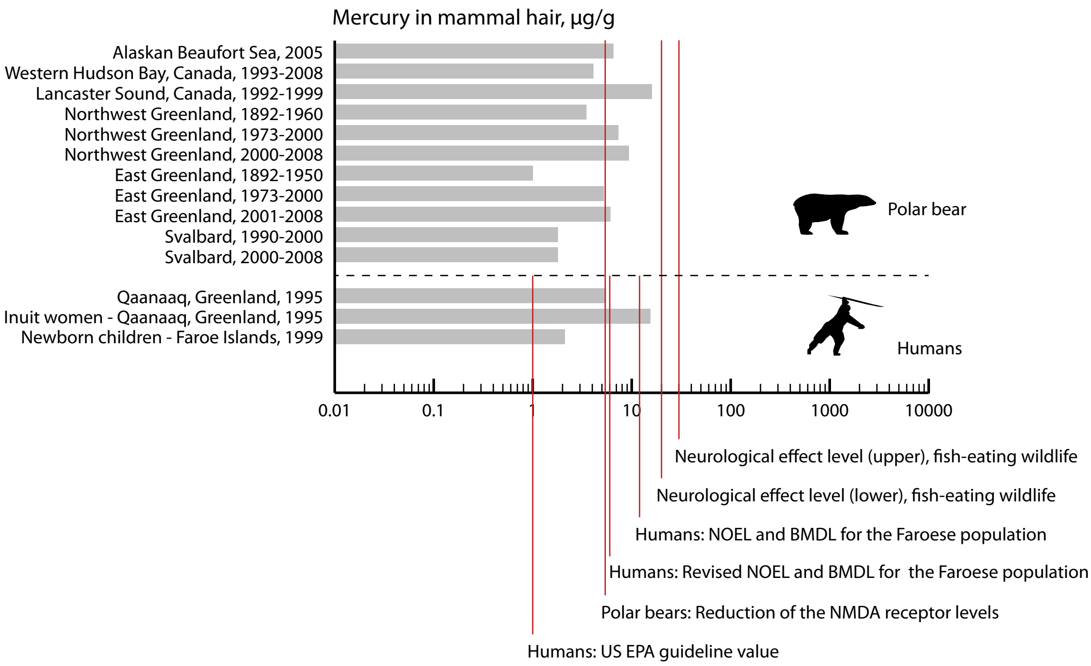
▶Blood and hair are useful tissues for reflecting recent mercury exposure. Blood and hair can be taken from live animals without causing harm.

© Rune Dietz

for those Arctic residents that consume them. Methylmercury can also cross the blood-placenta barrier and pass from mother to fetus; gestation and maternal milk are both important routes of mercury exposure in young animals.

Methylmercury concentrations in polar bear hair have been widely analyzed over time and across regions. Hair is a good material to use because it accumulates methylmercury from the blood and can be sampled from live animals in regions where polar bears are protected against hunting, as well from museum specimens that provide information on pre-industrial exposure to mercury. Guidelines drawn up by the World Health Organization and the UN Food and Agriculture Organization for mercury concentrations in human and wildlife hair were used in this assessment to identify the potential mercury risk for polar bears. Mercury levels in polar bear hair show wide variation across the circumpolar Arctic and indicate that mercury risk is greatest for bears in northeastern Canada.

▶Recent increased mercury concentrations in polar bear hair support the prediction that NE Canadian bears are at risk of mercury toxicity. NE Canadian seals are also at risk of mercury toxicity.



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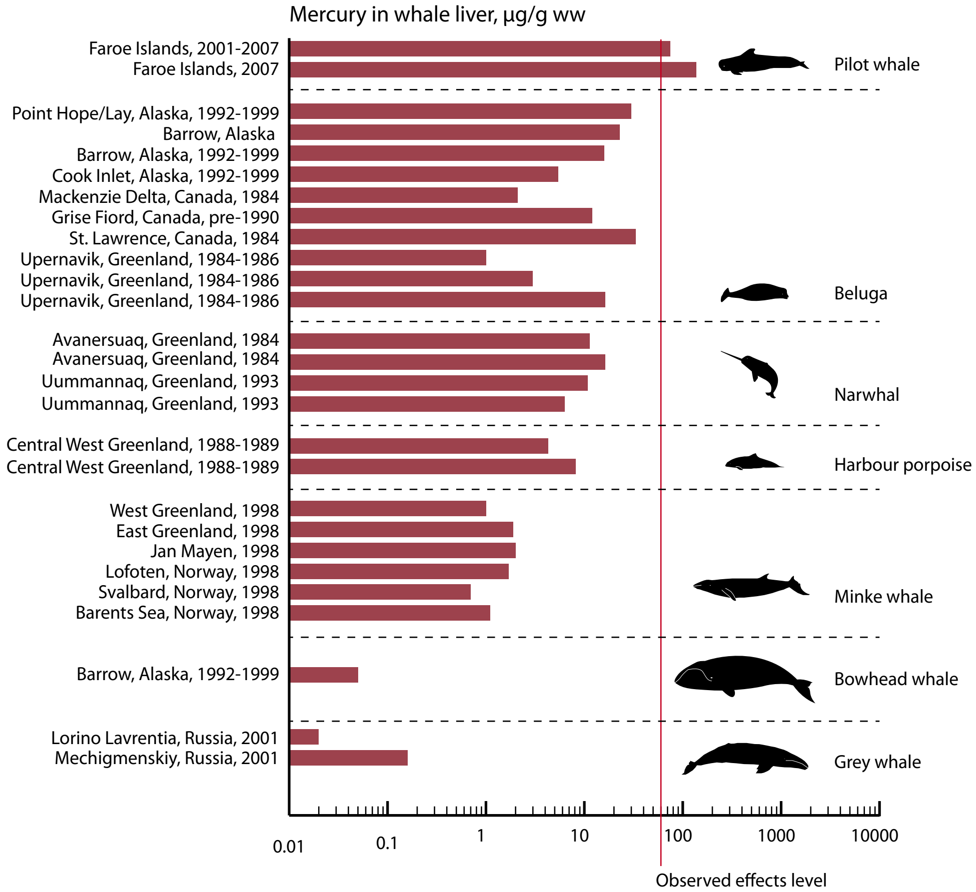


◄Differences in diet explain why baleen whales have relatively low mercury levels whereas toothed whale species have mercury levels that are approaching or exceed toxicological thresholds.

Toxicological effects of methylmercury in predatory freshwater fish include impaired spawning behavior caused by changes in brain chemistry. The mercury toxicity threshold for fish muscle is rarely exceeded in Arctic marine species. In contrast, Arctic freshwater species tend to have higher mercury concentrations than marine species and the generally accepted mercury toxicity threshold has been exceeded by several predatory species, including lake trout, northern pike and landlocked Arctic char.

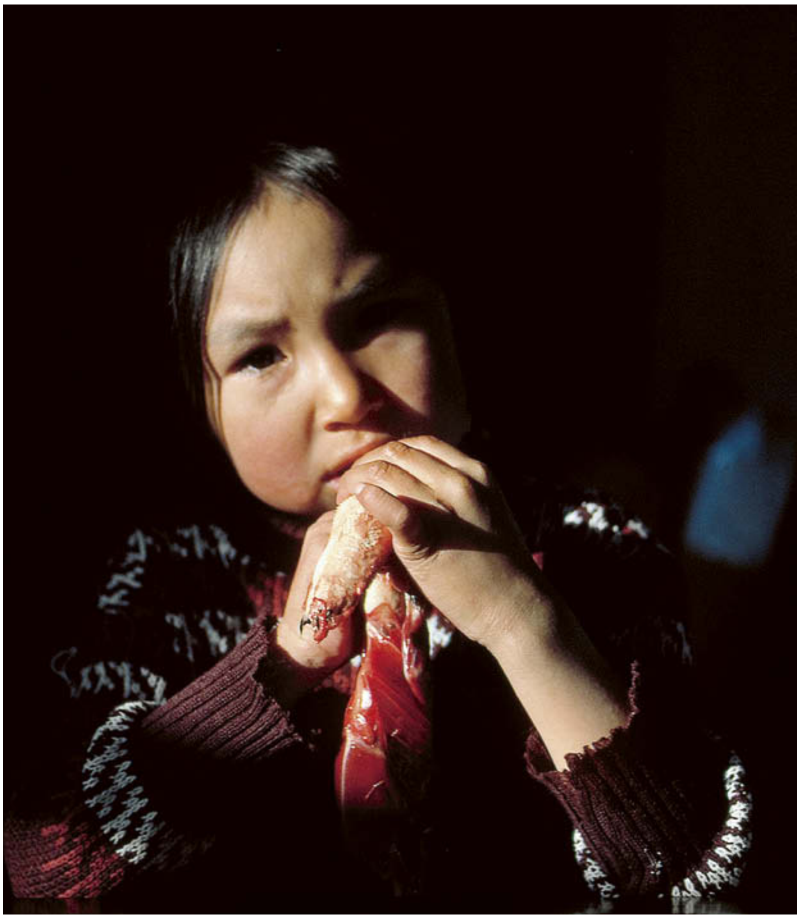
Birds transfer dietary mercury to eggs. As a result, mercury levels in eggs are a good indicator of mercury risk to reproduction in birds. Toxicological effects include reduced hatching success (embryos dying inside the egg), smaller clutches, and deformed embryos. Although mercury concentrations in most Arctic seabirds feeding on the pelagic food web do not appear to be high enough to affect reproduction or survival, there have been recent reports of methylmercury concentrations in the eggs of a number of marine birds breeding in the Arctic (ivory gull and black guillemot) that are at or above the effects thresholds.

◄Seabird egg datasets from Canada, the Faroe Islands and Norway confirm the pattern for more recent increasing trends in mercury concentration in the western Arctic relative to the eastern Arctic. Almost all the mercury in seabird eggs occurs as methylmercury.

Mercury and human health

A traditional diet based on marine mammals and fish is the main source of mercury exposure for Arctic indigenous peoples. The extent of the exposure via a diet rich in traditional/local food items depends on the species chosen, the tissues and organs consumed, the age and sex of the animal, and the time and place that the animals were caught. Arctic indigenous communities have long relied on hunting and fishing as the basis of their social, cultural, and spiritual well-being and so are particularly vulnerable to the impacts of mercury (and other contaminants) in these traditional/local foods. As a result, indigenous people are being faced with the need to balance the benefits conferred by this readily available source of essential nutrients and vitamins against the health risks from the contaminants they contain.

▼Inuit girl eating little auk in Savissivik, NW Greenland.



The situation is further complicated by the 'nutritional transition' which has been taking place for indigenous peoples all over the world. This is associated with industrialization, urbanization, and the globalization of markets, and involves a switch from traditional/local foods to a more 'western' diet high in refined carbohydrates and saturated fats. Within the Arctic, the nutritional transition is primarily linked to economic development bringing Arctic residents into greater contact with outside influences.

Potential for health risk

It has been known for some time that the potential toxic effects of mercury in humans include adverse impacts on the reproductive system, the immune system, and the nervous system. There is now evidence, including evidence from Arctic studies, that mercury may also affect the cardiovascular system.

Mercury concentrations in animals forming part of the traditional diet vary depending on whether they are from the land or the sea, their position in the food chain (in general, the higher up the food chain the higher the mercury levels), their age, and where they feed. There is also significant variation within the animal itself, with concentrations tending to increase in the order fat, muscle, kidney, and liver. This has a bearing on which parts of the animal may exceed guidelines for safe consumption and is reflected in dietary advice aimed at limiting mercury intake (see box on facing page). The chemical form of the mercury is also important: with mercury mostly present as (toxic) methylmercury in muscle, and in (less toxic) inorganic forms in kidney and liver.

High levels of other contaminants in marine foods, such as polychlorinated biphenyls (PCBs), can exacerbate the toxic effects of methylmercury in the diet.

Communicating risk of mercury exposure

Communicating risk is a difficult task and is most effective when undertaken with the engagement of the local community. As the following example shows, risk communication undertaken in a responsible manner can achieve highly beneficial results.

Pilot whale has always been an important part of the marine-based diet in the Faroe Islands. However, the mercury content of pilot whales is high and studies in the 1980s and 1990s showed that high mercury exposure in children born to mothers eating pilot whale meat could be linked to small but significant delays in brain development (language, attention, memory) that persisted throughout childhood.

Compared to other circumpolar countries, the situation in the Faroe Islands is unique in that the high mercury intake is due almost entirely to a single food item, the pilot whale. This has made it relatively easy for the authorities to issue guidance on how to reduce mercury exposure through changes in the diet. The 1998 guidance recommended that pilot whale liver and kidney should never be eaten, and that adults should only eat muscle ('meat') once or twice a month, while women who were pregnant, planning to become pregnant, or breast feeding – should not be eating it at all. In 2009, it was recommended that pilot whale should no longer be used for human consumption.

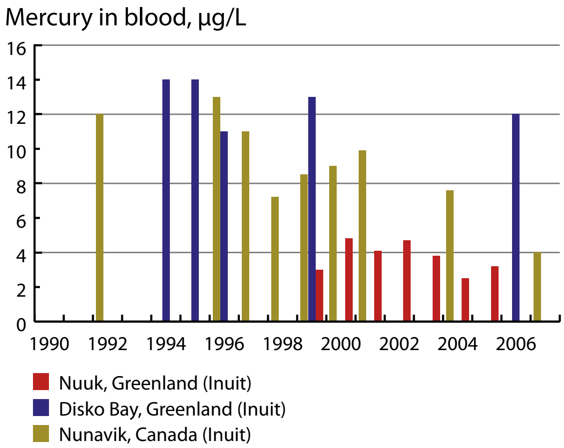
Pregnant women in the Faroe Islands have clearly followed the advice to avoid pilot whale in their diet, as there has been an almost eight-fold fall in blood mercury levels over the past two decades (1986 to 2009).

Trends in exposure

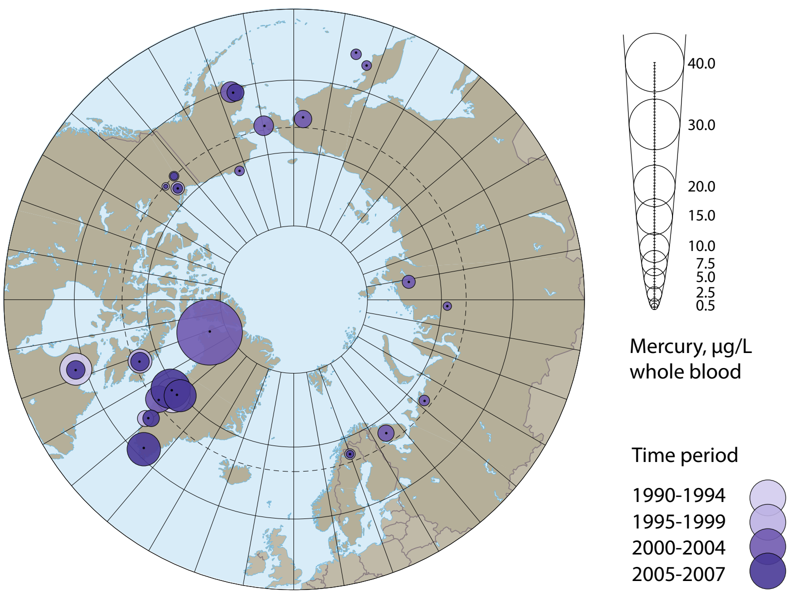
Mercury can be transferred across the blood-placenta barrier and the developing fetus and young children are particularly vulnerable to mercury exposure through their mothers. For this reason, health studies in the Arctic have a special focus on measuring mercury levels in the blood and hair of pregnant women. Among mothers, pregnant women, and women of child-bearing age, recent studies show that mercury exposure is greatest in coastal communities with a marine-based diet (Arctic regions of Canada and Greenland) and lowest in inland communities with a land-based diet (Russia, Sweden).

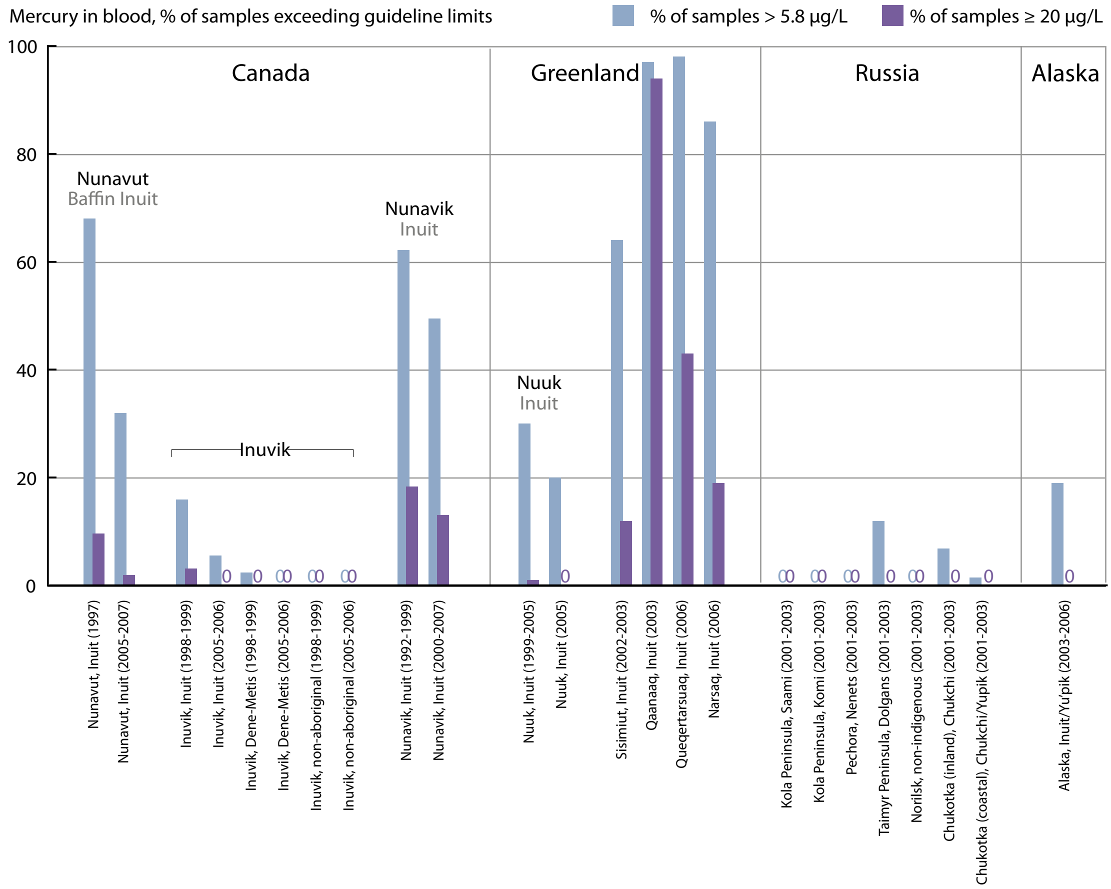
Blood mercury levels in mothers have generally decreased in almost all circumpolar regions studied since the 1990s. This includes parts of Alaska, Arctic Canada, and northern Sweden. Much of this decline is probably due to a switch away from the more contaminated traditional/local foods (in some cases possibly following dietary advice – see box), the general shift towards a more 'western' diet and possibly, in some cases, lower mercury levels in food species.

Guidelines for safe levels of mercury in blood have been established in Canada and the United States. By using these guidelines to examine all the datasets available, it is possible to see that



◄ ▼ Despite a general fall in maternal blood mercury levels, concentrations in some parts of the Arctic are still high, particularly in Inuit from West Greenland.

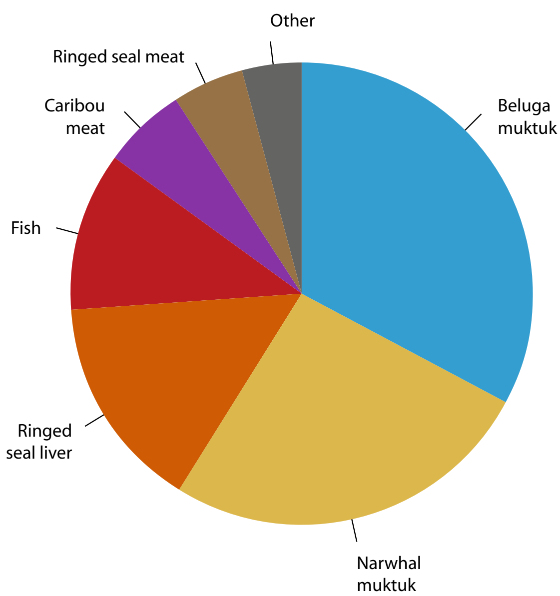




▶ The percentage of mothers and women of child-bearing age in Greenland that exceed guideline limits for mercury in blood is extremely high.

▶ Some Inuit women of child-bearing age in Canada and Greenland, that consume marine mammals, have mercury levels between three and ten times higher than people in other areas of the Arctic who rely on store-bought food.

the proportion of mothers and women of child-bearing age with blood mercury concentrations exceeding these guideline levels has decreased across the Arctic. However, mercury exposure in parts of the Arctic continues to be high. For example, blood mercury concentrations in over 90% of women of child-bearing age in some areas of Greenland still exceed the guideline levels, and a study on Inuit pre-school children in Nunavut, Canada, found that 59% of the children surveyed had a methylmercury intake that exceeded the acceptable intake level for children.



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◀ In the study of Inuit pre-school children in Nunavut, Canada, the top contributors to mercury intake from commonly consumed traditional foods were beluga and narwhal muktuk. Caribou meat, the most highly consumed traditional food was responsible for only 6% of the mercury intake due to its low mercury concentration.

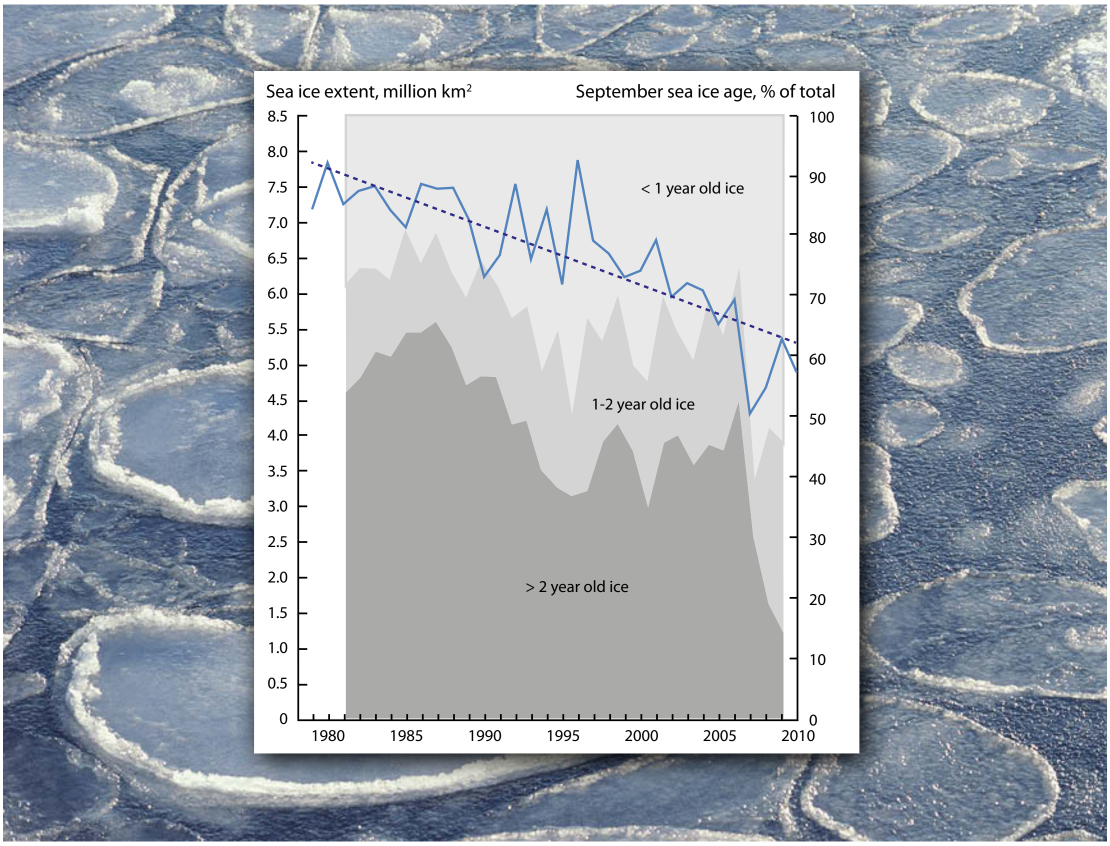
The impact of climate change

The Arctic is especially vulnerable to the increase in global warming that is predicted for the coming decades. Models and measurements suggest that by the end of the 21st century, the temperature increase in the Arctic is likely to have been double the global average. A temperature increase of this magnitude would cause unparalleled change in the Arctic environment. For the cryosphere – the frozen part of the Earth's surface – the critical warming will occur at around -2 °C to 0 °C. This is the point at which ice starts to melt and frozen land begins to thaw.

Effects on physical systems

Surface air temperature is increasing in much of the Arctic and the weather is becoming less predictable. Warmer temperatures are likely to produce a cascade of effects, many of which will impact on the mercury cycle. A loss of summer sea ice in the Arctic will mean that the sun's energy is no longer reflected back into space but instead warms the upper layers of the ocean, storing up heat that would feed back into the atmosphere in the following autumn. This would in turn cause changes in the atmospheric pressure patterns. Interestingly, a major change in the atmospheric pressure patterns across the Arctic over the past decade has resulted in more southerly winds. This change in the prevailing winds is likely to have altered the transport of mercury into and out of the Arctic.

Warming in the lower atmosphere is also causing major changes in the freshwater and terrestrial systems. Among many examples, the snow season is getting shorter, lakes have less ice, ice is breaking up earlier on rivers, glaciers and ice fields are shrinking, and permafrost is thawing. Although these effects in the physical



◄ Summer (September) sea ice extent is now declining at 11.2% per decade. Extending this trend (blue line) into the future suggests that the Arctic Ocean could be ice free in summer by around 2080 or sooner. In addition, the age of Arctic sea ice has changed dramatically in recent years (grey shading) with far less ice persisting for more than a year. This results in thinner ice that is easier to melt in summer. Sea ice acts as a barrier to the air-sea exchange of mercury – as sea ice declines, the potential for air-sea fluxes will increase.

Impacts on the mercury cycle

© Bryan & Cherry Alexander / Arcticphoto

Bromine emitted from refreezing leads is believed to be a major factor in the atmospheric chemistry that leads to enhanced mercury deposition in the Arctic. A decrease in sea ice may affect the distribution of these leads and thus future atmospheric mercury deposition in the Arctic.

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Inorganic mercury can only be converted into methylmercury when wetlands are not frozen. As warming is causing thawing to start earlier in the year and freezing to start later in the year, warming could translate into greater production of methylmercury in wetlands.

© USGS

Mercury deposited onto glaciers and ice sheets in snow and incorporated into the ice over decades, may be released into the environment as the ice melts. Glacier melt in particular has the potential to alter mercury levels in receiving water bodies, at least at local scales. Sea ice does not accumulate mercury in the same way as it is generally only a few years old at most.

© Galen Rowell / Corbis

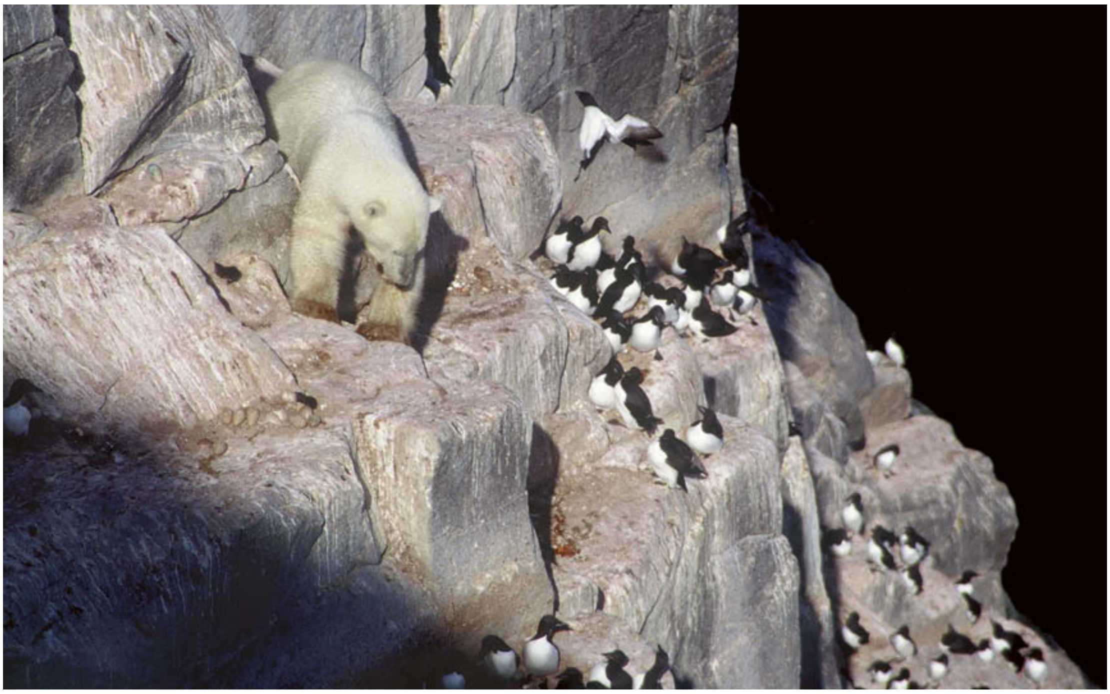
As permafrost thaws mercury is released. Permafrost temperatures have increased by up to 2 °C over the past three decades. This may be important for mercury deposited from the air and stored at the surface of the frozen ground because this mercury is thought to 'fast track' into Arctic food webs.

© Paul Hamilton

Arctic lakes have been losing their ice cover. The earlier opening of lakes to light in spring leads to higher levels of biological production, but what this means for the mercury cycle is not yet clear. As well as other effects, greater productivity in lakes could increase the rate of methylmercury production.

© Lowell Georgia / Corbis

River discharge from Arctic drainage basins has increased and is projected to continue to increase. Because mercury concentrations in Arctic rivers increase as flow increases, any increase in river discharge implies a corresponding increase in mercury inputs from rivers. Rivers are already a significant source of mercury input to estuaries and semi-enclosed bays of the Arctic Ocean.



© Kerry Woo

◀ When sea ice forms later in the year, hungry polar bears that are unable to hunt seals from the ice are forced to turn to other food sources.

environment will all affect the mercury cycle (see box for some examples), it has been argued that it is those climate change effects that impact on the production of methylmercury that may be the most important from the perspective of human and ecological health.

It has long been recognized that big changes are taking place within the wet environments of the Arctic (wetlands, marine and freshwaters). This is important because it is here that most of the processes changing inorganic mercury into methylmercury are taking place, and so it is here that most of the mercury risk to humans and wildlife is occurring.

Effects on food webs

There is little direct evidence of interactions between climate warming and mercury bioaccumulation in Arctic freshwater food webs. Nevertheless, the climate change effects most likely to drive change in freshwater systems (temperature change, change in water chemistry, change in the water cycle) will probably affect food webs in ways that will alter the uptake and transfer of mercury. Mercury bioaccumulation may increase in some food chains and decrease in others, with the net effect varying from place to place depending on regional differences in the structure of food webs and their responses to environmental change.

Key factors affecting mercury bioaccumulation in freshwater food webs are food availability, growth, and ecosystem productivity.

- **Food availability**. *Daphnia* (a type of water-flea) has higher levels of methylmercury than other freshwater zooplankton species in the High Arctic. Because their numbers are related to ecosystem productivity, any climate-driven increase in lake productivity could mean a greater transfer of mercury into fish that feed on *Daphnia.*
- **Growth**. Long-term warming of freshwaters is likely to increase fish growth rates which may, in turn, affect their bioaccumulation of mercury. This is because fish with higher growth rates tend to have lower mercury concentrations (the ‘biodilution’ effect).
- **Ecosystem productivity**. Mercury bioaccumulation is greatest in fish feeding at the tops of food chains. It has been speculated that climate warming may have consequences for mercury bioaccumulation in large predatory fish species. This may be due to changes in the distribution of species, productivity relationships, and/or the length of the freshwater food chain (i.e., number of species involved).

Climate-driven change in these ecosystem variables could influence the uptake and flow of mercury through the freshwater food webs, for example, through the introduction of invasive species.

Ringed seal feeding behavior and changes in mercury intake

A recent study examined possible links between feeding behavior and muscle mercury concentrations in ringed seals from the western Canadian Arctic. The seals were caught during the subsistence harvest (mainly in June and before the break-up of the sea ice) over the period 1973 to 2007. Ringed seals have a varied diet, but mainly consume Arctic cod during the ice-covered period.

The results showed a clear relationship between muscle mercury concentration and the length of the ice-free season the previous summer. This suggests that the length of the ice-free season may have influenced the ringed seal diet in the following autumn, which in turn suggests that changes in climate were indirectly responsible for the variation in mercury intake indicated by the change in muscle mercury levels. Because the length of the ice-free season in the Arctic is predicted to increase, it is possible that mercury concentrations in ringed seals may also increase.

Many of the climate-driven impacts predicted for marine food webs are associated with the progressive loss of summer sea ice. For example, polar bears use sea ice as a platform from which to hunt their main prey item, ringed seal. Less sea ice reduces these hunting opportunities, potentially changing the bear's mercury intake through a switch in diet. Another study found higher muscle mercury concentrations in ringed seals following ice-induced changes in feeding behavior (see box). Changes in the concentration and thickness of sea ice may increase access to areas that were previously inaccessible and so provide new feeding opportunities for ice-associated species such as beluga, narwhal and bowhead whales. The extent to which this will alter their exposure to mercury will depend on their ability to adapt to these changes.

A modeling study has suggested that an increase in water temperature of up to 1.0 °C as a result of climate warming could result in a several percent increase in methylmercury levels in Arctic species such as pilot whales and cod.

Change within the Arctic is now accelerating rapidly. It will be very difficult to predict how future climate change will affect mercury exposure to humans and the wider Arctic ecosystem. Climate change could also affect the extent to which the Arctic acts as a sink for mercury.

Future trends in mercury emissions

As long as global economic activities continue to increase, and current patterns, practices and uses are maintained, mercury pollution will continue to increase worldwide. Deciding how best to reduce these emissions and minimize their impacts on the Arctic environment and on human health requires a good understanding of how the Arctic Ocean and atmosphere will respond to emission reduction measures.

Projections for global mercury emissions to 2020 suggest that the development and implementation of technologies to reduce mercury emissions could have a significant impact. In a preliminary study, three different emissions scenarios were considered: **status quo** (current patterns, practices and uses continue, while economic activity increases in various regions), **extended emissions control** (mercury-reducing technologies currently used in Europe and North America implemented elsewhere and Europe's current emissions control measures implemented worldwide), and **maximum feasible technological reduction** (implementation of all available solutions and measures to reduce mercury).

Under the 'status quo' scenario, mercury emissions increased by around 25% by 2020 (relative to emissions in 2005). Most of the extra emissions are expected to occur in Asia and to come from the combustion of coal. Implementing the 'extended emissions control' scenario would more than halve the emissions projected for the status quo scenario and bring significant reductions compared to 2005 emissions levels. Meanwhile, the 'maximum feasible technological reduction' scenario reduces emissions by the greatest factor of all.

Assuming no changes in air movement patterns (due to climate change) the status quo scenario increases the annual flux of gaseous mercury to the Arctic by around 3% by 2020 (with increases greater in areas closest to the source regions), while the two remaining scenarios bring decreases of around 10%. This in turn could lead to increases in mercury deposition (amplified in the Arctic by atmospheric mercury depletion events) of around 5% under the status quo scenario, or decreases of up to 20% under the two remaining scenarios. There are many assumptions and uncertainties in

▼Rapid expansion of some economies has increased demand for cement, production of which is an important source of mercury emissions to air.

the model results, owing to a lack of knowledge about bromine chemistry and its impact on atmospheric mercury depletion events, and to the effect of re-emissions of mercury.

Oceans are the other major transporter of mercury to the Arctic. The Arctic Ocean is split into two main domains, with the eastern Arctic surface waters communicating predominately with the Atlantic Ocean (and carrying contamination from Europe and North America), and the western Arctic surface waters communicating predominately with the Pacific Ocean (via the Bering Strait), bringing contamination from Asian sources. This east-west split could explain the differences apparent in mercury levels in the top marine predators in each of these regions. It is not clear how these ocean transport systems might change in the future, but if Asian emissions increase in the future the western Arctic may see a greater increase in mercury levels relative to the eastern Arctic.

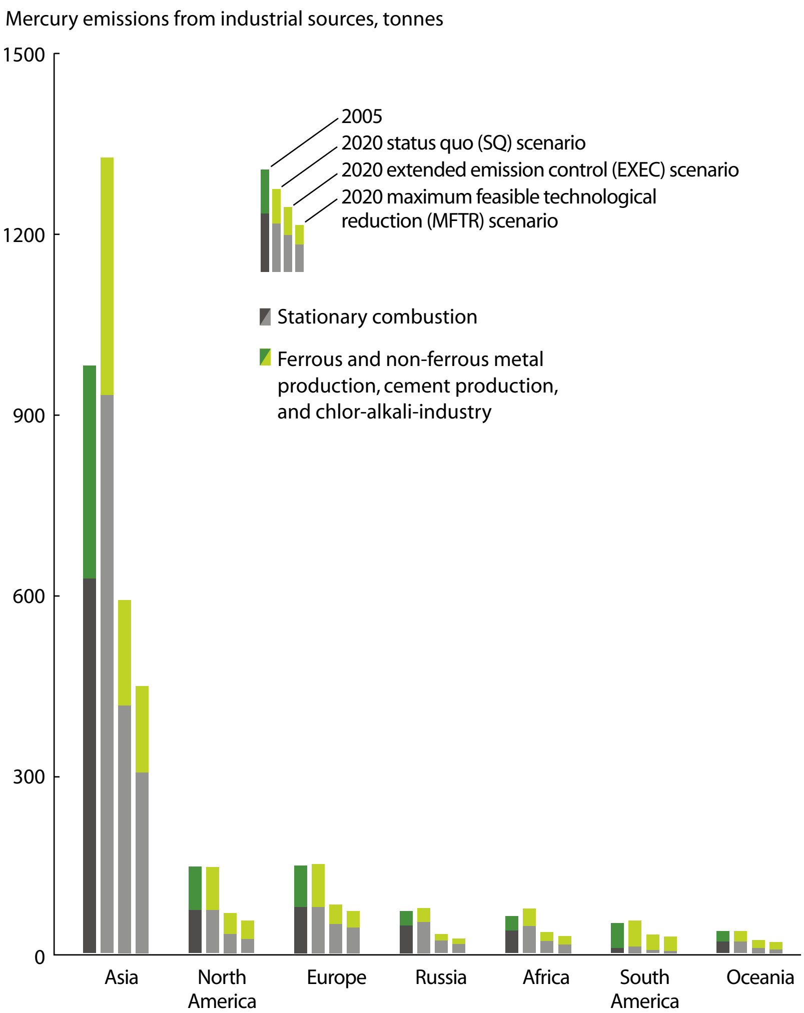
Given that mercury has a relatively short lifetime in the atmosphere compared to the ocean, any efforts to reduce emissions will be realized quickly, and a decrease in atmospheric transport of mercury to the Arctic could be expected to occur within a few years of implementing the changes. However, there may be a significant lag in the time taken for these decreases to feed through into mercury levels measured in ice, sediments and biota.

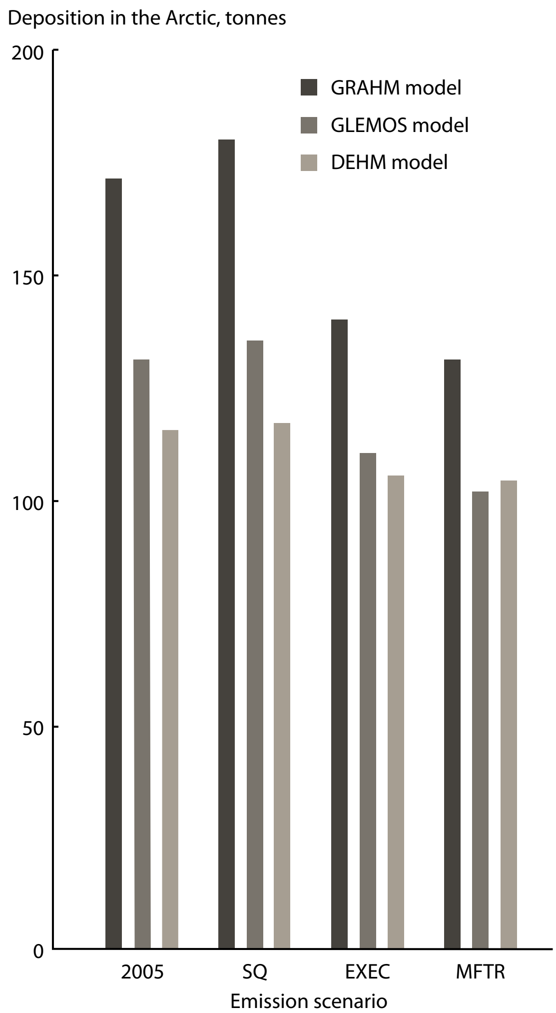
Recovery in the ocean can be expected to take a lot longer – up to 35 years in Arctic Ocean surface waters. Ocean models suggest that a 5% reduction in mercury emissions globally would lead to a 2.4% drop in the western Arctic Ocean and a 2.1% drop in the eastern Arctic Ocean by 2020, for example. Given the slow timescale of mercury circulation through the ocean, it is important that emissions reductions are implemented as soon as possible.

On the basis of these recovery times, it should be possible to calculate which mercury reduction measures would bring the greatest benefits, and at the smallest costs. Scientists are currently investigating these issues.

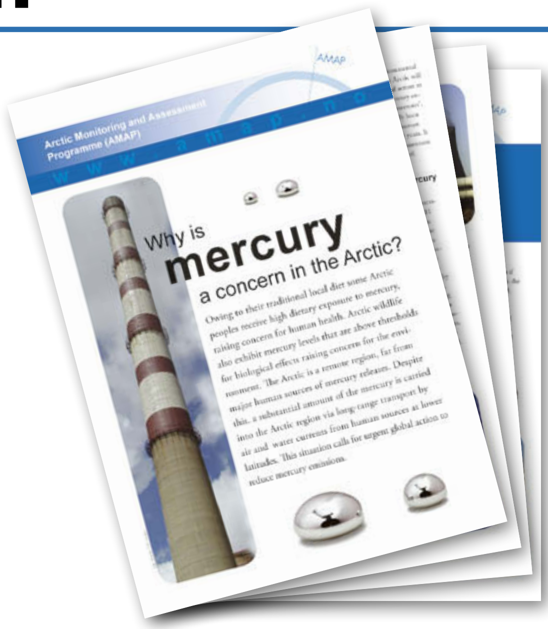
▼Simplified scenarios have been used to estimate possible global mercury emissions to air in 2020 relative to those in 2005.

▶The emission scenarios have also been used in three different models to estimate consequences for future deposition in the Arctic.





Need for action



Previous AMAP assessments have reported that a substantial amount of the mercury in the Arctic has arrived via long-range transport from human sources at lower latitudes and that, owing to their traditional diet some Arctic populations receive high dietary exposure to mercury, raising concern for human health. This situation has prompted calls for global action to reduce mercury emissions.

However, fundamental questions remain as to what controls mercury levels in the Arctic, and how (and when) these levels are likely to fall in response to controls on emissions. The cycling of methylmercury (one of the most toxic forms of

International action on mercury

Information on mercury in the Arctic has been reported by AMAP in 1997 and 2002. The 1997 AMAP report supported negotiations that led to the adoption of the Heavy Metals Protocol to the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP) in 1998. The Protocol targets mercury (and also lead and cadmium) and parties to the Protocol are required to reduce their total annual emissions to below the levels they emitted in 1990.

There have been 36 signatories to the Protocol (as of 1 March 2011), including all Arctic countries with the exception of the Russian Federation, and 30 countries have now also ratified. All Arctic countries have ratified the protocol, except for Iceland (which has signed but not ratified), the United States (which has 'accepted' but not ratified), and the Russian Federation. The Protocol entered into force in 2003.

In 2000, after the Barrow Agreement, the Arctic Council of Ministers called on UNEP to initiate a global assessment of mercury that could form the basis for appropriate international action, and in February 2001 UNEP's Governing Council decided to initiate the *UNEP Global Mercury Assessment*.

In 2003, UNEP agreed that there was sufficient evidence of significant global adverse impacts from mercury and its compounds to warrant further international action to reduce the risks to human health and the environment from the release of mercury and its compounds to the environment. In 2009, UNEP began a process aimed at negotiating, by 2013, a legally-binding international agreement to limit emissions of mercury. If implemented, this agreement has the potential to significantly reduce Arctic mercury contamination.

Since 2005, AMAP has worked closely with UNEP to support the UNEP mercury process and parts of the 2011 AMAP assessment on Mercury in the Arctic have been specifically developed to support the ongoing negotiations.

Action is also taking place at the regional level. Between 2003 and 2008, the Arctic Council endorsed the Arctic Contaminants Action Program (ACAP) 'Mercury Project' *Reduction of Atmospheric Mercury releases from Arctic States*. The project identified the main sources of mercury emission within the Arctic region and identified and prioritized possible reduction measures. Furthermore, risk communication has proved an effective means for helping reduce mercury exposure in some areas of the Arctic (see box on page 29).

Although there is not yet a legally-binding global agreement to reduce emissions of mercury, many countries are already taking steps to lower their emissions.

Costs to the global economy?

The impact of mercury pollution goes way beyond the Arctic, and if ignored could have significant economic effects for everyone. One recent study estimated that the 25% rise in mercury emissions projected to occur between 2005 and 2020 (if measures are not taken to reduce emissions) could cost the global economy USD 3.7 billion a year, due to diminished IQ associated with mercury exposure alone. Conversely, scenarios where mercury emissions are reduced by around 50% by 2020 are projected to bring a global economic benefit of between USD 1.2 and 1.8 billion a year. Put this way, it is clear that tackling mercury pollution is not only beneficial for the environment but also makes sound economic sense.

mercury and the one that biomagnifies through Arctic food webs causing some animals at the tops of food chains to exceed thresholds for biological effects) is paramount in this respect. The likely impact of future climate change in altering mercury delivery and fate in the Arctic is also extremely important.

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▶Large stockpiles exist in Europe, North America and elsewhere of mercury taken out of use in industrial applications. These stockpiles need to be stored properly and their future fate is under debate.

This AMAP assessment on mercury in the Arctic, attempts to address these questions and to provide the most up-to-date information currently available on global sources, pathways to the Arctic, and the biogeochemical cycling and fate of mercury in the Arctic, including the uptake and accumulation of mercury within the Arctic food web and the associated ecological and human health risks. The report also examines the potential for climate change to significantly alter mercury pathways and fate in the Arctic.

Mercury continues to present risks to Arctic wildlife and human populations. It is a particular concern that mercury levels are continuing to rise in some Arctic species in large areas of the Arctic. Risk communication and dietary advice have been used to reduce human mercury exposure in some regions of the Arctic, but to reduce human (and environmental) exposure to mercury in the Arctic will ultimately depend on global action to reduce the quantities of mercury entering the environmental reservoirs in which it has accumulated over the past 150 years. This assessment confirms the need for more concerted international action if mercury levels in the Arctic are to be reduced. Agreements such as those implemented by the United Nations Economic Commission for Europe (UNECE) and planned by the United Nations Environment Programme (UNEP) are therefore particularly relevant.