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Arctic Pollution 2002

Persistent Organic Pollutants
Heavy Metals
Radioactivity
Human Health
Changing Pathways

Contents

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Preface

The Arctic Monitoring and Assessment Programme (AMAP) is a group working under 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;*
- *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'. 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 series of five related reports: the AMAP Assessment 2002 reports, which are 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 2002 reports.

This report is the second '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 second phase (1998-2002) in relation to five priority areas: persistent organic pollutants, heavy metals, radioactivity, human health, and pathways of contaminants. The assessment described in this report builds upon the previous AMAP assessment that was presented in two volumes, the comprehensive Arctic Pollution Issues: A State of the Arctic Environment Report and its related scientific background document AMAP Assessment Report: Arctic Pollution Issues, published by AMAP in 1997 and 1998, respectively.

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 from Germany, the Netherlands, and the United Kingdom, 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 were 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 assessments, 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 assessments that provide the basis for this report. Special thanks are also due to the authors of this report, Annika Nilsson and Henry Huntington. The authors 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 from 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. However, this assessment could not have been delivered without the additional financial support received from Canada, Denmark, Finland, Norway, Sweden and the United States; and from the Nordic Council of Ministers and the Netherlands. These finances also support the participation of indigenous peoples organizations in the work of AMAP.

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 their second assessment for the consideration by governments of the Arctic countries. This report is prepared in English and translated into several other languages. The English language version constitutes the official version.

Rovaniemi/Ivalo, October 2002.

Helgi Jensson
AMAP Chair

Lars-Otto Reiersen
AMAP Executive Secretary

A Statement prepared by the Indigenous Peoples Secretariat on behalf of Arctic Council Permanent Participants: A Call for Further Action

The Arctic is our homeland. Places that others call remote are central to our existence and have been for millennia. We, the Indigenous Peoples of the Arctic, wish to protect a way of life based on a unique economic and spiritual relationship to the land. Yet, because the wild foods we eat and water we drink are inextricably linked to the overall health of the northern biosphere, our long-term health and survival as cultures and societies depends upon Arctic nation states acting as responsible stewards of the Arctic environment.

While enjoying the benefits of wage-based employment in the modern economy, Arctic Indigenous Peoples continue to use and occupy huge areas of land and ocean for hunting, fishing, trapping, herding, and gathering. The extent and intensity of this land use, including species harvested, is well documented. Indeed, many Arctic Indigenous Peoples have legally recognized and enforceable rights to the land they use. Even so, the interconnectedness of Arctic ecosystems makes multi-lateral cooperation for the protection of the environment a necessity for both Indigenous Peoples and Arctic nation states.

Recognition of the circumpolar dimension of the Arctic environmental issues remains the central political reality for both Arctic nation states and Indigenous Peoples organizations. The need for Arctic international cooperation is most clearly evident in matters relating to preserving and protecting Indigenous Peoples' traditional food and diet. The species harvested and eaten vary widely. They include the domestic reindeer and fish-rich diets of Nenets or Saami, the marine mammal-rich diet of the Inuit, to the importance of wild caribou and salmon to the Athabaskan and Gwich'in peoples. The central and most distinguishing feature of the modern Arctic indigenous economy continues to be its dependence on wildlife and the habitat that supports it.

To Arctic Indigenous Peoples persistent organic pollutants, heavy metals and radioactivity in traditional food is not just an environmental or public health issue.

As one Inuit Leader recently observed, the process of hunting and fishing, followed by the sharing of food and the communal partaking of one animal, is a time honoured ritual which links Indigenous Peoples to their ancestors and to each other. The power of this connection holds Indigenous Peoples together as peoples and gives them the spiritual strength and physical energy to survive the challenges they face. To discover that the food which for generations has nourished them and kept them whole physically and spiritually is now poisoning them is profoundly disturbing and threatens Indigenous Peoples' cultural survival.

Having learned of transboundary contamination problem in the Arctic through what were essentially reconnaissance studies, the Inuit Circumpolar Conference, Saami Council, and the Russian Association of Indigenous Peoples of the North became staunch supporters of and participants in AMAP. They appreciated the need for a detailed and comprehensive examination of the issue as a prelude to doing something about it.

Since the release of the 1997 AMAP assessment report, three more Indigenous Peoples' organizations have joined the Arctic Council – the Aleut International Association, the Arctic Athabaskan Council, and the Gwich'in Council International. These groups share the concerns about the long-term impact of contaminants.

The Indigenous Peoples of the Arctic acknowledge the instrumental role AMAP has played in a number of international processes that have a direct effect on our ability to remain on the land and continue to use its resources in ways of our own choosing.

It has raised significantly the profile of environmental contamination in the Arctic as a public policy issue. But it is not the reports alone that account for this. The inclusive manner in which they were developed over a number of years by scientists from many countries, and consensus decision-making by the programme ensured that the reports and resulting recommendations were well received and considered seriously by Arctic governments. Participation of the Arctic Indigenous Peoples has been an important part of this process.

Arctic Indigenous Peoples influenced the global POPs negotiations out of all proportion to their numbers. They were able to do so, in part, because they had learned much through AMAP about transboundary contaminants in the Arctic.

Indigenous Peoples of the Arctic continue to support AMAP's efforts to assess levels of contamination in the part of the world that includes our homelands. Indigenous Peoples will continue to be involved in projects in their regions. We are also pleased that the inclusive model of working with Indigenous Peoples' organizations that was developed in the first AMAP assessment has been adopted by the Arctic Climate Impact Assessment.

The Indigenous Peoples of the Arctic continue to see contaminants and climate change variability as a major threat to our collective survival as Peoples. We call on the Arctic States to continue supporting the work of AMAP and, through financial and other support, ensure the active involvement of the Arctic's Indigenous Peoples.

We also expect the success of the Stockholm POPs Convention, where Indigenous Peoples and AMAP data played a significant role, to be repeated with the global mercury assessment now underway, and in other processes in the future.

To that end, Arctic Indigenous Peoples call upon the nations of the world to increase efforts to develop international instruments to deal with the effects of mercury and other heavy metals that the threaten the human and environmental health of the Arctic and the world.

The Indigenous Peoples' Secretariat works on behalf of the six Arctic Indigenous Peoples Organizations that are Permanent Participants at the Arctic Council.

Executive Summary

of the AMAP 2002 assessment of Arctic pollution issues, as adopted by the AMAP Working Group, May 3, 2002.

The Arctic Monitoring and Assessment Programme (AMAP) was established in 1991 to monitor identified pollution risks and their impacts on Arctic ecosystems. In 1997 the first AMAP report, *Arctic Pollution Issues: A State of the Arctic Environment Report** was published.

The assessment showed that the Arctic is closely connected to the rest of the world, receiving contaminants from sources far outside the Arctic region. The report was welcomed by the Arctic Council Ministers, who agreed to increase their efforts to limit and reduce emissions of contaminants into the environment and to promote international cooperation in order to address the serious pollution risks reported by AMAP.

The AMAP information greatly assisted the negotation of the protocols on persistent organic pollutants (POPs) and heavy metals to the United Nations Economic Commission for Europe's Convention on Long-range Transboundary Air Pollution (LRTAP Convention). They also played an important role in establishing the need for a global agreement on POPs, which was concluded in 2001 as the Stockholm Convention. Persistence, long-range transport, and bioaccumulation are screening criteria under both the POPs protocol and the Stockholm Convention, to be applied to proposals to add substances to the agreements. Information from AMAP will be useful in this context in showing whether persistent substances are accumulating in the Arctic and are therefore candidates for control, and also in assessing the effectiveness of the agreements.

The Arctic Council also decided to take cooperative actions to reduce pollution of the Arctic. As a direct follow up of the AMAP reports, the Arctic Council Action Plan to Eliminate Pollution of the Arctic (ACAP) was created to address sources identified through AMAP. ACAP was approved in 2000 and several projects have begun. The AMAP information was also used in establishing priorities for the Arctic Regional Programme of Action to Prevent Pollution from Landbased Sources (RPA), developed by the working group on Protection of the Arctic Marine Environment (PAME), and adopted by the Arctic Council in 1998.

After the first assessment, AMAP was asked to continue its activities and provide an updated assessment on persistent organic pollutants (POPs), heavy metals, radioactivity, human health, and pathways in 2002. Five scientific reports and a plain-language report have been prepared. This Executive Summary provides the main conclusions and recommendations of the 2002 AMAP assessments.

International Agreements and Actions

As described above, the LRTAP Convention protocols and the Stockholm Convention are essential instruments for reducing contamination in the Arctic. However, they cannot have any effect until they are ratified and implemented.

It is therefore recommended that:

- **The UN ECE LRTAP Protocols on Heavy Metals and POPs be ratified and implemented.**
- **The Stockholm Convention on POPs be ratified and implemented.**

Specific recommendations for monitoring activities in support of these agreements are included in subsequent sections.

Persistent Organic Pollutants

The POPs assessment addresses several chemicals of concern, including both substances that have been studied for some time and chemicals that have only recently been found in the environment.

The 1997 AMAP assessment concluded that levels of POPs in the Arctic environment are generally lower than in more temperate regions. However, several biological and physical processes concentrate POPs in some species and at some locations, producing some high levels in the Arctic.

* AMAP, 1997. Arctic Pollution Issues: A State of the Arctic Environment Report. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xii+188 pp.
AMAP, 1998. AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xii+859 pp.

The present AMAP assessment has found that the conclusions and recommendations of the first assessment remain valid. In addition:

It has clearly been established that:
Certain Arctic species, particularly those at the upper end of the marine food chain as well as birds of prey, carry high levels of POPs. Marine mammals, such as polar bear, Arctic fox, long-finned pilot whale, killer whale, harbor porpoise, minke whale, narwhal, beluga, harp seal and northern fur seal, some marine birds including great skua, great black-backed gull and glaucous gull, and birds of prey such as peregrine falcon, tend to carry the highest body burdens.

Most of the total quantity of POPs found in the Arctic environment is derived from distant sources. The POPs are transported to the Arctic by regional and global physical processes, and are then subjected to biological mechanisms that lead to the high levels found in certain species. Several potential source regions have now been identified within and outside of the Arctic. A better understanding of local redistribution mechanisms has also emphasized the important potential role of local processes and sources in determining observed geographical variability.

There is evidence that:
Adverse effects have been observed in some of the most highly exposed or sensitive species in some areas of the Arctic. Several studies have now been completed on a number of Arctic species, reporting the types of effects that have been associated in non-Arctic species with chronic exposure to POPs, of which there are several examples. Reduced immunological response in polar bears and northern fur seals has led to increased susceptibility to infection. Immunological, behavioral, and reproductive effects as well as reduced adult survival has been found in glaucous gulls. Peregrine falcons have suffered from eggshell thinning and reproductive effects. Reproductive effects in dogwhelks are associated with exposure to tributyltin.

It is therefore recommended that:
- **AMAP be asked to further enhance studies aimed at detecting effects in Arctic species relating to exposure to high levels of POPs and to integrate this information with an understanding of general population effects and health.** Without this understanding, it will not be possible to assess whether proposed and existing controls can be expected to afford the necessary protection (e.g., under the LRTAP and Stockholm agreements).

There is evidence that:
The levels of some POPs are decreasing in most species and media in the Arctic, but the rates vary in extent, location and media or species being studied. The decreases can be related to reduced release to the environment. For example, declines in alpha-HCH in air closely follow decreases in global usage, but declines in marine biota are much slower due to a huge reservoir of the substance in the global oceans.

For other POPs, declines are minimal and some levels are actually increasing, despite low current emissions. This illustrates the long period that may pass between the introduction of controls and the resulting decrease in levels in biota, as has been observed for PCBs, toxaphene, and beta-HCH.

It is therefore recommended that:
- **AMAP be asked to continue trend monitoring of POPs in key indicator media and biota.** This will enable assessment of whether the measures taken in the LRTAP Protocol and the Stockholm Convention are being effective in driving down POPs levels in the Arctic.

There is evidence that:
POPs substances other than those included in the LRTAP Protocol and Stockholm Convention may be at or approaching levels in the Arctic that could justify regional and global action. For example, levels of the brominated flame retardants such as polybrominated diphenyl ethers (PBDEs), polychlorinated naphthalenes (PCNs), and some current-use pesticides such as endosulfan have been monitored in Arctic air and biota. PBDEs are increasing in the Canadian Arctic.

It is therefore recommended that:
- **AMAP be asked to maintain a capacity to detect current-use POPs in the Arctic.** This will help ensure that Arctic States have an early opportunity to respond to a trend indicating Arctic accumulation, thus allowing a proactive approach to minimize the contamination rather than having to respond to a more serious situation later.

Heavy Metals

The heavy metals assessment focuses on mercury, lead, and cadmium.

It has clearly been established that:
In the Arctic, mercury is removed from the atmosphere and deposits on snow in a form that can become bioavailable. Enhanced deposition occurs in the Arctic. This recently discovered process is linked to polar sunrise, and is unique to high latitude areas. The resulting enhanced deposition may mean that the Arctic plays a previously unrecognized role as an important sink in the global mercury cycle.

There is evidence that:
Some of the deposited mercury is released to the environment at snowmelt, becoming bioavailable at the onset of animal and plant reproduction and rapid growth. Although poorly understood, this process may be the chief mechanism for transferring atmospheric mercury to Arctic food webs.

It is therefore recommended that:
- **The Arctic Council encourage expanded and accelerated research on critical aspects of the mercury cycle and budget in the Arctic.** Such research should include long-range transport, mercury deposition mechanisms, processes leading to biological exposure and effects, and the influence of climate variability and change on these processes.

There is evidence that:
Despite substantial mercury emission reductions in North America and Western Europe during the 1980s, global mercury emissions may, in fact, be increasing. Mercury emissions from waste incineration are likely underestimated. The burning of coal in small-scale power plants and residential heaters, principally in Asia, are major potential sources of current mercury emissions. These emissions are likely to increase significantly due to economic and population growth in this region.

It is therefore recommended that:
- **The Arctic Council promote efforts at global, regional, and national levels to quantify all sources of mercury and report results in a consistent and regular manner to improve emission inventories.** Particular efforts should focus on measuring contributions made by the burning of coal for residential heating and small-scale power plants as well as by waste incineration.

There is strong evidence that:
There is a trend of increasing mercury levels in marine birds and mammals in the Canadian Arctic, and some indications of increases in West Greenland. The effects of these levels are not well understood. However, there are also examples of stable or decreasing levels in other regions, perhaps indicating the importance of local or regional processes.

It is therefore recommended that:
- **AMAP be asked to continue temporal trend monitoring and the assessment of effects of mercury in key indicator media and biota.** This will enable assessment of whether the measures taken in the LRTAP Protocol are being effective in driving down mercury levels in the Arctic.

There is evidence that:
Current mercury exposures pose a health risk to some people and animals in the Arctic. These risks include subtle neurobehavioral effects.

It is therefore recommended that:
- **In view of the fact that reducing exposure to mercury can only be addressed by regional and global action to reduce worldwide emissions, and acknowledging the assessment for global action undertaken by UNEP and its resulting proposals, the Arctic Council take appropriate steps to ensure that Arctic concerns are adequately addressed and to promote the development of regional and global actions.**

It has clearly been established that:
Dramatic reduction in the deposition of atmospheric lead has occurred in Arctic regions where the use of leaded gasoline is banned. Arctic-wide elimination of leaded gasoline use will reduce lead exposure in other regions of the Arctic. Although levels in wildlife and fish have not measurably declined, likely reflecting continued uptake from the large reservoir of lead deposited in soils and sediments, lead levels in the environment are expected to diminish over time if current trends continue.

It is therefore recommended that:
- **The Arctic Council support continued efforts to eliminate the use of leaded gasoline in all Arctic regions.**

It has clearly been established that:
Certain regions of the Arctic contain elevated lead levels in the environment because of past or current use of lead shot by hunters. Even though lead shot is banned in Alaska, for example, lead blood levels in endangered US populations of Steller's eiders are above known avian toxicity thresholds for lead poisoning, which may be responsible for observed reduced breeding success. In Greenland, lead shot appears to be a significant source of human dietary exposure to lead.

It is therefore recommended that:
- **The Arctic Council encourage a complete ban on the use of lead shot in the Arctic, and that enforcement be improved.**

There is evidence that:
Cadmium levels in some seabirds is high enough to cause kidney damage. Monitoring data on cadmium in the abiotic and biotic environment to date provide no conclusive evidence of trends or effects. However, cadmium accumulates in birds and mammals and not enough is known about possible effects.

It is therefore recommended that:
- **The monitoring of cadmium in the Arctic be continued to support human exposure estimates.**

There is evidence that:
Levels of platinum, palladium, and rhodium have increased rapidly in Greenland snow and ice since the 1970s. These elements are used in automobile catalytic converters to reduce hydrocarbon pollution. The toxicity and bioaccumulation potential of these elements are largely unknown, which prevents assessment of their potential impact in the Arctic.

It is therefore recommended that:
- **AMAP be asked to consider the need to monitor trends of platinum, palladium, and rhodium in the Arctic.**

Radioactivity

The radioactivity assessment addresses man-made radionuclides and radiation exposures deriving from human activities.

It has clearly been established that:
In general, levels of anthropogenic radionuclides in the Arctic environment are declining. Most of the radioactive contamination in the Arctic land environment is from the fallout from nuclear weapons testing during the period 1945 to 1980. In some areas, the fallout from the Chernobyl accident in 1986 is a major source. For the Arctic marine environment, a major source of radionuclides is the releases from European reprocessing plants at Sellafield and Cap de la Hague.

However, releases from the reprocessing plants have resulted in increases in levels of some radionuclides in the European Arctic seas during recent years, in particular technetium-99 and iodine-129. The present doses to the population are low but the present levels of technetium in some marine foodstuffs marketed in Europe are above the EU intervention levels for food to infants and are close to the intervention level for adults.

The technetium information adds further weight to the recommendation made by AMAP to the Arctic Council in Barrow in 2000 that:
- **'The Arctic Council encourage the United Kingdom to reduce the releases from Sellafield to the marine environment of technetium, by implementing available technology.'**

There is evidence that:
Radionuclides in sediments are now a source of plutonium and cesium-137 to the Arctic. Earlier releases such as those from Sellafield that have deposited in sediments in the Irish Sea, especially cesium-137 and plutonium, have been observed to remobilize so that these deposits are now acting as sources to the Arctic. Thus, even if operational releases of these radionuclides from reprocessing plants are reduced, releases from environmental sources such as contaminated sediment in the Irish Sea and the Baltic Sea will be observed in the Arctic.

It is therefore recommended that:
- **The Arctic Council support a more detailed study on the remobilization of radionuclides from sediment and its potential effect on the Arctic.**

It is apparent that:
There is continuing uncertainty about the amount of radionuclides present at a number of sources and potential sources in the Arctic. Access to information about civilian and military sources continues to be a problem.

It is therefore recommended that:
- **The Arctic Council promote more openness of restricted information from any sources.**

It has clearly been established that:
Compared with other areas of the world, the Arctic contains large areas of high vulnerability to radionuclides. This is due to the characteristics of vegetation, animals, human diets, and land- and resource-use practices. On land in the AMAP area, there is considerable variation in vulnerability due to differences in these characteristics. In contrast, vulnerability associated with releases of radionuclides to the marine environment is relatively uniform and similar to that for other areas of the world. Maps of vulnerable areas, when combined with deposition maps, can be useful in an accident situation. The information on vulnerability is of importance for emergency planning.

It is therefore recommended that:
- **AMAP be asked to clarify the vulnerability and impact of radioactivity on the Arctic environment and its consequences for emergency preparedness planning.**

It is apparent that:
When performing risk reducing actions, close links to assessment programs are important and interventions should be prioritized in relation to the extent and magnitude of threats posed by nuclear activities, especially in respect to accidents. Interventions themselves can also have negative effects for humans and the environment, and careful judgments have to be made together with environmental impact assessments prior to carrying out a project. It is the view of AMAP that this has not always been done in interventions adopted to date.

It is therefore recommended that:
- **Risk and impact assessment programmes be performed prior to implementation of action to reduce risk.**
- **Risk and impact assessments, including accident scenarios, be performed with regard to**

the transport of nuclear waste and fuel within the Arctic and nearby areas and with regard to planned storage and reprocessing within the Arctic and nearby areas.

It is apparent that:
The protection of the environment from the effects of radiation deserves specific attention. The current system of radiological protection is entirely based on the protection of human health. This approach can fail to address environmental damage in areas such as the Arctic that have low human population densities. Recently, an international consensus has emerged that the rapid development of a system and a framework for the protection of the environment needs further effort. The International Union of Radioecology (IUR), with support from AMAP, was one of the first international organizations to promote and present such a system and framework.

It is therefore recommended that:
- **AMAP be asked to take an active part in the continued efforts to address environmental protection, with special responsibility for the Arctic.** This should include the task of adding the need for protection of the environment into monitoring strategies and assessment tools.

It is noted that:
Since the previous AMAP assessment, nuclear safety programmes have been implemented in Russia at some nuclear power plants and other nuclear installations relevant to the Arctic.

It is therefore recommended that:
- **The Arctic Council continue its cooperation with Russia to improve the safety and safeguarding of nuclear installations and waste sites.**

Human Health

The human health assessment considered health risks associated with exposure to contaminants in relation to other lifestyle factors determining health. This assessment has extended geographical coverage and confirmed the conclusions and recommendations from the first assessment.

It has clearly been established that:
The highest Arctic exposures to several POPs and mercury are faced by Inuit populations in Greenland and Canada. These exposures are linked mainly to consumption of marine species as part of traditional diets. Temporal trends of human exposures to POPs have so far not been observed. Exposure to mercury has increased in many Arctic regions while exposure to lead has declined.

It is therefore recommended that:
- **The monitoring of human exposure to mercury, relevant POPs, including dioxins and dioxin-like compounds and other chemicals of concern, be continued in order to help estimate risk, further elaborate geographical trends, and begin to establish time trends of exposure.**

There is evidence that:
Subtle health effects are occurring in certain areas of the Arctic due to exposure to contaminants in traditional food, particularly for mercury and PCBs. The evidence suggests that the greatest concern is for fetal and neonatal development. In the Arctic, human intake of substances with dioxin-like effects is a matter of concern, confirmed by recent results from Greenland. Increasing human exposure to current-use chemicals has been documented, for example for brominated flame retardants. Others such as polychlorinated naphthalenes (PCN) are expected to be found in human tissues. Some of these compounds are expected to add to the total dioxin activity in humans. The AMAP human health monitoring program includes a number of measures of effects, ranging from biomarkers of effects at the molecular level to epidemiological outcomes.

It is therefore recommended that:
- **The human health effects program developed by AMAP be more extensively applied in order to provide a better base for human risk assessment especially concerning pre- and neonatal exposures.**

It has clearly been established that:
In the Arctic, diet is the main source of exposure to most contaminants. Dietary intake of mercury and PCBs exceeds established national guidelines in a number of communities in some areas of the Arctic, and there is evidence of neurobehavioral effects in children in some areas. In addition, life-style factors have been found to influence the body burden of some contaminants, for example cadmium exposure from smoking. In the Arctic region, a local public health intervention has successfully achieved a reduction of exposure to mercury by providing advice on the mercury content of available traditional foods. The physiological and nutritional benefits of traditional food support the need to base dietary recommendations on risk-benefit analyses. The health benefits of breast-feeding emphasize the importance of local programs that inform mothers how adjustments within their traditional diet can reduce contaminant levels in their milk without compromising the nutritional value of their diet.

It is therefore recommended that:
- **In locations where exposures are high, carefully considered and balanced dietary advice**

that takes risk and benefits into account be developed for children and men and women of reproductive age. This advice should be developed by national and regional public health authorities in close consultation with affected communities.

- **Studies of the nutrient and contaminant content of traditional food items be promoted in order to assess their benefits and to estimate exposures as a basis for public health interventions.**
- **Breast-feeding continue to be recognized as a practice that benefits both mother and child.** Nonetheless, if contaminant levels increase or more information indicates increased risk, the potential need for restrictions should continue to be evaluated.

It is noted that:
From the Arctic human health perspective, it is of utmost importance that considerations for global actions against POPs and mercury take into account the concerns for Arctic human health. The Stockholm Convention and the LRTAP protocols should be properly monitored in the Arctic to determine whether their implementation is effective in protecting human health.

It is therefore recommended that:

- **AMAP participate in the global monitoring of human exposure to be established under the Stockholm Convention on POPs.**
- **The Arctic Council monitor proposals for global action on mercury being undertaken by UNEP, and contribute as necessary to ensure that Arctic concerns related to human health are adequately addressed.**

Changing pathways

The assessment of changing pathways provides an introduction to the types of changes on contaminants pathways to, within, and from the Arctic that might be expected as a result of global climate change and variability.

There is evidence that:
The routes and mechanisms by which POPs, heavy metals, and radionuclides are delivered to the Arctic are strongly influenced by climate variability and global climate change. These pathways are complex, interactive systems involving a number of factors, such as temperature, precipitation, winds, ocean currents, and snow and ice cover. Pathways within food webs and the effects on biota may also be modified by changes to climate. Studies using global change scenarios have indicated the potential for substantial changes in atmospheric and oceanographic pathways that carry contaminants to, within, and from the Arctic. These effects mean that climate-related variability in recent decades may be responsible at least in part for some of the trends observed in contaminant levels.

It is therefore recommended that:

- **AMAP be asked to further investigate how climate change and variability may influence the ways in which POPs, heavy metals, and radionuclides move with respect to the Arctic environment and accumulate in and affect biota.** This will enable Arctic States to better undertake strategic planning when considering the potential effectiveness of present and possible future national, regional, and global actions concerning contaminants.

Setting the Stage

Environmental contaminants are a global problem. Their presence and role in the Arctic reflects the physical, biological, and social characteristics of the region, as well as the way the Arctic interacts with the rest of the world. Current concern about Arctic contaminants began with discoveries of high levels of persistent organic pollutants (POPs) in some indigenous inhabitants of the Arctic. Subsequent research confirmed that Arctic animals have elevated levels, posing a threat not only to the people who eat them but also to the animals themselves, and their ecosystems.

In 1997 and 1998, the Arctic Monitoring and Assessment Programme (AMAP) published a comprehensive assessment of what was then known about contaminants in the Arctic. In light of recent discoveries and new information, AMAP has prepared five new scientific assessments, covering persistent organic pollutants, heavy metals, radioactivity, human health, and changing pathways. In addition, this volume presents a plain-language summary of each of the scientific assessments. To set the stage, this chapter describes the previous assessment and what it led to, provides an overview of the Arctic and its special characteristics, and outlines the contents of the rest of the volume.

AMAP Phase I

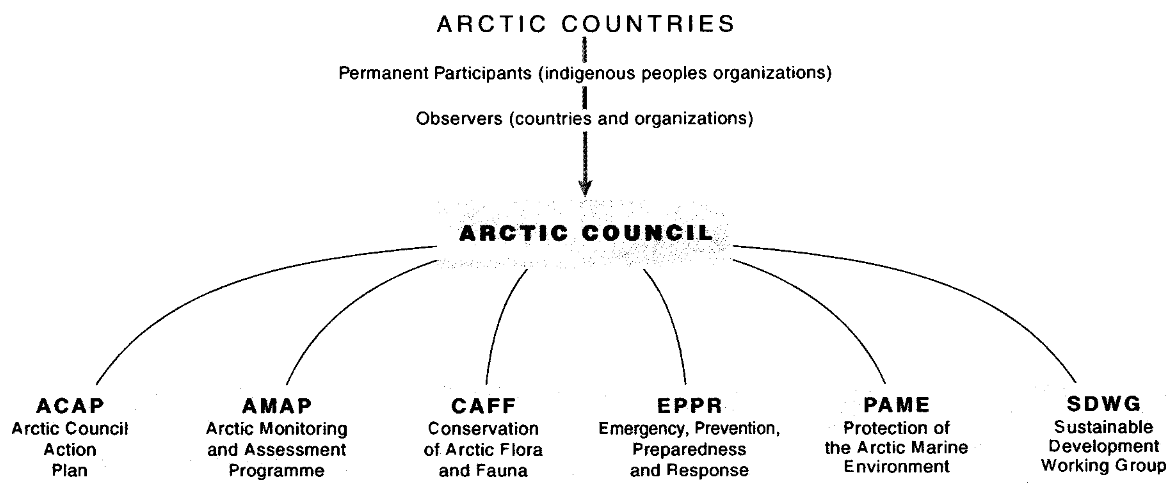
In 1991, the eight Arctic countries – Canada, Denmark, Finland, Iceland, Norway, Sweden, Russia, and the United States – initiated the Arctic Environmental Protection Strategy. Under this framework, the countries pledged to work together on issues of common concern. Recognizing the importance of the environment to the indigenous communities of the Arctic, the countries at that time included three indigenous organizations in their cooperative programs. In 1996, the eight Arctic countries created the Arctic Council, incorporating the Arctic Environmental Protection Strategy and expanding it to include sustainable development issues. They have also included three more indigenous organizations for a total of six permanent participants.

One of the programs created under the Arctic Environmental Protection Strategy and continued under the Arctic Council is the Arctic Monitoring and Assessment Programme. AMAP was designed to address environmental contaminants and related topics, such as climate change and ozone depletion, including their impacts on human health. Its specific task in Phase I of its existence was to prepare a comprehensive scientific assessment on these matters.

The 1998 scientific assessment

The AMAP Assessment Report: Arctic Pollution Issues, published in 1998, was the result of collaboration between over 400 scientists and administrators from all eight Arctic countries plus several non-Arctic countries and international programs. Its conclusions and recommendations were adopted by consensus of the eight Arctic countries.

The assessment described the geography, ecology, and people of the Arctic. It then re-



viewed the state of knowledge about pathways of contaminants; their levels, trends, and effects; human exposure; and potential threats. Its extensive recommendations addressed future research and monitoring, the need for remedial action, and the need for international agreements to reduce emissions of contaminants.

Overall, AMAP concluded that the Arctic remains a clean environment compared with most regions of the world. Nonetheless, the assessment warned that for certain contaminants, Arctic residents are among the most exposed populations in the world. This is especially true for Arctic indigenous people, whose traditional diets place them at the top of Arctic food webs. Through their dietary exposure, some groups are exposed to levels above national and international guidelines for daily intakes. The health risk was considered greatest for newborns and infants. Concerns were also raised about the potential effects on some wildlife populations.

Results from AMAP Phase I

The conclusions and recommendations from the first scientific assessment led to substantial progress in addressing the problem of contaminants. They raised the profile of environmental contamination in the Arctic as a public policy issue, and helped in the preparation of dietary guidelines in several countries.

At the time AMAP began its work, the United Nations Economic Commission for Europe (UN ECE) Convention on Long-range Transboundary Air Pollution was already considering whether it should take action on POPs and heavy metals. The data compiled by AMAP over the next several years established a strong case for restricting or eliminating several POPs. In 1998, a protocol to the Convention covering 16 POPs was adopted, as was a protocol on heavy metals.

As the protocols were being completed, the United Nations Environment Programme (UNEP) began negotiations for addressing 12 POPs worldwide. Here, too, Arctic data and Arctic countries were instrumental in promoting, negotiating, and concluding, in 2001, the Stockholm Convention on Persistent Organic Pollutants. Arctic indigenous organizations also played a significant role in the negotiations. They were able to do so in part because they had learned much from AMAP concerning transboundary contaminants in the Arctic. Indeed, the preamble to the Stockholm Convention explicitly recognizes the risks POPs pose to Arctic ecosystems and indigenous health and well-being.

The findings of the first AMAP assessment also led the Arctic Council in 2000 to ask UNEP to take action on mercury. As a result, UNEP is currently conducting a global study on mercury and is also tackling the issue of lead in gasoline.

The Arctic Council also decided to take cooperative actions to reduce pollution of the Arctic. In 1998, the Regional Programme of Action to Prevent Pollution of the Arctic Marine Environment from Land-Based Activities was adopted. As a direct follow-up of the AMAP scientific assessment, the Arctic Council Action Plan to Eliminate Pollution of the Arctic was created to address sources identified by AMAP. This plan was approved in 2000 and several projects have begun.

The assessment had made it clear that there was a general lack of data about contaminant levels in the Russian Arctic. A special project, *Persistent Toxic Substances, Food Security, and Indigenous Peoples of the Russian North*, was initiated to fill this gap. The work is sponsored by the Global Environmental Facility, Arctic countries, and others and is being coordinated by the AMAP Secretariat and the Russian Association of Indigenous Peoples of the North. Some of the first results are presented in the updated AMAP assessment.

In addition to its recommendations on contaminants, the AMAP assessment recommended further work on climate change and ultraviolet radiation. In 2000, the Arctic Council approved the Arctic Climate Impact Assessment, overseen by AMAP, its sister working group on Conservation of Arctic Flora and Fauna, and the International Arctic Science Committee. This impact assessment will deliver a report to the Arctic Council in 2004.

The Arctic

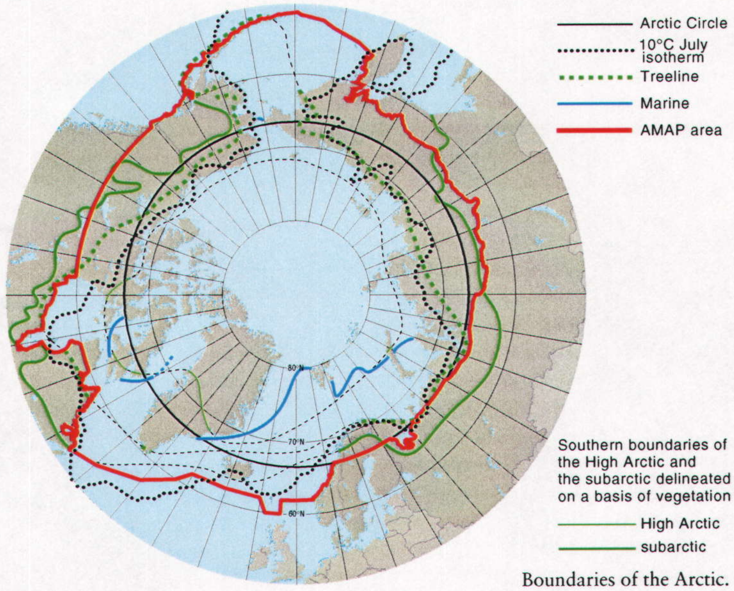
The behavior of environmental contaminants depends in part on the characteristics of the environment they are in. Several physical, biological, and cultural features of the Arctic are distinct from those of lower latitudes, with significant implications for contaminants. The previous AMAP reports contain general background chapters on geography, ecology, people, and pathways. The information in these chapters is still relevant. A brief summary is provided here for readers new to these topics.

Geography

The Arctic covers the northern part of the Earth; it has been given various boundaries (see map on top of the opposite page). Key characteristics, especially of the High Arctic, are dry and cold air, prolonged darkness in winter contrasting with continuous daylight in summer, permafrost over much of the land, and seasonal sea ice over much of the ocean.

The Arctic climate is variable both from place to place and from year to year. The ocean is a moderating influence, reducing seasonal temperature variation along the coast. Inland areas can experience annual ranges in temperature as great as 100°C. The extreme variability in climate and weather means that Arctic species must be prepared for a variety of conditions, or have the ability to wait several years to grow or reproduce.

The Arctic landscapes and seascapes include mountains and lowlands, wetlands and deserts, deep basins and shallow continental shelves, rivers and ponds, isolated islands and vast landmasses. Geologically, it includes the still-forming land of Iceland, and some of the oldest rocks in the world in Greenland. Across this diversity, snow and ice dominate the land and waters of the Arctic, shaping all that lives there.



Boundaries of the Arctic.

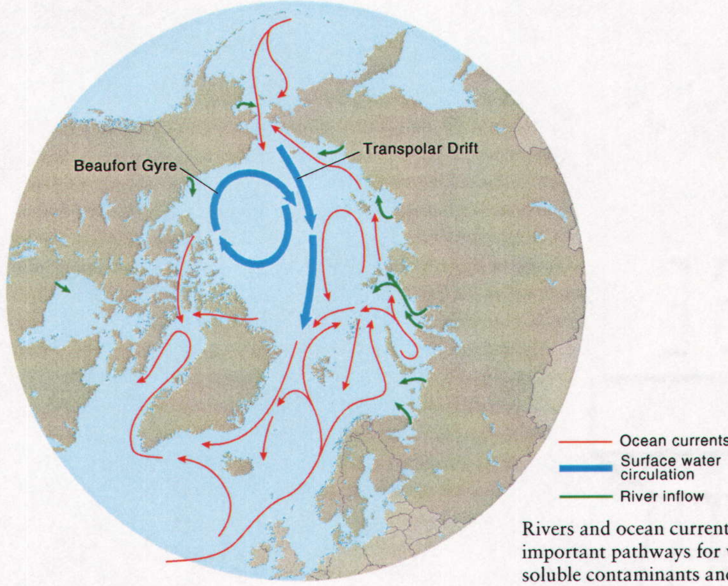
Pathways

Air, water, and ice carry contaminants great distances, to, from, and within the Arctic. In the global climate system, the Arctic cools the air and water warmed in lower latitudes. Cooler air can hold less moisture, and thus the Arctic is dry. As the cooling air releases rain and snow, contaminants are deposited as well. These contaminants end up on the ground, in meltwater in rivers, and in the top layer of the ocean, where biological productivity is highest. Sea ice can carry contaminants across the Arctic and release them in the productive melting zone of the North Atlantic (see map right).

Ocean currents are a slow but important pathway for contaminants to, within, and from the Arctic. The significance of ocean pathways appears higher than once realized. For radionuclides in particular, it is a major route from coastal sites outside the Arctic to marine food webs in the Arctic.

Rivers carry contaminants and process them through sedimentation and resuspension of particles. Lakes, deltas, and estuaries serve as sinks for contaminants in sediment.

The transport and deposition of contaminants follow seasonal patterns. In winter, the Arctic is home to a stable zone of high pressure centered over the Arctic Ocean and reaching far to the south (see map at bottom of page). This polar air mass becomes a trap for airborne contaminants, especially those generated in the industrial areas of Eurasia that are within the stable zone. In spring and summer, the energy from sunlight breaks up this system, causing greater mixing with air from lower latitudes.

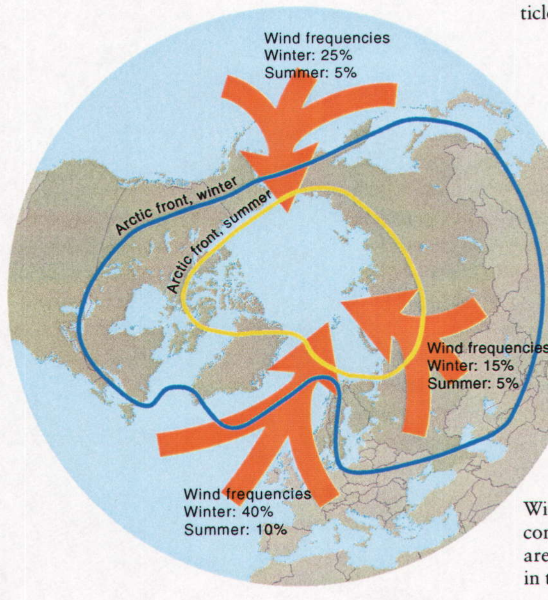


Rivers and ocean currents are important pathways for water-soluble contaminants and those that are attached to particles in the water.

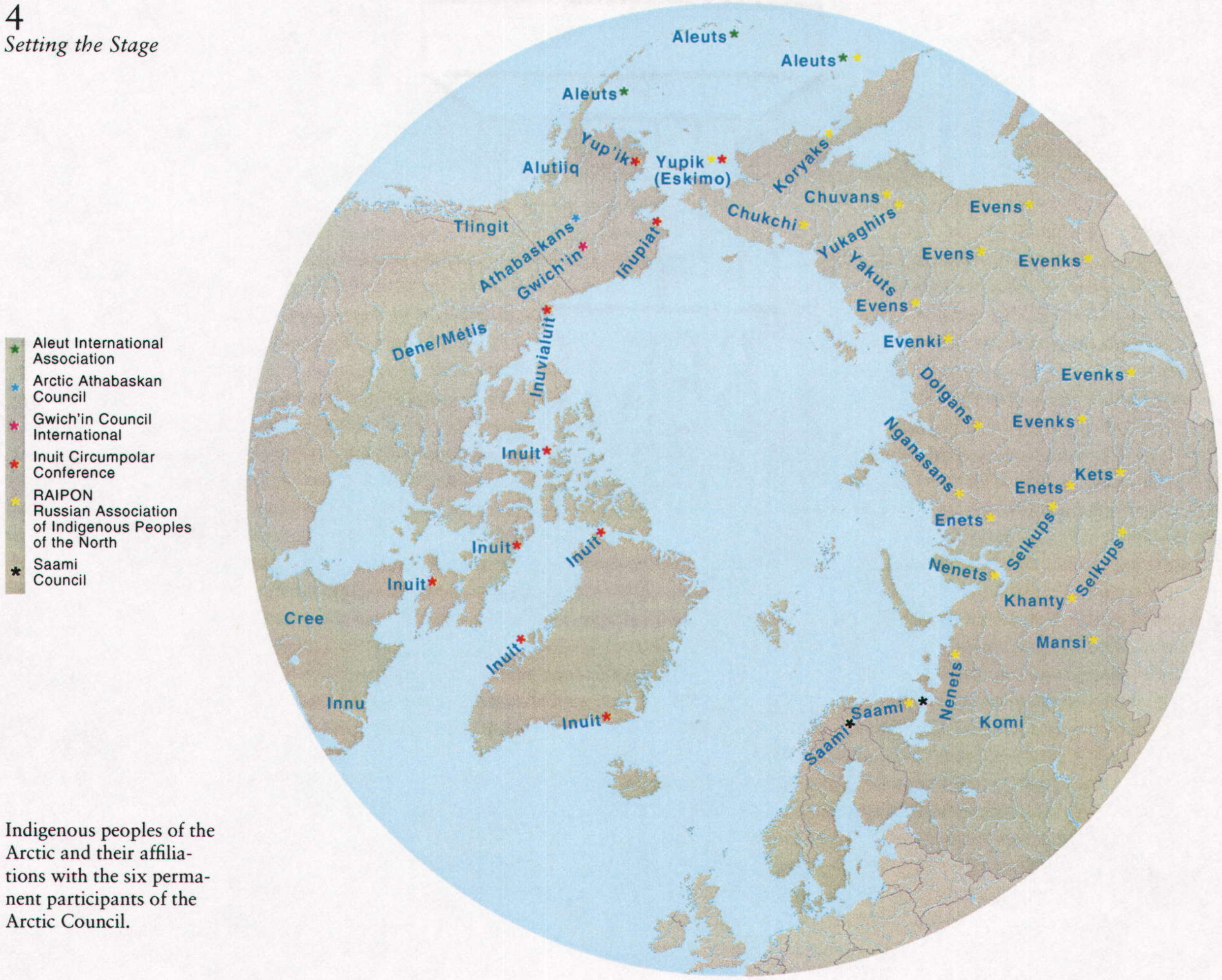
Ecology

In terrestrial, freshwater, and marine ecosystems, Arctic plants and animals have developed many strategies for coping with Arctic conditions. These include long periods of inactivity, the storage of nutrients and fat, the ability to grow and reproduce quickly when conditions are good, and flexibility in behavior. Arctic plants and animals also tend to be long-lived.

These characteristics, combined with the geography of the region, have a great influence on the uptake of contaminants in food webs.



Winds provide a fast route for contaminants from industrial areas to the Arctic, especially in the winter.



Indigenous peoples of the Arctic and their affiliations with the six permanent participants of the Arctic Council.

The ability to store fat is critical to many species, and predators tend to prefer fatty tissues for their great energy content. Many contaminants, especially among POPs, dissolve in fat, and thus become concentrated in Arctic animals. Moving up the food web, these concentrations increase in a process called biomagnification. This is especially prominent in the long, fat-dominated marine food webs.

Some contaminants are difficult for animals to excrete. Long-lived species can accumulate these substances throughout their lives, so that old animals have much higher levels than young ones. This process is called bioaccumulation. Scavengers can bring these contaminants back into the food web, keeping them available for long periods even without additional inputs.

Rapid bursts of productivity accompany the onset of favorable conditions, such as snowmelt in spring. When contaminants have been deposited in snow and ice, this burst can result in the uptake of contaminants available in meltwater. At other times, nutrient shortages may cause plants and animals to take up contaminants that have similar chemical properties to the unavailable nutrient elements.

When animals are inactive for long periods, they lose weight, thereby concentrating the contaminants that remain in their bodies. In extreme cases, contaminant concentrations in fatty tissues can increase greatly in marine mammals that fast for months at a time, such as pregnant polar bears. In that case, the problem is made worse as the mother bear nurses her cubs, injecting them with a heavy dose of contaminants dissolved in the fats of her milk.

People

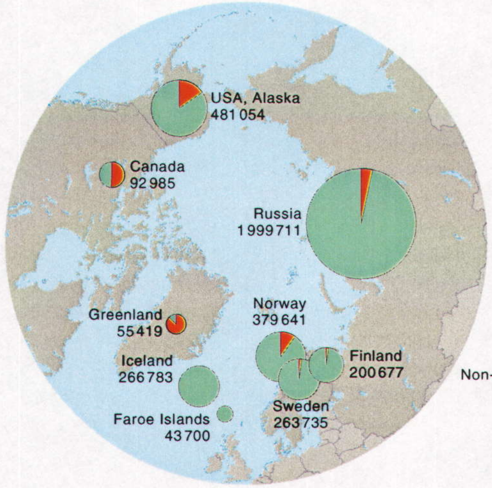
There are great economic, social, cultural, and demographic variations around the Arctic. These variations reflect not only geography and climate, but also national conditions and policies, as in Russia where economic hardship has caused many people to move south. The proportion of the population that is indigenous varies from 85% Inuit in Canada's Nunavut Territory, to 2.5% in the Saami region of Fennoscandia and the Kola Peninsula, Russia, to 0% in Iceland and the Faroe Islands.

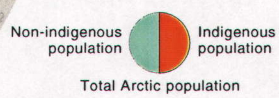
Historical factors are significant, too, including the rush to exploit whales, gold, fur, oil, fish, seabird eggs and down, and other natural resources around much of the Arctic. As large numbers of people moved into the region, they spread disease and caused social dislocation and competition for land and resources. At the same time, modernization brought benefits to Arctic communities.

Despite these challenges, Arctic indigenous people retain distinct cultures with long-standing traditions of land occupancy and resource use. Their hunting, fishing, trapping, herding and gathering take place over vast areas of land and sea. They also retain their close and complex relationship with the environment, including a wealth of detailed ecological knowledge and a powerful spiritual connection with the animals and places surrounding them. Traits and customs vary from group to group, but practices such as the sharing of foods are found throughout the Arctic, reflecting the need for a communal approach to survival in a harsh climate.

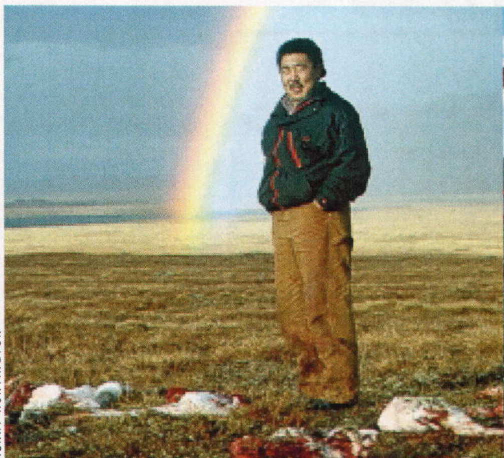
Today's Arctic residents range from urban dwellers in large cities to isolated families and small villages largely dependent on their local environment. Traditional hunting and fishing contrast with large-scale commercial fishing. The development of oil, gas, and minerals provides wealth, attracts new residents, and threatens landscapes supporting reindeer herders and others.

Contaminants enter this picture as another threat to the integrity of the Arctic way of life. The discovery that contaminants were present in breast milk was an unwelcome surprise. The fact that living one's life in the traditional manner and with a traditional diet posed a risk to one's children was deeply shocking. The traditional foods that had been a mark of cultural stability were turned into a pathway for toxic contaminants. For indigenous people, this problem raises fundamental questions of cultural survival, for it threatens to drive a wedge of fear between people and the land that sustains them. In response, Arctic indigenous groups have staunchly supported AMAP and related research, and have pushed hard for national and international action to combat the problem.





Total and indigenous populations of the Arctic in the early 1990s, by Arctic area of each country.



HENRY HUNTINGTON

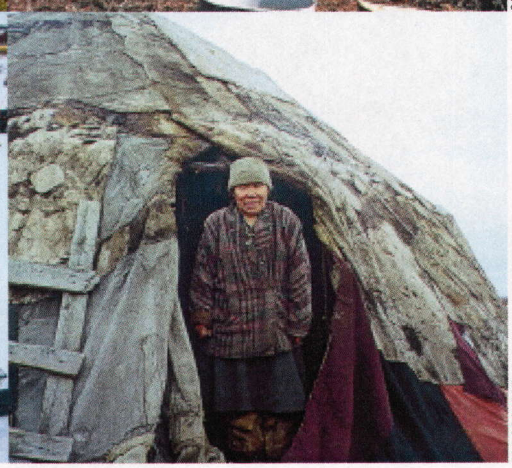
Iñupiat, Anaktuvuk Pass, Alaska.

GNWT/NWT ARCHIVES

Dene, Midway Lake, NWT, Canada.

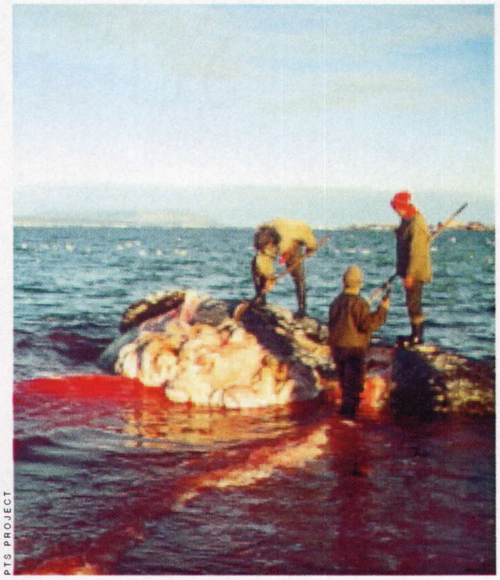
STAFFAN WIDSTRAND

Saami, Kautokeino, Norway.



PTS PROJECT

Chukchi, Kanchalan, Russia.



Samples were taken from a gray whale in the Lavrentiya Bay during the *Persistent Toxic Substances* project in Russia.

PTS PROJECT

Special concerns about interpreting data

The different contaminants found in the Arctic have substantial differences in sources, pathways, trends, and effects. Nonetheless, a few general points apply to the data presented in the subsequent chapters of this report.

First, identifying spatial trends is often complicated by a lack of standardization. This is particularly true for samples from plants and animals. Not only must collection and analytical methods and techniques be comparable, but researchers must take into account sex, age, and food-web structure. Although these requirements pose a problem for quantifying the differences from place to place, it is possible to identify general trends.

Second, determining temporal trends is also complex, particularly when other environmental changes have been occurring at the same time. The climatic regime of the Arctic has shifted dramatically from the conditions that prevailed during most of the 1970s and 1980s to those that prevailed during the 1990s, and these changes may have had significant effects on contaminant pathways. This period is exactly the time covered by most of the data available for the assessment of recent temporal trends. This raises the question of the extent to which observed trends may reflect changes in pathways as opposed to changes in, for example, emissions. As discussed in the chapter *Changing Pathways*, shifts in climate and weather can greatly alter contaminants pathways to and within the Arctic.

Third, there is still little information on effects of contaminants on Arctic biota. This is especially true for the effects of low-level, chronic exposures, which may result in subtle effects such as stress responses or reduction in overall fitness. Risk assessments often have to rely on comparisons between levels in the Arctic and threshold levels for effects that have been determined in other parts of the world, sometimes using other species. This may be more or less valid depending on the species and the contaminant of concern. Effects thresholds for Arctic animals are largely unknown.

The structure of this volume

Five scientific reports have been prepared for delivery to the Arctic Council in 2002 presenting the results of AMAP's second phase.* The main findings of the reports and the recommendations of the AMAP Working Group are contained in the Executive Summary. Each of the scientific reports is summarized by a chapter in this volume:

Persistent Organic Pollutants describes new findings in trends, levels, and effects of POPs, including several contaminants that have recently been detected in the Arctic. The implications of POPs for people are addressed in the chapter *Human Health*.

Heavy Metals reviews recent data and discoveries concerning mercury, lead, and cadmium. It also looks at the localized impacts of smelters in the Russian Arctic. As with the previous chapter, the implications of metals for people are addressed in the chapter *Human Health*.

Radioactivity covers the sources, pathways, uptake, and effects of radionuclides. Emphasis is on the behavior of radionuclides in ecosystems and on hazards connected with potential sources. In contrast to POPs and heavy metals, human health implications of radioactivity are addressed in this chapter.

Human Health examines what has been learned recently concerning Arctic people and the ways in which contaminants affect them. It describes the basic health parameters of Arctic populations as a basis for considering the potential impacts of contaminants.

Changing Pathways discusses the potential impacts of climate change on the ways in which contaminants are carried to the Arctic and taken up in Arctic food webs. The anticipated changes may greatly alter the distribution and trends of many contaminants throughout the Arctic.

The inside front cover has a circumpolar map, a list of species with their scientific names, and a list of units. The inside back cover has a list of contaminants with their abbreviations.

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* *AMAP Assessment 2002: Human Health in the Arctic.* ISBN 82-7971-016-7

AMAP Assessment 2002: The Influence of Global Change on Arctic Contaminant Pathways. ISBN 82-7971-020-5

AMAP Assessment 2002: Persistent Organic Pollutants in the Arctic. ISBN 82-7971-019-1

AMAP Assessment 2002: Heavy Metals in the Arctic. ISBN 82-7971-018-3

AMAP Assessment 2002: Radioactivity in the Arctic. ISBN 82-7971-017-5

Unintentional targets

THOMAS NILSEN

Persistent Organic Pollutants

The evidence that persistent organic pollutants affect Arctic wildlife is accumulating. On Svalbard, recent results indicate that polar bears with high levels of PCBs suffer from impaired defense against infections. High PCB levels may also be affecting cub survival. Effects of persistent organic pollutants have been documented in other Arctic species as well, including the northern fur seal, glaucous gull, peregrine falcon, and dogwhelk.

PCBs and a number of other organic pollutants have been regulated for several decades in Arctic countries. Recently they have also been regulated under a global convention. The levels in the environment are mostly a legacy of past emissions, and given enough time they will decline. However, some of the already-regulated persistent pesticides appear to have been used recently, and PCBs from old uses and equipment are still spreading in the environment. Moreover, additional persistent pollutants have started to arrive in the Arctic, and some of these are currently being produced in large quantities.

This chapter highlights sources of old and new persistent organic pollutants in the Arctic environment, their pathways, and their levels. It also discusses possible effects on wildlife. Effects on human health are treated in the *Human Health* chapter of this report.

Intentional use

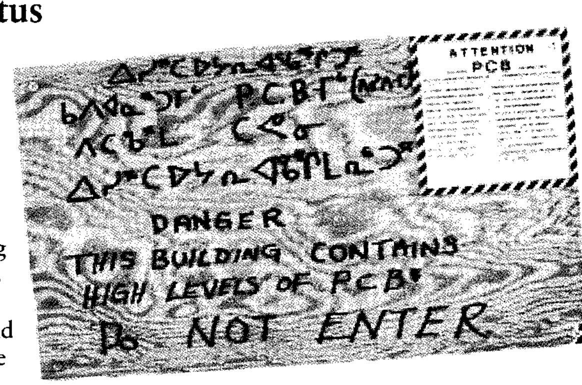
WRENMEDIA

Sources and regulatory status

The class of persistent organic pollutants, or POPs for short, covers a large number of chemicals with some common characteristics that make them potential problems in the environment. By definition, POPs are persistent, which means that they break down slowly in the environment. Persistent chemicals are more likely to travel over long distances and reach remote regions such as the Arctic. Once in the Arctic, some compounds may last even longer in the cold and dark environment than they would in more temperate climates.

Many POPs are taken up by organisms, either directly from their surroundings or via food. If the chemicals cannot be broken down or excreted as fast as they are taken up, they will accumulate in the organisms' tissues. Most POPs are poorly soluble in water but readily soluble in fat and therefore become concentrated in the fat of animals. At high enough levels, many POPs can have adverse effects on wildlife and on human health, including effects on reproduction, development, and resistance to disease.

The previous AMAP assessment showed that a number of POPs are present throughout the Arctic, including in regions where they have never been used. In addition to these 'legacy' POPs, most of which have been regulated, there are a number of persistent organic chemicals that are still in use. This section briefly describes the sources and regulatory status of most POPs covered in the updated 2002 AMAP scientific assessment.



BRYAN & CHERRY ALEXANDER

A warning sign for high levels of PCBs at an old DEW line station. Melville Peninsula, Nunavut, Canada. PCBs were used at many military radar stations.

PCBs are ubiquitous in the Arctic

PCBs, or polychlorinated biphenyls, are a group of heat-resistant and very stable chemicals that have been used in a number of industrial applications. The manufacture and use of PCBs have been banned, but they are still present in some existing products, such as sealants, paints in older buildings, and old electrical equipment. Most of the historical use of PCBs has occurred in the northern hemisphere.

PCBs have undoubtedly reached the Arctic via long-range transport, but there are a number of local sources as well. In several Arctic regions, mineral exploration, coal mining, and heavy industry account for the highest input. At Svalbard, Norwegian and Russian settlements are both sources to the local environment.

Harbors are newly identified sources, and high levels of PCBs have been found in the sediment of harbors in northern Norway and

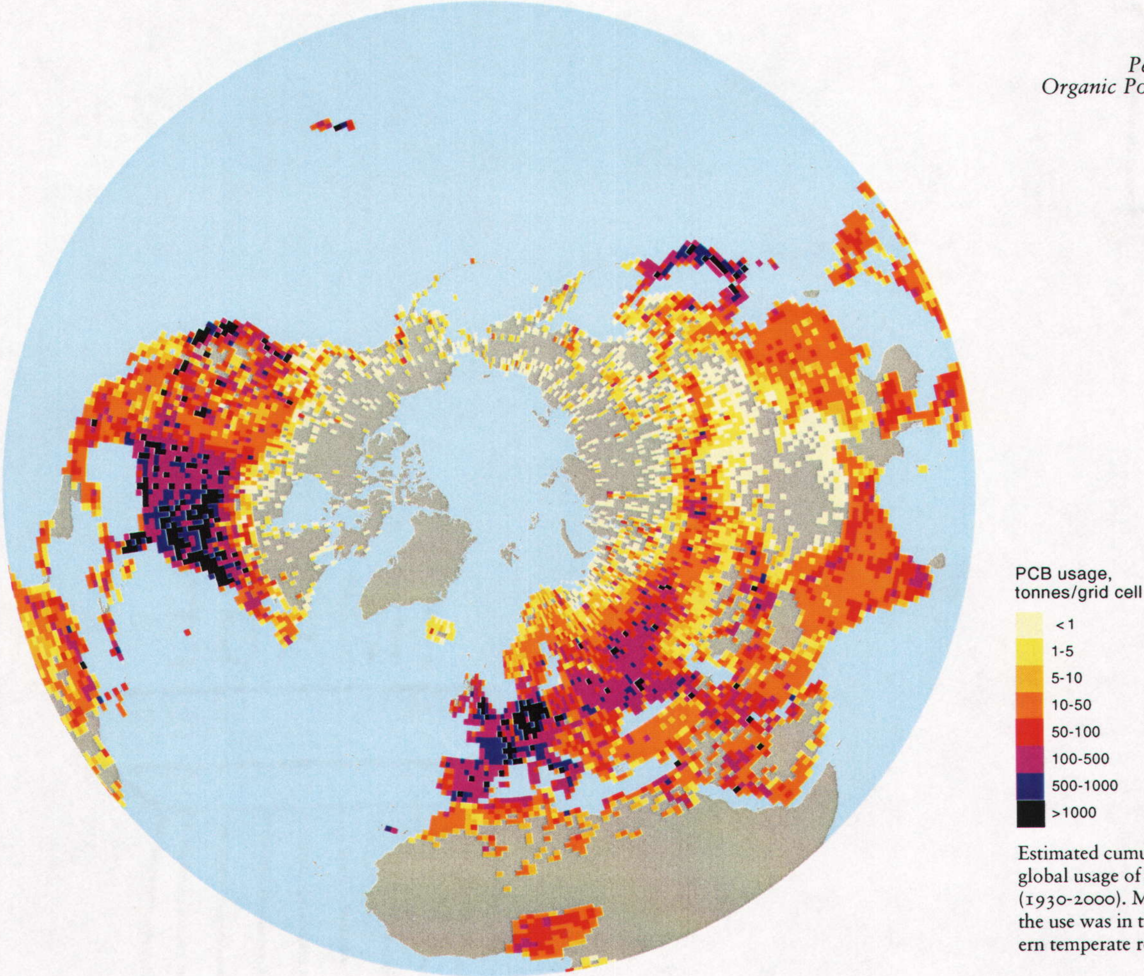
Conventions regulate some POPs

At a national level, the use and emissions of many POPs have been restricted since the 1970s. In 1998, the United Nations Economic Commission for Europe (UN ECE) negotiated a regional protocol on POPs under the Convention on Long-range Transboundary Air Pollution, the Aarhus POPs Protocol, which covers Europe, all states of the former Soviet Union, and North America. All AMAP countries except Russia are signatories to this convention. As of August 1, 2002, the following AMAP countries had ratified the POPs Protocol: Canada, Denmark, Norway, and Sweden.

The regional UN ECE agreement paved the way for global negotiations on banning POPs under the auspices of the United Nations Environment Programme. The Stockholm Convention on Persistent Organic Pollutants was opened for signature in May 2001. All AMAP countries have signed the Stockholm Convention. As of July, 2002, Canada, Iceland, Norway, and Sweden had ratified it.

Both agreements identify a number of specific POPs to be banned or whose use or emissions are to be restricted. They include industrial chemicals and by-products, such as PCBs, dioxins, furans, and hexachlorobenzene. Also included are a number of organochlorine pesticides: aldrin, chlordane, dieldrin, DDT, endrin, heptachlor, mirex, and toxaphene. Together, these are often called the 'dirty dozen'. Some POPs, most notably the pesticide hexachlorocyclohexane (HCH), are covered in the UN ECE Protocol but not the Stockholm Convention. For several of the listed substances, some limited use is allowed, for example DDT for fighting malaria.

The conventions also define criteria for including new chemicals based on their persistence, bioaccumulation, potential for long-range transport, and adverse effects. The Arctic is well suited as an indicator region for long-range transport. Monitoring data that provide information about the fate of chemicals in the Arctic will therefore be critical in identifying new POPs to be considered under the agreements.



Estimated cumulative global usage of PCBs (1930-2000). Most of the use was in the northern temperate region.

Russia. Because of much higher concentrations relative to non-harbor areas, harbors probably constitute a source for PCBs in the Arctic marine environment.

Other sources within the Arctic include abandoned military sites, specifically parts of the radar network established under NATO and built in the 1950s to detect missiles heading toward North America (e.g. DEW Line sites). In recent years, high levels of PCBs in soil have been found at two additional former military locations, Saglek Bay in northern Labrador and Resolution Island at the southeastern tip of Baffin Island. In Alaska, a large number of sites have been identified as known or potential sources of contaminants, not only of PCBs, but also of pesticides and polycyclic aromatic hydrocarbons (PAHs). Thule Air Base in Greenland is a local source of PCBs. On Jan Mayen, north of Iceland, old, dumped PCBs contaminate the local environment. Signs of contamination pointing to local PCB sources have recently been detected near small settlements in southern Greenland. Remedial action is underway for several of the sources mentioned above.

A recent inventory of PCB use in Russia shows that PCBs remain in many electrical installations, which slowly release this pollutant into the environment. The Arctic Council Action Plan to Eliminate Pollution of the Arctic (ACAP) has initiated a cooperative project to assist Russia in phasing out PCB use and in handling PCB-contaminated waste.

Svea Mine, Svalbard. Mining activities are a local source of PCBs.

BIRGER AMUNDSEN

Declining use of other chlorinated technical products

Chlorinated naphthalenes (PCNs) are chemically similar to PCBs and have many similar industrial applications. These include use in electrical equipment, lubricants, solvents, dyes, and sealants. They are also present as impurities in technical PCB and are formed during anthropogenic combustion processes.

One of the largest PCN producers ceased production voluntarily in the late 1970s. Otherwise, there is a general lack of information about production volumes and history. Use has declined in the past few decades, but in most countries PCNs are not prohibited. Air levels are highest in winter and the distribution pattern in the Arctic suggests a combustion source. PCNs have been detected in air and in marine mammals and birds.

Some PCNs have toxic properties similar to those of chlorinated dioxins, furans, and dioxin-like PCBs, and their proposed relative toxicities can be expressed as toxic equivalents (TEQs), see box below. A study of beluga from the Canadian Arctic showed that PCNs can account for a substantial portion of the TEQs.

Toxic equivalents (TEQs)
Dioxins, furans, and some PCBs and PCNs are thought to act via a similar toxic mechanism. The levels of these substances are sometimes expressed relative to the most toxic dioxin congener, TCDD. Toxic equivalents (TEQs) are the sum of the concentrations or amounts of different dioxin-like substances multiplied by their relative toxicities.

Other technical products are short-chain chlorinated paraffins, which are added to fluids used in metal-working to keep the fluids functioning at extremely high temperatures. They are also used in paints and sealants and in the leather-working industry. They can travel over long distances and have been detected in Arctic sediment and biota. Because of concern about their toxicity, the use of these chemicals is declining in favor of alternative products.

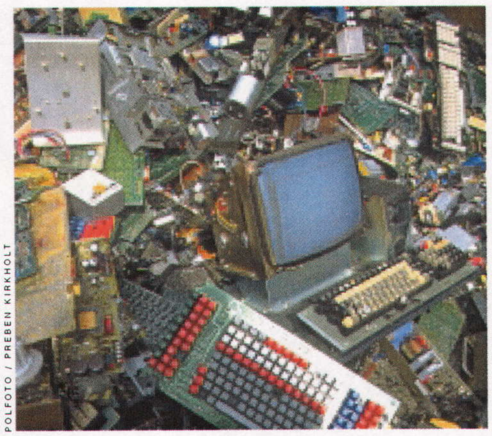
Use of brominated flame retardants is on the rise

To prevent fabrics and equipment from burning, many materials are treated with chemicals that contain bromine. Examples are polybrominated diphenyl ethers (PBDEs), hexabromocyclododecane, and tetrabromobisphenol-A (TBBPA). They are present in consumer products such as TV-sets, computers, building materials, foam cushioning, and textiles.

In some cases, brominated flame retardants can leach into the environment, where some of them are known to behave in a way that is similar to PCBs. PBDEs seem to travel over long distances in the atmosphere and some studies have shown that they can be toxic to the immune system and can affect neurobehavioral development. The environmental properties of other brominated flame retardants have not yet been very well investigated.

The use of brominated flame retardants has increased drastically in the past decade, and annual worldwide production is over 200 000 tonnes. Most of the use is in the industrial areas of the northern hemisphere that are potential source regions to the Arctic. The technical product penta-BDE is used primarily in North America but is being phased out in Europe, whereas other PBDE products are still widely used globally.

In areas outside the Arctic, PBDEs have shown up in human breast milk as well as in the tissues of several animal species. In North America levels are increasing. In Europe, levels in biota increased up until the mid-1980s and in humans until the late 1990s. In the Arctic, PBDEs have been detected in air and in biological samples from remote areas, although their levels are much lower than levels of some legacy POPs, such as PCBs. Recent results from southern Greenland also point to local PBDE contamination, possibly from consumer products used in the settlements.



POLFOTO / PREBEN KIRKHOLT

▶ Computers can be a source of brominated flame retardants.

Perfluorooctane sulfonates are extremely persistent

In regard to the environment, organic compounds with fluorine have until recently been discussed only in the context of ozone-depleting chemicals such as CFCs. However, the compound perfluorooctane sulfonate (PFOS) has come into focus because of its extreme persistence. It does not seem to break down under any circumstances. PFOS is mainly used as a stain repellent.

PFOS can leach from the materials in which it is used. Although not volatile itself, it seems to be capable of long-range transport by some as yet unknown mechanism. Little is known

Waste incineration at Narsaq, Greenland. Uncontrolled incineration is an important local source of dioxins.

about its potential to bioaccumulate or whether animals can break it down, but it has been detected in polar bears and seals in the North American Arctic and Svalbard.

The annual US production of PFOS was 2943 tonnes in 2000. The sole US producer plans to phase out production completely by 2003. Production in other parts of the world is not well documented.

Products that are chemically similar to PFOS are still in production. Their environmental fate is being investigated, but they have been detected in the air in regions outside the Arctic.

Industrial by-products are still not under control

Some POPs are produced as unintentional by-products in industrial processes. They include dioxins (PCDDs) and furans (PCDFs). Important sources are waste incineration without efficient temperature control and flue-gas cleaning, wood-burning stoves, metallurgical industries, and chlorine bleaching in pulp and paper production.

A UNEP review of global emission inventories for dioxin and furan emissions from northern Europe, Canada, the United States, and Japan points to the United States and Japan as the most important global source regions. Their releases amount to several kilograms of TEQs annually, whereas Canadian emissions are estimated at only a few hundred grams. Sweden, the only Nordic country in the survey, had emissions of only 22 grams.

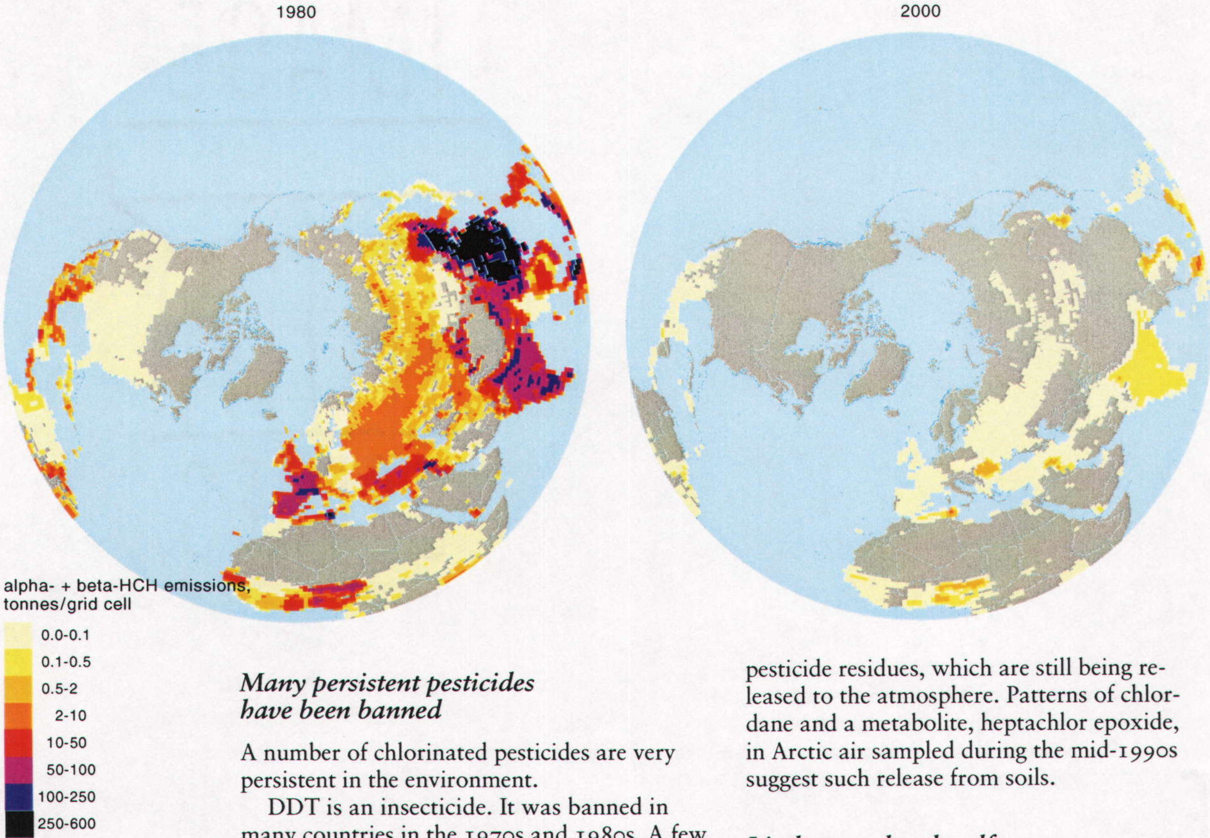
A model using information on sources and pathways shows the close relationship between source regions and the geographical distribution of deposition for dioxins and furans. Generally, air concentrations are low. The predicted deposition in eight communities in Nunavut, Canada, is highest in the south and east of Nunavut because of the preponderance of dioxin sources in the eastern United States and Canada. Russian and northern European sources are regarded as insignificant for Nunavut in comparison with those in the United States, Ontario, and Quebec.

Several other industrial POPs are found in the Arctic. Hexachlorobenzene (HCB) is a by-product in the production of chlorine gas and chlorinated compounds, including several pesticides. It is also a by-product of the metallurgical industry. It has been used as a fungicide. Known emissions cannot account for the levels of HCB in the atmosphere, so there may be sources that have not yet been identified. An alternative explanation is that previously deposited HCB is being revolatilized into the air.

A compound related to HCB is pentachlorobenzene, which has been used in dielectric fluids in PCB-containing transformers. Older PCB-containing devices are thus a potential source of this contaminant.

Breakdown products of octachlorostyrene have recently been detected in the Arctic. Emissions of this compound probably peaked in the 1960s. Historically important sources are magnesium production and chlorine production using a method that was abandoned in the 1970s.

Polycyclic aromatic hydrocarbons (PAHs) are a large group of compounds that are present in unburned petroleum and are produced when organic matter burns. Sources are ubiquitous and include the burning and coking of coal, production of aluminum, internal combustion engines, cooking on fire or hot coals, cigarette smoking, and forest fires.



Estimated emissions of alpha- plus beta-HCH in 1980 and 2000, showing a drastic decrease over this period.

Many persistent pesticides have been banned

A number of chlorinated pesticides are very persistent in the environment.

DDT is an insecticide. It was banned in many countries in the 1970s and 1980s. A few countries, such as China and India, still produce DDT for use in controlling malaria and other insect-borne diseases. The previous AMAP scientific assessment suggested some continuing use of DDT in Russia.

Toxaphene is another insecticide. It was primarily used in the cotton belt of the United States, but was banned in the United States in 1986. In Nicaragua, production continued until the early 1990s. The former Soviet Union and former East Germany were also major producers of this type of pesticide, but compared with the United States, use in Europe was limited.

Chlordane, heptachlor, dieldrin, endrin, aldrin, and mirex are other chlorinated pesticides covered by the Stockholm Convention. Chlordane has been used extensively in the United States for agriculture, home lawns and gardens, and termite control, and to a lesser extent in Western Europe, the former Soviet Union, and tropical Asian countries. In 1997, the sole US manufacturer voluntarily ceased production in all its national and international facilities. There is still some production in Singapore and China. World sales of aldrin and dieldrin ceased in 1991, while endrin production ceased in the mid-1980s. However, old stocks of these chemicals, particularly dieldrin, were donated to African countries from the mid-1980s to the 1990s for insect control. Releases to the environment have therefore continued.

Because chlorinated pesticides were deliberately applied to control insects, many agricultural and some non-agricultural soils contain pesticide residues, which are still being released to the atmosphere. Patterns of chlordane and a metabolite, heptachlor epoxide, in Arctic air sampled during the mid-1990s suggest such release from soils.

Lindane and endosulfan are still in widespread use

The use of technical hexachlorocyclohexane (HCH) began in 1943, and global consumption during the period 1948-1997 has been estimated at a total of 10 million tonnes. Technical HCH is a mixture of mainly alpha-, beta-, and gamma-HCH, which differ in their chemical structures. Gamma-HCH is an insecticide, whereas alpha- and beta-HCH are byproducts from the production of gamma-HCH and present in the technical product.

Technical HCH was banned in most western countries in the 1970s and in the Soviet Union in the late 1980s. China has been a major user but switched to lindane, which is pure gamma-HCH, in 1984. Lindane is also used in North America, Europe, and Asia, for seed treatment and other applications.

Endosulfan, a widely used insecticide, is also used in some Arctic countries. It is very toxic but less persistent than some other organochlorine pesticides.

Butyltin compounds are only partially regulated

Tributyltin (TBT) is a broad-spectrum pesticide used against algae, mites, fungi, and insects. TBT has been most widely used as a marine antifoulant on small boats, ships, and marine structures such as aquaculture pens, offshore oil rigs, and underwater pipelines. It may also enter the sea in runoff from agricultural areas, from boat repair yards, and from municipal wastewater and sewage sludge.

Mono- and dibutyltins are used primarily as heat and light stabilizers in the production of PVC plastic. The organotins have been shown to leach from PVC and other materials leading to contamination of food, drinking water, municipal water, and sewage sludge. Mono- and dibutyltins are also breakdown products of TBT in higher organisms.

TBT breaks down fairly quickly in water but can remain for a long time in sediments, especially in cold climates. Contaminated sediments are therefore potential environmental reservoirs for TBT, and may continue to be a source long after the industrial use of TBT has been curtailed.

Because it is extremely toxic to some marine invertebrates, many developed countries have restricted the use of TBT. Regulations vary, but generally, only controlled release formulations are permitted and TBT-based antifoulants are prohibited for boats smaller than 25 meters. The United Nations International Maritime Organization has agreed to a global ban, beginning in 2003, on the new use of TBT on ship hulls. After 2008, TBT-based antifouling paints must be removed from ship hulls or sequestered with an impermeable paint so that no leakage to the environment can occur.

Pathways to the Arctic

Even if there are local sources of POPs within the Arctic, they cannot explain current environmental levels. In many cases, the main sources are in mid-latitude industrial and agricultural areas, and the contaminants travel to the Arctic with air and water currents. Migrating animals also carry POPs to the Arctic. Long-range transport and subsequent biomagnification in Arctic food webs account for most of the concern regarding contamination of the Arctic by these substances.

Pathways can change with shifts in climate regime or long-term climate change. This is discussed further in the chapter *Changing Pathways*, including some specific changes that have occurred during the 1990s.

The atmosphere provides a fast transport route

Air is the most important transport route for volatile and semi-volatile pollutants. Under favorable weather conditions, air masses can transport contaminants from mid-latitudes to the Arctic within a few days or weeks.

Most POPs are semi-volatile and their transport is complex. In temperate and tropical regions, they are picked up by the winds as gases. When temperatures drop, they condense onto atmospheric particles and other surfaces, reaching the ground via rain, snow, or direct deposition onto land and water. However, they can revolatilize when weather conditions change, re-entering the atmosphere for further transport. Higher temperatures, storms, snowmelt, or icemelt in spring can also encourage revolatilization of POPs. Soils contaminated with PCBs in the past via atmospheric deposition are now releasing them back into the air to begin the transport process anew.

The role of atmospheric transport varies with the seasons. Generally, atmospheric long-range transport to the Arctic from source areas in North America and Eurasia is much higher in winter and early spring than in summer.

Ocean transport is slow but important

The role of ocean currents in transport is probably more important for contaminant levels in the Arctic than was previously thought. Water-soluble chemicals that are efficiently removed from the air by precipitation or air-to-sea gas exchange may reach the Arctic primarily via ocean currents. Beta-HCH is an important example.

Ocean transport is relatively slow and it can take many decades before POPs released in other parts of the world show up as pollution in the Arctic. This can create a time lag between emissions and increasing levels and possible effects in the Arctic and, conversely, between emissions reductions and decreasing levels in the Arctic environment. It also raises questions about how modern pesticides, which normally degrade fairly rapidly, behave in cold Arctic waters.

The precise importance of ocean transport for each compound depends on that substance's physical properties (see box below).

Water-solubility determines importance of ocean transport

Alpha- and beta-HCH were significant contaminants in technical HCH and were released to the environment with this pesticide. They differ in one important physical property: the solubility of the gaseous compound in water. The greater solubility of beta-HCH profoundly influences the relative importance of different pathways to the Arctic. Specifically, alpha-HCH is transported efficiently both by the atmosphere and ocean currents. Initially, when emissions were still substantial, air transport was most important. The solubility of gaseous HCH in water is greater at lower temperatures and the cold waters of the Arctic Ocean and the marginal seas became a sink. Alpha-HCH levels in air declined during the mid-1980s and 1990s because of a drop in technical HCH emissions, and ocean currents took over as the major transport route. Today, the Arctic Ocean has reached equilibrium with the atmospheric alpha-HCH concentrations, and in some areas is releasing it back to the atmosphere. In the central Arctic Ocean, the ice cap prevents this outgassing.

Due to its greater water solubility, beta-HCH is more efficiently scavenged by rain and snow than alpha-HCH. Most of its emissions have therefore been deposited closer to the source regions in high precipitation areas in the northern North Pacific, from where the Alaska coastal current can transport beta-HCH farther north into the Bering Sea. Thus, even during the years of high technical HCH emission, beta-HCH was most likely carried to the High Arctic mainly via ocean currents. With ocean transport being relatively slow, it will likely take longer for environmental levels of beta-HCH than alpha-HCH to reach equilibrium with emissions.

Rivers and sea ice can carry contaminated sediment

A route for contaminants that has been increasingly recognized in the past few years is sea ice that carries sediment from large rivers. Several great rivers flowing through industrial and algricultural regions drain into the Arctic Ocean. When their sediments reach the coast, some are incorporated into coastal ice.

The general movement of sea ice north of Eurasia is from the coast of the Kara Sea northward to the Siberian branch of the transpolar drift between the Franz Josef Land and Severnaya Zemlya archipelagos. Ice-bound particles possibly laden with contaminants may thus be carried out of the area and released when the ice melts. The main melting areas are east of Svalbard and in the Fram Strait. The importance of sea ice for contaminant transport remains an open question.

Levels and geographical patterns

Levels in the environment can be used to piece together a picture of how pathways distribute POPs throughout the Arctic from their sources.

The emerging picture suggests that differences in biological pathways may be much more important than was previously realized. Specifically, the fact that the same species may have different diets in different parts of the Arctic seems to be important in explaining different contaminant burdens in some populations. There is also new evidence that animals can carry contaminants between areas and environmental compartments, creating a biological pathway of as yet undetermined significance.

Another picture, which is consistent with the previous AMAP assessment, is that levels in the environment are influenced by proximity to known or suspected source regions. Generally, levels of HCHs are higher in the western North American Arctic than farther east, reflecting emissions in eastern Asia. By contrast, PCB levels are higher in the Eurasian part of the Arctic, especially around eastern Greenland, Svalbard, and the Kara Sea. Evidence from seabirds and several marine mammals points to releases of PCBs in Russia.

In the previous AMAP assessment, there was little information on toxaphene. New data show that this pesticide occurs throughout the Arctic, in some cases at rather high levels. Moreover, there are data that suggest current releases of regulated pesticides, specifically DDT and toxaphene, mostly in the Russian Arctic.

New contaminants are also showing up in the Arctic. These include brominated flame retardants in Canada, Greenland, the Faroe Islands, Norway including Svalbard, and Sweden, as well as PFOS in North America and Svalbard. TBT-related compounds have been detected in several species.

The following sections provide details about levels in different animals and compartments of the environment.

Air and precipitation data indicate fresh DDT use

New data on POPs in air are available from several land-based stations. The results for HCHs, chlordanes, and DDTs suggest rather uniform, low concentrations in Arctic air during the mid-to-late 1990s. DDT levels at Stórhöfdi, Iceland, suggest a fresh source. At Tagish, Canada, there is some inflow of DDTs that is linked to trans-Pacific transport. The DDT pattern at Amderma, Russia, differed from most other sites, suggesting recent use.

Concentrations of PCBs and HCB at Zeppelin (Ny-Ålesund), Svalbard, are higher than at the Canadian sites. The results suggest that the European Arctic continues to receive elevated PCBs compared to the North American Arctic. The data also indicate long-range transport of PAHs from Eurasian sources, with a signature typical of coal and oil combustion.

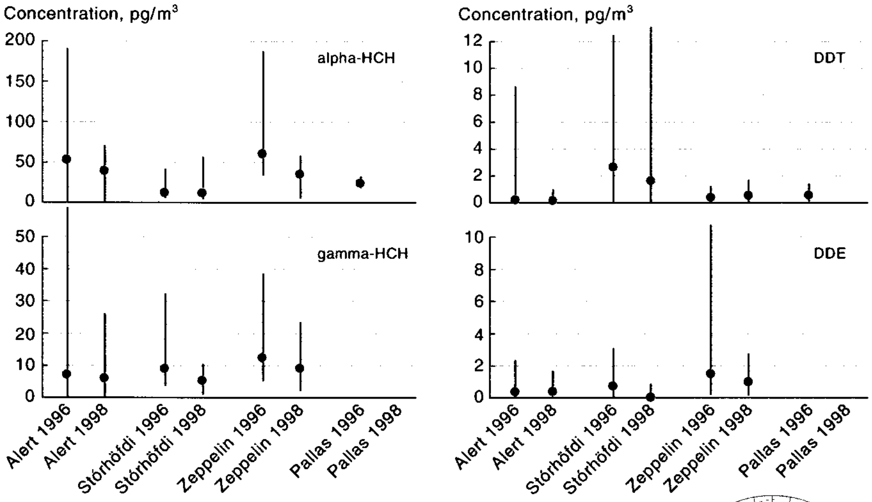
Many new contaminants have been detected in Arctic air. They include several current-use pesticides (endosulfan, methoxychlor, trifluralin, and pentachloroanisole), industrial by-products (trichloroveratrole, tetrachloroveratrole, and

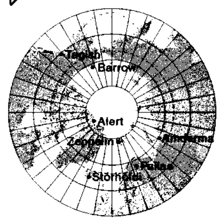
TORUNN BERG

Zeppelin station at Ny-Ålesund, Svalbard, is part of AMAP's air monitoring network.

octachlorostyrene), chlorinated naphthalenes, PBDEs, and short-chain chlorinated paraffins.

Snow accumulating on top of glaciers has been used to look at deposition of POPs. There are data from the summit of the Greenland ice cap and from Lomonosovfonna on Svalbard. The high flux of DDTs at Lomonosovfonna, nearly nine times greater than that at Summit, suggests a possible local source. HCHs, dieldrin, and endosulfan fluxes were also higher at Svalbard. The highest input of PCBs was at Summit.





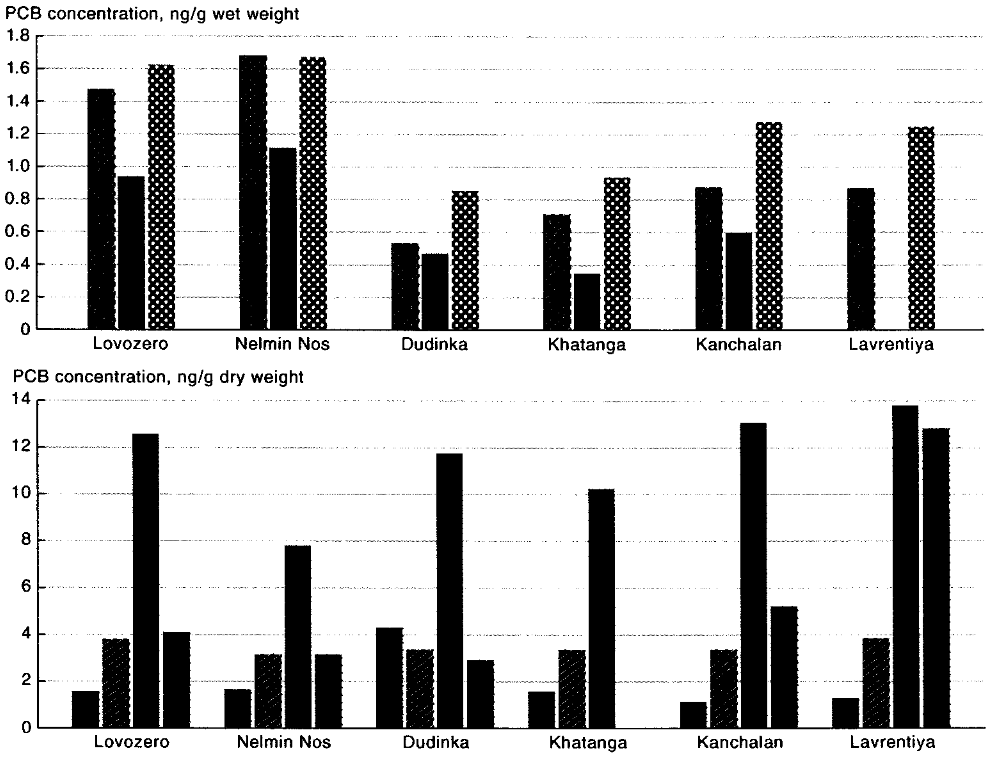
Average annual concentration of HCHs and DDTs in air. Bars indicate range in values. The map shows the monitoring station network for POPs in the Arctic.

Predatory birds and some Russian reindeer stand out in the terrestrial environment

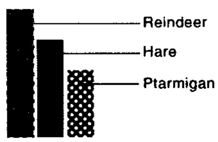
With the exception of predatory birds and organisms impacted by local sources, the Arctic terrestrial environment is among the least POPs-contaminated ecosystems in the world. Predatory birds that feed on migratory waterfowl have high levels of many legacy POPs, such as DDTs. New data from peregrine falcons in northern Norway and Sweden and from several other birds of prey in northern Norway show that brominated flame retardants are now also present.

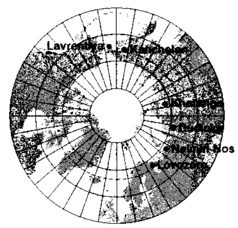
Concentrations of POPs in terrestrial biota other than predatory birds are generally orders of magnitude lower than in the freshwater and marine environments of the Arctic. New data for several terrestrial species from West Greenland confirm that POP levels in herbivores are very low. In soil, plants, and herbivores, the most prevalent POPs are HCB, HCHs, and lower-chlorinated PCBs. In predators, higher-chlorinated PCBs, chlordanes, and DDTs are more pronounced.

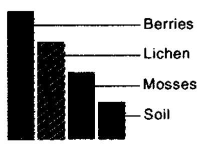
Since the previous AMAP assessment, some plant and soil data from four regions of Russia have become available. Levels are generally low but an order of magnitude higher than lichen in the Canadian Arctic. There were no strong spatial trends within Russia. However, some recent data on Russian reindeer and mountain hare indicate elevated dioxin and furan levels on the Kola Peninsula, probably connected to local emissions from smelters.



Concentrations of PCBs in terrestrial animals (liver tissue), berries, lichens, mosses, and soils from regions within Russia sampled in 2000-2001.







GUTTORM N. CHRISTENSEN

Bjørnøya (right) and Ellasjøen (below).

GUTTORM N. CHRISTENSEN

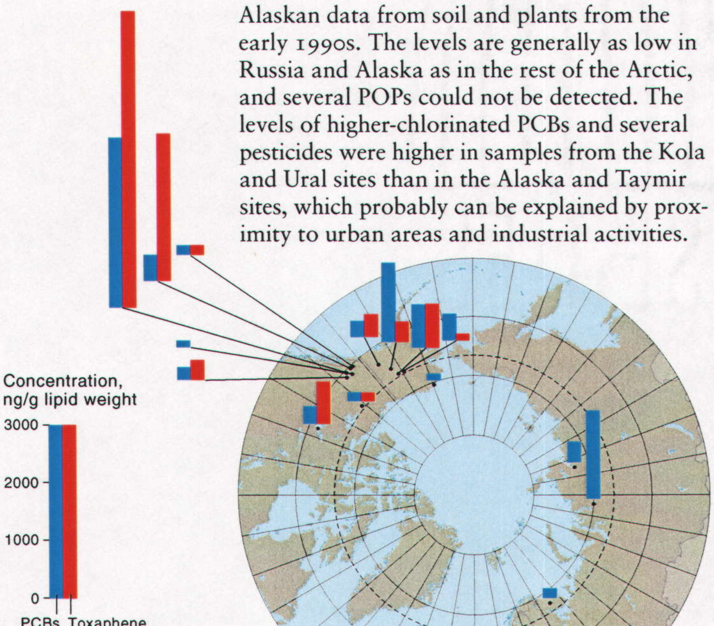
Birds connect marine and freshwater environments

In 1994, it became clear that fish in the lake Ellasjøen on Bjørnøya had exceptionally high levels of POPs. In 1999, Norwegian researchers initiated a study to investigate why. One question was the role of long-range transport, as there were no local sources on the island. Levels of POPs in air samples seem to be very similar to the levels measured in air samples from Svalbard, and levels of POPs in snow and rainwater samples from Bjørnøya are comparable with levels found in other Arctic areas. However, levels in fog are relatively high, leading to a suggestion that a relatively high precipitation rate and a high frequency of fog in this part of Bjørnøya could lead to a high deposition of the air-borne contaminants.

Another explanation for the high levels found in Ellasjøen could be the thousands of seabirds that breed close to the lake or use it as a resting area. Their guano contains elevated levels of POPs, especially PCBs, and they deposit it directly into the lake or in the catchment area of the lake. In another lake on Bjørnøya, with no nearby seabird colonies, levels of POPs are several times lower than in Ellasjøen.

One conclusion from this study is that seabirds can serve as a biological pathway carrying contaminants from the marine to terrestrial and freshwater environments. Data from a lake on Jan Mayen, an island north of Iceland, show that this pathway is not unique to Bjørnøya.

There are also some additional Russian and Alaskan data from soil and plants from the early 1990s. The levels are generally as low in Russia and Alaska as in the rest of the Arctic, and several POPs could not be detected. The levels of higher-chlorinated PCBs and several pesticides were higher in samples from the Kola and Ural sites than in the Alaska and Taymir sites, which probably can be explained by proximity to urban areas and industrial activities.



Spatial trends for PCBs and toxaphene in burbot in the Canadian, Russian, and Alaskan Arctic.

Local pollution is a problem in some freshwater environments

Freshwater biota in the Arctic generally have low levels of POPs compared with marine birds and mammals. The exceptions are fish in lakes and rivers that are contaminated via other routes than through the atmosphere. One example is in the lake Ellasjøen on Bjørnøya, south of Svalbard, where seabirds have been shown to transport contaminants from the marine environment (see box above). Another example is higher DDT and PCB levels in burbot from a lake near Fairbanks than in other lakes in interior Alaska, reflecting historical use of these compounds in the city of Fairbanks. Burbot from the Taymir-Dudinka area in Russia had similarly high levels. In other freshwater fish from Russia, POP levels, except for dioxins, are comparable to other parts of the Arctic. Dioxin levels in the Kola freshwater fish are elevated, similar to those in reindeer. Across the Arctic, toxaphene and PCBs are the contaminants that predominate in freshwater animals.

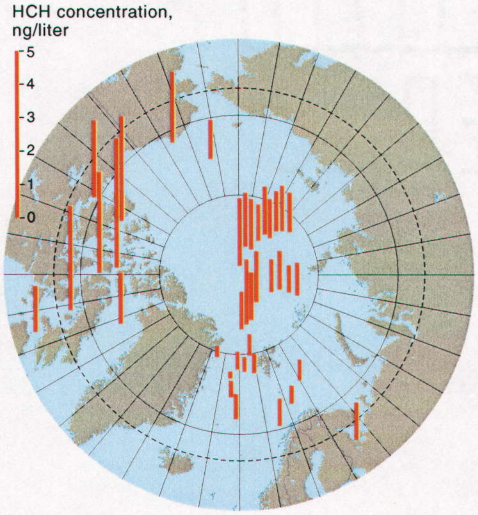
In the abiotic environment, new data from Russia confirm elevated POP levels in freshwater compared with levels observed in Canada and Norway. PCBs were the dominant POP in both water and sediment, followed by DDTs and chlorobenzenes. At one site, Nelmin Nos, DDT concentrations in sediment were 70 times higher than elsewhere. The high levels suggest fresh input into the environment in this region. With this exception, POP concentrations in sediment were similar to those previously reported for other areas of the Arctic.

SHEBA PROJECT OFFICE

The SHEBA research lab barely afloat. During the SHEBA project an icebreaker was frozen into the pack ice and left to drift for a year.

HCHs, PCBs, and toxaphene dominate in seawater

Several scientific cruises have gathered data on seawater since the previous AMAP assessment. HCH levels are higher north of North America than north of Eurasia. This geographical pattern is best explained by proximity to source regions in Asia.



Concentrations of sum-HCHs in seawater 1996-2000.

For PCBs, there are too few measurements to assess spatial trends. There are some other interesting observations, however. PCB concentrations are lower under the permanent pack ice than in open nearshore surface waters. This suggests that levels are related to air-sea exchange and possibly to biological activity. The highest PCB concentrations were found in the nearshore waters of the Canadian Arctic archipelago, southern Beaufort Sea, and northern Baffin Bay. Measurements from the Surface Heat Budget of the Arctic Ocean (SHEBA) Project show that PCBs seem to be delivered to the Bering Sea via runoff and spills, whereas the interior Arctic Ocean owes a significant portion of its PCB content to condensation and air-sea exchange.

Toxaphene data suggest a fresher, less degraded input to the White Sea than the other places where toxaphene has been measured.

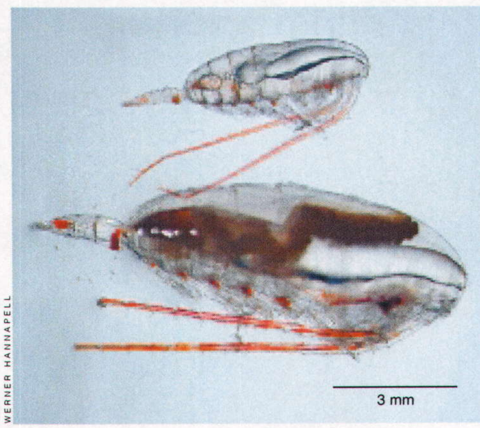
DDTs, chlordanes, dieldrin, and HCB are present at much lower levels than toxaphene, PCBs and HCHs. Sea-air exchange and melting snow and ice are important sources for DDTs and chlordanes to the marine environment.

Levels in marine invertebrates reflect food habits

Marine invertebrates provide a link from phytoplankton to fish, seabirds, and mammals in the Arctic marine food web. They carry not only nutrients, but also POPs. Understanding the dynamics of POPs in marine invertebrates is therefore a key to understanding POP trends in the marine ecosystem.

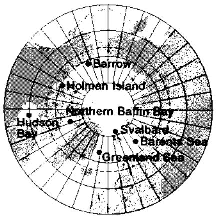
In general, marine invertebrates have low POP levels, consistent with their place low in the food web and their short life span. However, longer-lived bottom-dwelling invertebrates that scavenge the remains of fish and mammals have higher contaminant loads. One group of organisms that has been extensively sampled since the previous AMAP assessment is the calanoid copepods, a zooplankton group that dominates in open water in the high-latitude marine environment.

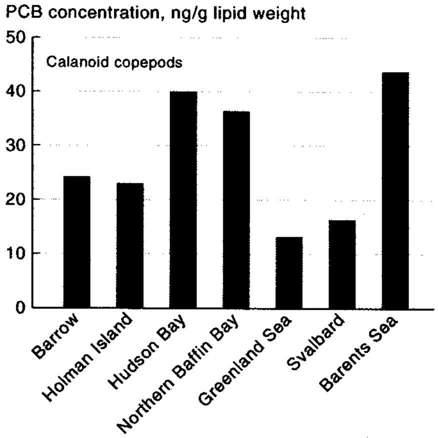
Copepods feed on phytoplankton. The most common POPs in these animals were relatively water-soluble compounds such as HCHs and some PCBs, followed by less water-soluble compounds such as DDTs, chlordanes, and HCB. The concentrations of DDTs and chlordanes were higher in the copepods than in the surrounding water, indicating some bioconcentration.



WERNER HANNAPELL

Two species of calanoid copepods, *Calanus finmarchicus* (above) and *Calanus hyperboreus* (below).



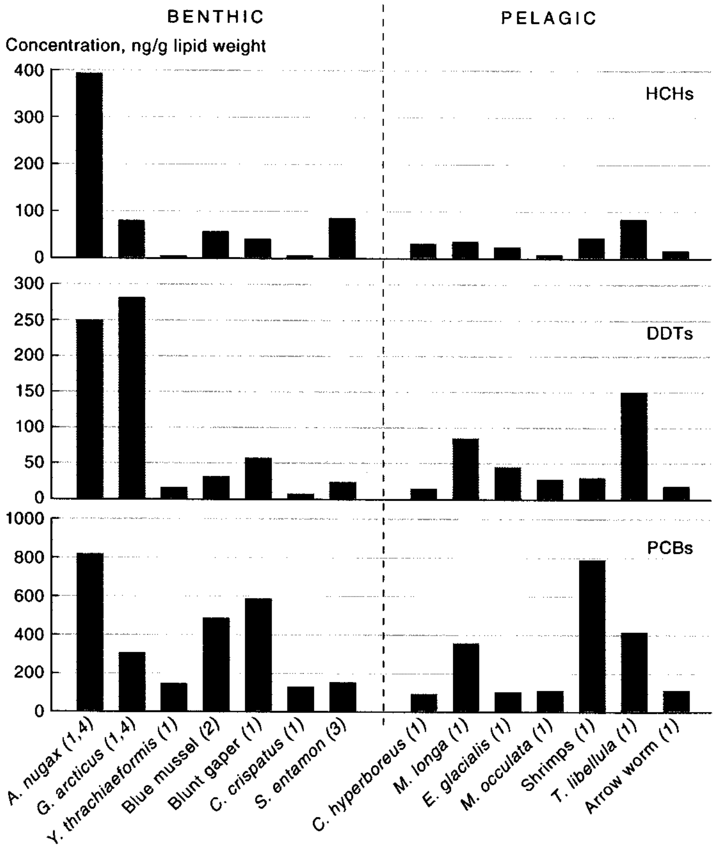


Barents Sea POP levels remain unexplained

Seabirds and marine mammals from the Barents Sea, Svalbard, and East Greenland have higher PCB and DDT levels than animals from Canada and Alaska. There are many ideas about the cause of this difference, including transport by contaminated ice from Russian rivers, but as yet no clear-cut answers have been found. The in-depth study of zooplankton and ice-associated amphipods does not show any clear geographical pattern that could provide an explanation. For example, PCB levels are higher in these organisms in the North American Arctic than in the Greenland Sea and north of Svalbard. Food web structure may be part of the explanation. More research is thus needed to understand the dynamics of contaminant transport around the Barents Sea, Svalbard, and East Greenland.

Averaged concentrations of HCHs, DDTs and PCBs in benthic and pelagic invertebrates from northern Baffin Bay (1), northern Quebec (2), northern Alaska (3), and Cumberland Sound (4).

The geographical pattern for POPs in zooplankton shows higher levels of HCB and HCHs in Alaskan and western Canadian waters compared with other parts of the Arctic. This probably reflects the proximity to recent sources in Asia. Toxaphene levels were lower at Alaskan sites than those in the eastern Canadian Arctic, reflecting proximity to North American sources.



The levels for ice-associated invertebrates were as low as those for the zooplankton. No clear geographical trend was apparent for PCBs, DDTs, and toxaphene. The only geographical difference was higher alpha-HCH levels in Fram Strait compared with the area north of Svalbard.

The study of ice-dwelling amphipods has increased understanding of their ecology and its relation to contaminant burden. The differing levels of fat-soluble POPs in these creatures indicate that diet may play an important role in the bioaccumulation of POPs. For example, the highest POP levels were found in a long-lived species that, as it grows larger, switches from eating phytoplankton to eating other zooplankton.

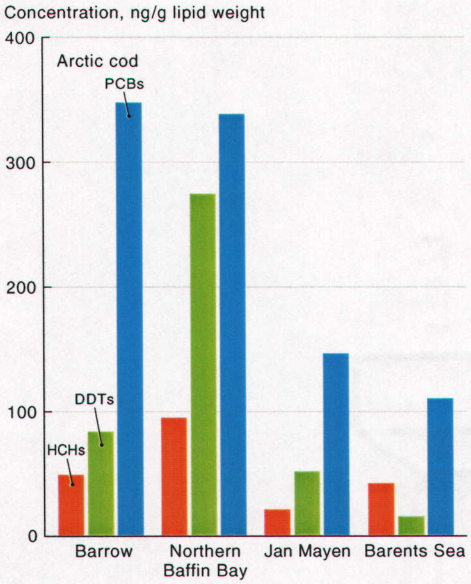
Bottom-dwelling, or benthic, invertebrates have a larger range of sizes and feeding ecologies than those living in the water column. Since the previous AMAP assessment, a number of new benthic invertebrates have been analyzed for POPs. Those that feed on animal carcasses can have very high POP concentrations. For example, the amphipod *Anonyx nugax* has concentrations in the same range as Arctic cod and the dovekie, a seabird. PCBs are the contaminant of greatest concern, but chlordane and DDT levels were also high in some species.

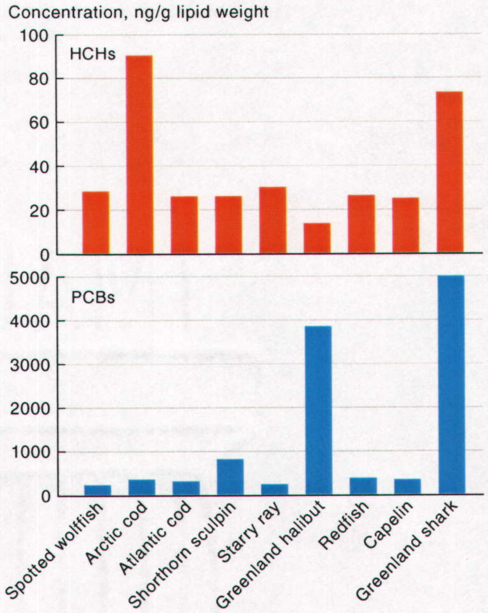
POP levels in the filter-feeding blue mussel are available for several locations. With one exception, the levels are low. PCBs are the most prominent contaminant, probably because they adhere to the sediments that the mussels filter to gather food. The one area with high contaminant levels was Kuujjauq in northern Quebec. This can probably be explained by a local PCB source. High TBT levels have been reported in blue mussel in harbors in northern Norway.

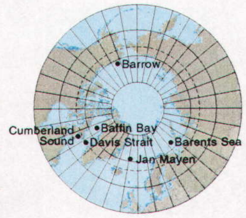
The Greenland shark stands out among marine fish

Arctic cod is an important link from invertebrates to marine mammals and seabirds. It is included in AMAP's monitoring program because of its circumpolar distribution. The geographical pattern indicates higher DDT levels in northern Baffin Bay than elsewhere in the Arctic. PCB levels were somewhat higher in North American Arctic cod, consistent with zooplankton but not with what has been seen in seabirds and marine mammals (see graph left on opposite page).

For some long-lived predatory fish, POP levels are high. The previous assessment mentioned high toxaphene levels in Greenland halibut from eastern Canada. Recent data from West Greenland confirm high POP levels in this species. New data on Greenland shark caught in Davis Strait and Cumberland Sound show levels in the same range as in other top Arctic predators, such as polar bear and glaucous gulls (see graph right on opposite page). DDT levels







◀ Concentrations of HCHs, DDTs and PCBs in Arctic cod.

Concentrations of HCHs and PCBs in Arctic marine fish from Davis Strait and Baffin Bay, and Greenland shark from Cumberland Sound.

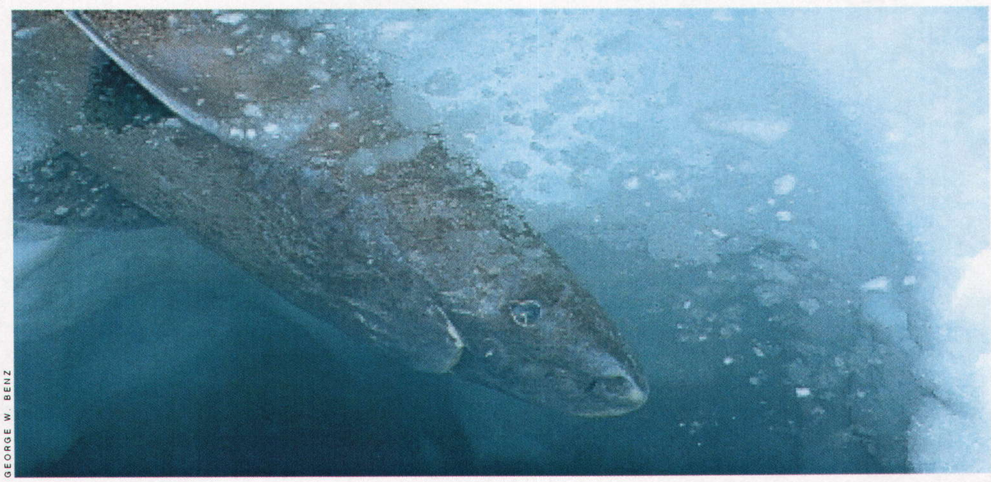
were among the highest ever measured in Canadian Arctic animals. The explanation is probably a combination of slow metabolism, long life span, and a high position in the food web.

Scavenging seabirds can have very high loads of POPs

There are about fifty species of Arctic seabirds. Their levels of contamination depend to a large extent on their different feeding habits. Some birds migrate to southern areas and their contaminant load also reflects what they eat during their migrations. For example, Greenland and Canadian kittiwakes, which overwinter in European waters and off the North American east coast, have high POP levels, as do kittiwakes from several sites in the Barents Sea.

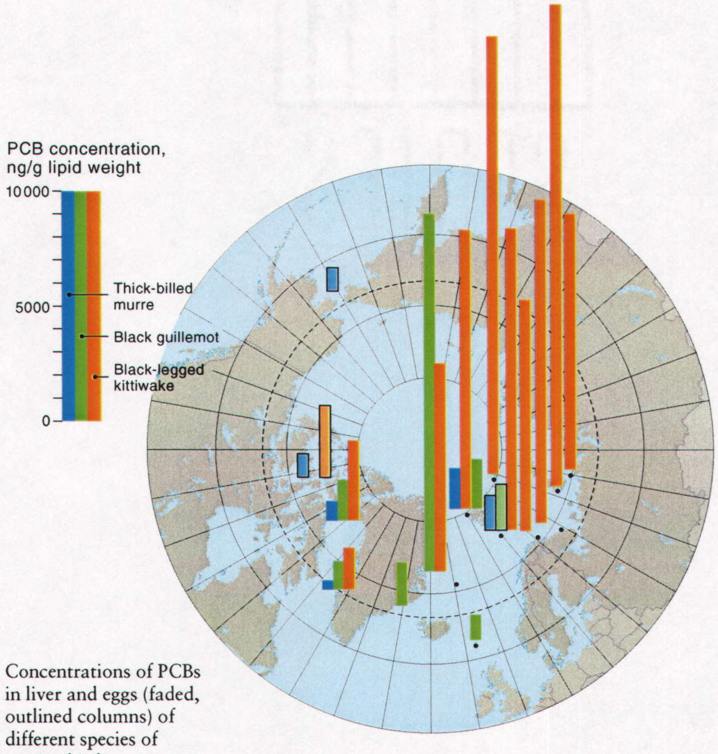
In the Arctic, POP levels are highest in the glaucous gull, the great skua, and the great black-backed gull, which are all birds that scavenge and prey on other seabirds and occasionally on carcasses of marine mammals. The glaucous gull migrates to the northern Atlantic region in winter, and the other two migrate as far south as southern Europe. Levels are also high in the ivory gull and northern fulmar, both of which scavenge.

The most prevalent contaminants are PCBs, DDTs, and chlordanes, but relative levels of these and other POPs vary by species. New data show that toxaphene is present in Canadian, Greenland, and northern Norwegian seabirds, with levels as high as those of PCBs. For some dioxins, furans, and dioxin-like PCBs, the levels in Arctic seabirds exceed levels in marine mammals by several orders of magnitude and are comparable to levels in seabirds from temperate North America and Europe. The levels are especially high in glaucous gulls from Bjørnøya. Some new chemicals have also been detected, most notably PBDEs. The levels of this chemical in Norwegian and Canadian Arctic birds are higher than in marine mammals in Canada but lower than in birds from the polluted Baltic Sea. Some individual glaucous gulls from Bjørnøya have PBDE levels as high as those of seabirds in the Baltic Sea.



GEORGE W. BENZ

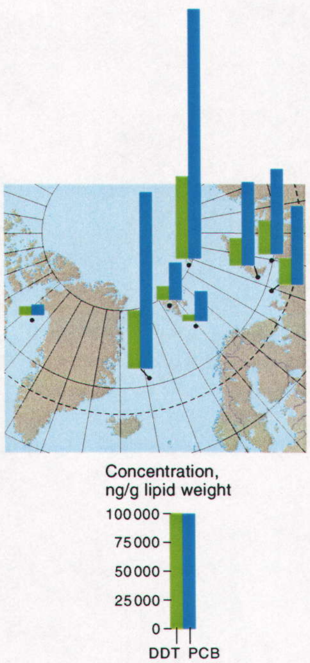
The Greenland shark is the largest fish and the only shark known to inhabit Arctic waters. Very little is known about its ecology, but there is some evidence that this shark can live more than 100 years. They eat seal pups and beluga whales, and thus live high in the food web.



Concentrations of PCBs in liver and eggs (faded, outlined columns) of different species of marine birds.

Mono-, di-, and tributyltins have also been found in these glaucous gulls. Polychlorinated naphthalenes (PCNs) have been detected in herring gulls and black-backed gulls in northern Norway.

POP levels in seabirds that do not migrate and have a circumpolar distribution, such as black guillemot, can be used to look at spatial trends. New data are available from Alaska, the Bering Sea, Baffin Bay, Greenland, Iceland, the Faroe Islands, Jan Mayen, and Svalbard. HCH levels were highest in the Baffin Bay birds, reflecting the generally higher levels of this contaminant in the Canadian Arctic and more recent use in Asia. PCB levels were highest at Jan Mayen, Norway. Glaucous gulls only migrate within very limited areas. The spatial trend for glaucous gulls shows the highest PCB levels at Franz Josef Land, Russia.

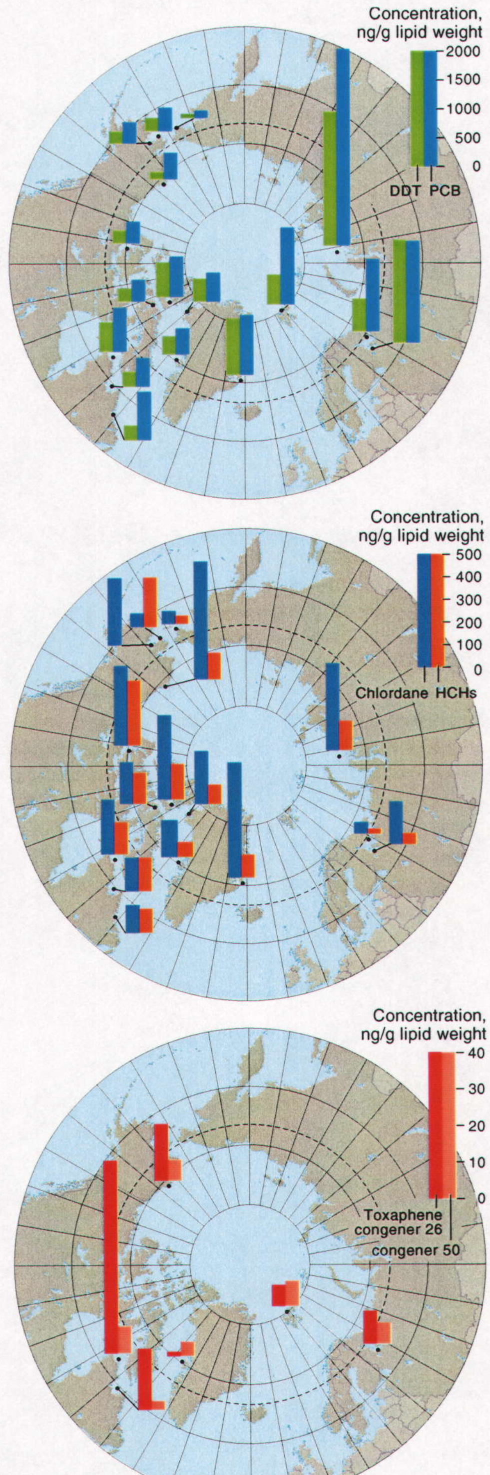


Concentrations of DDTs and PCBs in glaucous gull liver.

Seal data reveal high POP load in parts of the Arctic

The most abundant and widely distributed seal in the Arctic is the ringed seal. It feeds on fish and crustaceans. The most prominent contaminants in ringed seals are PCBs, chlordanes, and DDTs. Old and new data give a similar geographical picture of the contaminant load. Levels of PCBs and DDTs increase from west to east, with the lowest levels in Alaska and eastern Russia (Chukotka), moderate levels in the eastern Canadian Arctic and West Greenland, and higher levels in East Greenland and around Svalbard. The Svalbard seals have PCB levels four times higher than seals from the western Canadian Arctic and Alaska. In the Russian White Sea and the more easterly Kara Sea, levels were even higher than in the seals from Svalbard.

A number of studies have measured toxaphene in ringed seals, and the data show that this pesticide is an important contaminant throughout the Arctic. In some cases the levels are higher than for PCBs. The levels in ringed seals are highest in the Canadian Arctic, probably reflecting the extensive past use of toxaphene in North America. Harp seals on the ice edge east of Svalbard have surprisingly high toxaphene levels. This suggests that they are



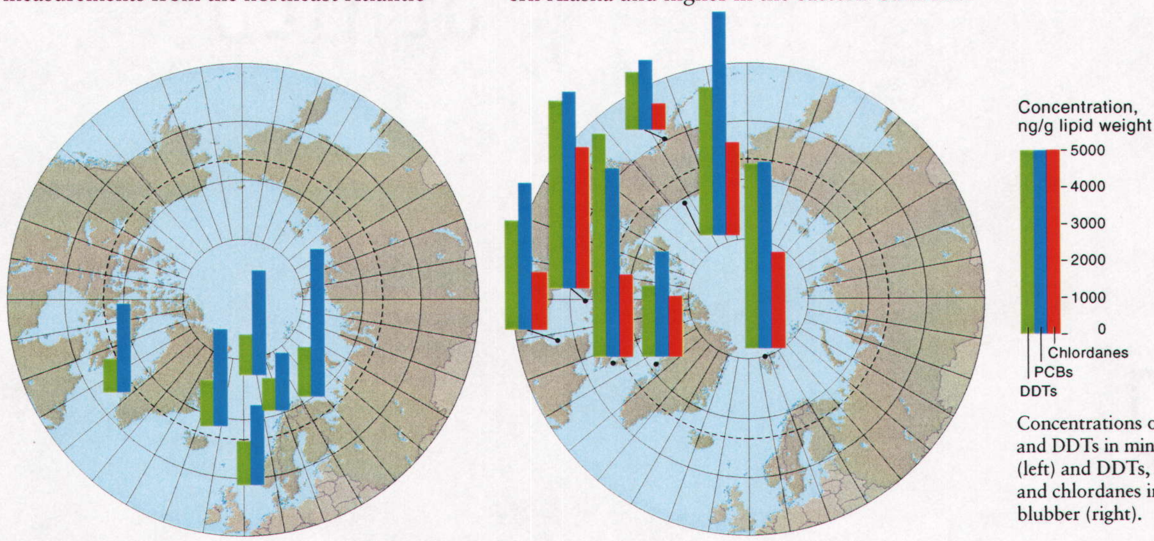
Concentrations of DDTs and PCBs (upper), chlordanes and HCHs (middle), and toxaphene (lower) in ringed seal blubber.

continuously exposed to fresh toxaphenes and may indicate the use and production of these compounds in spite of bans.

Low but detectable levels of mono- and dibutyltins have been found in Svalbard ringed seals and in Alaskan Steller's sea lions, in which tributyltins were also found.

Baleen whales have low loads of POPs

The North Atlantic minke whale is found across the Atlantic in both polar and northern temperate waters. It feeds mostly on fish and krill. PCB and DDT levels generally increase from west to east with the highest levels in the North and Barents Seas. The levels in recent measurements from the northeast Atlantic



Concentrations of PCBs and DDTs in minke whale (left) and DDTs, PCBs, and chlordanes in beluga blubber (right).

are two-to three-fold lower than those made in the early 1990s. The decline in POPs in these minke whales may reflect a change in feeding habits to almost exclusively krill after a collapse of the capelin stocks. The geographical differences in levels may reflect proximity to sources as well as differences in migration patterns and food habits, which are not well studied.

Gray whales make an annual round-trip migration between their breeding grounds in Baja California and the southern Gulf of California and their major feeding area in the northern Pacific Ocean. Gray whales mostly eat bottom-dwelling prey and thereby also ingest sediment and other bottom material. The only data on contaminants are from 17 whales sampled in Russian waters of the Bering Sea in 1994 and in one gray whale from Chukotka in 2000. DDT and PCB levels were comparable to other baleen whale species in other parts of the Arctic.

The bowhead whale lives in Arctic waters. The largest stock migrates between summer grounds in the eastern Beaufort Sea and Amundsen Gulf and winter habitat in the Chukchi and northern Bering Seas. The traditional native harvest occurs during the spring and fall migrations. The bowheads are exposed to a variety of contaminants via their prey, which is mostly plankton, but contaminant levels are generally low. The pattern of different POPs in bowheads matches the contaminant load in the surface waters of the Bering and Beaufort Seas.

Toothed whales can be very contaminated

The beluga or white whale is a small toothed whale feeding near the top of the marine food web. It is relatively long-lived. Belugas are found throughout the Arctic. The major POPs in beluga are PCBs, DDTs, chlordanes, and toxaphene. Levels are generally lower in southern Alaska and higher in the eastern Canadian Arctic and around Svalbard. Samples from Nunavut have also been analyzed for chlorinated naphthalenes, which accounted for about one tenth of the TEQs in those beluga. PBDEs are another new contaminant group present in measurable quantities in beluga.

In Alaska, free-ranging transient killer whales, which feed on marine mammals, have high POP levels compared with resident killer whales in Prince William Sound, which stay in one area and prey mostly on fish. The difference in contaminant burdens is probably caused by the different diets. The levels in the transient killer whales are similar to the populations in the Strait of Georgia/Puget Sound area at the border between Canada and the United States.

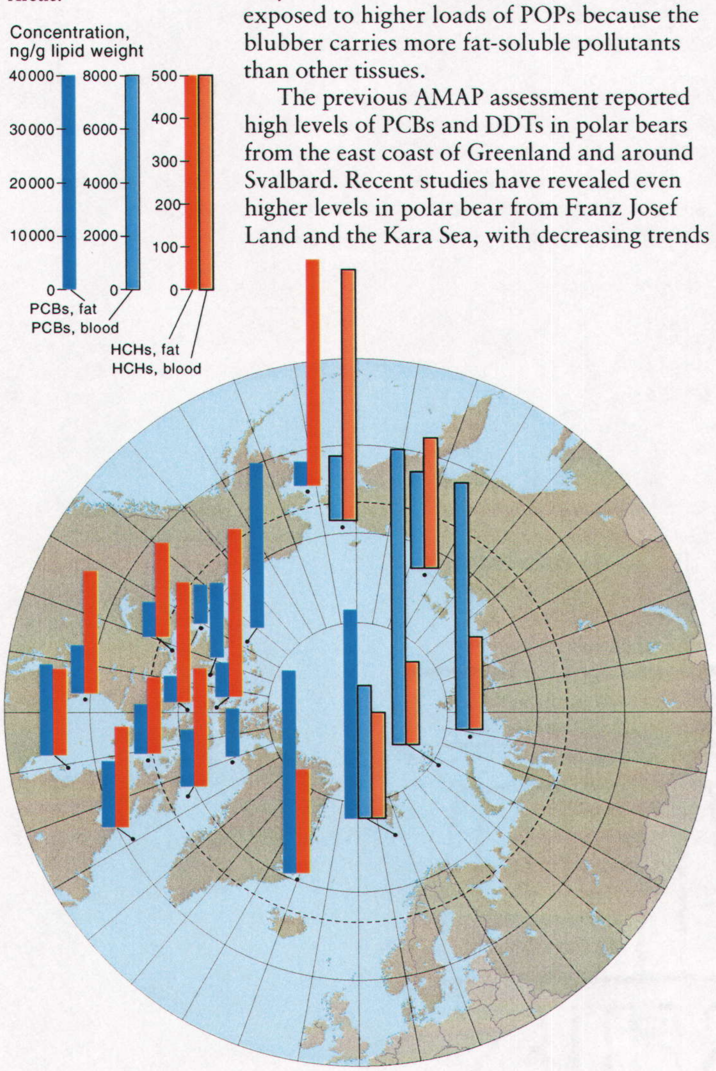
PCB and DDT levels in harbor porpoises off the west coast of Norway are comparable to those in porpoises from the polluted Baltic Sea and the Kattegat-Skagerrak passage between the Baltic and North Seas. Some of the porpoises from western Norway may have been exposed to local PCB sources. Levels in harbor porpoises from Greenland are much lower.

Norwegian and West Greenland harbor porpoises and Dall's porpoises from the Aleutian Islands have detectable levels of mono-, di-, and tributyltins.

PCB levels in pilot whales from the Faroe Islands are higher than for most other whales. Levels of several other POPs are also comparatively high. PBDE concentrations are an order of magnitude higher than in other Arctic marine mammals examined to date.

Narwhal from West Greenland and the Canadian Arctic have similar POP levels, whereas levels of PCBs, DDTs, and chlordanes were considerably higher in narwhal from Svalbard. Levels of HCHs, HCB, and toxaphene were quite consistent across the sites sampled.

Concentrations of PCBs and HCHs in adult female polar bears. Data from AMAP phase 1 (fat) and recent studies (blood). At Svalbard, PCB levels measured in fat are approximately five times higher than in blood from the same animals. If this relationship is the same in other areas, high fat PCB concentrations can be expected in bears in the Russian Arctic.



Polar bear PCB levels point to possible regional sources

Polar bears are top predators in the marine food web. They are distributed throughout the Arctic and range over large areas in search of food. They follow their main prey, ringed seals and bearded seals, as the edge of the sea ice moves south in fall and winter and north in spring and summer. Often, polar bears eat only the blubber from the seal, and are thus exposed to higher loads of POPs because the blubber carries more fat-soluble pollutants than other tissues.

The previous AMAP assessment reported high levels of PCBs and DDTs in polar bears from the east coast of Greenland and around Svalbard. Recent studies have revealed even higher levels in polar bear from Franz Josef Land and the Kara Sea, with decreasing trends eastwards and westwards from this region. This may imply a significant source of PCB pollution in Russia. The contaminant load in these polar bears also indicates that there may be significant sources of DDT and chlordane in this part of Russia.

There are also new polar bear data from Alaska, where PCB levels are lower than in polar bears from Hudson Bay, Canada, and Svalbard. In Alaska, the highest levels were in bears from the southern Beaufort Sea. The Alaska bears had higher HCH levels than polar bears elsewhere in the Arctic.

There have been several suggestions to explain why some polar bear populations have much higher PCB levels than others. These include proximity to sources and contaminant transport by ice from source regions. New information about what polar bears eat might shed more light on the issue. Most polar bears feed on ringed seal, especially the blubber. However, east of Svalbard, an unusually high number of bears feed on harp seals. These seals migrate from the Russian White Sea and may serve as a biological pathway from Russia to Svalbard. Moreover, blubber from adult harp seals has higher POPs concentrations during the molting season in June, compared with ringed seals sampled at the same time. The results suggest that the season, availability, and biological condition of polar bear prey may play an important role in biomagnification of POPs in the marine food web.

Though PCBs have been the major contaminant of concern in polar bears, other POPs are present as well. Most notable is PFOS. Levels in some polar bear liver samples from northern Alaska are high enough to make this one of the most prominent POPs. PFOS has also been detected in blood of ringed seals in eastern Canada and in Svalbard and in Alaskan northern fur seals.

Recent measurements show the presence of toxaphene in Svalbard bears. Their fat also contains PBDEs, along with several unidentified brominated compounds.

Arctic fox

Arctic foxes are very opportunistic in their food habits and can be part of both the marine and terrestrial food webs. On land, the foxes feed on lemmings, birds, bird eggs, and caribou carcasses, whereas coastal foxes may also eat marine invertebrates and fish in summer. During the winter and spring they scavenge on the remains of seals killed by polar bears and on seal placentas. Arctic fox also prey on newborn seal pups. Their feeding habits influence both their position in the food web and their contaminant load. Foxes in Canada, inland Iceland, and Alaska generally have lower POP levels than do foxes along Iceland's coast and on Svalbard. Iceland's coastal foxes have PCB levels higher than Svalbard polar bears.

Time trends

Comparing previous and current levels of contaminants can give an indication of new sources as well as information about the effects of bans or other political actions to limit emissions. Interpretation of time trends must also take into account possible changes in pathways, as is discussed in the chapter *Changing Pathways*. This is especially true for trends comparing the 1990s with previous decades, because of a shift in climate regime that has affected wind patterns, precipitation, and ocean currents.

In general, the levels of several banned persistent organic pesticides have declined or otherwise mirror historical usage. However, there are some notable increases in air during the 1990s for DDTs, dieldrin, and endosulfan. Increases for endosulfan have also been seen in beluga

Some HCHs have not declined as much as expected based on decreased use. In fact, levels of beta-HCH have increased in some areas, probably because old emissions are only now reaching parts of the Arctic via ocean transport. The time trend for toxaphene is also complex, with both increases and declines reported.

For PCBs, levels have generally decreased, but with varying rates in different parts of the Arctic. In polar bears and belugas, the decline has leveled off since the mid-1990s.

Not all contaminants are decreasing. Data from seabirds, belugas, and seals indicate that levels of the brominated flame retardant PBDE are increasing. This product is still in use.

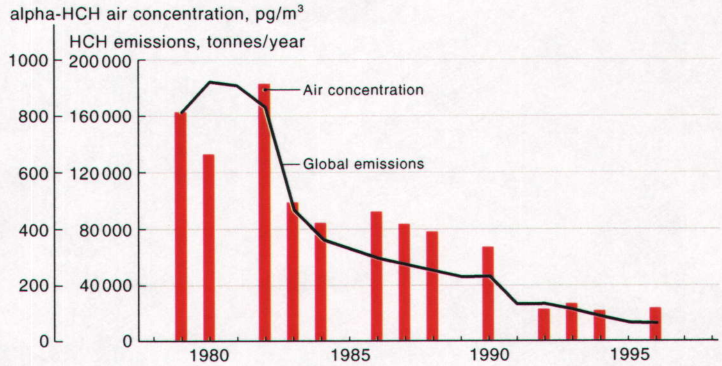
The following sections give more detailed information about the different time series.

Air samples show trends in atmospheric concentrations

Air sample data mirror atmospheric transport of contaminants. The most reliable time trend data are from Alert, Canada. At Alert, DDT concentrations increased significantly over the period 1993 to 1998, and the chemical signature implies a continued source of technical DDT entering the Arctic atmosphere. HCHs declined during the same period, as did chlordane levels. Dieldrin concentrations increased significantly. The concentrations of alpha-endosulfan also increased significantly at Alert, which can probably be explained by continued use in North America.

For PCBs there was a definite reduction in air concentration at Alert from 1992 to 1998, whereas other stations showed no clear downward trend. Also, for PAHs, there was no consistent trend.

Longer time-trend data for HCHs clearly show how reduced use has an impact on air transport to the Arctic, decreasing the load to the environment.



Emissions of technical HCH and concentrations of alpha-HCH in Arctic air.

Ice cores show declining input

Snow collected in glaciers and transformed into ice can give a historical record of POPs deposition. In the spring of 2000, a core of ice was collected at the Lomonosovfonna Ice Cap on Svalbard that represents a historical record of the past 70-80 years. It gives the first detailed picture of deposition in the European Arctic. For all the measured contaminants, the maximum concentration occurred below the snow surface, indicating that inputs have declined in recent years.

The results indicate that DDT levels probably peaked before the 1970s in most of the areas that are sources to Svalbard. The levels were unusually high compared with some other pesticides, which may reflect past DDT use in nearby communities. An unexpected result was that the concentration of HCHs in the ice core was higher than for the other POPs. The highest concentrations were similar to 1993 levels in water from the Yenisey River, the most contaminated of the large Russian rivers. HCHs, being volatile, would normally evaporate and the levels may thus have been even higher when the snow fell. The snow near the surface, reflecting recent input, had levels that were similar to current levels in lake and river water. The recent downward trend in HCHs is consistent with what has been seen in air and water samples.

Falcon eggs and freshwater fish show declining POP levels

Eggs from Alaskan peregrine falcons have been analyzed to look at time trends for the terrestrial environment. From 1979 to 1995, the levels of dieldrin, DDTs, chlordanes, and PCBs declined. The trend was weaker for PCBs than for the other contaminants.

In the North American Arctic, some time trend conclusions can be drawn by comparing burbot liver samples collected in Fort Good Hope in the years 1986, 1988, 1994, and 1999. Slow declines in all major organochlorines and toxaphene were observed, although the rate of change varied with the chemical and the year. Russian burbot data from 1988 and 1994 indicate declines in HCHs and DDTs.

Seabird eggs provide wealth of time trend data

One way to look at time trends is to analyze archived samples. One such a study has been carried out on seabird eggs collected between 1975 and 1998 from Prince Leopold Island in the Canadian High Arctic. During egg formation, POPs are transferred to the egg via lipids.

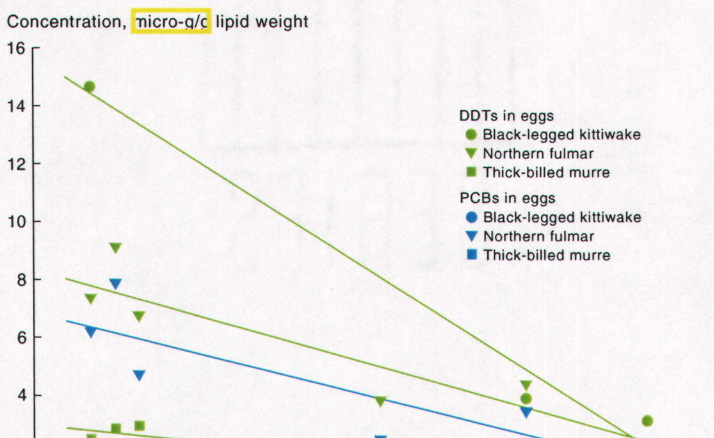
Climber on cliff with northern fulmar and egg. Bird eggs collected on Prince Leopold Island in the Canadian Arctic provide important information about temporal trends of POP levels.

BIRGIT BRAUNE

The contaminant burden in the egg reflects residues assimilated by the female over a long period. In migratory birds, eggs also integrate the exposure from a number of different locations.

Levels of PCBs, DDTs, and HCB decreased in all the bird species studied during this period. The most dramatic declines were in kittiwake eggs. These birds migrate to industrial areas, and the declines are similar to what has been seen in birds from polluted areas such as the Baltic Sea. Chlordane, dieldrin, and mirex levels decreased in kittiwake eggs, but not in the eggs of other birds.

Concentrations of DDTs and PCBs in seabird eggs collected between 1975 and 1998 on Prince Leopold Island.



The story about HCHs in the North American Arctic is mixed and provides a lesson about the role of biomagnification in temporal trends. For total HCHs, the levels in bird eggs increased, driven by beta-HCH. Alpha-, beta-, and gamma-HCH all continue to be delivered to the Arctic by seawater flowing through the Bering Strait. Moreover, the Arctic Ocean may work as a major reservoir of these contaminants. However, only beta-HCH biomagnifies, and this component drives the temporal trends for total HCHs in higher-trophic-level organisms. In other words, the decline in total HCHs that would be expected based on reduced global use is delayed partly because beta-HCH biomagnifies. Another reason for the delay is that ocean currents are still delivering beta-HCH into the Arctic Ocean from the Bering Sea.

Some measurements in bird livers from Prince Leopold Island provide data on dioxins, furans, and dioxin-like PCBs in kittiwakes, fulmars, and murres. Reported as TEQs, levels were lower in 1993 than in 1975. Within this general picture of declining levels, however, there was an increase in dioxins and furans in murre livers and an increase of dioxin-like PCBs in fulmar livers.

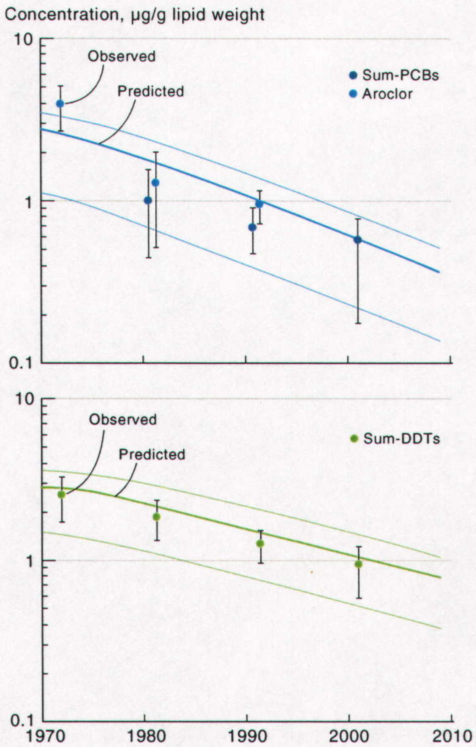
The Canadian data also suggest that levels of toxaphene and PBDEs have increased from 1975 to 1993.

Another time trend in several seabird species was carried out in northern Norway, looking at eggs from 1973, 1983, and 1993. There was a significant decline in PCBs and DDTs.

Model based on seals predicts future DDT and PCB declines

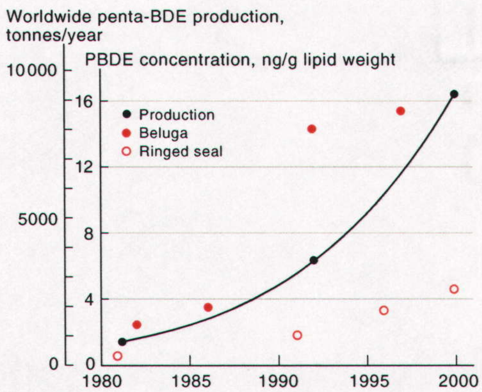
Ringed seals collected by hunters in the three Canadian communities of Ausuittuq and Ikajutit in Nunavut and Holman in the Northwest Territories have been used to compare current contaminant levels to those in the 1970s. The most striking declines are for DDTs and PCBs. HCH concentrations showed no significant change, but the proportion of beta-HCH increased over this time period. A similar increase in beta-HCH has been reported for seawater during the 1980s and 1990s. Chlordane levels increased in Holman and Ausuittuq, in contrast to falling PCB and DDT concentrations. The concentration of dioxins, furans, and dioxin-like PCBs remained constant between 1981 and 2000.

What will happen to ringed seal contaminant levels in the future? By modeling the historical input to the environment along with biological factors that affect the levels in the animals, it has been possible to make some predictions. Contaminant levels in ringed seals do not seem to lag behind inputs, probably because the seals can excrete the contaminants



Observed and predicted trends for PCBs and DDTs in ringed seal from Holman Island, Northwest Territories.

and because of population turnover. Therefore, PCB and DDT levels are predicted to decline substantially over the coming decade. The predicted rapid decline should not be extrapolated to other species as lifespan and position in the food web have a major influence. For example, levels in polar bears and belugas do not decline as fast. Neither should the expected decline be extrapolated over longer time frames or to other contaminants.



Comparison of temporal trends of PBDEs in ringed seal and beluga in the Canadian Arctic with estimated global production of penta-BDE over the same period.

PBDEs are on the rise

Not all contaminants are decreasing. Studies of beluga blubber from southeastern Baffin Island, Canada, show that the levels of PBDEs have increased from 1982 to 1996. The levels are low compared to PCBs in the same animals, but the levels doubled in only three years. The trend parallels PBDE increases in fish and in herring gull eggs from the Great Lakes in North America. A similar increase has also been seen in ringed seal from Holman Island, Canada, with a doubling of concentration in 4.5 years, and in seabirds from Prince Leopold Island, Canada. If nothing is done to reduce emissions and current trends continue, PBDEs may reach the same levels as PCBs in a few decades.

There are no temporal trends for PBDEs in the European Arctic, but data from the Baltic Sea indicate declines after a previous exponential increase in the 1980s. The penta-BDE product has been withdrawn in Europe and this shows the close relationship between discontinued production and use and decreased environmental concentration.

Declining concentrations in polar bear are leveling off

In the Canadian Arctic, the most striking time trend is a strong decrease in DDTs in polar bears from Hudson Bay from 1968 to 1999. The decline started from comparatively high DDT levels, probably connected to use in local communities and a military base to control insects during the 1950s and 1960s. After a ban on DDT and the closing of the military base in the mid-1970s, local DDT input into the environment decreased drastically. For other contaminants, trends could only be detected from 1991 to 1999. HCB, alpha-HCH, and PCBs decreased, whereas there were no significant changes in chlordanes, DDTs, dieldrin, beta-HCH, and total HCHs. In spite of the recent declines, PCB levels in Hudson Bay polar bears were almost as high in the late 1990s as they were in the late 1960s. This is in sharp contrast to the large declines in PCB contamination in the Great Lakes and in the North Atlantic.

In Svalbard polar bears, PCB levels decreased rapidly in the early 1990s, more so than in the bears from Hudson Bay. However, the decrease has now leveled off and PCBs in Svalbard polar bears have probably reached a steady state with the global distribution of PCBs. Current results indicate that further decreases in PCBs in the Arctic may be slow. In contrast to the bears from Hudson Bay, beta-HCH did decline in the Svalbard bears.

Biological effects

POPs have a range of potential effects on animals. A sensitive target is the immune system, where new information reveals that effects are apparent among some Arctic populations of polar bear, northern fur seals, and glaucous gulls. Current contaminant levels may also pose a threat to reproduction and brain development in wildlife. POPs interacting with hormones, especially during development in the womb or at a very young age, is probably a common link between many effects.

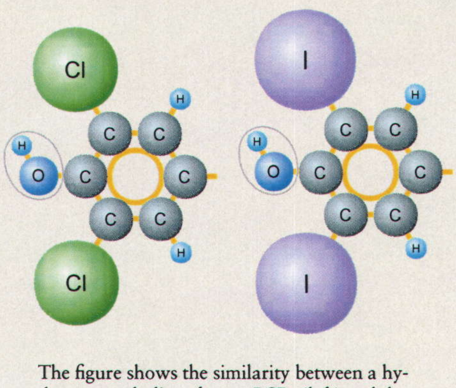
Hormone disruption may be a common link

New information on the mechanisms behind the toxic effects of POPs points to common underlying mechanisms involving disruption of the hormone system. Thyroid hormones have been a particular focus. These hormones control fetal brain development and behavior, as well as growth, metabolism, and reproduction throughout the life of the animal.

Some of the effects on the thyroid seem to be caused not by the contaminants themselves but by substances that the body has created in trying to detoxify the contaminants. Of special importance are metabolites that attach to the protein complex that normally transports thyroid hormone and vitamin A in the body. This leads to imbalances of thyroid hormones or vitamin A or both. Imbalance in vitamin A can cause a suppression of the immune system, increased susceptibility to cancer, and skin lesions, and can disrupt reproduction, growth, and development. Some POPs, especially dioxins and PCBs, are known to affect vitamin A balance in the body.

POPs can also influence the levels of thyroid hormones by increasing or decreasing the normal breakdown of this hormone in the body. The PCB metabolites hydroxy-PCBs can influence a regulatory pathway that is important in fetuses, and can thus affect fetal brain development. Additionally, exposure to POPs is known to lead to greater production of specific enzymes in the liver, which are involved in the breakdown of thyroid hormones.

Several POPs also affect sex hormones, for example by binding to the receptor for estrogen. Sometimes the result is an estrogen-like activity, sometimes the opposite. Slight changes in the levels of sex hormones can have dramatic effects on an animal.



The figure shows the similarity between a hydroxy metabolite of some PCBs (left) and the hormone thyroxin (right). This structural similarity allows hydroxy-PCB to fit into a hormone receptor, which in turn can lead to a range of effects.

Many sensitive targets

The toxic properties of POPs on wildlife have been recognized since the 1960s. The effects of POPs on reproduction are numerous. In birds, they include eggshell thinning, decreased egg production, dead or deformed chick embryos, and changes in mating and parental behavior. In mammals, POPs are known to alter hormone levels, reduce sperm production, and decrease the survival of offspring. In fish, documented effects of POPs include decreased survival of eggs and larvae, failure to mature sexually, and smaller-than-normal gonads.

Even more sensitive than the effects on reproduction may be the influence of POPs on the immune system. Several parts of the immune system are known to be vulnerable and the insidious result is to reduce an organism's defense against infections. The immune system is especially vulnerable during development before and just after birth. In mammals, the period after birth coincides with exposure via milk from the mother, which can contain high levels of POPs.

The brain is another sensitive target for POPs, especially during pregnancy and just after birth. During this period, a disruption that may result from relatively low levels of POPs can cause permanent damage to the brain in a way that similar low POP levels would not do in an adult.

An effect of POPs that has been documented since the publication of the previous AMAP assessment is on bone development. Dioxin-like substances appear to decrease bone density. Arctic studies on effects on bone have just started.

A common link between many effects may be disruption of the hormone system (see box on left).

Females transfer POPs to their young

Females transfer substantial amounts of POPs to the next generation. In birds and fish, this occurs via the eggs, and in mammals, directly to the fetus and via breast milk.

In marine mammals, mother's milk can have extremely high fat content to help the young animal grow rapidly during the short summer season. Because POPs dissolve in fat, they concentrate in the fat of mother's milk and thus transfer readily to the nursing young. In some species, such as harp seal, the transfer via milk is accentuated because the female does not eat during the nursing period and POPs are further concentrated in her diminishing fat stores, including her milk.

For many of the effects of POPs, including behavioral, immune, reproductive, and neurotoxic effects, there may be critical developmental windows, where effects in the young occur at lower exposure levels than in adults. Exposures in the womb and via breast milk are thus likely to be especially problematic.

Mother's milk is a major source of POPs for newborn marine mammals.

Starvation can lead to high POP levels

Most POPs dissolve in fat and accumulate in the fatty tissues of animals, such as the liver or parts of the body that specifically store fat. Some of the contaminants are in the blood or other organs. In the Arctic, many animals go through periods of fasting, when they use stored fat for energy. This leads to an increase in contaminant concentrations in the remaining fat, as well as in the blood and in other organs. This increases the risk that sensitive systems, such as the brain or reproductive organs, will be exposed to toxic levels.

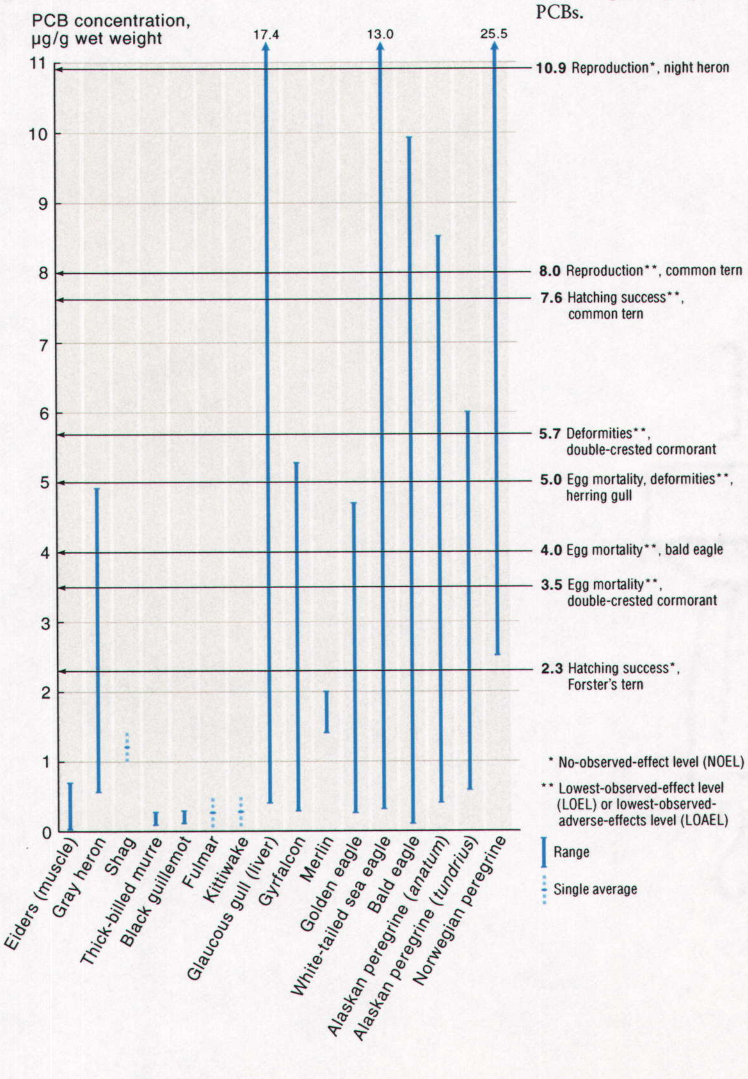
A study of Arctic char showed that females can lose about 80% of their fat during spawning and overwintering. Males lost a little more than 50%. Another study of Arctic char showed that this fat loss can have dramatic consequences for contaminant levels in sensitive organs. At the same time that the overall PCB concentration in the body dropped by 20%, PCB concentrations in the brain increased six-fold and concentrations in the liver doubled.

Experiments on Arctic char have also shown that the combination of high PCB levels and long-term fasting that is typical for high-latitude fish can compromise their response to stress and disease.

Birds of prey are still vulnerable

Birds of prey are known to be very sensitive to some persistent organic pollutants. Their health in relation to POP levels has been followed for many years. The previous AMAP assessment found that Canadian peregrine falcons still had high levels of many POPs. For PCBs and chlordanes, levels in the 1990s were even higher than in the 1980s. Eggshell quality had not improved and the conclusion was that this Canadian population might still be threatened.

New data from Alaska covering the period 1979 to 1995 complement this picture. In eggs from the American peregrine, which nests in the forested interior, a number of POPs were detected. Although concentrations declined over time, there was evidence for both cumulative and individual contaminant effects. Eggshells were still thinner than normal eggshell thickness in the pre-DDT era. Moreover, levels



Ranges of concentrations of PCBs in Arctic bird eggs (or otherwise indicated tissues) compared with thresholds for avian effects. The comparison should be used with caution because of problems with extrapolating data across species and differences in quantifying PCBs.

of dieldrin, oxychlordane, and PCBs were higher in unsuccessful nests (nests without chicks) than in nests that produced at least one young. The PCB levels exceed those known to cause reproductive problems in other wild bird species. Eggs from unsuccessful nests also had higher mercury concentrations, which may also have affected reproduction, see chapter *Heavy Metals*.

New data on bald eagles from the Aleutian Islands indicate that the population on Kiska, one of four studied islands, had reduced reproduction that was associated with high levels of DDE.

Several waterfowl species in Canada also had POP levels high enough to cause concern about reproductive effects according to the previous AMAP assessment.

For European birds of prey, the previous AMAP assessment concluded that Fennoscandian merlin and white-tailed sea eagles in Norway, Sweden, and Russia had contaminant levels that could affect their reproduction, even if the Norwegian and Swedish populations seemed to be recovering from previous declines caused by pollution. New data on organochlorines in Norwegian birds of prey show similar contaminant levels today. PBDEs are present in Norwegian white-tailed sea eagle and peregrine falcons in Norway and Sweden at fairly high levels, but there are no effects thresholds for PBDE with which the levels can be compared.

Mixed picture for terrestrial mammals

The previous AMAP assessment concluded that mink in northern Quebec and otters in northern Sweden, both of which feed mainly on fish, have PCB levels high enough to cause concern about effects on reproduction as well as on neurobehavioral development of the young. There is no new information about these species.

There is new information, however, about POP levels in Canadian wolverines and wolves, where the wolverines have PCB levels high enough to raise concern about subtle neurobehavioral effects.

For terrestrial herbivores (ptarmigan, hare, reindeer, sheep, and muskox), new data from West Greenland, the Faroe Islands, and Russia generally show very low POP levels that are nowhere near known effect levels. However, dioxin levels in some reindeer and mountain hare from the Kola Peninsula are rather high in relation to effects thresholds in other species, but potential effects are difficult to evaluate.

Local contamination may cause concern for freshwater fish

In most freshwater environments, POP levels are not high enough to cause concern for the health of the fish. But there are exceptions. One is Arctic char in the lake Ellasjøen on Bjørnøya, where high PCB levels affect liver enzymes.

The previous AMAP assessment noted that toxaphene levels in burbot in some Canadian lakes were high enough to potentially affect bone development. New Canadian data show a slow decline in toxaphene levels in Lake Laberge in the Yukon Territory and in the Mackenzie River in the Northwest Territories. Researchers looking for effects on bone development did not find any problems.

An Alaskan study of burbot has compared POP levels in 1999 with those in 1988. The data imply that most of the contaminants in the fish are from older releases into the environment. Moreover, the levels have for the most part decreased. The levels did not exceed known effect levels. However, PCBs in burbot from Fairbanks, Yukon Flats, and Lake Laberge were close to or exceeded the levels that are known to induce liver enzyme activity in other fish species (see map on page 16).

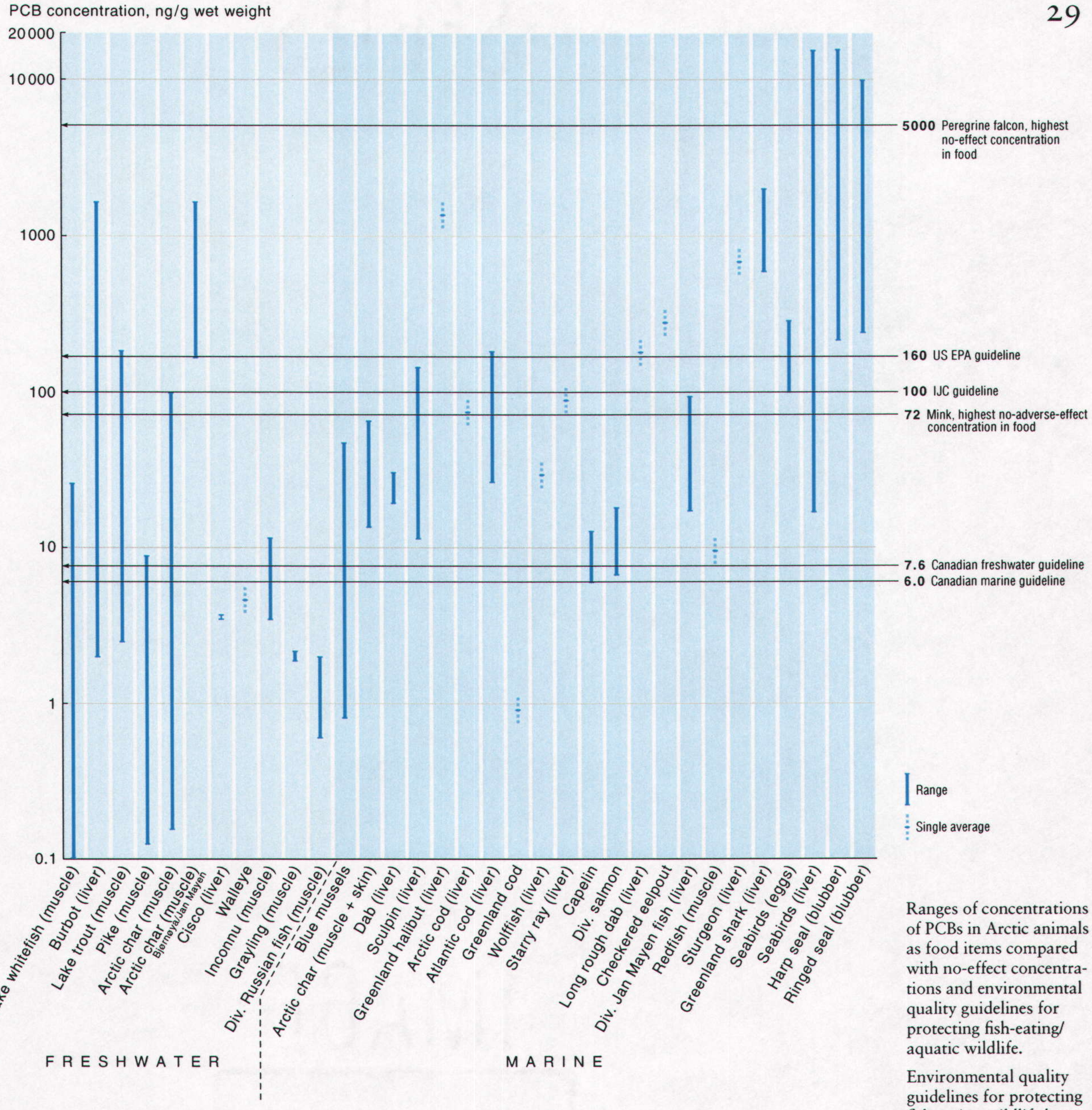
Imposex found in marine invertebrates

For most contaminants, levels in marine invertebrates are low enough not to cause any concern for biological effects. The exception is TBT, a compound that is toxic to some species at extremely low levels. In dogwhelk, a small mollusk, TBT causes the females to develop a penis and also makes them sterile. This condition is called imposex, and has been observed in harbors in West Greenland, Iceland, northern Norway, the Faroe Islands, and Svalbard.

A study of dogwhelk in harbors along the Norwegian coast has revealed that some degree of imposex occurred everywhere except for four of the study locations in northern Norway. In Iceland, the level of imposex decreased considerably from 1992-93 to 1998, after the use of TBT as an anti-fouling agent had been restricted in 1996. Imposex in Faroe Island dogwhelks is widespread and no change has occurred from 1996 to 2001. In West Greenland harbors, elevated TBT levels were found in blue mussel in 1999.

JORUNDUR SVAVARSSON

The dogwhelk is a marine mollusk that is extremely sensitive to TBT.



Ranges of concentrations of PCBs in Arctic animals as food items compared with no-effect concentrations and environmental quality guidelines for protecting fish-eating/aquatic wildlife.

Environmental quality guidelines for protecting fish-eating wildlife have been established by several organizations and countries. They are based on contaminant levels in fish and known thresholds for effects in fish-eating wildlife. Biomagnification rates for different substances have then been used for back-calculating the fish concentrations that should not cause effects in fish-eating species.

PCBs disturb nesting behavior in some seabirds

At the time of the previous AMAP assessment, it was clear that contaminant levels among several seabirds were high enough to raise concerns about effects on reproduction. This assessment confirms this conclusion. Moreover, in some species, some contaminant effects on behavior and reproduction have been studied in more detail.

Even in the early 1970s, there were observations that glaucous gulls on Bjørnøya did not behave normally. Bjørnøya is a hot spot of PCBs (see box on page 16) and levels are higher than at most other studied sites in the Arctic. Recently, high PCB levels in Bjørnøya glaucous gulls have been correlated with increased time spent away from their nests. The results suggest that individuals with high PCB loads need more time to gather food than do birds with lower loads. The underlying cause could be that PCBs disrupt the birds' hormone systems or affect their nervous system. New results confirm hormone effects in this glaucous gull population. The end result is that the birds do not have sufficient energy to reproduce successfully.

Moreover, females with high PCB levels in their blood were more likely to have nonviable eggs in their nests than females with lower PCB levels. The chicks of females with high PCB levels were also in worse physical condition. Finally, high PCB levels decreased the probability of survival of adult birds. In long-lived birds, population growth rate is

Overview of toxic properties of various POPs. ▼= suppression or decrease, ▲ = induction or increase.

	Reproductive/ developmental effects	*Neurotoxic effects*	*Liver enzymes*	*Immune effects*	*Effects on thyroid and vitamin A*	*Cancer*	*Other*
Aldrin and dieldrin	▼ Reproduction		Induces liver enzymes	Suppresses immune system		Non-mutagenic. Increased liver tumors	
Chlordanes	▼ Reproduction		Induces liver enzymes	Suppresses immune system		Non-mutagenic tumor promoter	
DDT and metabolites	Egg-shell thinning in bird eggs. ▼ Reproduction		Induces liver enzymes	Suppresses immune system	▼ Thyroid weight		Overstimulation of adrenal cortex
HCB	Fetotoxic. Deformities. ▼ Reproduction		Induces liver enzymes	Suppresses immune system	▼ Thyroid hormones. ▲ Thyroid stimulation hormone. ▲ Thyroid weight	Non-mutagenic tumor promoter	▲ Porphyria (a blood disease causing skin and nerve damage)
alpha-HCH	No information		Induces liver enzymes			Non-mutagenic tumor promoter	
beta-HCH	Estrogenic		Induces liver enzymes	Suppresses immune system	▲ Thyroid weight	Non-mutagenic tumor promoter	
gamma-HCH (lindane)	Estrogenic and antiestrogenic. ▼ Reproduction		Induces liver enzymes			Non-mutagenic tumor promoter	
Mirex	▼ Reproduction		Induces liver enzymes	Suppresses immune system		Non-mutagenic. Induces tumors	
Toxaphenes	Fetotoxic. ▼ Reproduction		Induces liver enzymes	Suppresses immune system	▲ Thyroid-weight. ▲ Thyroid-stimulating hormone	Mutagenic, potent carci-nogen. Inhibits cell-to-cell commu-nication	▲ Bone brittleness in fish. Overstimulation of adrenal gland
Endosulfan	Fetotoxic. ▼ Reproduction		Induces liver enzymes	Suppresses immune system		Non-mutagenic	
Dioxin, furans, dioxin-like PCBs, and metabolites	Fetotoxic. Deformities. ▼ Reproduction	Permanent changes in learning, behavior, memory	Induces liver enzymes	Thymic atrophy. Suppresses immune system	▼ Thyroid hormones. ▼ Vitamin A	Non-mutagenic tumor pro-moters. Affects cell-to-cell communi-cation	▲ Porphyria
Other PCBs	Fetotoxic. Deformities. ▼ Reproduction	Permanent changes in learning, behavior, memory. Decreased dopamine (a neurotransmitter)	Induces liver enzymes	Suppresses immune system	▼ Thyroid hormones. ▼ Vitamin A	Non-mutagenic tumor pro-moters. Affects cell-to-cell commu-nication	▲ Porphyria Overstimulation of adrenal cortex
Short-chain chlorinated paraffins	Fetotoxic Deformities. ▼ Reproduction	▼ Motor perform-ance	Induces liver enzymes	No information	▼ Thyroid hormone. ▲ Thyroid-stimulating hormone	Non-mutagenic. ▲ Peroxisome proliferation. Inhibits cell-to-cell communication	
Poly-chlorinated naphthalenes	Embryotoxic. ▼ Reproduction		Induces liver enzymes				
PBDE (flame retardant)	Estrogenic and antiestrogenic	Permanent changes in learning, behavior, memory	Induces liver enzymes	Suppresses immune system	▼ Thyroid hormone. ▼ Vitamin A	Non-mutagenic	
PFOS/PFOA	▼ Reproduction					Non-mutagenic, tumor promoter . ▲ Peroxisome proliferation. Inhibits cell-to-cell communication	
TBT and metabolites	Imposex in invertebrates. Deformities. ▼ Reproduction		Inhibits liver enzymes	Suppresses immune system		May be carcinogenic	

very sensitive to adult survival rates. This suggests that high exposure to PCBs may have a considerable effect on the size of this glaucous gull population. Another study found signs of suppression of the immune system in these same gulls, indicating that they may suffer decreased resistance to infections.

Laboratory studies in which glaucous gulls chicks were fed Arctic cod and seabird eggs from the Barents Sea indicate effects on hereditary material (the chromosomes). The importance of POPs and other contaminants for these effects needs to be confirmed.

Black guillemots near a PCB-contaminated former military site at Saglek Bay, Canada, show multiple effects on the liver. This implies that PCBs affect the health of these birds.

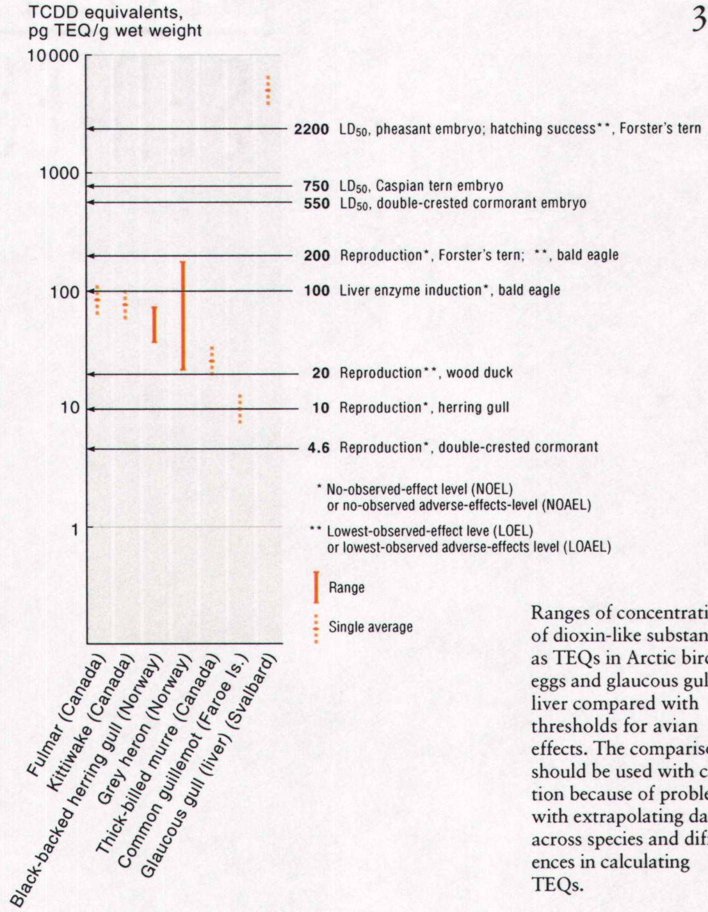
Effects of POPs have also been observed in shag from the central Norwegian coast. PCBs in eggs seem to affect the weight of the hatchling. There may also be a correlation with effects on vitamin A in the hatchling. The observed effect of PCBs on hatching success in shag is consistent with known effect levels in other birds.

For most bird species, there are no studies of effects, and the only way to judge the potential impact of POPs is to compare contaminant levels with levels that are demonstrated, through laboratory or field studies, to affect the health of other bird species (see diagram on page 27). Based on such comparisons, grey heron from the Norwegian west coast have PCB levels high enough to raise concern about hatching success. PCB levels in great skua, great black-backed gulls, and some glaucous gull populations (particularly from Bjørnøya) exceed most thresholds for reproductive effects in other bird species. Levels of POPs with dioxin-like activity may be approaching values high enough to cause concern about reproductive effects in Canadian thick-billed murres, kittiwakes, and fulmars, and in grey herons from the west coast of Norway. Dioxin-like PCBs in glaucous gulls from Svalbard are above all thresholds for reproductive effects as well as the threshold for effects on liver enzymes.

Eiders and alcids (guillemots, murres, and dovekies) feed lower in the food web. With the exceptions noted above, their contaminant levels are below known effect levels. However, an analysis of POP levels in their diet show that DDT and PCB levels in some of their potential prey exceed environmental quality guidelines for protecting fish-eating wildlife (see diagram on page 29).

PCB levels in toothed whales raise concern about toxic effects

A comparison between observed levels in Arctic species and known-effect levels in other species raises concerns about effects in Arctic toothed whales. For most species (long-finned pilot whale, beluga, killer whale, narwhal, and harbor porpoise), the PCB levels reported in this AMAP assessment are high enough to cause concern about subtle neurobehavioral effects and effects on reproduction and on vitamin A metabolism. In cases such as harbor porpoises from northern Norway, some resident killer whales and all transient killer whales from Alaska, and some long-finned pilot whales from the Faroe Islands, there may also be concern about PCBs affecting the immune system and reproduction.



Ranges of concentrations of dioxin-like substances as TEQs in Arctic bird eggs and glaucous gull liver compared with thresholds for avian effects. The comparison should be used with caution because of problems with extrapolating data across species and differences in calculating TEQs.

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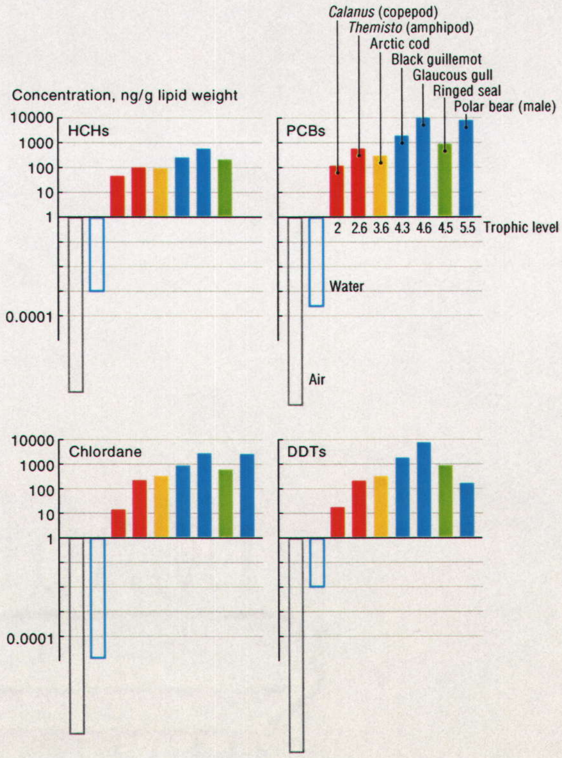
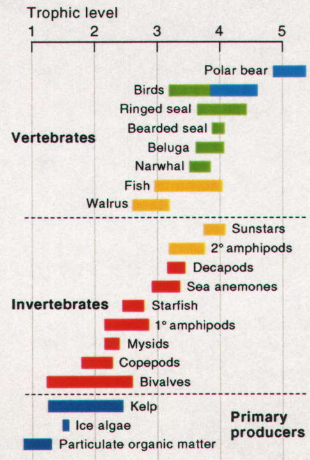
Killer whale. One of the toothed whales where PCB levels are a source of concern.





The marine food web structure observed during the Northwater Project. Shown in the panels are average concentrations of selected compounds in air, water, and biota at various trophic levels.

Food web studies provide insight about biomagnification

Animals can eliminate some contaminants, whereas other contaminants accumulate in their bodies in higher concentrations than in the surrounding environment. When they fall prey to carnivores, the contaminants are passed up the food web. If the predator cannot get rid of the contaminants, the contaminant load will be higher in the predator than in the prey, reflecting the sum of all the contaminants it has ingested from all its prey. This is called biomagnification and is an important criterion when judging whether a chemical is a potential environmental problem. Contaminants with high biomagnification factors are more likely to reach toxic concentrations in top-level predators, including people, and are thus good candidates for regulatory action.

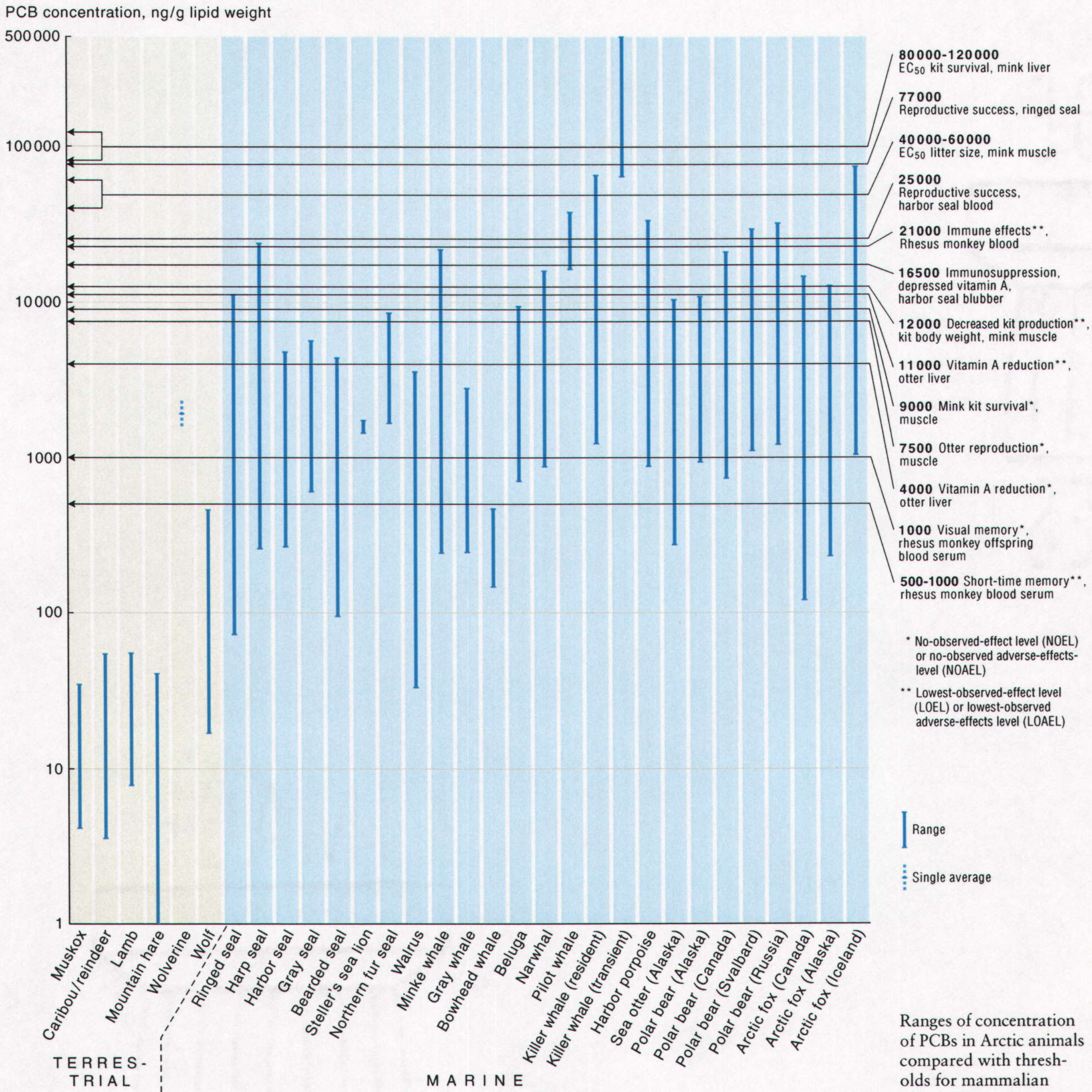
Two new food web studies provide insight into the fate of POPs in the marine environment. One is from the Barents Sea near Bjørnøya looking at copepods and euphausiids at the lowest trophic level, followed by predatory amphipods, fish, and avian predators. The concentrations of POPs were low in zooplankton and fish, but were biomagnified by 10-1000 times in seabirds, with the highest concentrations in glaucous gulls.

The other food web study was done in the Northwater Polynya in northern Baffin Bay. A polynya is an area of open water surrounded by sea ice that remains open throughout the winter. The contaminant levels were highest in seabirds and ringed seals and much lower in zooplankton at the lower trophic levels, which is consistent with previous food web studies in both Arctic and temperate waters.

As judged by the biomagnification factors obtained from these studies, significant biomagnification takes place when seabirds prey on fish and zooplankton. The seabirds have to eat large amounts of fish and zooplankton to get enough energy. Moreover, they have no way of returning the contaminants back to the water and are thus dependent on metabolizing and excreting them. Fish, on the other hand, can to a certain degree sustain equilibrium with the surrounding water via their gills.

Seabirds in the Barents Sea have higher contaminant levels than seabirds in the Northwater Polynya, despite levels in fish and zooplankton being fairly similar. The explanation is probably that the diets of Svalbard seabirds include a larger percentage of higher-trophic-level organisms. The extremely high biomagnification factor in glaucous gulls suggests that they scavenge as well, ingesting the tissues of other top-level predators.

The relative contribution of different POPs also changes between the different trophic levels. In fish and zooplankton in the study, HCHs, HCB, and chlordanes predominated. This is consistent with zooplankton and fish having a very limited ability to metabolize POPs. In seabirds and mammals, in contrast, DDTs, PCBs, and breakdown products of HCB and chlordane became more important, especially those breakdown products that are not readily excreted.



Ranges of concentration of PCBs in Arctic animals compared with thresholds for mammalian effects. The comparison should be used with caution because of problems with extrapolating data across species and differences in quantifying PCBs.

A look at the contaminant load in the diets of these animals shows that DDT and PCB levels exceed some or all environmental quality guidelines for protecting fish-eating wildlife.

Baleen whales generally have much lower POP levels than toothed whales. However, minke whales have high enough PCB levels to raise concern about subtle neurobehavioral effects and effects on reproduction and on vitamin A metabolism. Gray whales have levels that are high enough to raise the possibility of subtle neurobehavioral effects.

Seals, sea lions, and walrus: immune effects seen in northern fur seal

The previous AMAP assessment concluded that PCB levels in several seal species were high enough to raise concern about subtle neurobehavioral effects. At some sites, contaminant levels were also close to levels that could be associated with effects on the immune system. The species included in the assessment were harp, ringed, harbor, and grey seals. Based on comparisons with effects levels in other species, the new assessment confirms this picture. The mean PCB levels also raise concerns about effects on the levels of vitamin A and on reproduction.

The new assessment also includes some disconcerting information about the health of northern fur seals in relation to environmental contaminants. A large part of the world's population of northern fur seals has its breeding rookeries on the two largest Pribilof Islands, St. Paul and St. George, in the Bering Sea. The current stock is only half of its historical size and is listed as depleted under the US Marine Mammal

Protection Act definition. The St. George subpopulation underwent an unexplained decline of 4-6% per year for more than a decade prior to a study that started in 1997. Long-term monitoring has suggested that the population decline is, at least in part, due to pups dying at sea just after they have been weaned.

The Aleut population of the villages on St. George and St. Paul are dependent on an annual subsistence harvest of subadult male fur seals, both as part of their culture and as a major source of protein. Aleut concern over the population decline prompted a closer look into the cause and its possible connection to contaminants. The study revealed that fur seal pups with higher POP levels in their blood also had immune systems that were less able to respond to infections. Moreover, PCB levels were correlated with reduced levels of vitamin A and thyroid hormone, which can indirectly affect immune function. The high POP levels can probably be explained by fur seals' feeding on fish that are high in the food web. Perhaps more important is their extensive migrations as far south as California and Japan, where they feed on fish that are even more contaminated.

The role of POPs is also being investigated in the decline of the population of Steller sea lions in the eastern Aleutian Islands. Steller sea lions in the eastern Gulf of Alaska and southeastern Alaska are flourishing, whereas those in the western Gulf of Alaska and the Aleutian Islands are endangered. The Steller sea lions from the eastern Aleutian Islands excrete much higher levels of PCBs and DDTs in their feces than animals elsewhere. Recent data indicate correlations between POP levels and immune effects similar to those seen in northern fur seals. The high POP levels in the Steller sea lions are probably related to a local source or a strong influence from the Bering Sea.

In another part of the Arctic, the northwest Barents Sea, east of Svalbard, the focus has been on harp seals. These seals have elevated liver enzyme activity, a biomarker that can indicate a challenge by contaminants. Although no correlation was found between liver enzyme activity and PCB levels, there was a correlation between the activity of an enzyme controlling the male hormone testosterone and the contaminant toxaphene.

For walrus, there have been no studies of effects, and the assessment has to be based on comparisons between contaminant levels and effects thresholds in other species. Generally, contaminant levels are known to correlate with the diet of walrus. Individuals or populations that feed on other marine mammals have high levels, whereas walrus that eat mostly shellfish have much lower levels. In the previous assessment, concern was raised about PCBs being high enough to cause subtle neurobehavioral affects in walrus from eastern Baffin Island, eastern and northeastern Hudson Bay, and Svalbard. For eastern Hudson Bay and Svalbard, the levels were also high enough to raise concerns about reproduction, based on a comparison with effects in mink. New data show that walrus from East Greenland should be included in this group. For eastern Hudson Bay walrus, which had the highest contaminant load, there were also concerns about levels being high enough to suppress the immune system.

High PCB loads put the health of polar bears at risk

In polar bears, there have been strong suspicions that contaminants might affect their ability to fight infections as well as their ability to reproduce. New studies confirm these suspicions and the results indicate that the population status and health of polar bears from McClure Strait and eastern Hudson Bay in Canada, East Greenland, Svalbard, Franz Joseph Land, and the Kara Sea may be at risk.

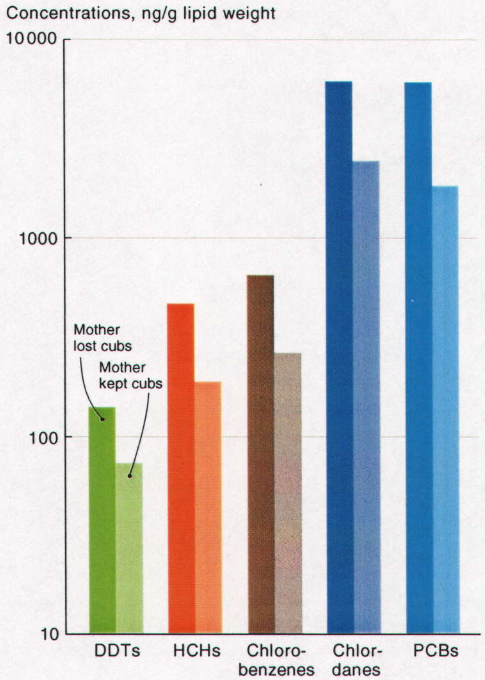
The contaminants that raise the most concern in polar bears are PCBs. Previous concerns about health effects were in part based on comparing PCB levels to contaminant loads that are known to affect the health of other species. Such comparisons have inherent weaknesses, particularly for polar bear. One reason is that the mix of contaminants in polar bears is different from other species, because polar bear are able to metabolize some PCBs better than others. Another reason is that polar bears have delayed implantation, which would allow a contaminant to act on a fertilized egg for some time before implantation. Many species with delayed implantation are known to be especially sensitive to reproductive effects of contaminants. A third reason is that polar bears go through periods of fasting, during which POP levels in the blood and sensitive organs may reach much higher levels than in an animal with consistent fat levels. Periods of fasting may also correspond with decreased disease resistance because of nutritional deficiency.

To better understand the biological effects of POPs on polar bears, researchers in Norway and Canada have looked for direct signs of health effects in the polar bears. The physiological parameters used in this study included a number of hormones and components of the immune system that contaminants are known to affect. Another sign of effects is how often a female reproduces and whether her cubs survive. In this study, the females could be followed via satellite transmitters. Because only pregnant polar bears den for the entire winter, the denning of a particular female indicated that the animal was reproducing.

The study compared Svalbard polar bears that had high PCB levels with Canadian bears that had lower levels. At Svalbard, an unusual number of cubs did not survive, and there were indications that the female's reproductive cycle was shorter than the normal three years. The fact that the females in Svalbard could breed sooner also suggests that cub survival may be impaired. One reason could be that the cubs receive a high load of PCBs from milk at a vulnerable period of growth and development. PCB levels were higher in cubs-of-the year than in their mothers. There are, however, other possible explanations for poor cub survival rates, such as high population density. It is therefore not yet possible to make a causal link with PCBs.

There are some other signs in the Svalbard polar bear populations that reproduction may be impaired. Specifically, there is lack of older females with cubs-of-the year compared with some other polar bear populations.

Other studies have also shown associations between contaminant loads and possible reproductive effects, but it is difficult to draw firm conclusions about how contaminants



Concentrations of POPs in polar bear milk of females with cubs after emerging in March from dens in the Cape Churchill area, Hudson Bay. The data are grouped according to whether the female still had her cubs the following fall, or had lost them.

affect the health of the animals. In a Canadian study of polar bears from southwestern Hudson Bay, females who had lost their cubs had higher contaminant concentrations than females whose cubs survived. In another study, the levels of the male hormone testosterone were low in male bears with high loads of PCBs. This hormone plays a crucial role in sexual development. Vitamin A and thyroid hormones are also lower when the PCB load is high. However, it is unknown whether this affects the bears' health or ability to reproduce.

In the Norwegian-Canadian study, there was a correlation between contaminant levels and effects on the immune system. To follow this up, an experiment was conducted to see how the immune system responded to a challenge. The researchers gave the animals a vaccination containing a few common viruses and a bacterial toxin. Four to six weeks later the animals were recaptured to look for antibodies against these viruses and the toxin. The results from the vaccination experiments suggest that PCBs are indeed associated with decreased resistance to infections, and that the health of polar bears with high PCB loads may be at risk.

The previous AMAP assessment reported cubs with abnormal genitalia, so-called pseudohermaphrodites. The first two were found at Svalbard in 1996, and since then several more cases have been reported from Svalbard and from other parts of the Arctic. The frequency at Svalbard is 2-4% of the females, but the severity of the condition is variable. The females appear to reproduce normally. It is still unknown whether pseudohermaphrodism in polar bears has any connection to contaminants.

An assessment of contaminant levels in polar bears as they relate to known effect levels in other species complements the picture of a species under threat from pollution. PCB levels in polar bears are high enough to raise concern about subtle neurobehavioral effects and effects on vitamin A. At several sites in Alaska, Canada, East Greenland, Svalbard, and in Russia, levels are high enough to raise concerns about reproduction. At Franz Josef Land, the Kara Sea, and Svalbard, levels are high enough to cause concern about suppression of the immune system. The source of contaminants is the diet, with PCBs in blubber from ringed and harp seal exceeding all environmental guidelines for protecting aquatic wildlife.

PCB levels in Arctic fox raise concern about toxic effects

In the previous AMAP assessment, PCB levels in Arctic fox from Svalbard raised concern about subtle neurobehavioral effects as well as effects on reproduction, cub survival, and immune suppression. At the time, data for Arctic fox were only available from Svalbard. New data are available on contaminant levels in Arctic fox from Barrow and the Pribilof Islands, Alaska; Holman Island, Northwest Territories, Canada; and inland and coastal areas of Iceland. The PCB levels in the populations from Alaska, Canada and inland Iceland are considerably lower than those reported earlier for Svalbard foxes. Arctic fox from coastal Iceland have much higher PCB levels, which are more comparable to those seen previously on Svalbard. Compared with effects levels in other species, there is some concern about the potential for subtle neurobehavioral effects and effects on vitamin A levels. The Canadian foxes may also be at risk for reproductive effects and decreased cub survival. In addition, the coastal Iceland foxes are at risk for immunosuppression. Data on dioxin-like contaminants in Pribilof Arctic foxes also indicate a possible risk for immunosuppression.

ELISABETH LIE

Polar bear sampling to study the effects of PCBs.

On individuals and populations

It is difficult to establish a causal link between contaminants and effects in wild animals. It is clear, however, that there is a correlation between high loads of contaminants in some animal populations in the Arctic and effects on their resistance to infection, reproduction, and behavior. Some of these effects are only apparent as subtle changes in the physiology of an animal, for example changes in the immune system or hormone levels. Nevertheless, AMAP considers the evidence strong enough to conclude that contaminants do have effects on some species of Arctic wildlife in that they can threaten the survival and reproductive success of individual animals.

The extent to which these effects can threaten local populations is another question. Here, there is no clear answer. If effects on individuals are sufficiently widespread, a population can become vulnerable, especially if it is exposed to other stresses, such as new disease-causing organisms or changes in access to prey. In such cases, the margin of safety for a population may no longer exist. The conclusion is thus that some contaminants, particularly PCBs, dioxin-like substances, DDTs, and TBT, may pose a population-level threat to some Arctic wildlife populations.

Summary

Persistent organic pollutants are present throughout the Arctic environment.

PCB levels in some areas are high enough to affect the health of individual animals, particularly their ability to fight infections. This is true for polar bears around Svalbard and probably also for polar bear populations closer to Russia, for northern fur seals in the Bering Sea, and for glaucous gulls on Bjørnøya, south of Svalbard. In the glaucous gull population, PCBs also affect nesting behavior and adult survival. In many animals, there is no documentation of effects, but based on knowledge from effects levels in other species, PCB levels are high enough to raise concerns about effects on resistance to disease, reproduction, and neurobehavioral development. PCBs are banned by both regional and global regulations. Local sources are indicated in the region of the White Sea, the Kara Sea, and the eastern Barents Sea. A recent inventory of uses in Russia shows that PCBs remain in many existing electrical installations. There are also examples of local PCB contamination in Alaska, Canada, Greenland, and Norway (including Jan Mayen and Svalbard), mostly from military sites, earlier uses, or dumped material. There is thus a need for more remedial actions for PCBs within the Arctic.

Levels of dioxin-like substances raise concern about reproductive effects in some Arctic seabirds and about effects on the immune system in Arctic fox, killer whales, and northern fur seals. Some sources, such as waste incineration and the metallurgical industry, have not yet been adequately addressed.

Many persistent organic pesticides have been banned and their levels in the environment are declining. However, there are several signs of fresh input of DDT in the Barents region and of toxaphene in the White Sea. This shows either that these pesticides are still used or that old stocks are leaking into the environment and thus need attention. DDTs are still a concern for the reproductive health of birds of prey. The pesticide lindane, or gamma-HCH, is still used in source regions to the Arctic. Its levels in the marine environment have not declined.

For persistent organic pollutants that are now regulated on a global and regional basis, the situation in the Arctic is likely to improve. This is not the case for other POPs, including brominated flame retardants (PBDEs). Levels of PBDEs are still low compared with PCBs, but are likely to rise unless there is a change in the expected increase in world production. In addition, the extremely persistent compound PFOS, used as a stain repellant and in other applications, is present at elevated levels in some Arctic animals. Very little is known about the behavior in the environment of chemicals of this kind and their potential effects.

Several important steps have already been taken to address the threats POPs pose to the Arctic environment, such as the Stockholm Convention and the UN ECE POPs Protocol. This AMAP assessment shows the continued need to bring Arctic concerns about POPs to the attention of these international policy fora to ensure continued emphasis on Arctic needs.

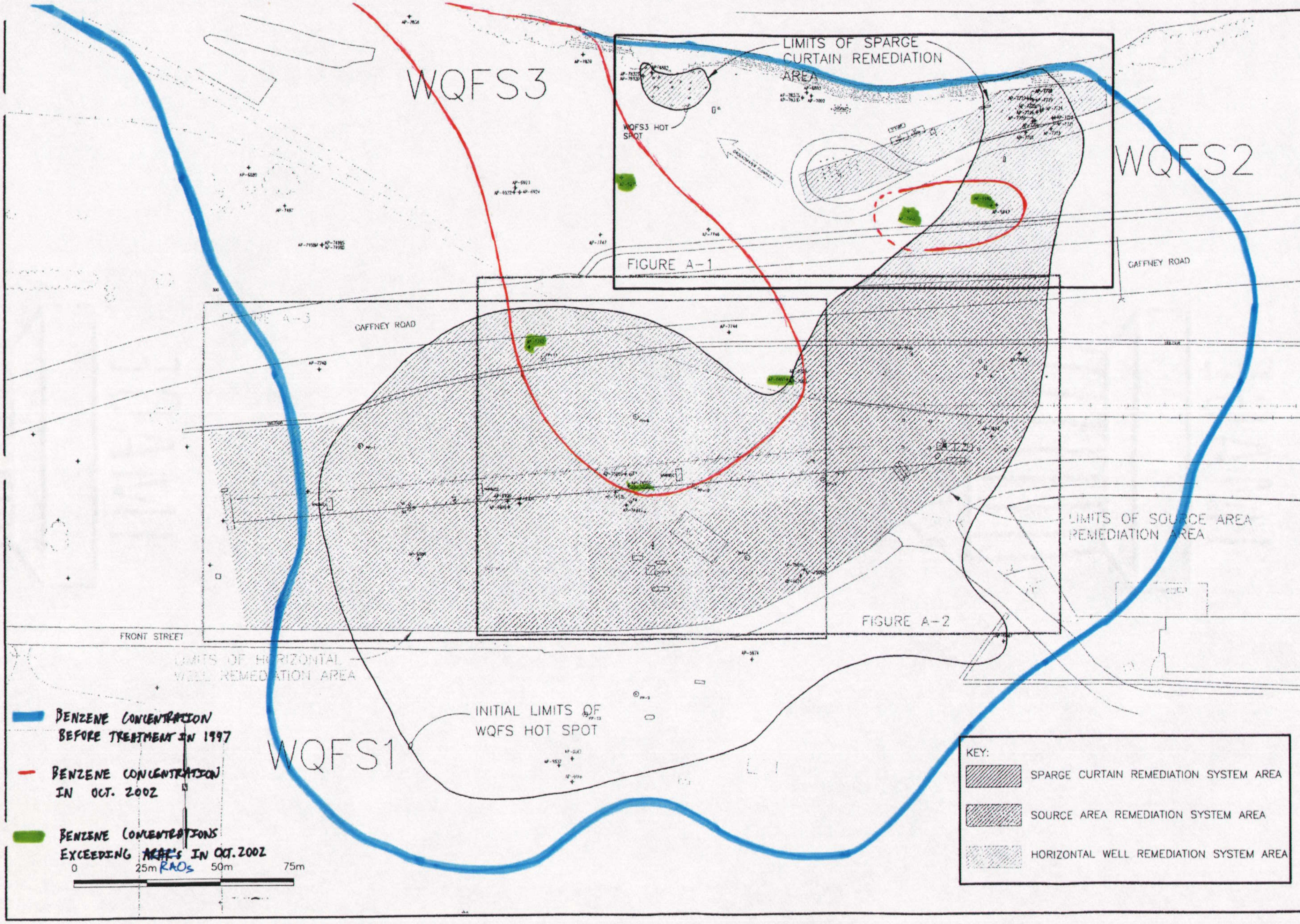


Figure 3
WQFS1 And WQFS2
Remediation Areas

POST CONSTRUCTION REPORT
WQFS1 AND WQFS2 REMEDIATION
SYSTEM MODIFICATIONS
Fort Wainwright, Alaska - June 2002

North Wind Environmental, Inc.
Anchorage, Alaska 99501

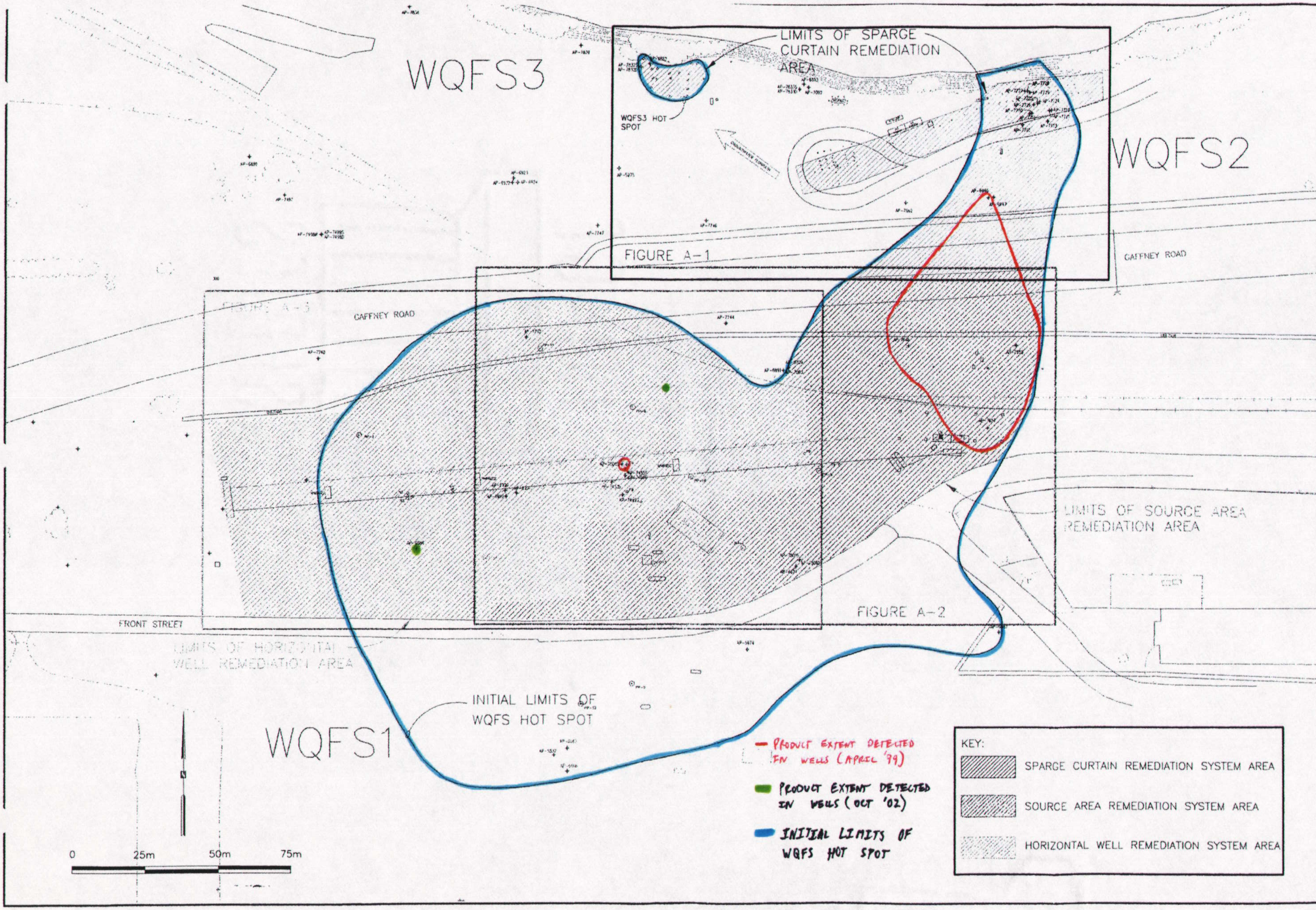


Figure 3
WQFS1 And WQFS2 Remediation Areas

POST CONSTRUCTION REPORT
WQFS1 AND WQFS2 REMEDIATION SYSTEM MODIFICATIONS
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North Wind Environmental, Inc.
Anchorage, Alaska 99501

Spring sun, 78°N

SHEBA PROJECT OFFICE

Heavy Metals

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

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

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

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

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

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

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

Coal-burning power plant, 40°N

POLFOTO / T.C. MALHOTRA

Introduction

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

The previous AMAP report assessed a wide range of metals and concluded that the ones raising most concern about effects in the Arctic are mercury and cadmium. They have no known biological function but bioaccumulate (see table), can be toxic in small quantities, and are present at high levels for a region remote from most anthropogenic sources. For both metals, a primary emphasis was on increased understanding of the possible biological effects of the levels that have been documented in Arctic animals. A third metal of concern was lead. Lead is also toxic, but environmental levels of lead appeared to be decreasing as a result of the change to unleaded gasoline in most countries. Other metals, such as nickel and copper, were of local concern, especially near large smelting operations.

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

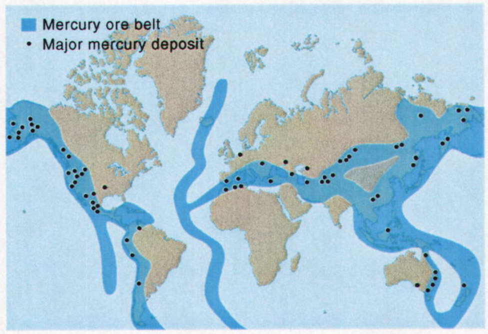
Mercury: sources and pathways

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

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

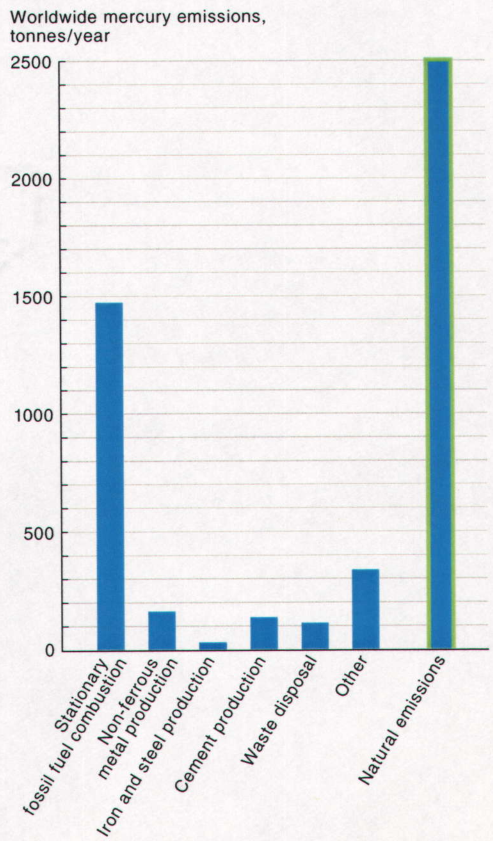
Human activities release mercury

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



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

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



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

Current international actions on metals

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

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

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

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

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

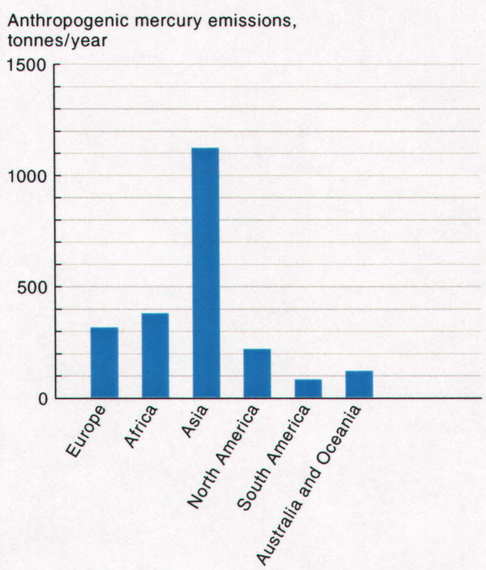
responsible for about two-thirds of these emissions.

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

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

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

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



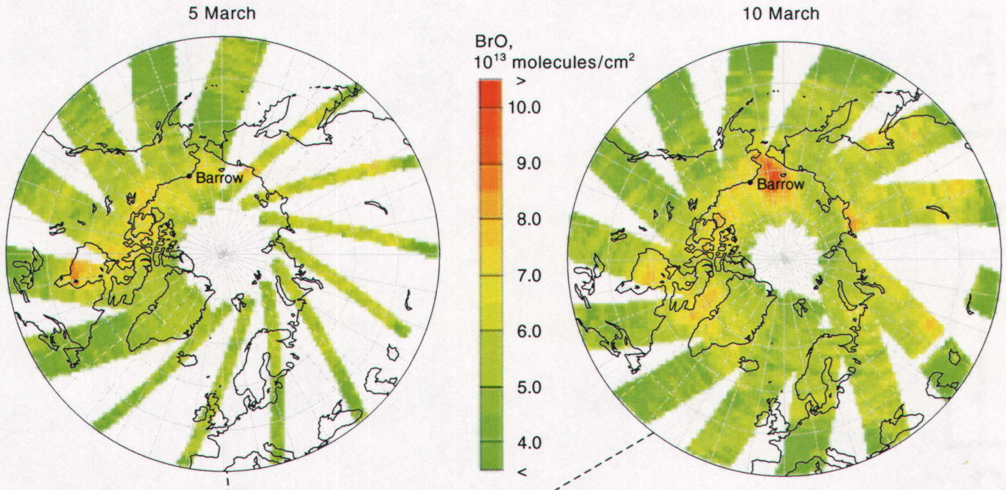
Global anthropogenic emissions of mercury to the air in 1995 from different continents.

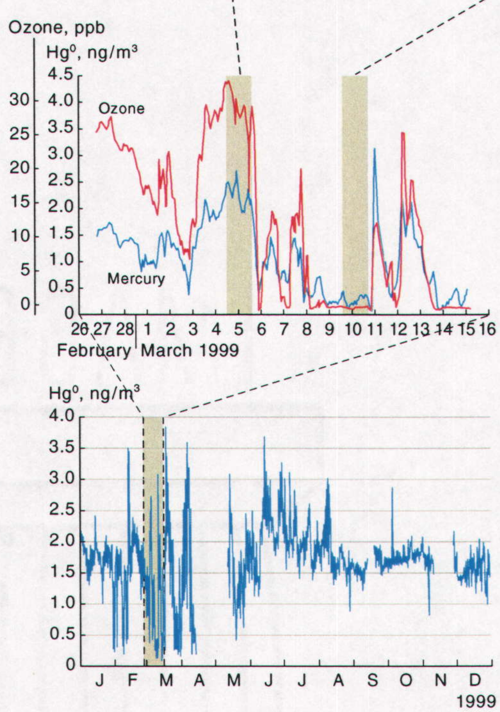
Volatility ensures global distribution

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

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

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





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

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

Polar sunrise leads to mercury depletion in air

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

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

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

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

Mercury can take many forms

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

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

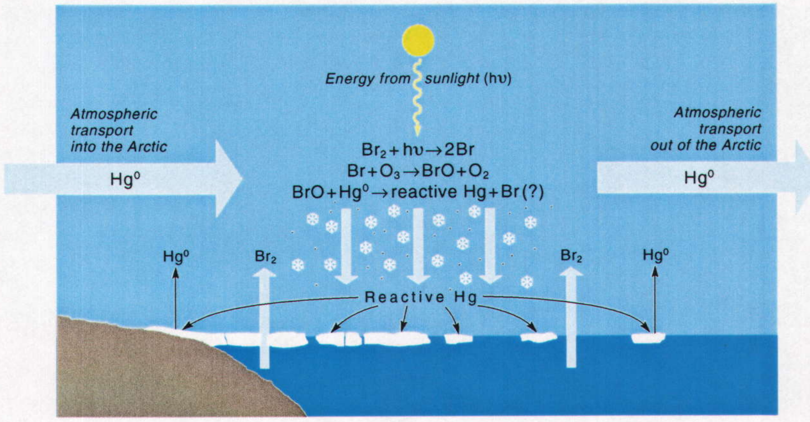
Reactive mercury – mercury that reacts readily with other molecules, and deposits very quickly from the air.

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

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

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

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



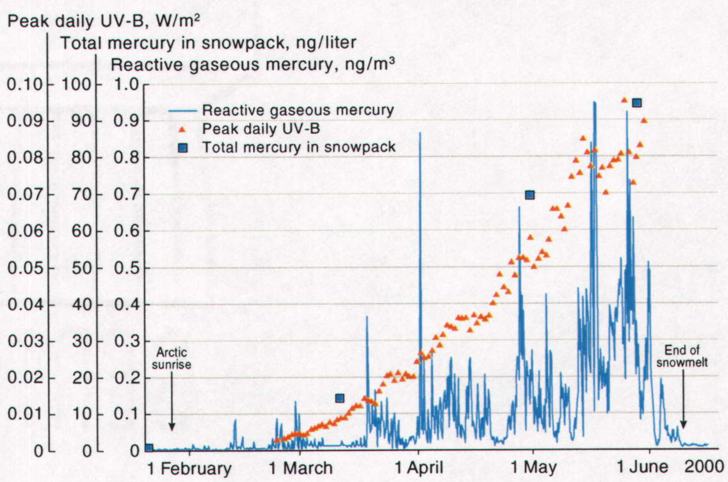
Reactions involving sunlight and bromine remove gaseous elemental mercury from the atmosphere (mercury depletion) and transfer it to the surface as reactive mercury. Part of the reactive mercury may reach the food web; part is re-emitted as Hg^0.

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

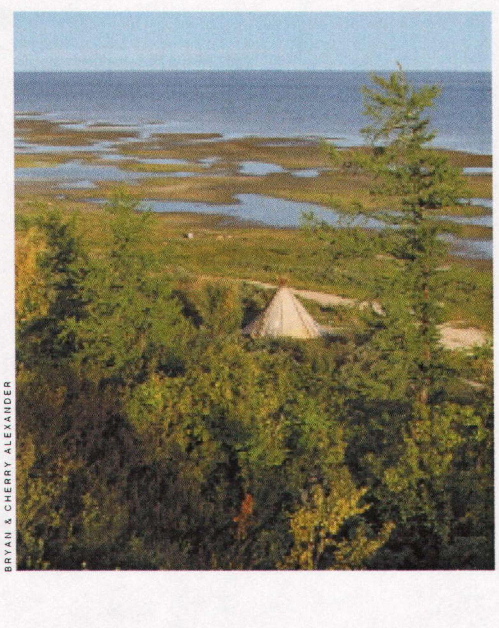
Mercury enters the food web

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

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



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



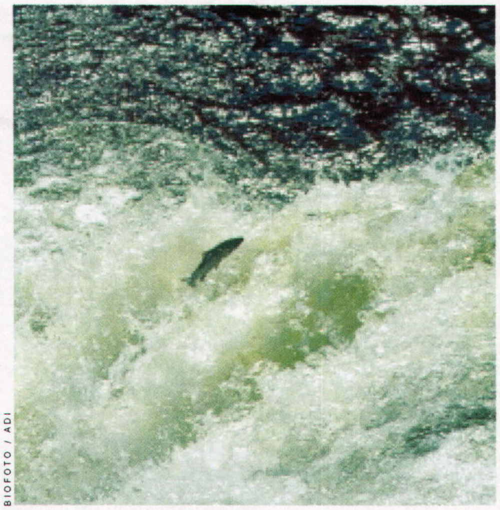
BRYAN & CHERRY ALEXANDER

Ob Estuary. Eurasian rivers transport mercury to coastal estuaries.

Rivers and biological pathways can be locally important

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

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



BIOFOTO / ADI

Migrating salmon can serve as a biological pathway for mercury.

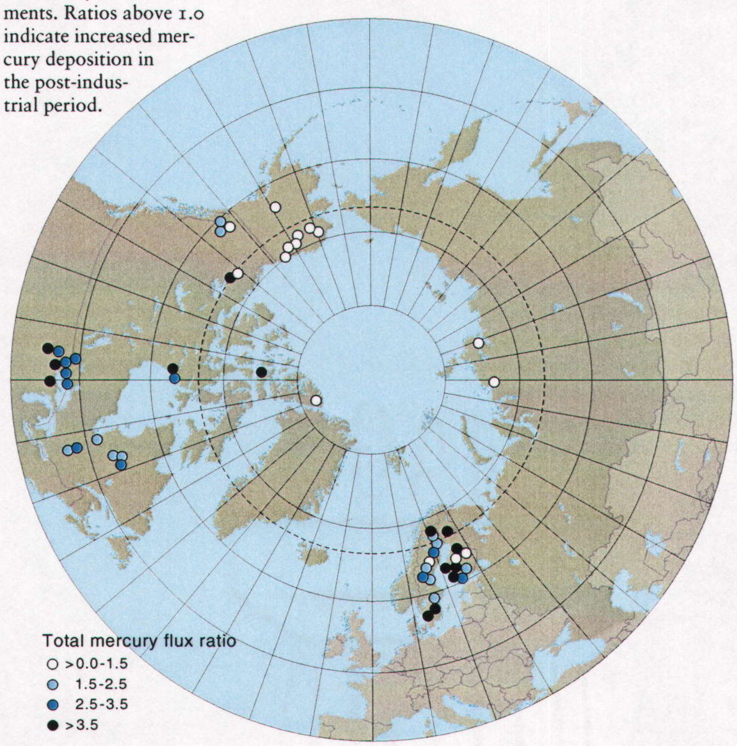
has been transported by Pacific salmon to the lakes and streams of the eastern Bering Sea coast.

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

Ocean pathways are not well understood

Atmospheric deposition, including mercury depletion events, and river inputs supply mercury to the ocean. Mercury is removed from the upper layers of the ocean by settling of particles or by emission of gaseous mercury to the air. The cycling of mercury and its eventual fate in the ocean, however, are poorly understood, especially for the Arctic. Some mercury enters the food web and some is buried in sediments, but the linkages between mercury depletion events and mercury concentrations in marine biota have not been determined. It seems likely that the mercury exchange between atmosphere and ocean in the Arctic differs significantly from other oceans simply because of ice cover. Sea ice forms a barrier to the gaseous emission of mercury accumulated in the upper ocean layer, but the potential of this barrier to enhance mercury concentrations in the marine environment has not been evaluated.

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



Mercury time trends

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

Diagenesis may affect metals profiles in sediments and peat bogs

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

Mercury levels are higher than in pre-industrial times

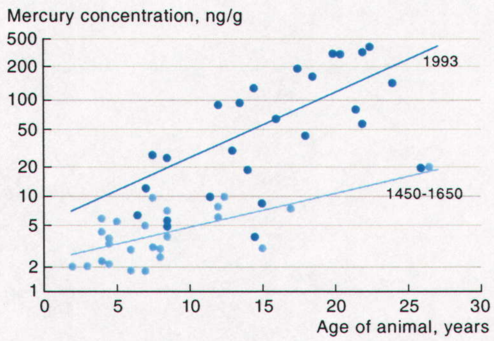
Lake sediments in Greenland show that mercury increases started by the late 19th century, and perhaps as early as the 17th century. Recent concentrations are on average three times higher than in pre-industrial times. Similar results have been found across Eurasia, with increases highest in the west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

In North America, similar geographic patterns emerged, with higher increases in southeastern lakes near mercury sources in eastern North America. By contrast, no increase has been seen in the sediment in some lakes remote from source regions. This includes YaYa Lake in the Yukon Territory, Lake Hazen on Ellesmere Island in the Canadian High Arctic, and lakes on the Arctic coastal plain of Alaska.

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

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

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



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

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

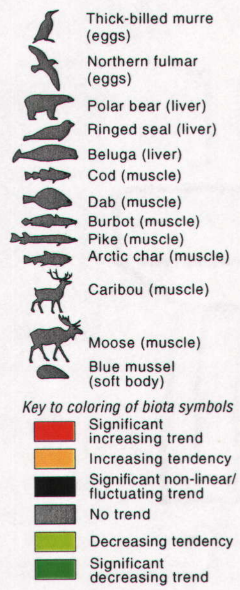
Recent trends vary

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

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

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

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



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

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

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

BIOFOTO / SØREN BREITING

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

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

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

A need for further studies

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

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

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

Mercury levels and effects

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

GEOLOGICAL MUSEUM, COPENHAGEN

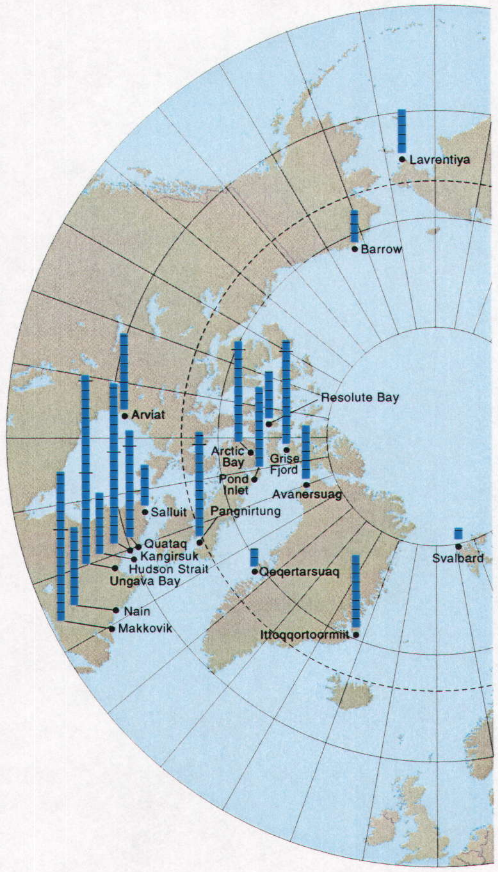
▶ Mercury ore (cinnabar).

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

Mercury can have a variety of toxic effects

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

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



Spatial trends in mercury concentrations in ringed seal liver.

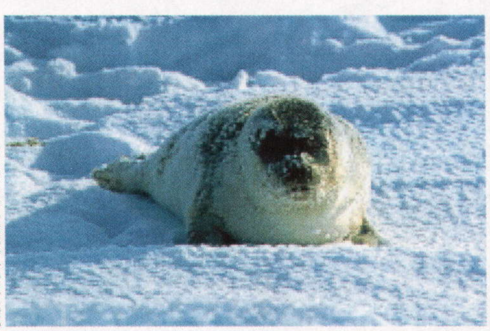
Mercury is significant in the marine environment

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

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

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

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

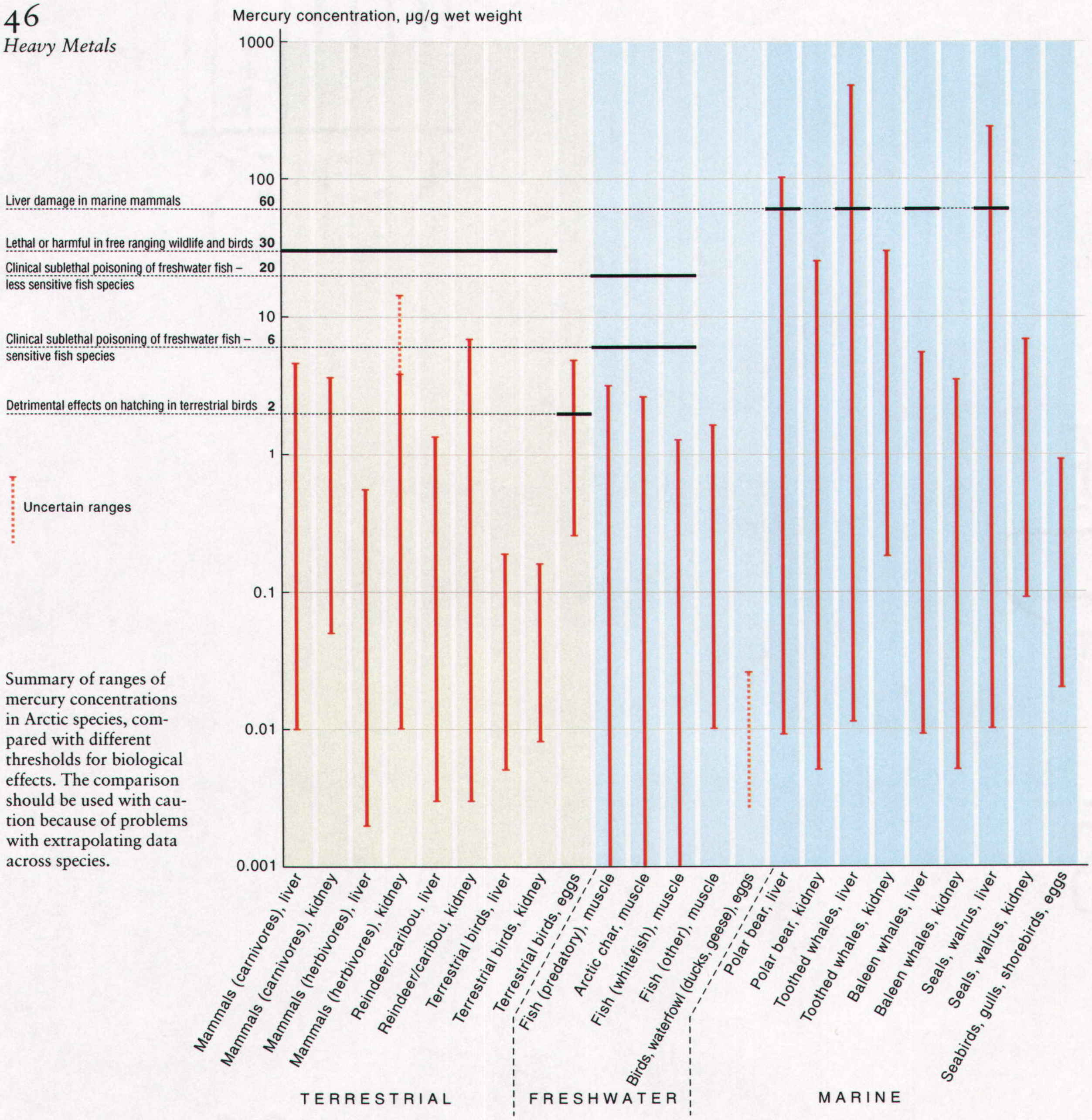


BIOFOTO / CLAUS BIRKBØLL

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

Seabirds and some whales may be vulnerable

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



Summary of ranges of mercury concentrations in Arctic species, compared with different thresholds for biological effects. The comparison should be used with caution because of problems with extrapolating data across species.

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

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

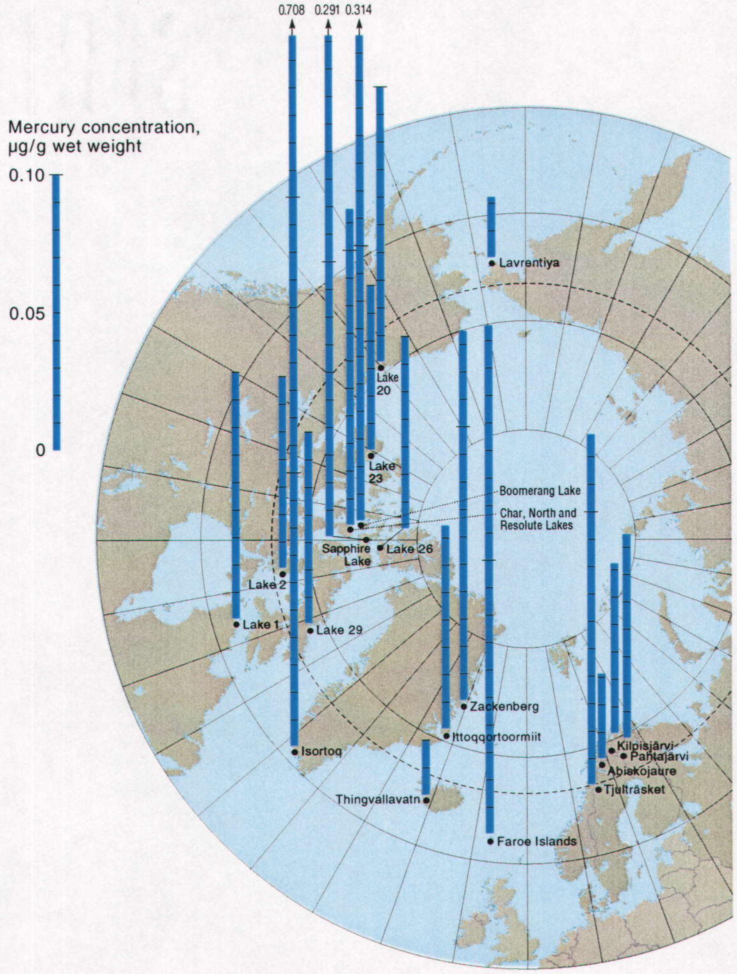
Less is known about freshwater and terrestrial environments

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

There are large variations in mercury concentrations in Arctic char in the AMAP area. Overall, the levels are below the Canadian subsistence food guideline of 0.2 micrograms per kilogram. However, there are areas such as southwestern Greenland, lakes near Qausuittuq in Arctic Canada, and the Faroe Islands, where levels exceed the Canadian subsistence food guideline. The variability can be seen even in limited geographical regions. For example, in Sweden, levels in the lake Tjulträsket were four times higher than in the lake Abiskojaure (Ábeskojávri), without any obvious explanation.

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

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



Spatial trends in mercury concentrations in landlocked Arctic char muscle.

BRYAN & CHERRY ALEXANDER

Ice fishing for Arctic char, Igloolik, Nunavut.

Other factors affect mercury in freshwater biota. As discussed above, the presence of selenium may alter the effects of mercury within an organism, or lower the uptake of mercury. This effect could explain a lack of correlation between mercury levels in fish and in sediments in some lakes. Water chemistry, especially acidity, and food web structure also affect mercury availability and uptake. Acidification, for example, can greatly enhance the process of methylation, producing a higher proportion of bioavailable methylmercury.

Evidence of effects in peregrine falcons and grayling

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

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

Is it time for global action?

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

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

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

Lead – success for political action

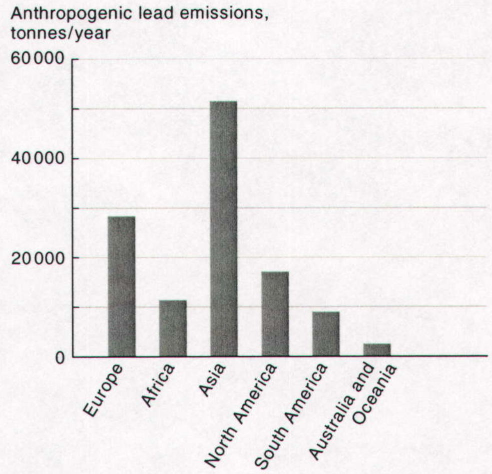
Lead is a dense, soft metal with many uses. Lead is also toxic. Altered behavior resulting from lead affecting brain and nerve tissue is the most widely recognized effect of lead poisoning. Lead also interferes with many enzymes, most notably those associated with the production of hemoglobin and cytochromes.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

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

Eurasia is the major source region

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

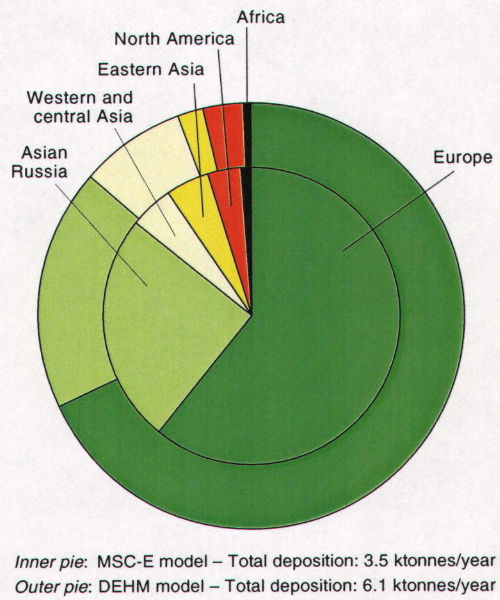
The transport of lead follows seasonal patterns. Lead levels in airborne particles are lowest in early fall, and at this time of the year lead reaching the Canadian Arctic comes mostly from natural sources in the Canadian Arctic Archipelago and West Greenland. In late fall and winter, airborne lead comes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



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

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

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



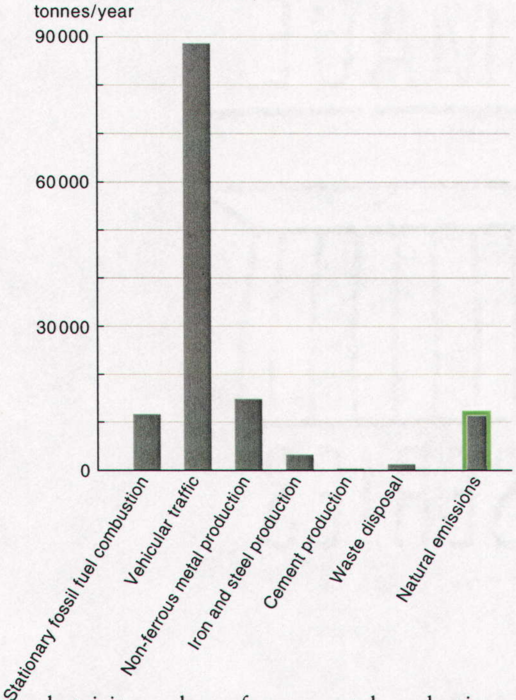
Different air transport models give different estimates for total lead deposition in the Arctic in 1990, but agree well on the source regions for the lead.

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

Leaded gasoline has been the most important source

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

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



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

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

Lead is declining in the abiotic environment

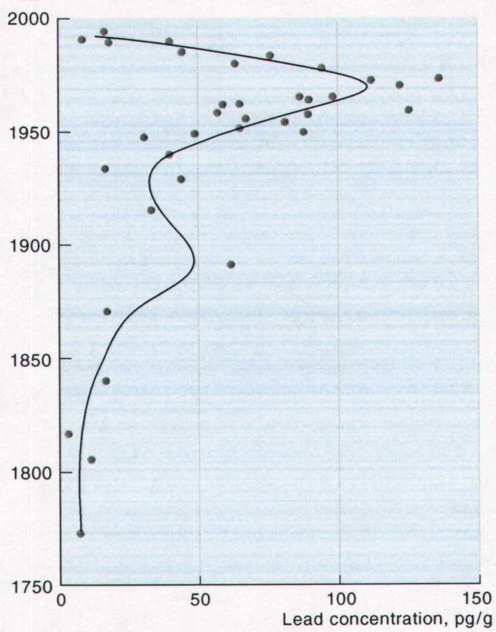
Lead deposition patterns across the Arctic are in some ways similar to the patterns seen in mercury. In the Canadian High Arctic, in the

POLFOTO / JENS DRESLING

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

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

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



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

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

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

... but levels in many biota are stable

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

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

BIOFOTO / SVEN HALLING

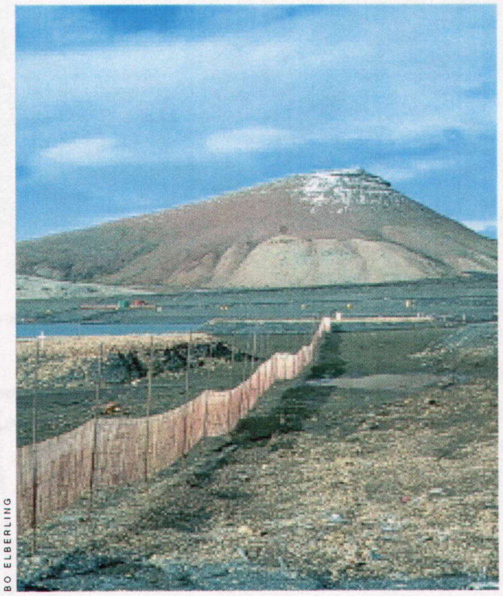
Reindeer are used to monitor temporal trends in metals in Sweden.

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

Local lead levels connected to ores and mining

Some of the richest deposits of lead ore are found in the Arctic, for example at the Red Dog Mine in northwestern Alaska, the Polaris and Nanisivik Mines in the Canadian Arctic, and the now-closed Black Angel Mine in West Greenland. The high levels of lead in the rocks at these sites means that levels in nearby streams and lakes were already high before the mining began. But mining activities in many cases greatly increased releases to the surrounding waters.

Caribou near the Red Dog Mine in northwestern Alaska have elevated levels of lead in liver and feces, as might be expected in a mineral-rich area. The observed levels, however, are not high enough to cause concern for toxic effects.



BO ELBERLING

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

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

Lead shot creates problems for birds

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

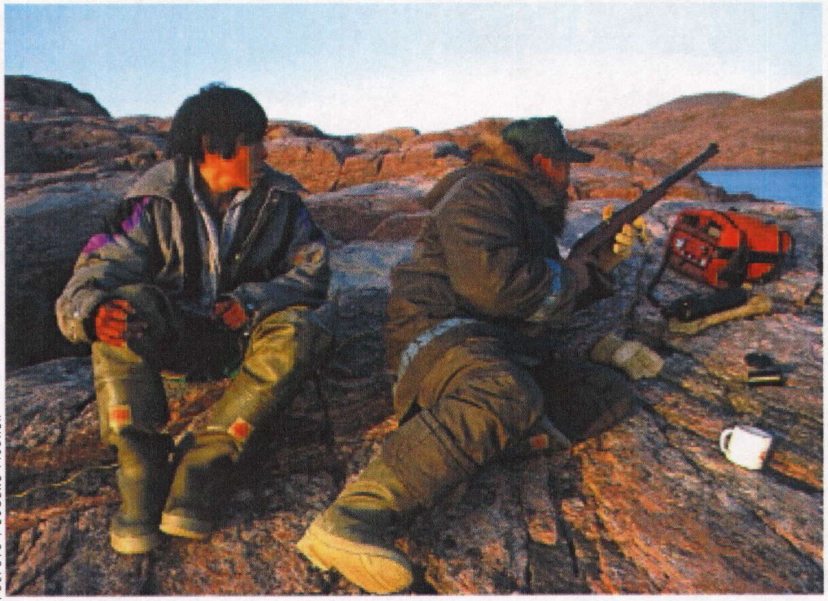
Steller's eiders in Alaska have levels of lead in their blood that are above avian toxicity thresholds for lead poisoning. These birds have suffered from reduced breeding success. Analyses of livers and kidneys from the eiders show that some levels are high enough to cause concern about toxic effects.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

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

Notes of caution and possible new threats

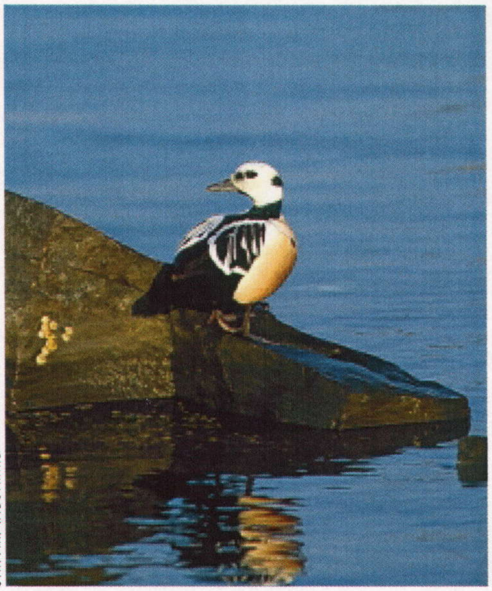
Globally, lead emissions have declined sharply following the introduction of unleaded gasoline. But not all sources of lead are well documented, and levels in some parts of the Arctic do not appear to follow the declining trend. Furthermore, local natural and man-made sources such as mines, mineral outcrops, and lead shot may have a significant impact on local plants and animals. In cases such as the Steller's eider, which is endangered in the United States, effects on an already limited breeding area may have a major impact on the population.

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



POLFOTO / EUGENE FISCHER

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

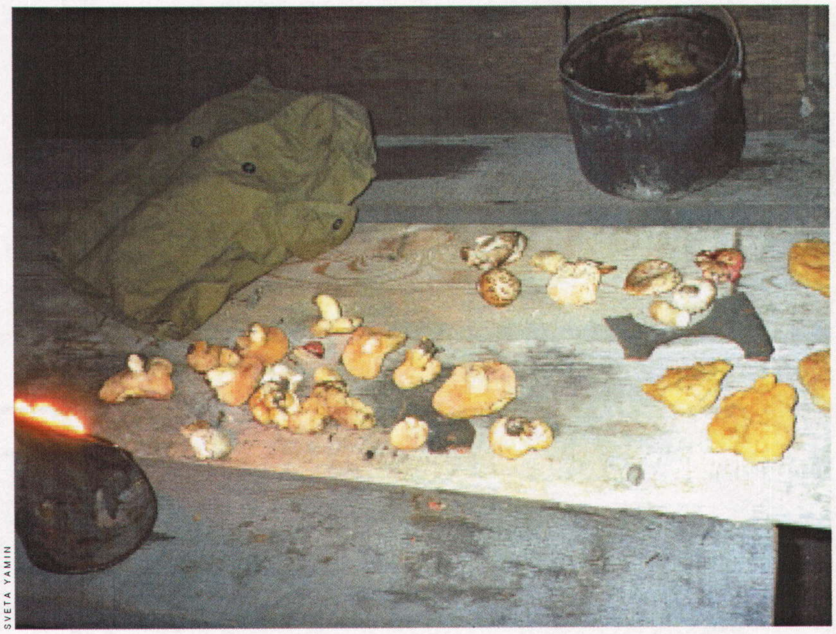


STAFFAN WIDSTRAND

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

Cadmium – still largely unknown

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



SVETA YAMIN

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

Cadmium is widespread with localized hot spots

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

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

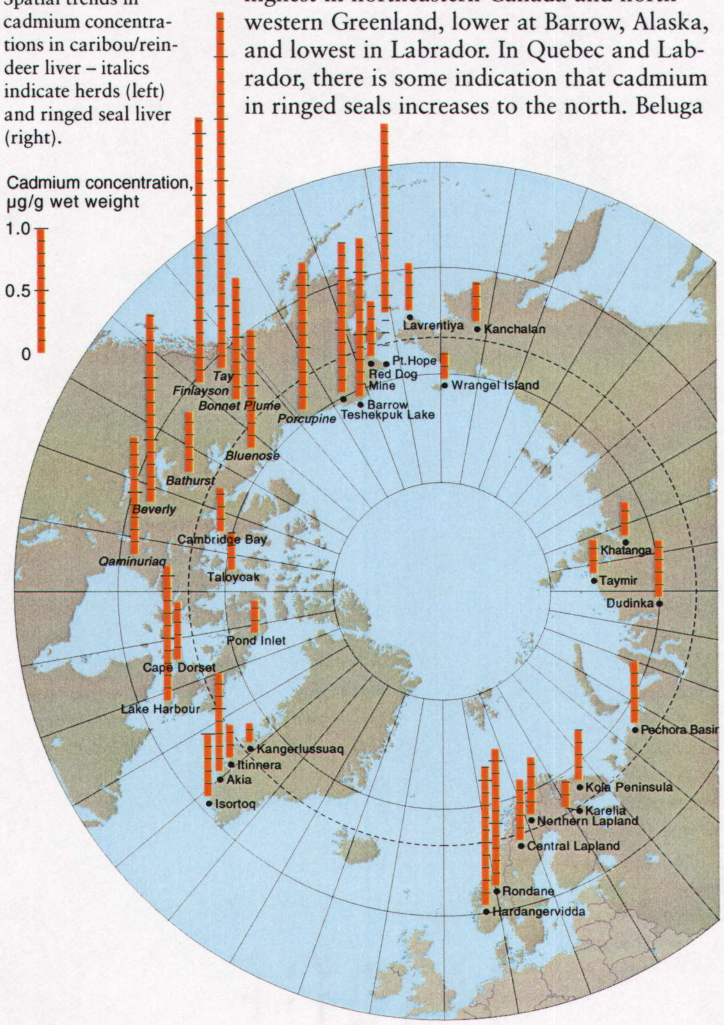
Levels of cadmium in ringed seals are highest in northeastern Canada and northwestern Greenland, lower at Barrow, Alaska, and lowest in Labrador. In Quebec and Labrador, there is some indication that cadmium in ringed seals increases to the north. Beluga whales show an increase from west to east across Alaska and Canada. Narwhals appear to have lower levels in West Greenland than in the eastern Canadian Arctic, and females have higher levels than males. Levels in polar bear are highest in eastern Canada and northwestern Greenland.

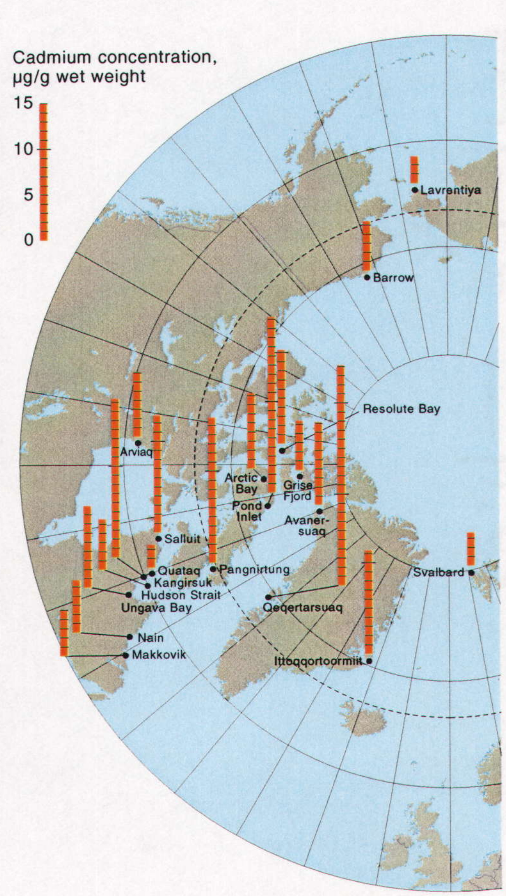
Other regional patterns have been found, too. Walrus in Alaska have high levels of cad-

SHEBA PROJECT OFFICE

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

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

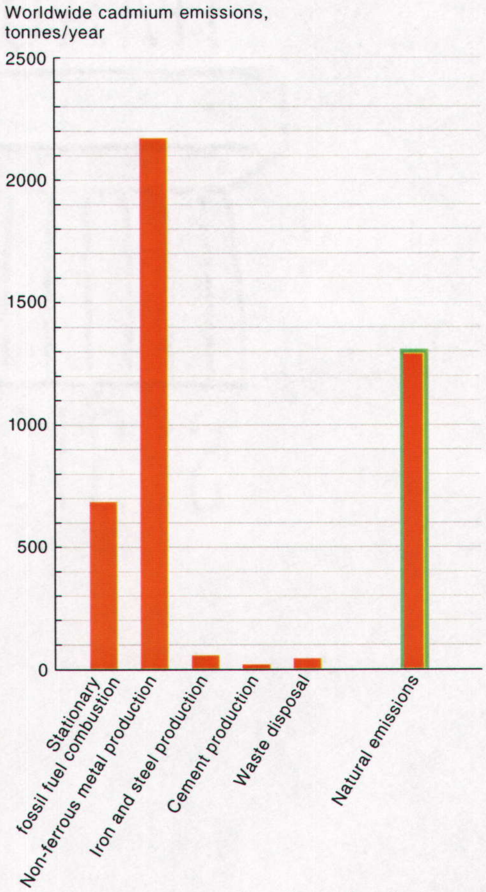




mium, indicating local sources or particular food web pathways. In Faroe Islands gray seals, females have higher liver concentrations of cadmium than males and other seal species. The reason for this difference is not known.

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

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



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

Human activities are a major source

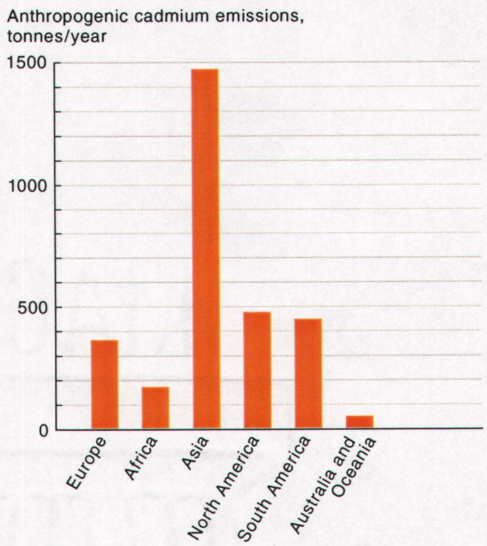
The processing of zinc ore is the major source of cadmium emissions to the atmosphere. Non-ferrous metal production accounts for nearly three-quarters of global anthropogenic cadmium emissions to the atmosphere. Burning of coal accounts for most of the remainder, with some contributions from other activities,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

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

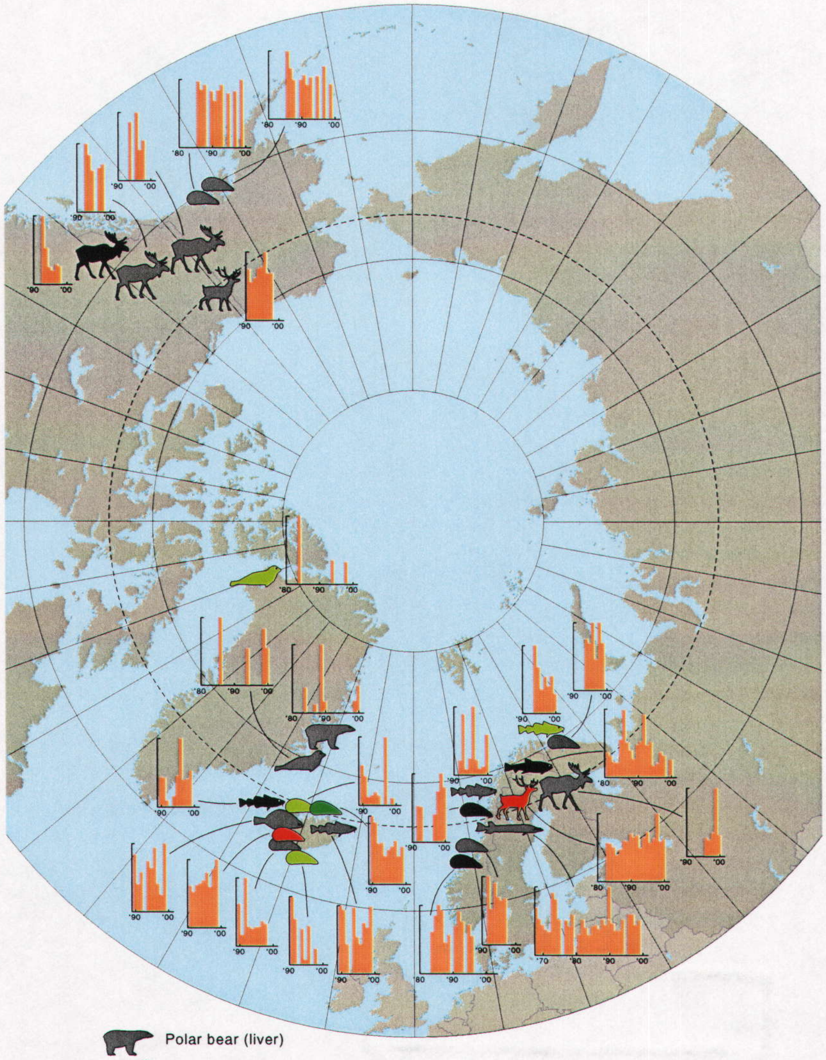
The global significance of human releases can be seen in the ice core records from the Greenland Ice Sheet. Cadmium deposition in the 1960s and 1970s was eight times higher than in pre-industrial times. Since the 1970s, however, deposition has declined steadily. Emissions from non-ferrous metal processing,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

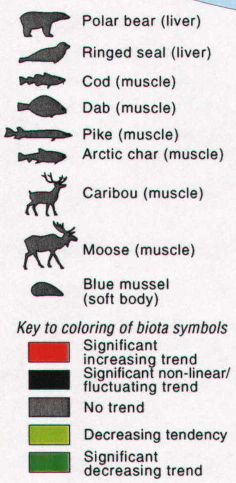
River transport of cadmium to the Arctic is comparable to the amount transported by the atmosphere. As with lead, most of the cadmium is in the form of suspended particles.

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



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





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

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

Recent cadmium time trends vary

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

In recent years, trends across the Arctic vary. Mosses in northern Sweden show stable or declining levels of cadmium. By contrast, cadmium in liver of reindeer from northern Sweden increased significantly between 1983 and 2000, though it remained the same in muscle. Moose kidneys in the same region, however, showed no significant change in cadmium levels from 1996 to 2000. The same is true for moose in the Yukon Territory from 1993 to 1998. Other studies of terrestrial animals have not gone on long enough to produce evidence of changes.

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

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

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

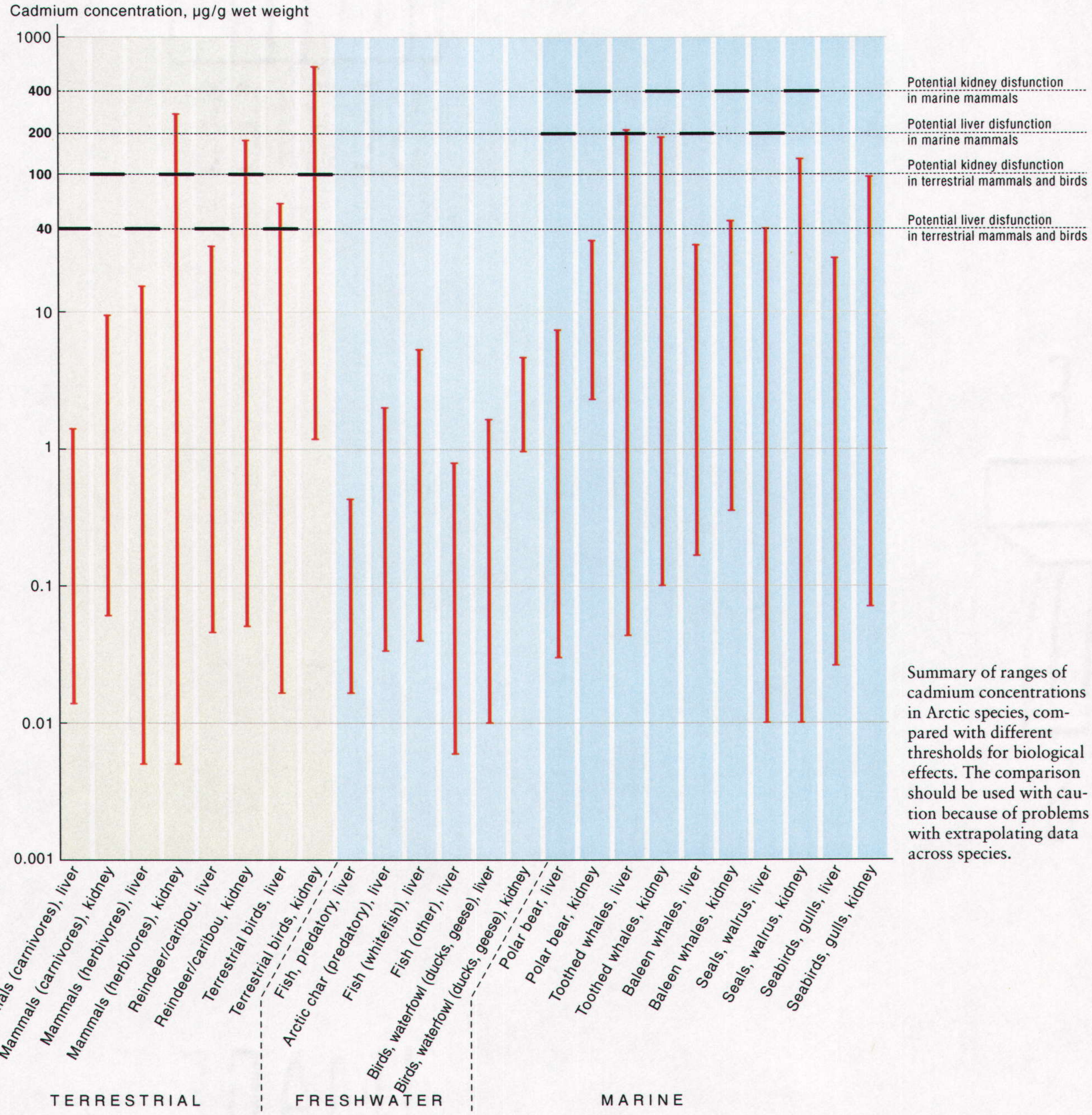
Cadmium accumulates in birds and mammals

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

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

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

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



Summary of ranges of cadmium concentrations in Arctic species, compared with different thresholds for biological effects. The comparison should be used with caution because of problems with extrapolating data across species.

Some levels indicate possible effects

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

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

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

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

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

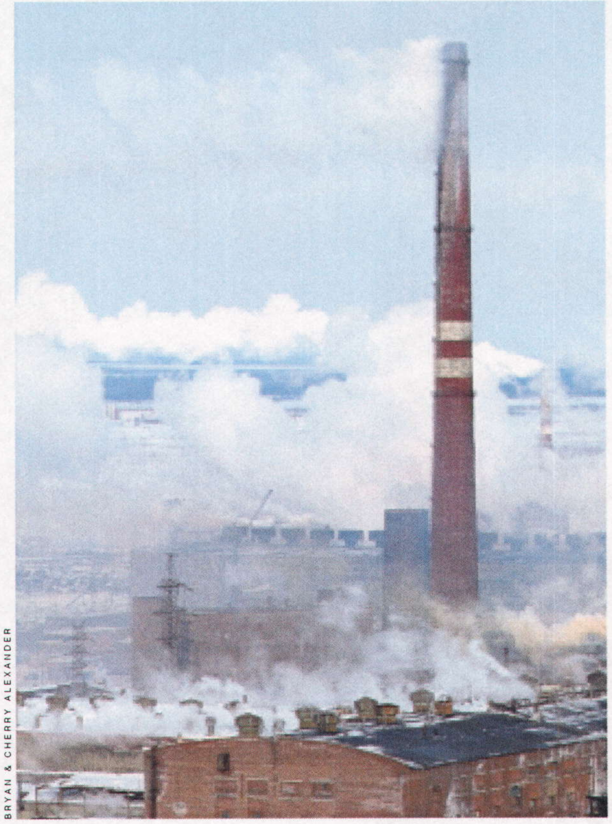
In studies of lake trout exposed to different levels of cadmium, researchers found that cadmium affected foraging behavior, resulting in lower success at catching prey. Decreased thyroid function as a result of cadmium exposure has also been documented. Both responses indicate a low response threshold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

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

Uncertainty remains

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

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



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

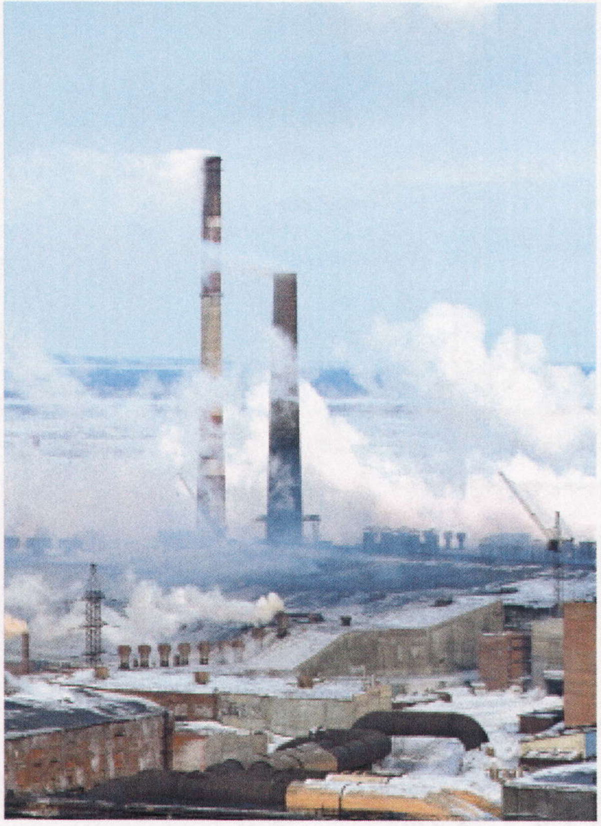
Damaged forest around Monchegorsk.

Severe local pollution around smelters

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

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

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



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

Damage surrounds the smelters

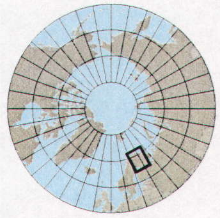
The damaged areas surrounding the smelters can be divided into three zones. Weather patterns and local topography determine the shape of each zone. First, the forest-death zone extends for up to 15-20 kilometers around Nikel and Monchegorsk, and up to 80 kilometers downwind at Norilsk. In this zone,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

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

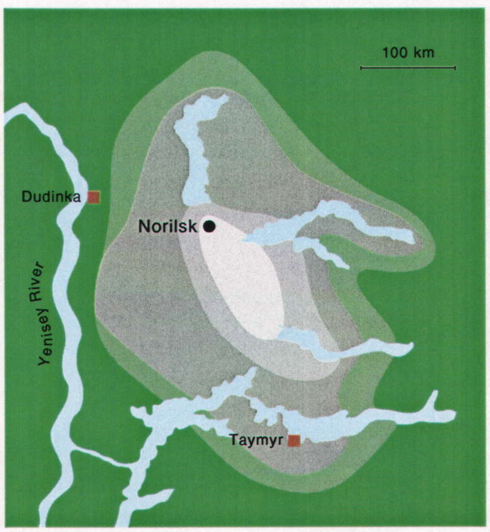
At Nikel and Monchegorsk, a non-visible damage zone extends up to about 150 kilometers. In this zone, the effects of emissions are primarily changes in the physiological functioning and microscopic structure of plant tissues.

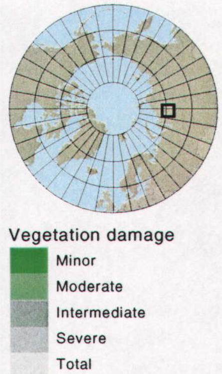
Ecological impacts are extensive

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

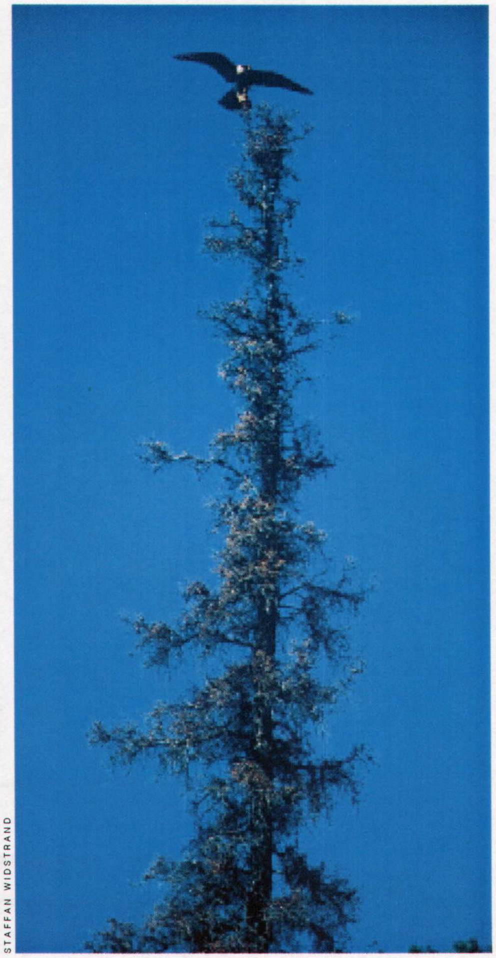


Extent of vegetation damage on the Kola Peninsula due to the combined effects of metal and acidifying substances.





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


STAFFAN WIDSTRAND

Conifer and peregrine falcon – two sensitive species.

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

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

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

Summary

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

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

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

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

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

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

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

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

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

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

Sellafield

Radioactivity

The Arctic is more vulnerable than most other parts of the world to the consequences of contamination from airborne radiocesium. The higher vulnerability in the Arctic arises from the unique characteristics of food webs, the use of land, and land cover in this region.

Most radioactive contamination in Arctic lands is derived from fallout from atmospheric nuclear tests conducted during the period 1945 to 1980. In some areas, fallout from the 1986 accident at the Chernobyl nuclear power plant is also a major source of contamination. Levels from these sources are declining with time as the radionuclides decay.

A major source of radionuclides in the Arctic marine environment is releases from European plants that reprocess spent nuclear fuel. In contrast to the declining levels for other radionuclides, the levels of technetium-99 and iodine-129, which are long-lived fission products from reprocessing, are increasing in the Arctic marine environment.

The greatest radiation threats in the Arctic are associated with accidents resulting in releases of radionuclides to the environment. These include accidents involving nuclear reactors. Another environmental hazard is posed by the large stockpiles of radioactive waste in the Arctic. Efforts to reduce risks associated with these activities are ongoing, but much still remains to be done.

This chapter addresses radioactive contamination in the Arctic and its potential consequences for human and ecosystem health. The previous AMAP assessment focused on current sources, levels, and radiation doses to humans. The emphasis this time is on the behavior of radionuclides in ecosystems, the hazards associated with potential sources, and how best to address these hazards.

Closing Chernobyl

A concern for human and ecosystem health

Radioactivity is a concern for human and ecosystem health because radioactive material emits ionizing radiation that has the ability to damage living cells.

Radioactivity and radiation dose

Radioactive materials contain unstable atomic nuclei. When the nuclei decay to stable forms, they emit ionizing radiation. The activity is measured as the number of disintegrations per second. The unit is the becquerel (Bq).

The health effects of radioactivity are related to the dose received. The unit of dose is the gray (Gy). A more important unit for assessing human health effects is the sievert (Sv), which measures effective dose. One sievert is equal to the effect in humans caused by one gray whole body dose of gamma radiation.

In regulating nuclear activities, 1 millisievert (0.001 sievert) is used as a yearly dose limit for exposures of members of the public to all man-made radiation. It corresponds to an increased risk of fatal cancer of 0.005%, or one additional cancer case among 20 000 exposed individuals.

The global average individual dose from natural sources of radiation is 2.4 millisieverts per year. However, this dose varies as a function of geology and other conditions.

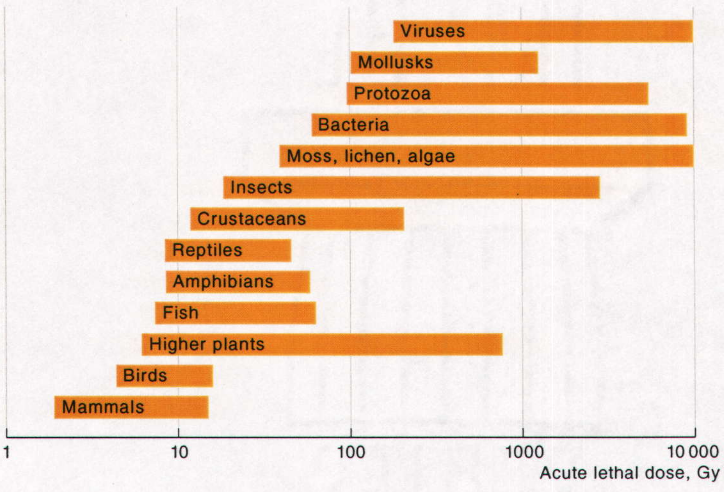
Cancer is the major human health concern

At low doses, the main human health concern is that radiation may increase the risk of cancer and/or cause genetic effects by inducing damage to the DNA. When radiation leads to genetic damage in the egg or in the early developmental stage of sperm, such damage can affect fetal development or make a person more susceptible to disease. The probability of cancer and reproductive damage increases with the dose.

For low doses, radiological protection assumes that no threshold exists below which there is no risk of damage. Thus, for low doses, the probability of adverse effects is considered to be proportional to dose.

At high doses, the effects are not a matter of probability. Radiation kills cells, causing local burns, organ damage, and radiation sickness.

Sensitivities of various organisms to acute lethal dose of ionizing radiation.



The severity of effects is directly related to dose. If the dose is high enough, the individual will die.

The goal of radiological protection efforts is to ensure that practices involving potential radiation risks are justified, dose limits are complied with, and doses are kept as low as reasonably possible.

New focus on ecosystem health

Specific consideration of radiation doses and effects on wildlife, plants, and ecosystem health is a relatively new development. Traditionally, radiological protection has focused on protecting humans with the assumption that this would also protect other components of the ecosystem. However, during the past few years an international consensus has been reached on the need to develop systems that can explicitly assess any potential harm to ecosystems and their components resulting from exposure to radionuclides.

Experience from laboratory studies and accidents has established that radiation can cause a number of detrimental effects in biota, including mortality, reduced reproduction, and genetic damage. Nevertheless, current knowledge about effects on wild plants and animals is limited and subject to large uncertainties. Moreover, there is little consensus on the relevance of these effects in the context of risk management. A better understanding of ecological effects and their uncertainties requires a framework for risk and impact assessment that can take into account the sensitivities of various species and ecosystems.

Factors that influence sensitivity include exposure pathways, the extent of uptake to biota, and dose–effect relationships. These can be ecosystem dependent and, for example, may vary with the availability of nutrients and biological productivity. They are also species dependent, examples being high bioaccumulation of technetium-99 in lobsters and the radiosensitivity of pines compared with other trees.

Acute lethal doses can vary by several orders of magnitude among and within species. However, effects on reproduction and population health may occur at much lower doses than those that would kill an organism. There is very little information about the effects of low chronic exposures.

The work of assessing the effects of radiation on ecosystems is still in its early stages, and AMAP is taking an active part in this effort (see box on opposite page). The ultimate purpose of an assessment framework is to define doses or concentrations at which effects in the environment would be expected to be minimal, with an acceptable degree of confidence and in broad harmonization with standards used to assess other hazardous substances.

International efforts

By highlighting inconsistencies among the management and regulatory approaches for radioactivity and other environmental pollutants, AMAP activities have played a key role in driving the development of a framework for assessing ecosystem effects of radiation. AMAP is also playing a part in continued efforts, for example by the International Union of Radioecology (IUR), which was one of the first international organizations to actively promote the need to focus on non-human biota and to propose a system for impact assessment. The IUR initiative has subsequently been carried forward in projects funded by the European Union, including one on environmental effects of radionuclides in the Arctic. To date, one of the main outputs of this work has been the selection of reference organisms. In this regard, the Arctic poses some special challenges because of the low number of species and high vulnerability.

Plankton sampling in Disko Bay, Greenland.

Proposed terrestrial reference organisms	*Proposed aquatic reference organisms*
Lichens and bryophytes	Benthic bacteria
Gymnosperms	Macroalgae (marine)
Monocotyledons	Aquatic plants (freshwater)
Dicotyledons	Phytoplankton
Soil microorganisms	Zooplankton
Soil invertebrates	Mollusks
Herbivorous mammals	Polychaetes (marine)
Carnivorous mammals	Insect larvae (freshwater-benthos)
Bird eggs	Pelagic fish (planktotrophic)
	Benthic fish
	Pelagic fish (carnivorous)
	Carnivorous mammals
	Benthos-eating birds
	Fish eggs

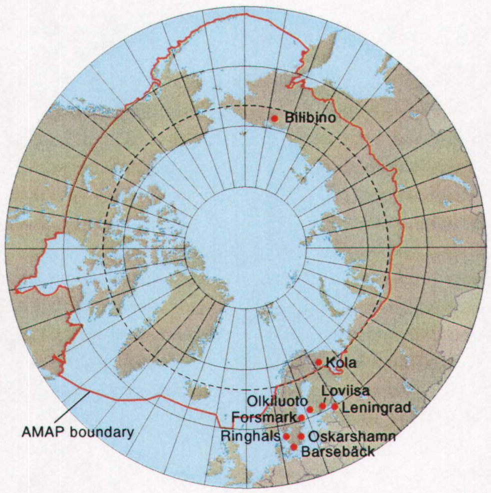
Risk management

Radiation risks can be reduced by specific measures to protect the health and safety of workers, the public, and the environment. A judgment has to be made as to what measures are feasible based on prevailing technical, social, and economic circumstances.

In this context, a risk analysis consists of the following steps: 1) Defining the facility and operation; 2) Identifying the hazards; 3) Characterizing the hazards that present the greatest risk; 4) Postulating and analyzing possible scenarios; and 5) Estimating the consequences. The results of the risk analysis process are used to consider and analyze options for prevention, preparedness, and response strategies.

The previous AMAP assessment identified a number of existing and potential sources of radioactivity in the Arctic. Some risk analyses of these sources have been included in the updated AMAP assessment. They address vulnerabilities and hazards associated with potential accidents involving nuclear power plants operating in or within 1000 kilometers of the Arctic, nuclear-powered vessels, interim storage of spent nuclear fuel, improperly stored fuel elements, and decommissioned vessels containing spent nuclear fuel.

For current radioactive contamination, the focus of the updated assessment is on new information about levels in the environment.



There are several nuclear power plants in the vicinity of the Arctic, and two plants within the AMAP area. Finland has two nuclear power plants both situated on the Baltic Sea coast: Loviisa on the Gulf of Finland, and Olkiluoto on the Gulf of Bothnia. Two reactor units are in operation at both sites. Sweden has four sites with nuclear power plants situated both on the east coast (Forsmark and Oskarshamn on the Baltic Sea) and the west coast (Ringhals on the Kattegatt and Barsebäck on Öresund). In Russia, there are two nuclear power plants in the Arctic: the Kola plant on the Kola Peninsula and the Bilibino plant in the Chukotka Region. The Leningrad nuclear power plant, situated outside the Arctic near St. Petersburg, is also of interest for the AMAP assessments.

Nuclear power plants

Two nuclear plants are located in the Arctic, at Kola and Bilibino in Russia. There are also several nuclear power plants within 1000 km of the Arctic. Under normal operating conditions, routine releases from these plants are small and contribute little to radiation levels or doses in the Arctic. The dominant radiological risks are those associated with potential accidents. AMAP has attempted to estimate the risks associated with accidents at the Kola nuclear power plant using a specific accident scenario.

THOMAS NILSEN

Kola nuclear power plant.

Model shows health risk associated with potential Kola plant accident

The Kola nuclear power plant has four 400 megawatt pressurized-water reactors. An accident here may have graver consequences than one at Bilibino, which has four smaller reactors that are only 11 megawatts each.

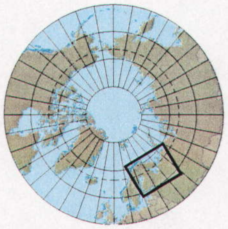
Recent studies focusing on northwest Russia and northern Norway have looked at the consequences of hypothetical accidents at the Kola plant. A severe accident would obviously lead to significant doses close to the plant. Another concern is whether there would also be significant consequences farther away in adjacent Arctic areas in the short or long term. Radionuclides efficiently transfer to some Arctic ecosystems, where they can remain for a long time. An assessment therefore has to include long timescales. The scenarios that were chosen for calculating doses after a hypothetical accident represent worst-case events and their consequences.

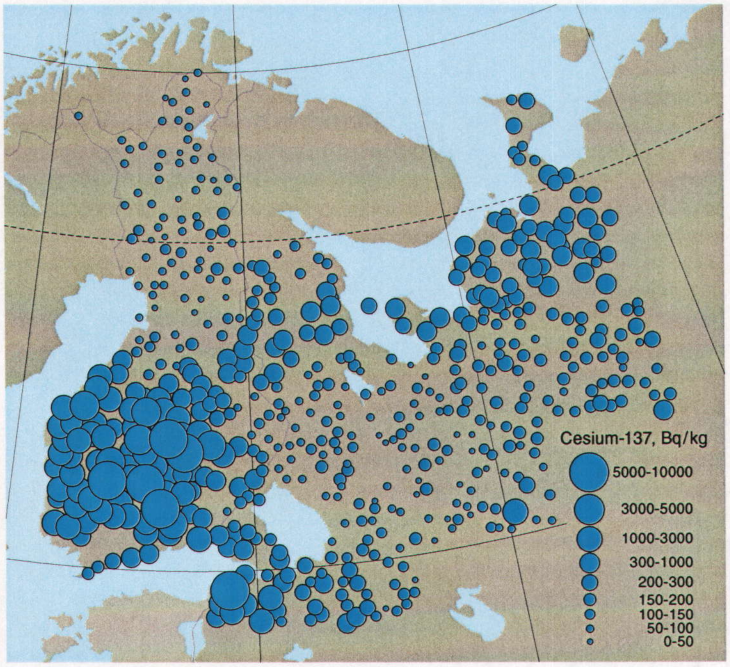
The highest individual external doses outside the plant facility would occur in the most contaminated areas, but they are too low to result in any acute radiation damage. Doses received after eating contaminated food are initially lower than external doses, but increase and become more important with time. Doses vary spatially depending on differences in deposition, type of land cover, and associated food production. Reindeer herders and others who consume high quantities of reindeer meat would receive significantly higher annual individual doses of radiocesium from food than other inhabitants of the same region. For the high-consumption groups, reindeer meat contributes most of the internal dose during the first year after deposition. For other people, dairy products and sheep meat are the largest contributors. Doses of strontium-90 are very low for all inhabitants.

It is predicted that reindeer herders and others with high reindeer consumption would get annual ingestion doses that exceed 1 millisievert for several decades after the accident, with much higher doses in the first few years. For other population groups, the consequences vary geographically. If the deposition occurred in northern Norway (Troms (Romsa) and Finnmark (Finnmárku)), ingestion doses could exceed 1 millisievert for a few years after the accident, whereas this period would be about 10 years if the deposition occurred in Murmansk Oblast. Potential consequences in other areas were not assessed.

This scenario confirms that residents of Arctic ecosystems are particularly vulnerable to radiocesium contamination and that the vulnerability persists for many years after deposition. Although those who consume larger quantities of reindeer meat are particularly vulnerable, other people could potentially be exposed to high doses, especially if they consume many local products. The results clearly show the need for an effective emergency preparedness and response system, and the application of countermeasures, should a major accident ever occur at the Kola nuclear power plant.

A comprehensive survey of cesium in Finland and northwest Russia was carried out in 2000. The map shows cesium-137 concentrations in the top three centimeters of the humus layer.





Update on contamination from Chernobyl

One nuclear power plant accident has already had consequences for the Arctic: the explosion and fire at the Chernobyl nuclear power plant in the Ukraine in 1986. This plant was more than a thousand kilometers from the Arctic Circle. Nevertheless, radioactive material from the explosion was carried by the wind and spread over large areas, including parts of the Arctic. This source of radioactive contamination was described in the previous AMAP assessment. The major contaminated area outside the immediate vicinity of Chernobyl extends from the Leningrad region of Russia across southern Finland to parts of Sweden and Norway. A comprehensive survey of humus layers in 2000 in parts of the contaminated area in Finland and northwestern Russia provides a picture of levels of radiocesium (see map). Fourteen years after the accident, the fallout from Chernobyl is still evident in the higher levels of cesium-137 in the whole southwestern part of Finland and in the area southwest of St. Petersburg in Russia.

Progress in reducing risks associated with nuclear power plants

A number of programs have been initiated to improve the safety of nuclear activities in or near the Arctic, especially at nuclear power plants in Russia. Most of the programs are based on cooperation between Russia and other Arctic countries.

Bilibino nuclear power plant consists of four small, water-cooled, graphite-moderated reactors. Efforts at Bilibino have focused on improving the safety of day-to-day operations. Projects have targeted training for plant staff, providing an analytical simulator to enhance training effectiveness, providing safety maintenance equipment and technology, and establishing improved communication links with Moscow.

Efforts at the Kola plant are also directed toward improving the safety of day-to-day operations and upgrading critical plant safety systems. The projects have focused on developing emergency operations instructions, upgrading the confinement system, and improving the engineering safety systems. Projects are also in place to perform safety assessments, to teach staff how to perform plant safety analysis, and to provide a full-scale simulator to enhance staff training.

The Leningrad nuclear power plant, located outside St. Petersburg, consists of four reactors. Safety enhancement efforts are similar to those at the Kola plant. Projects are in place for developing emergency operations instructions, providing modern safety maintenance tools and techniques, and performing in-depth safety assessments. In addition, projects are underway to provide an improved fire detection system and an emergency response program.

In the case of an emergency, it is critical that accurate information is available promptly for emergency response. Upgrading of the emergency notification system at the Leningrad and Kola nuclear power plants has been continued. There is now an automatic environmental radiation monitoring and notification system in place. These are based on satellite communication and should allow automated message transmission and direct communications with central Russian authorities as well as to the Nordic countries, independent of ground communications. Further networks have also been established, and soon all Russian nuclear power plants except Bilibino will have direct emergency communication links with central government agencies responsible for nuclear and radiation emergencies.

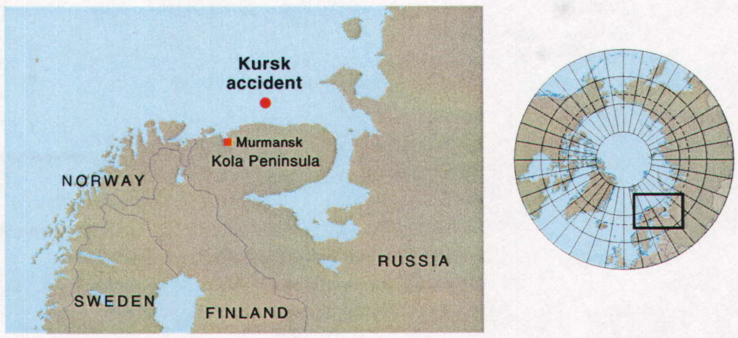
Nuclear-powered vessels

There are several locations within the Arctic where nuclear-powered vessels are being built, based, maintained and decommissioned. The size of the reactors on nuclear vessels is typically about one tenth of that of a typical nuclear power plant reactor. However, the number of operating reactors and their maintenance and decommissioning create an increased potential for accidents. The AMAP 2002 assessment contains updated information on the status of submarine decommissioning in the Russian Northern Fleet and associated waste management issues.

Since the previous AMAP assessment, the nuclear submarine *Kursk* was lost in the Barents Sea and was subsequently recovered.

The Kursk accident did not lead to environmental contamination

On August 12, 2000, the Russian submarine *Kursk* sank in international waters north of the Kola Peninsula in the Barents Sea. It was powered by two small nuclear reactors, which, as designed, automatically shut down during the accident. The submarine was not carrying any nuclear weapons. In 2001, the *Kursk* was raised, transported, and moored on a floating dock in Roslyakov near Murmansk.



The *Kursk* accident site.

Several expeditions monitored levels of radioactivity in the water and sediment, both while the *Kursk* was at the bottom of the Barents Sea and during the recovery operation. There was no indication of radionuclide leak-

The barge *Giant-4* transporting the salvaged wreck of the *Kursk*.

age from the submarine and the results show that the accident and subsequent recovery of the *Kursk* did not lead to any significant releases of radioactivity to the Arctic environment.

The recovery of *Kursk* has substantially reduced the risks of radionuclide releases from its reactors to the marine environment. However, until the fuel is removed and transported to proper storage, the potential for releases of radionuclides into the environment will persist.

Doses to the public are a minimal risk from a sunken submarine lying intact on the sea floor. Local seabed contamination may, however, be a concern should leakage of radionuclides occur. The major threats to humans are associated with atmospheric releases from submarine reactor accidents.

Storage of spent nuclear fuel and other wastes raise concerns

The decommissioning of nuclear submarines in the Russian Northern Fleet is continuing. As of November 2001, a total of 109 nuclear submarines had been taken out of operation. Of these, 41 have been dismantled and 68 are

PER-EINAR FISKEBECK

Andreeva Bay – the main Northern Fleet facility for storing nuclear waste.

moored awaiting dismantling. Fifty of these submarines contain spent nuclear fuel. It is expected that a further 18 to 20 submarines will be dismantled each year. During operations that involve handling of spent nuclear fuel, there is an increased risk of accidents that might cause both local and widespread atmospheric contamination.

Some of the spent fuel from refueling and decommissioning has been transported to Mayak, in the Urals, for storage and reprocessing. However, most of it is still in temporary storage on the Kola Peninsula. Although the temporary storage facilities pose a smaller threat for acute accidents with widespread atmospheric contamination than accidents in operative reactors, some of the temporary storage is causing serious local contamination, which may be spreading into the marine environment.

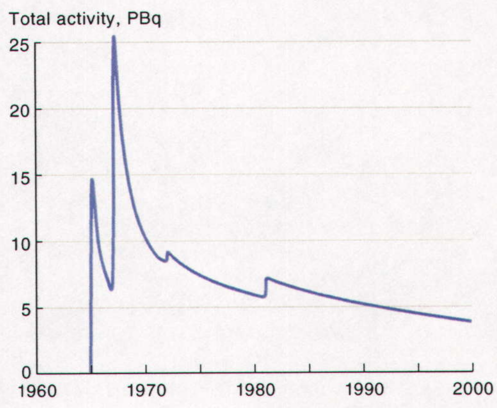
Several programs address the waste situation, which, in addition to spent fuel, includes solid and liquid radioactive wastes from submarines and other nuclear-powered vessels. An effort is also underway to launch projects related to remediation of the Andreeva Bay site that contains the largest concentration of radioactive wastes in northwest Russia. Other projects include developing a mobile processing facility for liquid nuclear wastes and new interim storage for spent nuclear fuel derived from decommissioned submarines. Large amounts of spent nuclear fuel and radioactive wastes are currently stored at the Atomflot facilities near Murmansk, including the floating storages vessels *Lepse*, *Imandra*, and *Lotta*. The *Lepse* is in a particularly poor condition and there has long been a desire to remove the spent fuel and radioactive waste from the vessel and store it elsewhere.

Since the previous AMAP assessment, the overall approach of these programs has been to adopt an integrated solution and a cooperative effort in which all the major steps from generation to disposal of the waste have to be evaluated before making any decision about options for resolving the issue. These projects represent ongoing cooperation to reduce the risks associated with radioactive wastes in the Arctic. Many other projects are being considered and may be initiated in the near future.

Amount of radioactive waste dumped at sea has been overestimated

Until 1991, the Soviet Union dumped radioactive waste in the Arctic Seas, including submarine reactor compartments containing spent nuclear fuel and part of the reactor compartment of a nuclear icebreaker. This resulted in local contamination around the dumping sites, but according to previous assessments by AMAP and by the International Atomic Energy Agency (IAEA), the major risks of releases are in the longer term, after the containment material corrodes. The IAEA study concluded that risks to members of the public from these dumped wastes are small.

There have been efforts to estimate the total content of radioactive material in the dumped

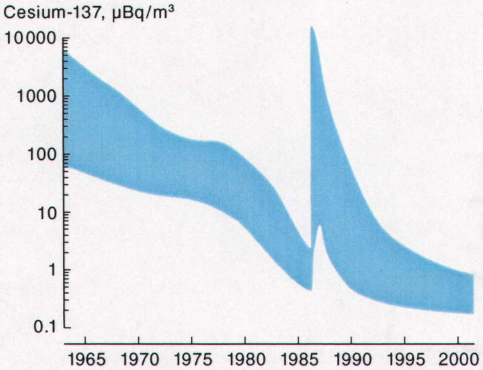


► Total activity of radionuclides in nuclear reactors dumped in the Kara Sea.

submarines and the icebreaker reactor, both by an international project and within Russia. Previous Russian estimates, from 1993, were published in the so-called White Book. The most recent estimates show that the White Book underestimated the activity in the reactor compartment from the *Lenin* icebreaker and overestimated the total activity of submarine reactors containing spent nuclear fuel. Recent analysis of the revised figures, also taking into account the physical decay of radionuclides present in the dumped ship reactors, shows that the White Book overestimated the total activity in all the reactors dumped near Novaya Zemlya by more than a factor of three.

Nuclear detonations and nuclear weapons accidents

The previous AMAP assessment concluded that fallout from atmospheric nuclear weapon tests conducted from the 1940s through 1980 was the major source of anthropogenic radionuclides in the Arctic environment. Radioactive contamination from these tests is declining.



The range of aerosol cesium-137 concentration from the atmospheric tests was declining in northern Finland until the Chernobyl accident in 1986.

The largest atmospheric detonation anywhere took place at the Soviet test site at Novaya Zemlya in October 1961. There have also been several underground nuclear detonations in the AMAP area. The largest of these were conducted by the Soviet Union in Novaya Zemlya in October 1973 and by the United States at Amchitka, Alaska, in November 1971.

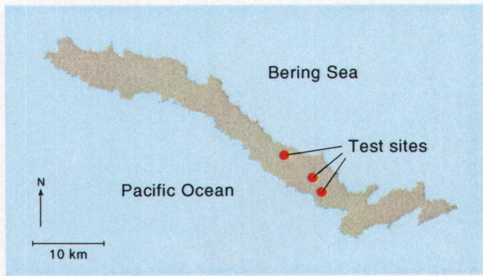
Updates on the local situations at Novaya Zemlya and Amchitka

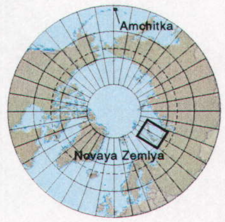
The tests at Novaya Zemlya resulted in local contamination. Since the previous AMAP assessment, two new reports on the subject have been published. Surveys have documented radioactive contamination in four areas: Chernaya Bay on the Yuzhny (South) Island, Sukhoy Nos Peninsula on Severny (North) Island, Bashmachnaya Inlet on Yuzhny Island, and the tidal area of the Matochinkin Shar Strait.

Chernaya Bay was the site of a near-surface explosion in 1957 as well as several other tests. The epicenter of the near-surface explosion is the most contaminated zone in the archipelago. In 1978, gamma radiation levels were as high as 5 microsieverts per hour. There are also traces of radioactive contamination of land areas from an above-water explosion in 1961 and from an underwater explosion in 1955.

There is also new information about the United States test site on Amchitka, where three underground tests were carried out between 1965 and 1971. When the previous AMAP assessment was written, no detailed sampling of this site had been carried out since the late 1970s. However, routine sampling and monitoring of the test site for increased radiation levels have been ongoing since the 1970s. Modeling of the movement of radionuclides in the environment of the Amchitka site had indicated that discharge from groundwater to the ocean could have started as early as 1975, ten years after the first underground tests at the site.

In 1996, leakage of radionuclides to the terrestrial and freshwater environments was reported by an environmental organization. The marine environment was not addressed in the report. In response, a federal, state, tribal, and non-governmental team conducted a freshwater and terrestrial sampling program in 1997, with additional sampling in 1998. At the Long Shot test site, where leakage of radioactive gases to the near surface occurred in 1965, elevated levels of tritium in freshwater were observed in 1997. Contrary to the claims of some environmentalists, the results of the 1997 and 1998 sampling did not pro-





Contaminated sites on Novaya Zemlya, where the Soviet Union carried out weapons tests (above), and the Amchitka test sites, where the United States conducted tests (left).

Amchitka.

vide any evidence of the leakage of radionuclides from the underground explosion cavities into the terrestrial and freshwater environment on Amchitka. In addition, the hydrogeological regime at Amchitka does not provide the physical means for transporting the radionuclides from the test cavities to the reported surface location.

These results do not mean that leakage from the Amchitka underground nuclear tests is not occurring or will not occur. Modeling of the movement of groundwater predicts that leakage to the marine environment could occur over timescales of 20 to 3000 years. There have also been some concerns raised about geological forces acting on Amchitka, with suggestions that stresses around a major fault could open a fracture from the island into the marine environment. These suggestions are still open to scientific debate. Assessments of the role of geological forces acting on underground island test sites to create a 'fast pathway' for radionuclide leakage could be relevant to both Amchitka and Novaya Zemlya.

Thule Airbase. Member of the American clean-up crew removing a contaminated revolver from the accident site.

Update on local contamination at Thule

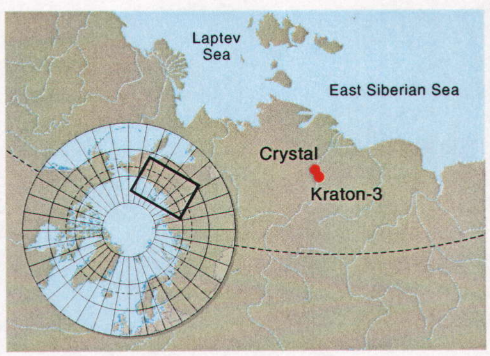
In 1968, an American strategic bomber crashed on the sea ice in Bylot Sound near the Thule Airbase in northwest Greenland. It carried four nuclear weapons, and some of the plutonium in these weapons was dispersed into the environment as a result of the aircraft explosion and subsequent fire. Most of the debris and contaminated ice was removed from the area. Some of it, however, sank through a crack in the ice or could not be recovered from the ice. The ice-embedded material was dispersed into the water column during the following summer when the ice melted.

Plutonium adheres strongly to particles. Measurements at Thule show that it is associated with particles in bottom sediment. The distribution of the contamination is uneven, and previous estimates of the amount of plutonium in the sediment did not fully take this into account. A more recent estimation method provides more accurate results. So far, only six sediment cores have been analyzed, but the results indicate that the quantity of plutonium in marine sediments at Thule is comparable to the amount that was estimated to have been lost (2.5-3 kg). Nonetheless, there remain substantial uncertainties in such estimates of the quantity of plutonium in Bylot Sound sediments.

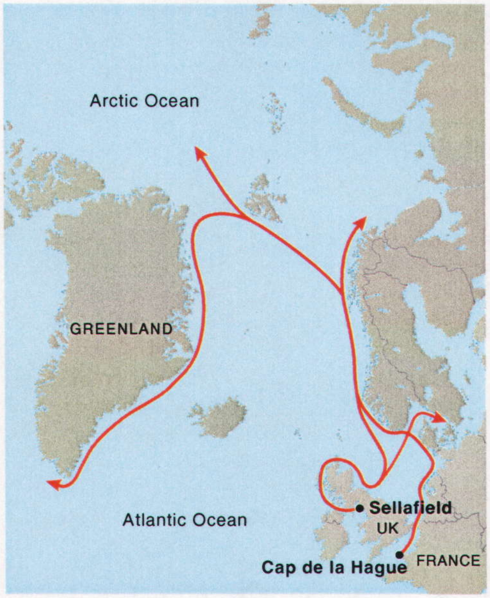
Some animals live buried in the contaminated sediment or on the sediment surface. Plutonium concentrations in these organisms are generally one to two orders of magnitude lower than in the surface sediment, showing that the plutonium is not very bioavailable. One bivalve sample had a much higher level, which was probably due to chance ingestion of a hot particle rather than accumulation of bioavailable plutonium. Levels in most animals living in the sediment are low and the plutonium is not readily transported to surface waters.

Local contamination from civilian nuclear detonations

From 1967 to 1988, the former Soviet Union conducted a number of civilian nuclear detonations to assist in mining and construction work. At three sites in or near the Arctic, the detonations led to severe local contamination, as discussed in the previous AMAP assessment. New information from the Kraton-3 and Crystal sites in the Sakha Republic shows that local contamination of the sites remains, despite earlier clean-up efforts. In the immediate vicinity of the Kraton-3 site, the plutonium concentration in lichen in the early 1990s was 780 times higher than background. However, the contamination is highly localized: a few kilometers away from the site, the levels are much lower. Measurements of the bottom sediment of the Markha River near the explosion site show that there has been a migration of plutonium to the river, with a potential for remobilization and transport over larger areas.



▶ Kraton-3 and Crystal, two of the sites where the former Soviet Union used civilian nuclear detonations.



◄ European reprocessing plants and the ocean pathways that carry radionuclide-contaminated water to the Arctic.

Sellafield (upper photo) and Cap de la Hague (lower photo).

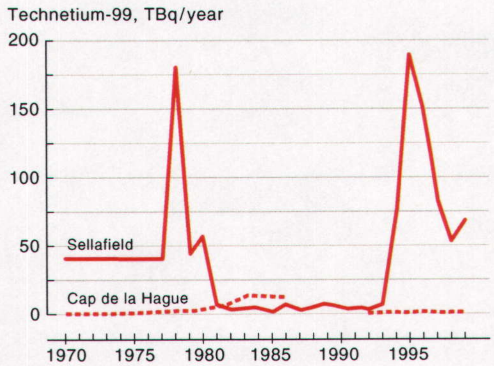
Reprocessing and transport of spent nuclear fuel

Fuel reprocessing is carried out to recover uranium and plutonium from spent nuclear fuel for reuse in reactors. Only 5-10% of spent fuel worldwide is subjected to reprocessing. Most spent fuel from reactors is instead retained on-site in interim storage. During reprocessing, the radionuclides are brought into solution. Waste solutions containing large amounts of radionuclides have been discharged to the environment during this process. There is a well-documented history of discharges of various radionuclides to the environment, with cesium-137 dominating liquid discharges. The potential for accidental releases to the environment of radionuclides in a liquid solution is greater than for all other stages of the fuel cycle. The reprocessing plants that are most relevant to the Arctic are Sellafield on the northwest coast of England and Cap de la Hague in northern France.

European plants have increased releases of some radionuclides

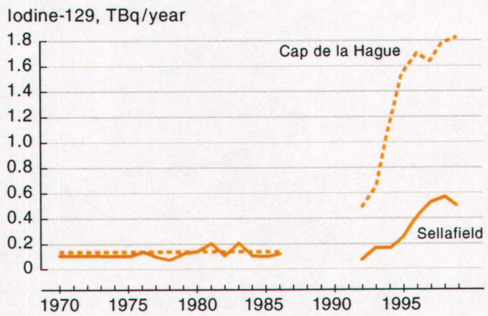
Liquid radioactive waste from the Sellafield and Cap de la Hague plants has been discharged via pipelines into the Irish Sea and the English Channel, respectively, since the 1950s. Water-borne radionuclides, including cesium-137, have been traced in northward-flowing currents and have been detected in the Arctic Basin.

In the late 1970s, there was a significant reduction in routine releases from Sellafield. In 1994, British Nuclear Fuels at Sellafield started treating a backlog of old waste in an Enhanced Actinide Removal Plant. The removal is effective for a number of radionuclides, but not for technetium-99. This treatment of old waste resulted in a considerable increase in the discharge of technetium-99, reaching levels similar to those during the previous peak releases of this element in the mid-1970s. This radionuclide is a long-lived fission product with a half-life of 213 000 years. Technetium-99 is soluble in water and can thus be transported over large distances in the marine environment.



Discharges of technetium-99 from Sellafield and Cap de la Hague, showing recent increases from Sellafield.

The discharge of iodine-129 also increased during the 1990s, especially from Cap de la Hague, where a new plant was put into operation in 1990. Iodine-129 is an extremely long-lived fission product with a half-life of 16 million years. It is water-soluble and its release has been detected and traced within the Arctic

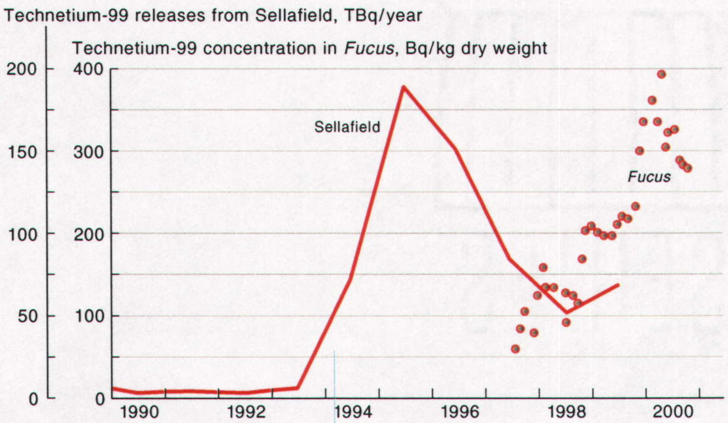


Discharges of iodine-129 from Cap de la Hague and Sellafield.

Ocean. The total discharge is ten times higher than the total amount in the ocean from natural sources and from iodine-129 generated by weapons testing.

Fuel reprocessing is a major source to the Arctic marine environment

The previous AMAP assessment showed that the input of cesium-137 from nuclear reprocessing plants is evident along the Norwegian coast and in the Arctic Ocean. Since then, the increased discharges of technetium-99 and iodine-129 have led to increasing levels of these radionuclides in the Arctic marine environment, in contrast to the declining trends for other radionuclides. A time series from Hillesøy on the northern coast of Norway shows a steep increase of technetium-99 in seaweed in the late spring and early summer of 1997.

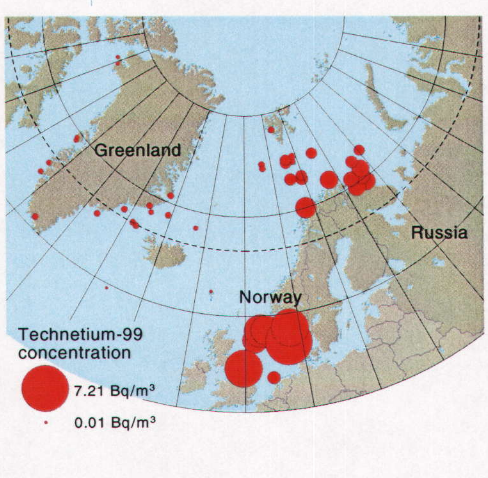


Technetium-99 releases from Sellafield and activity in *Fucus* seaweed at Hillesøy, northern Norway.

An analysis of the data suggests that the technetium-99 resulted from the rapid increase in discharges from Sellafield in the spring of 1994. Elevated levels of technetium-99 have also been detected in the southern Barents Sea. The spatial distribution, with higher activities near the coast, is consistent with current understanding of the prevailing ocean currents. At present, Sellafield is the main contributor of technetium-99 to Arctic waters.

Many radionuclides bind tightly to particles and are likely to accumulate in sediments relatively close to the source of discharge. Plutonium is one example. Several hundred kilograms of plutonium from nuclear fuel reprocessing have accumulated in the sediment of the Irish and North Seas. Measurements in seawater show that some of the plutonium in the sediment is being remobilized and transported via ocean currents into the Norwegian Sea, the Barents Sea, and eventually into the Greenland Sea and Icelandic coastal currents (see box on opposite page). Analysis of the ratios of different isotopes of radionuclides shows that the primary source of plutonium in these waters is still fallout from past nuclear testing. Through the remobilization of plutonium, however, Sellafield is indirectly the second most important contributor of man-made plutonium in Arctic seawater.

Taking into account the inventories of radionuclides from reprocessing that were presented in the previous AMAP assessment, it is clear that the reprocessing of nuclear fuel has been and still is a major source of anthropogenic radionuclides to the Arctic marine environment. The current doses to Arctic inhabitants from these sources are small. There are, however, some uncertainties about the transport to, and effects of radionuclides in the Arctic. Therefore, there is a need for further assessment of the individual and collective doses from radionuclides discharged from these and other sources. There is also a need to consider impacts on Arctic populations and the environment when evaluating discharge reduction measures.Technecium-99 discharges can be reduced using available technology, but this step has not yet been taken.



Technetium-99 distribution in seawater in 2000.

Transport of spent fuel in the Arctic is a potential risk

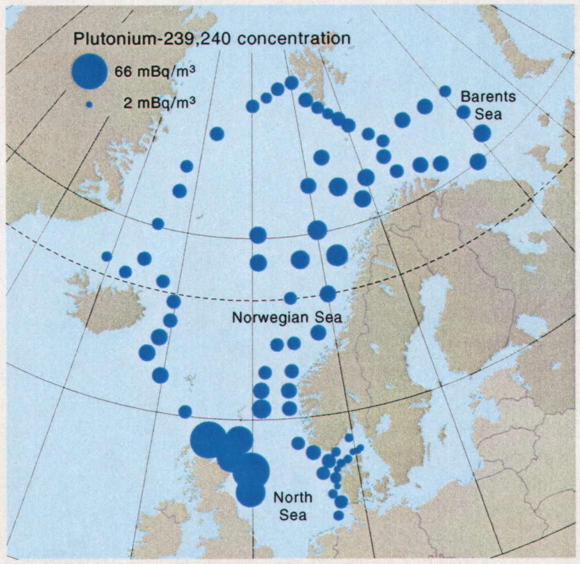
Spent nuclear fuel for reprocessing is sometimes transported by ships, as is the resulting reprocessed fuel. Between 1992 and 1999 there were six shipments of plutonium and high-level waste from France to Japan and one shipment of mixed oxide reactor fuel from the United Kingdom to Japan. There are suggestions that shipments in the future may use the Northern Sea Route, north of Russia. There are also ongoing discussions of shipping spent fuel from Europe to northern Russia via Murmansk for processing in Russia.

If such shipments are carried out in a manner consistent with international guidance and existing conventions, they pose only minor risks to human health. However, even if such risks are low, possible release scenarios should be considered and thorough impact assessments should be performed. The possible transfer of spent nuclear fuel in Arctic areas has caused controversy, and will continue to do so if the concerns are not addressed properly.

Old discharges still act as sources for the Arctic

The sediments of the Irish Sea accumulated large quantities of plutonium and radiocesium when discharges from Sellafield were high during the period 1970-1985. During the last decade it has become clear that these elements are not permanently deposited in marine sediments. Due to biological and chemical processes, radiocesium and plutonium are now being released in transportable forms and reaching the Arctic marine environment. The annual contribution from Irish Sea sediments has been estimated to be 50-80 trillion becquerels cesium-137 and about one trillion becquerels plutonium. This is more than the amount of these radionuclides currently being discharged by the two European nuclear fuel reprocessing plants. Plutonium and cesium-137 derived from these areas are transported to the Arctic via the Norwegian Coastal Current.

The Baltic Sea also constitutes a major source of cesium-137 to the Arctic. The Baltic was heavily contaminated by the Chernobyl explosion in 1986, and levels in the water are still high. Outflow from the Baltic in 2000 was 40 trillion becquerels of cesium-137, almost as high as the outflow from the Irish Sea sediments.



Plutonium in seawater in 1995. In the Norwegian and Barents Sea, levels are elevated above the expected fallout background levels.

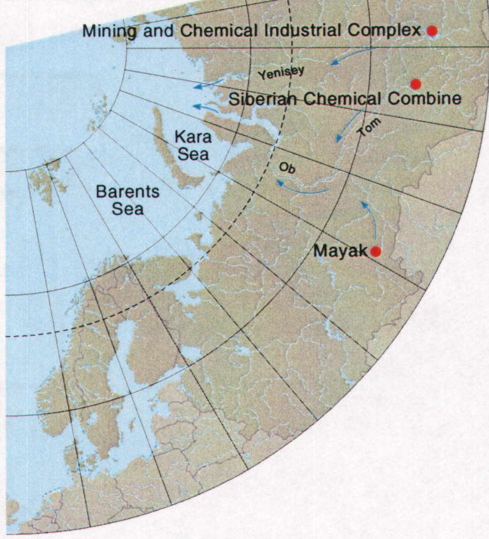
Russian nuclear facilities

Discharges from Russian nuclear facilities within the Arctic have had a minor impact on the overall radioactive contamination. However, there are three major Russian nuclear facilities located far from the Arctic that need to be considered because they discharge into river systems that eventually reach the Arctic Ocean. They are Mayak and the Siberian Chemical Combine, both in the Ob basin, and the Mining and Chemical Industrial Complex on the Yenisey River. Because discharges from these plants have historically been high, there is concern about whether they have contaminated the Arctic and whether future accidents could lead to further contamination.

Mayak was built in 1948 to produce weapons-grade plutonium. The plant and its local contamination are described in detail in the first AMAP assessment. A joint Norwegian-Russian expert group has investigated several accident scenarios and their potential to contaminate the Arctic. The scenarios included an explosion in a storage tank, a tornado at the highly contaminated Lake Karachay, dam breaks or controlled releases from storage basins that would contaminate the Techa River, a tributary to the Ob, and groundwater contamination from Lake Karachay reaching the Techa River.

Looking at worst-case scenarios, transport of strontium-90 in the river system could lead to a significant increase in contamination of the lower reaches of the Ob. For example, a dam break could lead to strontium-90 concentrations five times higher than the background level. Cesium-137 and plutonium would be much less mobile in the river system. For all scenarios, the predicted environmental concentrations of radionuclides in the Ob Bay are much lower than radiation safety standards set to protect people. Overall, the potential doses to Arctic biota and human populations associated with hypothetical accidents at Mayak involving discharge of radionuclides to water are very low. Accidents that involve discharges to air could, however, have serious consequences for the Arctic.

The Siberian Chemical Combine is located near Tomsk. Past activities produced large amounts of liquid, solid, and gas-aerosol radioactive waste, most of which is stored in warehouses and underground storage facilities. Some of the liquid waste is discharged directly into a sedi-

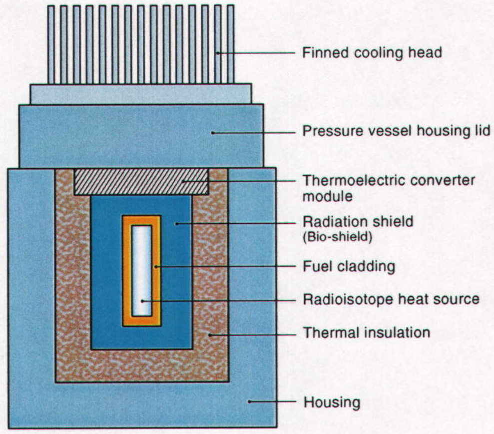


Russian nuclear facilities with historically high discharges.

mentation reservoir, which is connected to the Romashka River and eventually into the Ob. The major contribution to radioactivity in the wastewaters has been from reactors with single-pass core coolant systems, which were decommissioned some time ago.

In the past few years, the release of radionuclides to the open water environment has been reduced, but previous discharges led to a significant accumulation of radionuclides in bottom sediment, biota, and the floodplain. The concentration of radionuclides decreases considerably with distance from the source. It thus appears that most of the discharges from the Siberian Chemical Combine are effectively removed during transport and are not found either in the lower reaches of the Ob or in the Ob Estuary.

The Mining and Chemical Industrial Complex at Krasnoyarsk includes a reactor facility, a radiochemical plant, and storage for spent fuel assemblies. The releases of contaminated water have decreased considerably since the two reactors at the site were shut down in 1992. However, the bottom sediments and the floodplain are contaminated with long-lived radionuclides such as cobalt-60, cesium-137, and europium-152. Contamination from the Mining and Chemical Industrial Complex is detectable in the Arctic about 2000 kilometers downstream. The radioactivity concentrations this far away are a thousand times lower than in the zone next to the facility, but still observable. The results thus suggest that transport of long-lived radionuclides from the area near the facility is low and that the discharges from the Mining and Chemical Industrial Complex have had a minor impact on radioactive contamination of the Arctic Ocean.



▶ Schematic drawing of a radioisotope thermoelectric generator (RTG).

Radioisotope thermoelectric generators

Radioisotope thermoelectric generators (RTGs) provide sources of power that are completely self-contained and can operate in any weather conditions. They have a long service life and are reliable, making them suitable for powering various devices in remote areas and areas with harsh climates, such as the Arctic.

The dominant radioactive material used in RTGs is strontium-90 titanate. It is a chemically stable fuel element that is not affected by extreme weather conditions or high temperatures. RTG radioactive fuel is in a leak-tight, multi-envelope container made of heat- and corrosion-resistant material. This arrangement is designed to maintain the integrity and effectiveness of the containment material during the entire service life of the generator and during possible emergencies.

Being close to an RTG is not a health hazard as the radioactive material is well contained and shielded. In terms of contamination of the environment, the greatest threat from RTGs occurs if they are broken open during transport or as a result of malicious damage. The shields are designed to withstand accidents and natural disasters, and so the most likely cause of a breach is vandalism. If an RTG is breached, the released radioactive material can be detected and recovered. The fuel is in the form of hockey-puck sized pieces of ceramic material, selected for its strength, fire-resistance, and low water solubility. Moreover, it is in an inert form that is not easily taken up by plants and incorporated into the food web.

The United States is using ten RTGs as power sources for data collection and communications equipment at a seismic observatory on Burnt Mountain in Alaska. The observatory is run by the U.S. Air Force and is used to verify compliance with nuclear test ban treaties. In August and September 1992, a tundra fire encroached on the Burnt Mountain site, damaging some data cables. The power equipment was not disturbed. The fire raised concern among nearby inhabitants about the safety of using a radioactive material as the power source. In response, the U.S. Air Force conducted an evaluation of the safety of RTGs and alternative power sources. While the RTGs were deemed safe, community concern resulted in a decision to remove the RTGs and replace them with a system using batteries charged by solar power and a diesel generator. Planning for this has started.

STAN READ

▶ Burnt Mountain, Alaska, where RTGs have been used as power sources.

In Russia, RTGs are used to power automated meteorological stations in uninhabited polar areas. Moreover, a network of RTG-powered navigational facilities has been established for new sea routes at high latitudes. In the Arctic, no losses have been reported, but incidents outside the Arctic in connection with emergency dumps from helicopters transporting RTGs show that the risks of losing devices during transport have to be taken into account. On the coast of the Kola Peninsula, one RTG has been vandalized and the radioactive material left exposed. The fuel element itself was intact and was completely recovered. There was thus no subsequent contamination of the environment.

RTGs at lighthouses on the coast of the Barents Sea are being replaced by solar panels.


KLAZ ARVIDSSON / WINDH · JAN TOVE / NATURFOTOGRAFERNA

Cloudberries, Taavauvoma, northern Sweden. Radiocesium transfer to some berry species is higher than to others. The highest recorded transfer rates are for cloudberries, a typical Arctic species that grows in boggy areas where radiocesium is likely to be mobile. Transfer is also high to bilberries, which are distributed more widely and grow on drier types of soil.

Arctic pathways and vulnerability

The effects of radioactive contamination will depend on the extent to which organisms are exposed to radionuclides. For people, a key factor in vulnerability (or sensitivity) to radioactive contamination is dietary habits and how these relate to the pathways of radionuclides in the food web. Vulnerability is a measure of how much radioactivity reaches humans through the food web for a given input to the environment. In the past few years, it has become clear that the most highly exposed people are not necessarily those in the most contaminated areas, especially some years after the initial contamination. This is because, for a given food, the transfer rate can be higher in one area than another, outweighing differences in atmospheric deposition. Understanding the physical and biological behavior of various radionuclides in the environment is as important as quantifying the extent of radioactive contamination. Combining this knowledge with information about the extent of environmental contamination provides a basis for planning emergency preparedness and response and for setting priorities for nuclear safety measures.

Terrestrial ecosystems

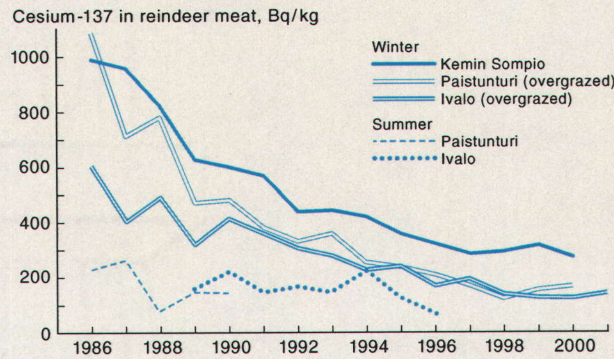
High transfers of radiocesium in Arctic terrestrial ecosystems are a major factor contributing to the enhanced vulnerability of the Arctic. Radiocesium transfers efficiently into many food products. One typical example is the lichen → reindeer/caribou → human food chain. Another is that mushrooms and berries can be very efficient in concentrating radiocesium.

The transfer to animals can vary seasonally, due to changes in animal diet, and can also vary spatially. For instance, radiocesium uptake from soil is greater from organic soils than from more highly mineralized soils. The type of soil can thus be important in determining vulnerability in a specific area. The type of vegetation can also have a major impact both on the transfer to food products and on how fast levels decline after initial deposition (see box below).

Focus on reindeer meat

Reindeer meat often has a high radiocesium content. In summer, when reindeer eat several hundred different species of green plants, levels are lower than during the long winter. When snow covers the ground, reindeer survive by digging for lichen and plants beneath the snow cover and by nibbling at lichen from tree branches. Lichens are efficient collectors of radiocesium from fallout.

Food availability affects the amount of time it takes radiocesium levels in reindeer meat to decline and also explains some of the spatial variation. Data from three reindeer cooperatives in northern Finland illustrate the point. Global fallout levels were similar in the three areas and two of them also had similar fallout from Chernobyl. The major difference in the trends in the concentration of cesium-137 in winter reindeer meat is probably related to the availability of lichen on the ground. The northernmost area, Paistunturi, (Báišduottar) is a rather barren reindeer-herding district. Levels here have declined faster than in the other two areas due to the limited lichen cover. The reindeer are forced to choose other foods with lower radiocesium concentrations. Currently, the levels in reindeer meat are similar to those in the Ivalo area, which received only small amounts of Chernobyl fallout, levels of which have been declining since 1986 with an effective ecological half-life of six years. In contrast, in Kemin Sompio, which contains mainly pine and spruce forest with more lichen available for the reindeer herds, levels of cesium-137 in the reindeer meat still remain fairly high 15 years after the Chernobyl accident.



Post-Chernobyl time series for cesium-137 concentration in reindeer meat in three areas of Finland. Levels are higher during winter, when no green vegetation is available.

Focus on mushrooms

The previous AMAP assessment identified mushrooms as a potentially important source of radiocesium for consumers. Mushrooms are very important food items in Russia, whereas the Saami population does not traditionally eat large quantities of mushrooms. In late summer and fall, mushrooms are also important fodder for reindeer, moose, and sheep. Where there is high radiocesium deposition, the consumption of mushrooms by animals can be a significant indirect route of radiocesium intake by people.

Mushrooms may be very contaminated in areas with high fallout, but new data from a survey of several mushroom species in Finnish Lapland shows low cesium-137 concentrations. The highest levels were found in the non-edible *Cortinarius armillatus*. Of the edible species, the highest levels were found in *Rozites caperata*, *Lactarius trivialis*, and *Suillus variegatus*. Mushrooms are an important contributor to radiocesium body burdens if consumers do not boil the mushrooms prior to consumption.

Freshwater ecosystems

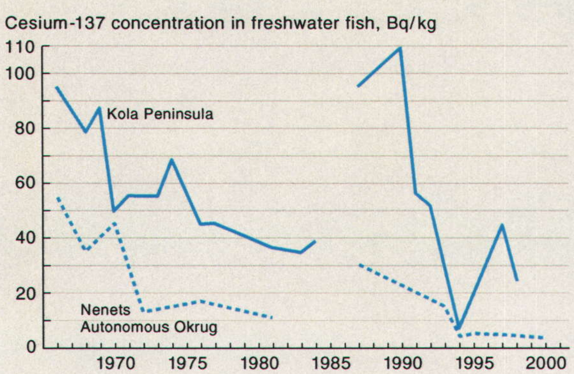
Transfers of radiocesium in Arctic freshwater ecosystems contribute to the enhanced vulnerability of the Arctic. The particular situation in a lake or river depends on how fast the water is replaced and on the characteristics of the surrounding soils. Shallow lakes with low water turnover would be more sensitive than deep lakes and rivers directly after a contamination event, simply because the contamination will not be as diluted. In the long run, the size and soil characteristics of a lake's catchment area become more important. Boggy catchments with a high content of organic matter in the soil, which is common in many Arctic areas, are efficient in transporting cesium. Snow and ice cover will affect the response of a lake, especially in the short run.

Focus on fish

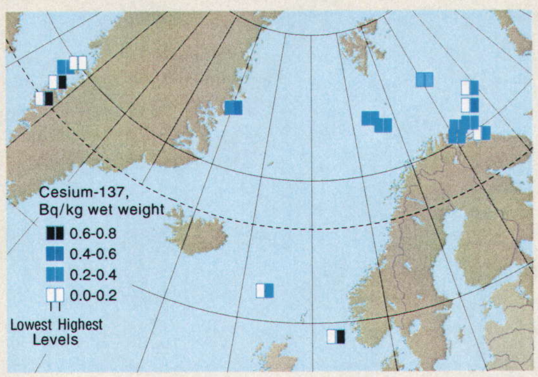
A number of fish species have been analyzed in four different lakes in northern Finland: Inarijärvi (Anárjárvi), a large regulated lake; Apukkajärvi, a small, highly eutrophic lake; and Äkäsjärvi and Jerisjärvi, which are small lakes. The feeding habits of the fish affect their cesium levels. Predatory species such as pike, perch, and burbot have the higher cesium concentrations in all the lakes compared to whitefish and vendace. The slight increase in radiocesium levels in predatory fish the first two years after the Chernobyl accident has disappeared, and levels are now lower than before the accident. Differences in the surface areas of the lakes did not seem to affect concentrations in the fish.

New data from freshwater fish in two parts of Russia show that fish caught on the Kola Peninsula, mainly in lakes, have higher levels than fish caught in the Nenets Autonomous Okrug, mainly in rivers. The explanation may be a combination of the Kola Peninsula being affected by Chernobyl fallout and the fact that levels in rivers are generally lower than those in lakes.

There are also some measurements for marine fish. The concentrations are low.



Dynamics of cesium-137 in freshwater fish from the Kola Peninsula and the Nenets Autonomous Okrug.



Cesium-137 concentration in marine fish 1995-2000.

MAGNUS ELANDER

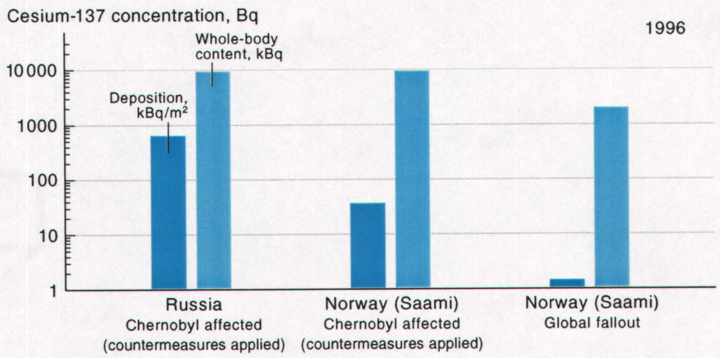
Feeding reindeer supplementary food is a way to bring down cesium levels in the meat before slaughter.

If fallout occurs in the winter, the radionuclides will not enter the water until they are released to runoff in the spring.

In fish, the concentration of cesium is affected by the amount of potassium in the water. There is a similar relationship between strontium and calcium. Lakes in natural or semi-natural areas often have low levels of nutrients such as potassium, making them more vulnerable than lakes in agricultural areas where fertilizer runoff raises the level of some nutrients. Another factor is the feeding habits of fish. Predatory fish can have levels more than a hundred times higher than those of non-predatory fish.

Radionuclides can transfer to foods long after deposition

In the Arctic, there are high transfers of radiocesium and long ecological half-lives in various food products. This means that radiocesium contamination previously deposited is still being transferred to food products. The extent of this transfer depends on the time since deposition and the type of ecosystem. In temperate areas with fertilized soils, radionuclide contamination of food products rapidly decreases in the first few months of the next growing season following deposition. In contrast, natural and semi-natural ecosystems in the Arctic often retain cesium-137 in food products for a long time. Therefore, in some Arctic areas, global fallout and Chernobyl fallout are still sources of food product contamination that need to be taken into account.



Whole body content of some populations groups of cesium-137 after Chernobyl, showing how countermeasures applied in Chernobyl affected areas effectively reduced exposure.

Implications for intervention

Actions in response to contamination can reduce exposures. Such actions include advice about what to eat, giving uncontaminated feed to semi-domesticated reindeer, and changing animal management practices. The countermeasures that were put in place in some areas after the Chernobyl accident drastically reduced the dose to people. Maintaining options to reduce human exposures depends on governments' putting effective countermeasures into place. It is more difficult to implement effective and long-lasting countermeasures in semi-natural and natural ecosystems, such as those prevailing in the Arctic.

◀ Post-Chernobyl diet-advice brochure from the Swedish National Food Administration.

Developing maps of vulnerable areas prior to an accident would provide a very useful tool in emergency response. In combination with estimates of deposition, such maps would make it possible to identify the areas where countermeasures are most needed.

Human exposure

The first AMAP assessment noted that the exposure of general populations in the Arctic to the primary radionuclides in fallout is about five times higher than in temperate areas. For smaller population groups within the Arctic, exposures could be more than 50 times higher than those of the average inhabitants.

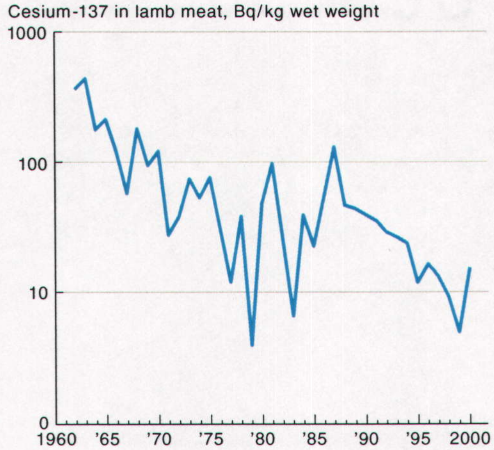
Many post-Chernobyl studies have demonstrated that the highest exposures do not necessarily occur in the most contaminated areas, especially in the mid- to long-term after the accident. The reason, as explained above, is variation in soils, vegetation types, and food webs. For people, food habits and the application of countermeasures to reduce exposure can have dramatic effects on dose. Examples of countermeasures include dietary advice and feeding uncontaminated food to reindeer to reduce radionuclide concentrations in the meat before slaughter.

The previous assessment identified several groups that receive higher doses than the average Arctic inhabitant. A common factor is that they rely heavily on terrestrial food products, such as reindeer or caribou meat. Mushrooms and freshwater fish are other important sources. The lowest anthropogenic doses were those in Greenland and Iceland, mainly because marine foods are more important in the diet.

The current assessment complements the previous picture with new data from the Faroe Islands and from an in-depth study of some communities in northwestern Russia.

The Faroe Islands

The previous AMAP assessment made dose assessments for populations in many parts of the Arctic. The Faroe Islands were not included, and therefore complementary information is provided in this report. The graph to the left depicts radiocesium concentration in lamb meat in the Faroe Islands over the period 1960-2000. There have also been several measurements in milk and drinking water. The dose to the average resident of the Faroe Islands has been estimated at 3.5 millisieverts. When compared with the doses to the average populations of other countries estimated earlier, this shows that the population of the Faroe Islands has received the second highest average dose in the Arctic. The highest doses (11.6 millisieverts) to the average residents were received by the inland population of Northern Canada.

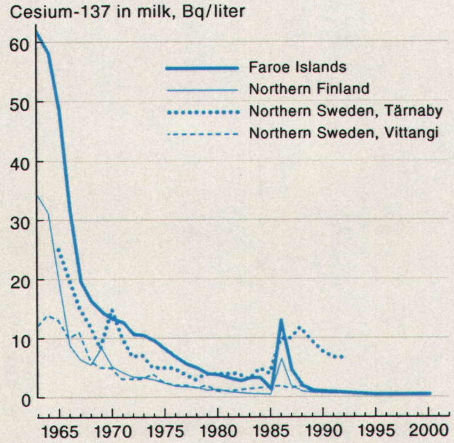


Cesium-137 levels in lamb meat in the Faroe Islands. Prior to the 1990s, samples were collected from different localities.

Focus on milk

Grazing animals in the terrestrial environment provide a major pathway of radionuclide exposures to people. It is therefore of interest to study the levels in such species. Since the previous AMAP assessment, new data have become available on cesium and strontium activity in cow's milk from Finland, the Faroe Islands, Iceland, Norway, Russia, and Sweden. All time series show a peak in the early 1960s varying from 15 becquerels per liter in Sweden to nearly 100 becquerels per liter in the Faroe Islands. After the Chernobyl accident, there was virtually no fallout detected in some parts of Sweden, whereas one Swedish location, northern Norway, and the Faroe Islands had peak values of up to 20 becquerels per liter.

The milk measurements have been used for calculating ecological half-lives. A general picture is that half-lives are short during the first year after fresh fallout and then become longer and longer, unless new fallout changes the contaminants load in the environment. For example, at a Finnish dairy in an area affected by Chernobyl fallout, the effective ecological half-life for cesium-137 was less than a year-and-a-half in the years immediately after the accident but almost ten years by the late 1990s. Another conclusion is that ecological half-lives vary geographically.



Cesium-137 concentration in cow's milk.

STAFFAN WIDSTRAND

Nenets nomads.

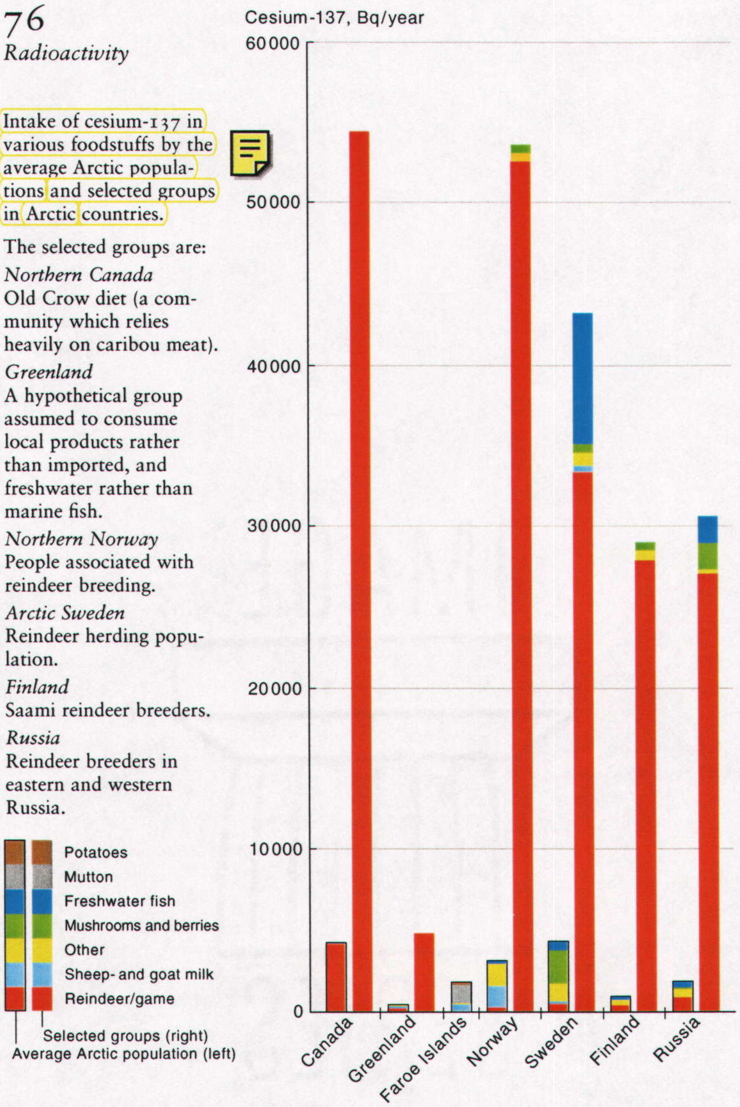
Northwest Russia

The new Russian data are for three different population groups living at the sites indicated on the map: indigenous people, mainly reindeer herders and their families; rural residents and inhabitants of small villages and settlements with a mixed diet; and the population of big ports and cities, whose inhabitants mainly consume food products from outside the region.

Dietary surveys showed that rural inhabitants consume, on average, two to four times less reindeer than the reindeer herders and their families. Their fish consumption is similar to that of reindeer herders. Urban inhabitants consume only small quantities of reindeer meat. The food products with the highest activity concentration are reindeer, mushrooms, and freshwater fish. The concentration of cesium-137 in these foods is two orders of magnitude higher than in locally produced agricultural food products. The activity concentrations in natural products were higher on the Kola Peninsula than in the Mezen districts and the Nenets Autonomous Okrug. The activity concentrations in agricultural products were similar in all three regions.

The dose estimates show that reindeer herders on the Kola Peninsula have an internal dose of 0.18 millisieverts per year on average. Reindeer consumption is by far the most im-

Study areas for human exposure assessment in Russia.



Intake of cesium-137 in various foodstuffs by the average Arctic populations and selected groups in Arctic countries.

The selected groups are:

Northern Canada
Old Crow diet (a community which relies heavily on caribou meat).

Greenland
A hypothetical group assumed to consume local products rather than imported, and freshwater rather than marine fish.

Northern Norway
People associated with reindeer breeding.

Arctic Sweden
Reindeer herding population.

Finland
Saami reindeer breeders.

Russia
Reindeer breeders in eastern and western Russia.

portant source of radiocesium. The rural group not associated with reindeer herding had an average internal dose of 0.07 millisieverts per year, or approximately one-third of that of the reindeer herders. Reindeer meat is the most important source of radiocesium in this group as well, but fish, mushrooms, and berries were also significant contributors. The doses for the urban group were a thousand times lower than for the herders, ranging from 15 to 25 microsieverts per year.

In summary, current doses to inhabitants in the Russian Arctic are much lower than during the 1960s when global fallout from atmospheric testing was being deposited. Individual doses on the Kola Peninsula are higher than in the other two study regions.

Summary

The major sources of radioactive contamination of the Arctic environment remains fallout from atmospheric nuclear weapons testing in the period 1945 to 1980, discharges from European spent nuclear fuel reprocessing plants, and fallout from the 1986 accident at the Chernobyl nuclear power plant in the Ukraine. Doses to humans are derived mainly from global fallout and fallout from the Chernobyl accident.

In general, levels of radionuclides in the Arctic environment continue to decline. The exceptions are seawater levels of the long-lived water-soluble fission products technetium-99 and iodine-129. These increases originate from nuclear fuel reprocessing in Western Europe. The current doses to the inhabitants of the Arctic from radionuclides originating from spent nuclear fuel reprocessing plants are small. The uncertainty surrounding the pathways to, and effects of these radionuclides in the Arctic show that further assessment is needed. Impacts on the Arctic should be considered when evaluating discharge reduction measures.

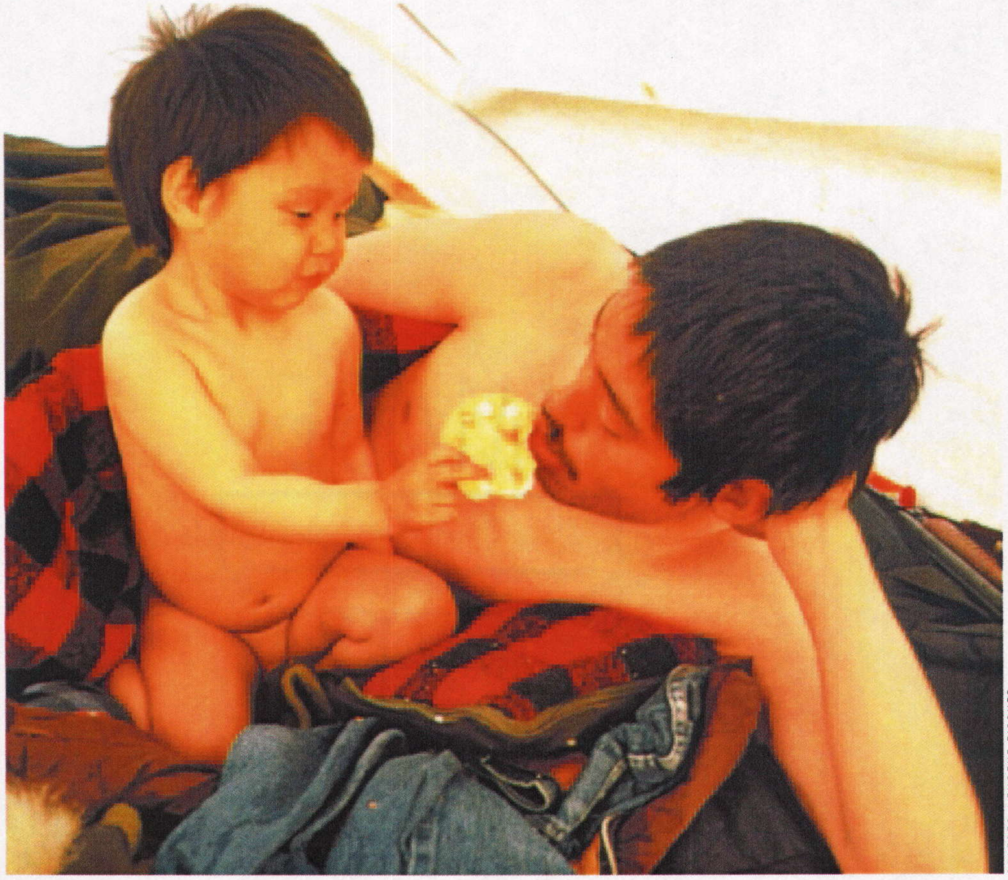
Radiation accidents are a major concern. The greatest threats posed by nuclear activities are associated with potential accidents in nuclear reactor operation and the decommissioning of nuclear-powered vessels. For example, models show that a major accident at the Kola nuclear power plant in Russia resulting in substantial releases of radioactive materials to the atmosphere would require countermeasures to avoid high radiation doses to the region's population. Major efforts are underway to reduce radiation risks connected with nuclear reactors and radioactive waste handling. However, further improvements in nuclear safety and radioactive waste management are still warranted.

Since the previous AMAP assessment, a nuclear submarine accident occurred in the Arctic, when the submarine *Kursk* of the Russian Northern Fleet was lost in the Barents Sea after an explosion on board. The *Kursk* has been recovered and monitoring shows that the accident did not result in any measurable releases of radionuclides to the Arctic environment.

To reduce the risk and to mitigate the consequences of possible future accidents, work is being done on risk management and risk analysis of nuclear activities and assessments of the vulnerability of Arctic areas. This gives a basis for improved emergency prevention, preparedness, and response for nuclear incidents.

For human health, there is increasing recognition that vulnerability and dose can vary a great deal, even over geographically limited areas. Because of high transfer and long ecological half-lives, vulnerability assessments need to take into account previous deposition.

Previously, the focus of radiation protection has been on the protection of human health. A new initiative in which AMAP has participated and that is highlighted in this report is an attempt to develop a basis for protecting the environment from the effects of radiation.



At the nomad camp

POLFOTO / EUGENE FISCHER

Human Health

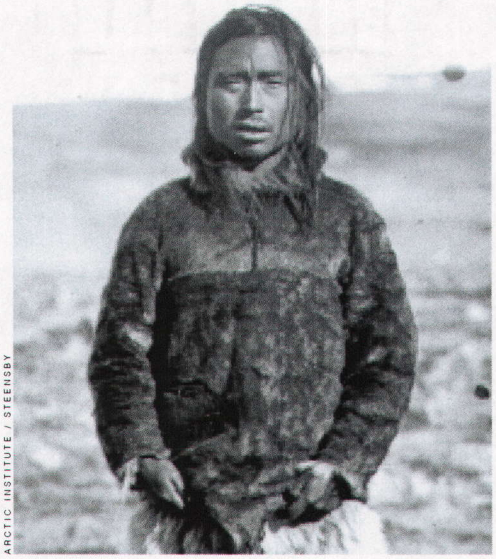
In some Arctic populations, contaminant levels are high enough that they can affect children's mental development. Contaminants may also be affecting children's resistance to infections. In addition, there are concerns about effects on hormones that are important for growth and sexual development. The major source of these contaminants is from eating marine mammals. These are the same foods that provide important nutrients, energy in a harsh climate, and also a sense of identity in a time of rapid cultural change.

This situation challenges the international community to prevent further input of persistent contaminants into the global environment. Of highest priority is the need to lower emissions of mercury and POPs. The situation also poses a challenge at the local level. How should public health officials and community leaders advise people about their eating habits? How should the cultural and health benefits of traditional foods be weighed against the health risks of the contaminants they contain?

This chapter examines human health and contaminants in the Arctic in the context of changing cultures, lifestyle, and food habits. The focus is on persistent organic pollutants and heavy metals. The effects of radioactivity on human health are discussed in the chapter *Radioactivity*.

At the youth club

PER FOLKVER / BAM


ARCTIC INSTITUTE / STEENSBY

Inuit boy, Greenland, 1909.

Health and culture

AMAP has a mandate to evaluate the combined effects of pollutants in the Arctic. But human health is much broader than just pollutants. From a public health perspective, the human environment is the sum of physical, chemical, biological, social, and cultural factors that affect people's well-being. Aside from data on levels and effects of pollutants, any evaluation of combined effects thus has to include information about nutritional status and socio-economic context, among other things.

Inuit boy, Greenland, 1994.

This knowledge is also directly relevant for understanding the effects of contaminants on human health. For example, lifestyle factors such as smoking and health indicators such as obesity may influence contaminant levels and effects. Moreover, changes in smoking, drinking, and dietary habits can make it difficult to single out contaminants as the cause of an observed change in health.

Finally, knowledge about the broader health perspective is important when the results of contaminants studies are used, for example by public health officials communicating with, or giving advice to, local communities.

A starting point in creating a context for contaminants and human health is to learn about Arctic cultures and how cultures and the lives of people are changing. The previous AMAP assessment gave a detailed presentation of different population groups in the Arctic. Among great diversity of culture, there are some common themes. For example, most indigenous communities still live close to their environment and use local resources for food.

Over the past 50 years, the population in most regions of the Arctic has increased dramatically. The main reasons are decreases in infant mortality and fewer people dying of infectious diseases. Safer water supplies, better sewage disposal, the development of rural hospitals, and community-based health care have helped prevent and improve the treatment of injuries and illness.

Better transportation infrastructure has also brought major changes. Imported foods are now readily available and accepted. Tobacco and alcohol reach the Arctic on a scale not previously possible. Modern communications have made western culture visible even in the most remote settlements, spurring further cultural change.

In most regions, government policies and modern lifestyles encourage indigenous peoples to reside in fixed locations instead of moving with the seasons. Survival often depends on a complex web of government-funded economic support combined with employment in various community service jobs. Cash incomes have become increasingly important, as the lifestyle has become more similar to western society.

Traditional activities such as hunting and gathering still play an important social role, tying people in a community together at a time when both culture and social networks are stressed by the influences of western culture. In some areas, and for some groups of people, traditional activities also play a role in the local economy.

A common theme across the Arctic is the extremely rapid pace of change. This has had a major impact on people's health, both positive and negative. A case history of life among Inuit in North America and Greenland gives a glimpse of the social and cultural changes among one group of Arctic people.

A case history of changes in Inuit culture and health

Naval visit by HMS *Bulldog* and USS *Nautilus* at Nuuk, Greenland, 1860. Painted by Aron from Kangeq. Reproduced by permission from Her Majesty the Queen's Reference Library, Amalienborg, Copenhagen.

The Inuit of Alaska, Canada, and Greenland are descended from people who migrated from northeastern Asia across the Bering land bridge between 4500 and 20 000 years ago. The first contact between Inuit and Europeans was at the end of the 10th century. By the late 15th century, European whalers had started hunting in the Baffin Bay area and, a century later, several European countries started to explore and colonize parts of the Arctic. The central Canadian Arctic and Northern Greenland, however, remained isolated until the early 20th century. Contact and colonization was accompanied by cultural change. Christianity replaced traditional beliefs, and the Inuit adopted some of the tools brought by the Europeans, even if traditional hunting methods were used until the early part of the 20th century in most regions.

The colonizers also brought new infectious diseases to the Arctic, with devastating consequences. Only a few years after colonization, there was an epidemic of smallpox in Greenland. In 1800, another epidemic wiped out whole districts. During the following centuries, respiratory infections, influenza, smallpox, and typhoid fever killed a substantial part of Greenland's population.

The new diseases hit Alaska particularly hard. Russian and European explorers introduced syphilis, which became epidemic in the Aleutians and southeastern Alaska during the 18th and 19th centuries. In 1900, an influenza epidemic, 'The Great Sickness', killed thousands of people and destroyed entire villages. By the late 18th century, tuberculosis was well established. It remained common for 150 years, with very high death rates.

These and other infectious diseases remained a serious threat to people's health until the 1950s, even if the first extremely disruptive years after colonization were followed by periods of relative tranquility. Aside from a number of disease epidemics, starvation and chronic malnutrition were common.

The changes brought by the colonizers had a large impact on population numbers. In the 16th-18th centuries, the population of North American and Greenland Inuit was probably around 75 000. By 1900, it had declined to 35 000. During the 20th century, the population slowly recovered as mortality decreased and fertility increased. By 1970, the Inuit population had reached its pre-contact level again.

From isolated self reliance to integration

The colonization of the Arctic had a profound impact on the way of life in Inuit communities. Before contact, they were relatively isolated, self-reliant societies based on fishing and hunting. In the past 50 years, many Inuit communities have become partially integrated into the economy of their respective national states, and the world. Village economies have become based more and more on wage earning, even if

ANNIE GIÆVER

STAFFAN WIDSTRAND

Saami life, 1930 and 1997.

RCTIC INSTITUTE / JETTE BANG

PER FOLKVER

Carving up a seal, 1939 and 1994.

unemployment is still common. Infrastructure and housing have changed, often with local people merely watching as outside workers do the construction. Travel, radio, television, and, lately, the internet have increased contact with the rest of the world. The population has grown and many people have moved to larger communities. In the process of modernization, non-Inuit people have moved into the communities, where they often hold well-paid jobs and influential positions.

Modernization has also affected aspects of people's lifestyles that are closely connected to health. On the positive side, fewer people are killed in accidents. Traditional Inuit life was extremely perilous. Many hunters died young, leaving their wives and children behind in poor social conditions. Another positive development is that most people now have better access to health care. Housing conditions, sanitation, and food security have also improved, which has led to decreased transmission of infectious diseases. Seasonal starvation has disappeared, improving overall resistance to infections.

On the downside, the transition to more store-bought food has brought changes in eating habits, which in combination with a more sedentary lifestyle have increased the risk of obesity. This in turn has led to an increased risk of diabetes. Together with smoking habits, obesity is also connected to cardiovascular diseases. There is some evidence that Inuit have a genetic predisposition – an inherited sensitivity – to arteriosclerosis (clogged blood vessels), but that their traditional diet of marine mammals and fish offers protection against this and related heart diseases.

Travel and migration have brought new infectious diseases, including HIV. Tuberculosis is again on the rise after having been a seldom-seen disease.

Increased access to alcohol and tobacco is closely connected to ill health. Smoking is a risk factor for many cancers and also for cardiovascular diseases and chronic lung disease, which are important health problems among modern Inuit. Many communities have prohibited alcohol, but in others alcohol is responsible for the majority of health problems. It is a factor in many accidents with all-terrain vehicles and snowmobiles. It is also the largest contributor to a high prevalence of violence and suicide among Inuit. Since the 1970s, suicide has become a major cause of death, especially among young men in Greenland.

The influx of non-Inuit, rapid growth in population, and the increasing concentration of people in larger settlements have profoundly altered the social structure of Inuit communities. Together with other socio-cultural changes, stress and psychological problems have become more common.

In summary, social changes have increased physical survival in all age groups among the Inuit. However, this increase has probably come at the expense of mental and social health. The disease pattern in the future will depend on whether current lifestyle trends can be turned in a more healthy direction.

Statistics reflect health status

Many of the themes in Inuit history appear throughout the Arctic, but there are also differences. Some of these similarities and differences are reflected in population and health statistics. The statistics also gives a basis for comparing the health status of groups of people and for monitoring changes over time.

The recent regrowth of the population in parts of the Arctic is reflected in a high proportion of young people compared with the average European population. This is particularly true for Alaska, Canada, Greenland, and the Saami regions.

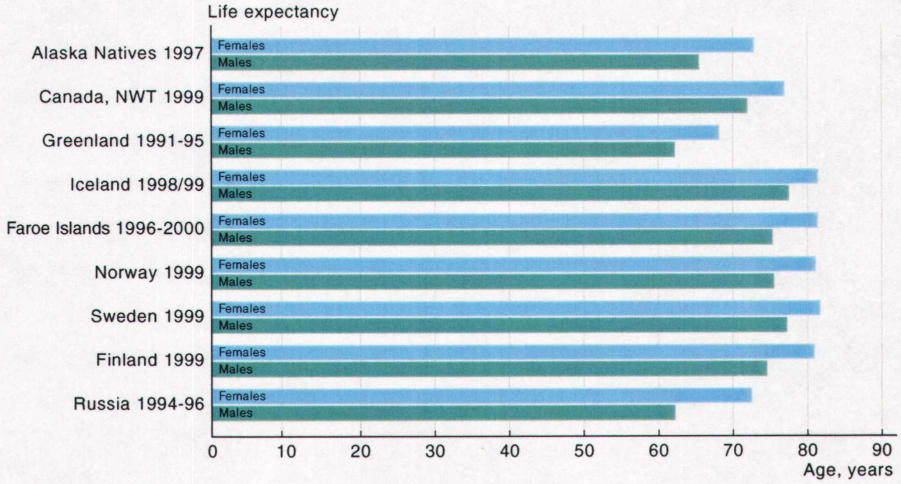
In most parts of the Arctic, life expectancy has improved. However, in many areas it is still low compared with respective national rates. For example, in Russia, life expectancy among indigenous peoples is 10-20 years lower than the Russian average.

In most countries, the largest single contributor to an improvement in life expectancy is that fewer children die soon after birth. Other factors include an overall improvement in health status as a result of safer drinking water, control of infectious disease, and access to health care. Infant mortality has decreased in recent decades, but in Greenland, Canada, and Alaska, it is still more common than the respective national rates. Infant mortality is also very high among Russian indigenous groups.

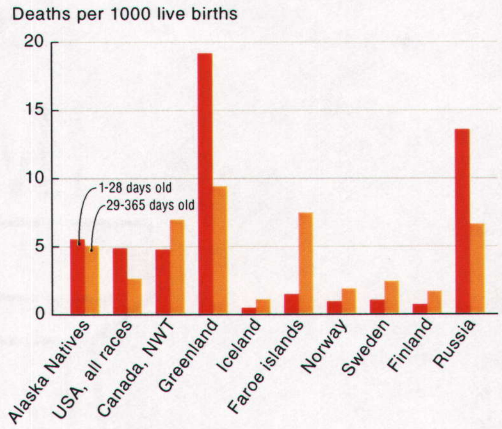
Throughout the Arctic, injuries, for example in accidents, and suicide are the most common causes of death in adults under 45. Suicide is a major problem, especially among men. Wide variations exist and may reflect differences in cultural stress, economy, or rates of depressive illness. Injuries and infections are the most common causes of ill health.

For people over 45, heart disease, strokes, and cancer are the most common causes of both disease and death, with some regional variation. These lifestyle-related diseases reflect a new trend with connections to a more sedentary lifestyle and to smoking. Obesity and diabetes have increased from very low levels and are now as common in the Arctic as they are in most developed western countries. In Russia, injuries, infectious disease, especially tuberculosis, cardiovascular disease, parasites and respiratory disease are common. Many health problems are related to alcoholism.

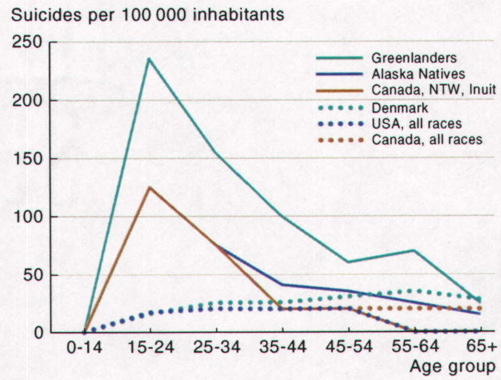
Infections kill far fewer people than in earlier times. However, respiratory infections in infants are still much more common than among other population groups. For adults, some sexually transmitted diseases are more common. Among Canadian and Greenland Inuit, the rates of gonorrhea and chlamydia are 10 to 100 times higher than in southern Canada and Denmark.



▲ Life expectancy in the 1990s.

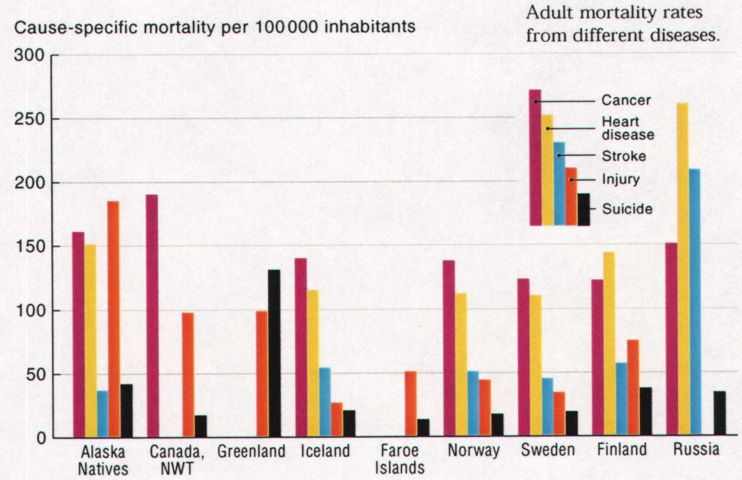


◄ Infant mortality rate in the mid 1990s.



◄ Suicide mortality rates in different age groups during the 1980s.

▼ Adult mortality rates from different diseases.



Food and other lifestyle factors

The way we live – our lifestyle – can have a great impact on health. It includes the everyday activities of work and leisure, our relationships to the people around us, and our food habits. The different components of a life style are often difficult to separate from one another. For example, eating together and sharing food provide not only nutrients and energy, but also play a role in affirming social and cultural ties. Our everyday activities of work and leisure influence whether we eat country foods, such as game and wild plants, or groceries bought with money earned in employment.

Among Arctic indigenous people, country foods still play an important role in nutrition and well-being. For many people, these traditional foods are also a source of community spirit, pride, and self-respect, and are a way to educate children about a culture. In Greenland the word used for traditional Inuit food – *Kalaalimernit* – literally means little pieces of Greenlanders, as opposed to the word for imported food – *Qallunaamernit* – which means little pieces of Danes. The traditional Inuit foods are thus considered the necessary building blocks of Inuit. They can provide health, bodily warmth to withstand the cold climate, strength, and well-being in a way that imported foods simply cannot.

The role of traditional foods has also received increasing attention because food is the major source of contaminants for people in the Arctic. Knowing dietary habits is therefore important in estimating exposure.

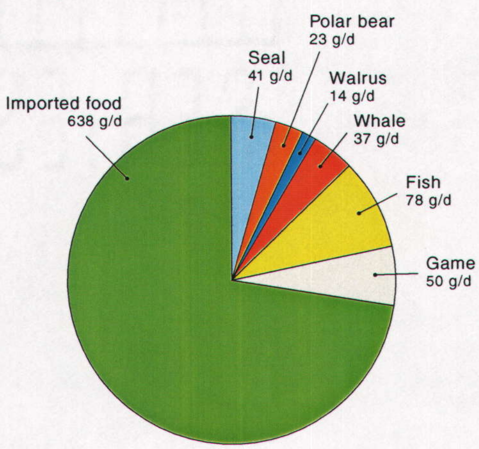
The use of tobacco, alcohol, and drugs are other major aspects of lifestyle that have direct implications for health. Smoking is also a source of contaminants.

Food habits are changing in Greenland and Canada

In spite of the many benefits of traditional foods, eating habits have changed over the past 50 years. This is illustrated by the fact that people get a larger share of their energy requirements from store-bought food than in the past. In North America and Greenland, indigenous peoples get between 60 and 90% of their food from the store.

The changing times can also be illustrated by differences between young and old people. Interviews with three generations of adult women in Nulax, British Columbia (outside the Arctic), showed that there had been a steady decline in the use of traditional foods because of restrictions associated with fish and game laws, better availability of market food, and increasing employment that left less time for traditional harvesting. In Baker Lake, Northwest Territories, where caribou is a key component of the traditional diet, consumption decreased from over 250 grams per day in the late 1960s to less than 70 grams by 1989.

Among Baffin Inuit, teenagers eat less than half the traditional foods that middle-age people consume. Among Greenland Inuit, people older than 60 ate more than 40 meals a month of seal, whale, wild fowl, or local fish, whereas 18-24 year-olds had half as many traditional meals. In general, men eat traditional food more often than women.



Estimated daily intake of traditional and imported foods in East Greenland in 2001.

Country foods are still important in Russia

In Russia, the trend toward more market food is not as clear. More market foods are transported to rural settlements, but high prices in combination with low incomes and strong traditions still make people rely heavily on country foods. For example, the indigenous people of the Taymir Peninsula still eat 400 grams of reindeer meat per day. A recent dietary survey of pregnant women from northern Siberia showed that indigenous mothers ate 320 grams of reindeer per day, which is ten times higher than non-indigenous mothers in nearby towns. The indigenous women also ate twice as much fish and three to five times as much game.

PAVEL ABRYUTIN

Coagulated blood is a traditional Chukchi food.

Scandinavia, Iceland, and the Faroe Islands have western diets with local influences

In Scandinavia, Iceland, and the Faroe Islands, the diet is typically western, but with an emphasis on local resources. For example, fish is often on the dinner table in Iceland and in the coastal areas of northern Norway. In the Faroe Islands, meat and blubber from pilot whales are still important foods and many people eat them several times a month. For women of childbearing age, there have been food advisories based on the heavy load of contaminants in the whales, and recent research following pregnant women indicates that they have drastically decreased their consumption. In northern Scandinavia, local products such as reindeer meat, lamb in some areas, fish, berries, and mushrooms are more common foods than in the rest of Scandinavia. A recent dietary survey of Norwegian Saami showed that their diet was changing toward a more typical Norwegian diet.

Changes affect health

The gathering and hunting as well as the preparation of traditional foods are activities that require a lot of energy, particularly as they often involve hard physical exercise in low temperatures. An early dietary survey, from 1926, showed that a traditional Inuit hunter in East Greenland could have an energy intake one and a half times that which is normal today. The energy came almost exclusively from meat and fat from marine mammals. As wage earning and the market economy have gradually replaced the local economy, these physical activities have been replaced by the much less energy-demanding tasks of picking up and preparing food from the supermarket. If energy

intakes are not reduced accordingly, people are likely to get fat and increase the risk for diseases that are associated with being overweight. In some cultures, such as the Dene/Métis in Canada, the problem is compounded by store-bought food having higher energy content than traditional food. The traditional foods are often high in protein and fats and low in carbohydrates, whereas the imported foods often have high fat and sugar content but may have low nutritional value.

Market foods lack important nutrients

Dietary changes can also lead to specific nutritional deficiencies. For example, local fish products are usually not replaced by the equivalent products from the store but by cheaper alternatives that do not provide the same amounts of calcium, vitamin D, and iodine. In Nuuk, the capital of Greenland, the average iodine intake is only half of the recommended value. In Greenland villages, where people eat more country foods, iodine intake is sufficient. Another example is that fish skin and bones are important sources of calcium for many Inuit. Fish fillets from the store lack this needed nutrient. Calcium is especially important in the context of contamination, since deficiencies may increase the body's uptake of heavy metals. Traditional Inuit foods, especially muktuk (whale skin and blubber), meat, and liver from whales, seals, and seabirds, are also rich in selenium. This trace nutrient is thought to play a role in protecting against some of the damage from mercury.

Marine fatty acids protect against heart disease

One of the most important benefits of a marine diet is the high content of certain fatty acids that can protect against reduced flow of blood to the heart muscle and related heart diseases. These are the n-3-fatty acids, which are produced by plankton in the sea and passed along to fish and marine mammals in the marine food web. They are also present in high proportions in the fat of game animals such as hare, deer, caribou, and muskox that graze on plants in the wild. The fat from farm animals derives from feed that contains fatty acids that are less healthy.

Lower intake of the healthy fatty acids and a higher proportion of other fats may also play a role in increasing the risk for diabetes. This disease has been relatively rare among Inuit, but has become more common in the past 30 years.

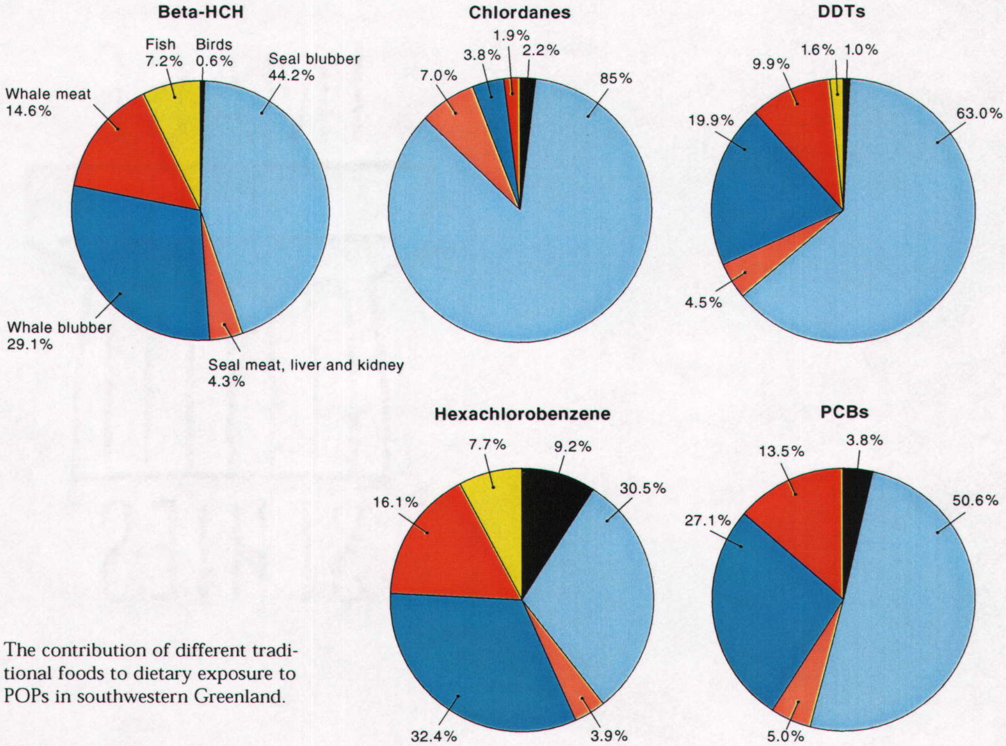
The high intake of marine fatty acids may contribute to strokes caused by bleeding in the brain, a cause of death that is relatively common among some Inuit groups. However, the benefits from protection against heart disease probably outweigh this increased risk.

The composition of lipids in the blood depends not only on what a person eats, but also on inherited abilities to convert lipids from one form to another. There are differences among population groups in this inherited ability. Inuit as a group seem to be less able to create some very important fatty acids from other fatty acids in the diet. This makes it extra important to get these nutrients via animal foods, emphasizing the health value of the traditional diet.

The n-3 fatty acids are also important in brain development in the growing fetus and for the proper development of vision.

Food is a source of contaminants

It is well known that many contaminants accumulate in the animals that Arctic people eat. Persistent organic pollutants accumulate especially in fatty tissues, such as the blubber of marine mammals. Birds can also have high levels, especially in the liver. Heavy metals, such as cadmium and mercury, accumulate in muscle, kidney, and liver of both marine and terrestrial animals.

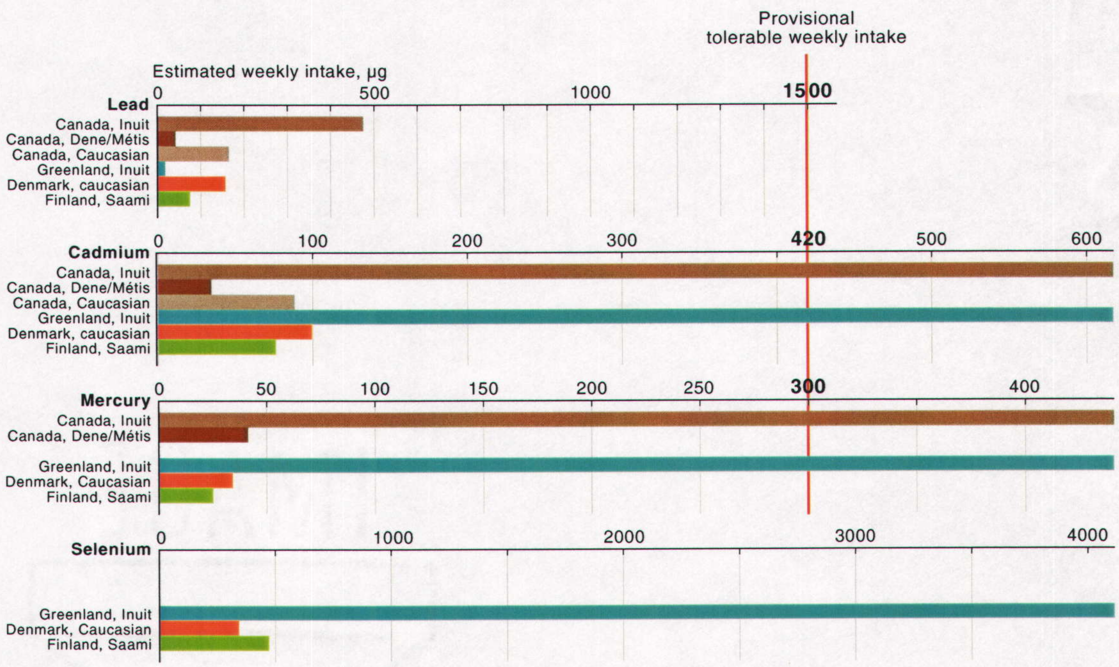


The contribution of different traditional foods to dietary exposure to POPs in southwestern Greenland.

Knowing dietary habits and the contaminant levels in various foods, it is possible to estimate exposure. The picture will differ both among individuals and among population groups depending on what people eat.

Most Canadian Dene/Métis fall well below the Canadian guidelines for exposure to persistent organic pollutants. However, for toxaphene and chlordanes, average intakes are much closer to guideline values, which some individuals exceed.

The picture for Inuit of Baffin Island and Greenland raises more concern. For Baffin Inuit, mean intake of chlordanes and toxaphene in the late 1980s exceeded Canadian dietary guidelines. Recent studies, from 1998-99, show that Baffin Inuit mean intakes continue to exceed the dietary guidelines for chlordanes and toxaphene, to say nothing of the most highly exposed individuals. Preliminary results from dietary studies in West Greenland show that the traditional diet leads to an intake of chlordanes and PCBs that exceeds the tolerable daily intake. It is thus clear that a substantial number of Inuit have higher exposures than are considered acceptable.



Estimated weekly intakes of lead, cadmium, and mercury as they relate to WHO public health guidelines for provisional tolerable weekly intake. Selenium may protect against mercury toxicity.

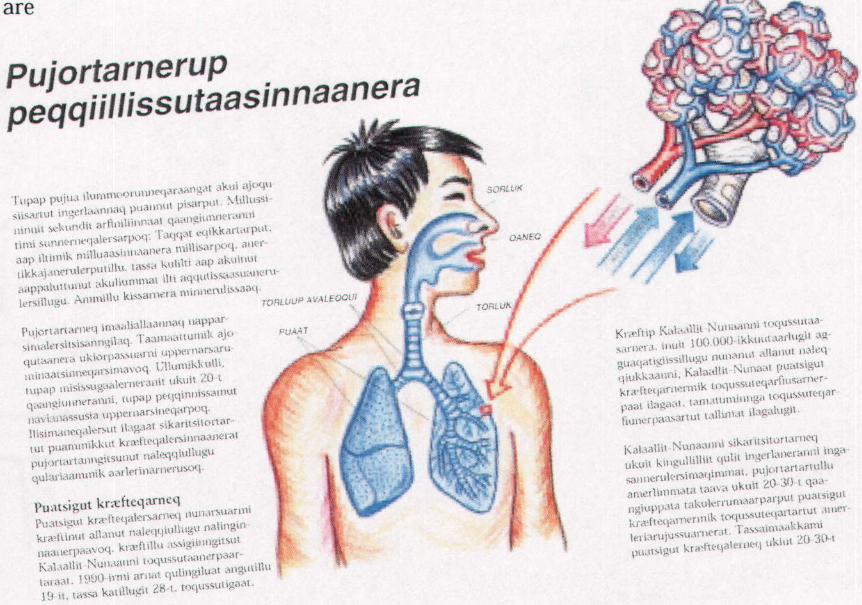
Similar calculations have been made for heavy metals (see diagram at bottom of this spread). Some populations with a high intake of meat from marine mammals exceed dietary guidelines for mercury and cadmium. The levels of metals vary tremendously between animals and among the various organs in an animal. Moreover, some forms of the metals are more easily taken up than others.
In general, the liver and kidney of large marine and terrestrial animals and the liver of fish have the highest metals concentrations. Caribou and moose liver can contain high concentrations of lead, cadmium, and mercury. Because the mercury in these organs is not readily taken up by the body, however, the most important sources of mercury are meat from seals and toothed whales. For some population groups, freshwater fish, especially predatory species such as northern pike, can be an important dietary source of mercury.

Seabirds and bird liver are important sources of lead. The use of lead shot in hunting adds to the lead burden in human food. One boiled murre served as soup can yield as much as 50 micrograms of lead, which is about a quarter of the provisional daily intake proposed by WHO. A Russian study of metal levels showed that children in some remote areas of the Kola Peninsula had high enough lead levels to cause concern for their health. The lead most probably comes from lead shot.

Smoking is extremely common

Tobacco smoke contains a number of substances that are well known to affect people's health. They include more than 50 cancer-causing substances. Smoking is also known to cause lower birth weight. Tobacco smoke is a major source of cadmium, a contaminant that has been linked to kidney dysfunction, brittle bones, and reduced fertility.

The nicotine in cigarette smoke is broken down by the same enzymes in the body that take care of organochlorine contaminants. There are studies showing that the levels of these contaminants are higher in the blood of smokers than in blood of non-smokers among Arctic population groups.

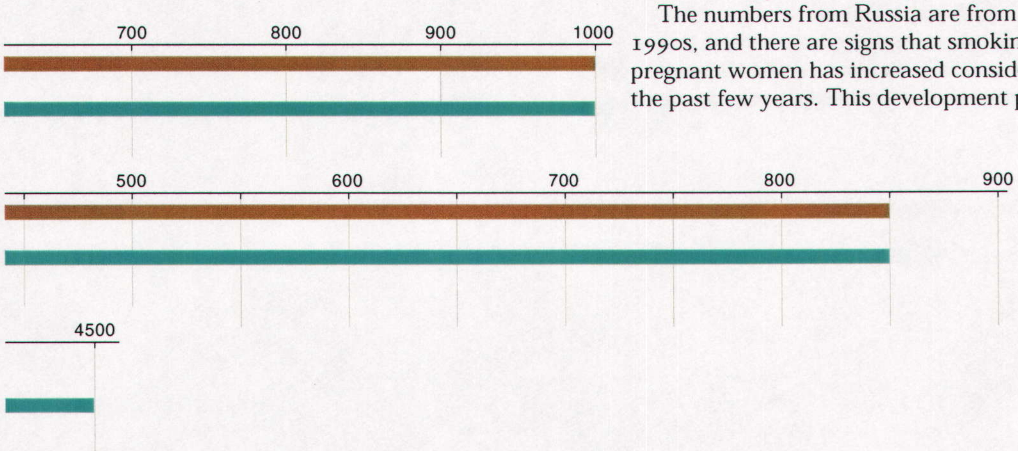


Advice against smoking, Greenland.

In many Arctic populations, smoking is very common and is one factor behind the increasing prevalence of heart diseases, chronic lung disease, and many cancers. Lung cancer, which is closely related to smoking, is at least as common among indigenous people in the Arctic as among other groups of people.

High levels of smoking among pregnant women are a particular concern as smoking is a well-known risk factor for the health of the child. In a survey in Greenland, about 60% of the pregnant women answered that they smoked daily. The numbers are somewhat lower in Russia, Norway, and Finland but still high. In northern Russia and Norway, approximately one in five pregnant mothers smoked daily. In Finland, 12% of the women giving birth said they smoked daily.

The numbers from Russia are from the mid-1990s, and there are signs that smoking among pregnant women has increased considerably in the past few years. This development parallels



ARCTIC INSTITUTE / HELGE BANGSTED   TORBEN LARSEN   STAFFAN WIDSTRAND   TORBEN LARSEN   PER FOLKVER / BAM   TORBEN LARSEN

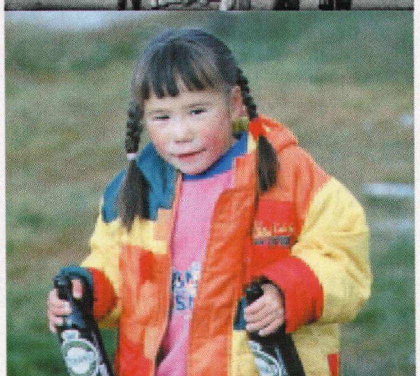
Smokers 1922-2002.

the increase in western contacts and western-style advertising. Women with university-level education and high socio-economic status smoked the most, indicating that smoking has become associated with high status. This is in contrast with the situation in Western Europe, where women who smoke often have only lower education.

Alcohol causes problems in many communities

Trying to estimate alcohol and drug consumption or illegal drug use is notoriously difficult. However, there is no doubt that alcohol and drugs have caused health and social problems in many Arctic communities. Surveys of Greenland residents have shown that 39% of the men and 12% of the women meet the criteria for binge drinking or high alcohol consumption. Among Inuit in Arctic Canada, between 13 and 29% have problems with alcohol. In a survey among Alaska Natives, 29% of the men and 21% of the women report binge drinking. This can be compared with a national US rate of 14%. In the Russian Arctic, alcohol use has increased since Perestroika. It is especially a problem among men.

Young Inuit girls in a *Tuborg* beer marketing campaign at Qaqortoq, Greenland, 1906.



Inuit girl collecting empty beer bottles for recycling, 1996.

One study has looked at the effects of alcohol in terms of deaths from disease and accidents. The picture varied considerably among regions. The risk of vehicle accidents was much higher in Canada than in the Nordic countries and higher still in Alaska and Russia. Alaska, Russia, and Finland had the highest mortality from homicide. Most problems were more serious in northern areas than farther south. Greenland, the Faroe Islands, and Iceland were not part of the study.

Alcohol abuse poses a special problem in connection with pregnancy as alcohol can affect the growing fetus. The result can be lower birth weight and brain dysfunction. In severe cases, growth is impaired and the child develops characteristic facial features. These severe effects are called fetal alcohol syndrome. From 1988 to 1994, the Alaska Native health care system documented fetal alcohol syndrome at a rate of 4.2 per thousand live births, a much higher rate than in the US population (0.3-1 per 1000). It is quite possible that fetal alcohol syndrome is common in other Arctic populations, but there is no documentation. In Scandinavia and Russia, alcohol abuse during pregnancy is fortunately scarce in most indigenous cultures. An ongoing project by AMAP's Human Health group will add new knowledge on this issue.

Cocaine and marijuana represent large problems in many Alaskan and Canadian Arctic communities. Their use has a seasonal variation and there may be links to seasonal depression, which is common in countries with very short winter days. Injection drugs seem to be as common in northern areas as they are farther south.

Environmental contaminants and their effects

A large number of environmental contaminants can potentially affect people in the Arctic. Most of them can be included in the broad categories of persistent organic pollutants, heavy metals, and radionuclides. Descriptions about the sources, pathways, and general biological effects of these substances are given in the previous chapters. This chapter focuses on how persistent organic pollutants and heavy metals may influence the health of people living in the Arctic. The emphasis is on sensitive targets, such as the brain, hormones important for sexual development, and the body's defense against infections. The effects are likely to be subtle and it is difficult to establish a cause–effect relationship with contaminants. Nevertheless, new results since the previous AMAP assessment show that the mercury levels present in some Arctic populations can cause subtle effects on fetal brain development. The growing brain of a fetus is also sensitive to PCBs. PCBs are also implicated in effects on young children's defense against infections.

The growing brain is very vulnerable to mercury

Many toxic chemicals can affect the nervous system. Especially sensitive is the growing brain of a fetus. Mercury is one of the pollutants that raises concern. The risks are con-

nected with a chemical form of mercury called methylmercury, which accumulates in marine and aquatic food webs.

The effects of methylmercury first became apparent in children whose mothers had eaten foods that were contaminated with very high levels of methylmercury. Recently it has become clear that much lower exposure to methylmercury may also have effects, though they are much more subtle. The new knowledge comes from three epidemiological studies, one in the Faroe Islands, one in the Seychelles, and one in New Zealand. In none of the studies did the children have any apparent signs of mercury poisoning. The average hair mercury concentrations in these studies varied between 4.3 and 8.8 micrograms per gram, with a significant number of infants having levels above 10 micrograms per gram.

In the Faroe Islands study, the children's performance in neurobehavioral tests showed that mercury levels had an effect on fine motor function, attention, language, visual-spatial abilities, and verbal memory. The New Zealand study also found some adverse effects from mercury exposure, whereas no correlation between mercury exposure and neurobehavioral effects was found in the Seychelles study. Interpreting these somewhat conflicting results has been a major challenge, but it appears that mercury levels that are currently considered 'safe' can affect the brain development of a child in its mother's womb. The individual may never be aware of any effects as there are no apparent symptoms, but even small changes in brain development can have implications for daily life. In the Faroe Island study, it was calculated that a doubling in prenatal exposure to mercury corresponded to a delay in child development of 1-2 months during the first seven years of life. It is not known how significant such a delay will be when the child grows up.

Several Arctic populations exceed mercury guidelines

AMAP's circumpolar survey of contaminants in maternal blood shows that the mercury levels in the Faroe Islands are not unique in the Arctic, and that some other groups are exposed to similarly high or higher levels.

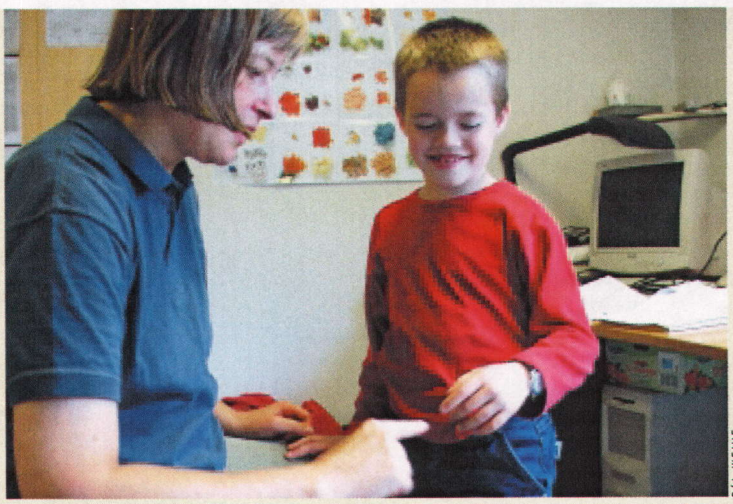
There is no international agreement on a new 'safe' level, or reference dose for mercury, below which there are no known effects and which can thus be used to justify public health actions. One point of departure has been 12 micrograms per gram in the mother's hair, which is in the same range as WHO's recommendation of 10-20 micrograms per gram. The US Environmental Protection Agency applies a safety factor of ten, which results in a reference

Measuring neurobehavioral effects

Measuring subtle changes in neurobehavioral development is a challenge. There is a battery of different tests looking at coordination, reaction time, and memory. The pictures show two of the tests that were used to study Faroese children in an epidemiological study looking for effects of mercury. Test scores were compared with the mercury exposure the children had while they were still in their mother's womb.

In the upper picture, the doctor examines the fine motor skills and coordination abilities of a Faroese boy by asking him to move his arm forward so that his fingertips will touch hers. He will next have to do the same task with closed eyes, to see how well he remembers the movement he did before.

The lower picture shows what is called the evoked potentials examination. The girl is watching a screen with a changing chessboard pattern. This will create well-defined nerve impulses to the visual cortex in the brain. The electrodes on her head measure how fast these impulses travel, and an amplified signal shows up on the measuring device. Mercury is known to have an effect on this signal.



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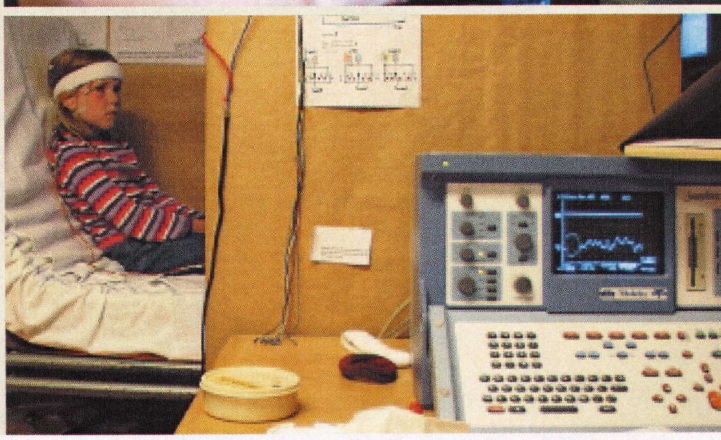

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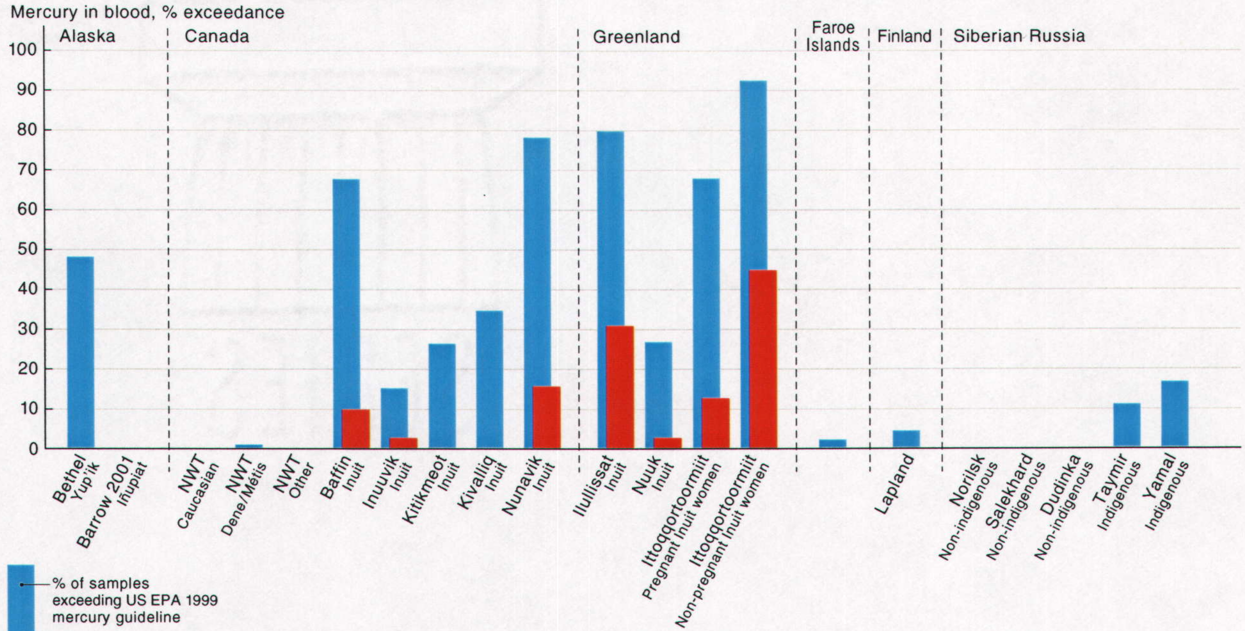
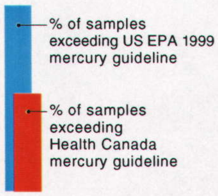




Mercury levels in blood of women of reproductive age as they relate to US EPA and Canadian guidelines for increasing risk range.

dose of 1.2 micrograms per gram in maternal hair. This is equivalent to a cord blood concentration of 5.8 micrograms per liter. Health Canada has guidelines that a maternal blood level between 20 and 100 micrograms of mercury per liter indicates increasing health risks, and that levels above 100 micrograms per liter constitute a health risk.

A large proportion of Greenlandic women exceed the stricter US EPA guideline, and many women also exceed the Canadian guideline of 20 micrograms per liter. Among Canadian Inuit, a few women exceed the Canadian guideline whereas about a third exceeded the stricter US EPA levels. Among the Yup'ik in western Alaska, almost half of the mothers exceeded the stricter US EPA levels.

In Siberia, none of the mercury levels exceeded the 20 microgram per liter guidelines, but in two regions (Taymir and Yamal) some women exceeded the stricter limit.

In summary, high mercury levels appear to pose a threat to children's development in some Arctic populations.

Mercury mechanism stresses protective role of marine foods

The mechanisms behind the effects of methylmercury on the central nervous system are not well understood. One possible explanation could be that mercury increases the production of reactive oxygen in the body. This oxygen has a chemical form that is different from the oxygen in air It is produced in several natural processes in the body. While there are natural defenses against this aggressive form of oxygen, mercury might diminish some of these defense mechanisms. Other factors might enhance the defenses. They include beneficial nutrients such as selenium, which together with marine fatty acids is known to decrease oxidative stress. Traditional marine diets are thus both the source of harmful methylmercury and of beneficial nutrients.

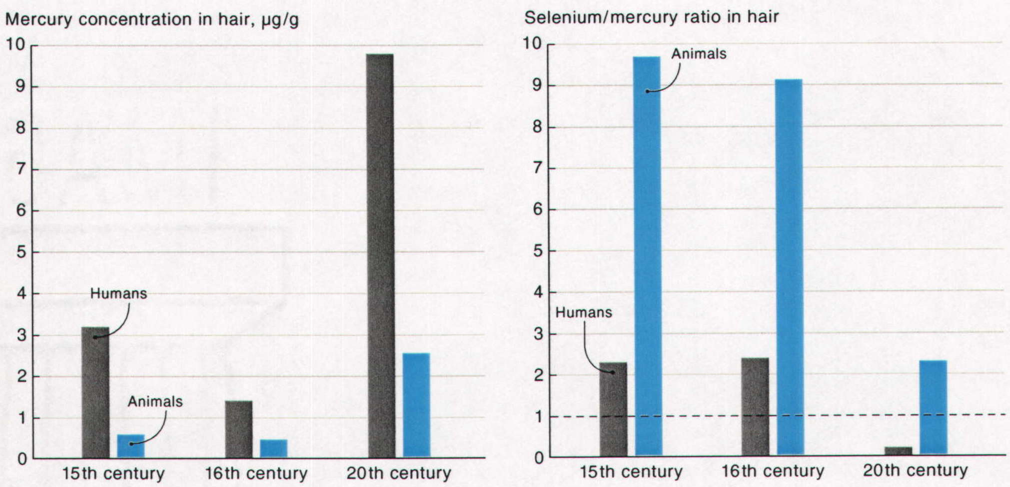
Mercury can be measured in hair from people or animals, and preserved hair samples have been used to determine a time trend for this contaminant. The human hair samples show

►► Selenium/mercury ratio in hair of humans and animals from Greenland.

► Mercury concentrations in hair of humans and animals from Greenland.

▼ Mummies from 15th and 16th century graves in Greenland have provided hair which can be analyzed for mercury to show historical levels of this metal in people and their diet.

HN LEE / GREENLAND NATIONAL MUSEUM



that mercury levels in Inuit are three-fold higher in the 20th century compared with the 15th and 16th centuries. In animal hair from seal and reindeer, similar increases are seen. At the same time, selenium levels in human hair have decreased because of changing eating habits. In animal hair, there is no similar decrease in selenium. Selenium may counteract the toxic effects of mercury. However, the lower levels of selenium may not be adequate to prevent the effects of the higher levels of mercury. Thus, there may now be an impact on human health that was not as likely in the past.

Some POPs can also affect brain development

Some organic pollutants can also affect the development of children's brains. Most knowledge about low exposure through the food web comes from studies outside the Arctic. The focus has been on PCBs. The effects that have been linked to PCB exposure in the womb include lower birth weight, slower growth, poorer visual recognition memory, deficiences in psychomotor development, and poorer intellectual functioning. Some of these effects appear to be irreversible. Although much larger quantities of PCBs are transferred to nursing infants by breast feeding than across the placenta in the womb, virtually all the neurobehavioral effects have been linked specifically to exposure before birth. This indicates that the embryo and fetus are particularly vulnerable to these substances.

PCBs were measured in the same Faroese study that looked at the effects of mercury. In this case, however, it has been difficult to specifically pinpoint PCBs as the cause of the effects on behavior. There were some indications that both contaminants had the same effect on the nervous system, potentially making the effect worse when both mercury and PCBs are present.

The levels of exposure in the epidemiological studies looking specifically at PCBs are lower than for the most highly exposed Arctic populations. Comparing the results from the circumpolar study of contaminant levels in maternal blood with public health guidelines again provides a disturbing picture, especially for Inuit who rely heavily on marine mammals in their diet as well as for some non-indigenous groups.

Health Canada's maternal blood guideline for PCBs sets the level of concern at 5 micrograms per liter and the action level at concentrations above 100 micrograms per liter.

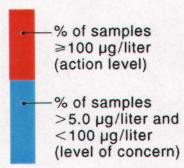
In the Canadian Arctic, the proportion of the samples from Inuit women from Northwest Territories and Nunavut that exceeded the level of concern ranges from 16 to 73%, although none exceeded the action level. In Greenland, a high proportion (50-95%) of women of child-bearing age exceeded the level of concern. In one area, Ittoqqortoormiit, 12% of the pregnant women also exceeded the Canadian action limit. More than half of the non-pregnant women exceeded this limit. There is no apparent explanation for the differences among different groups of women.

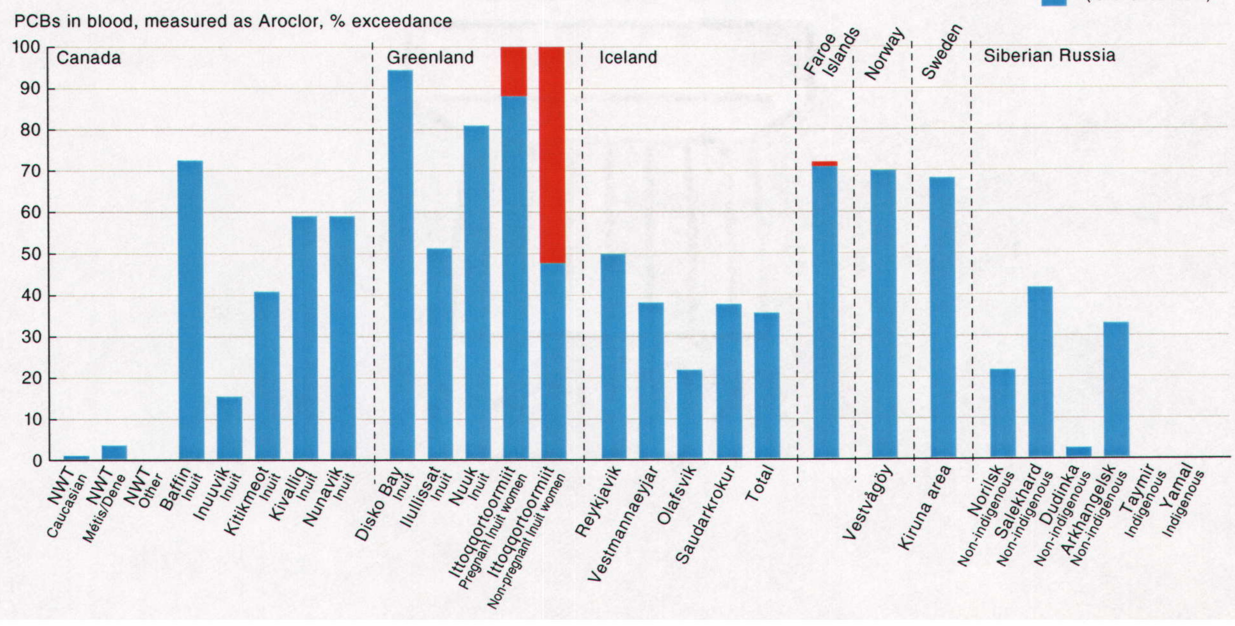
Although the situation is worst in Greenland and among Canadian Inuit, a number of women in other population groups also exceed the level of concern. They include non-indigenous women in Russia, Iceland, Norway, and Sweden.

Hormone mimics may disturb reproduction

It is well known that high levels of organic pollutants can lead to reproduction problems in wildlife. The causes range from the animals having gross changes in the reproductive tract to changes in mating behavior. During the 1990s, it has become clear that there is a common link between many of the reproductive problems. Many organic pollutants can disrupt the endocrine system, the hormones in the body. Some of the endocrine disruptors mimic the female sex hormone estrogen, whereas others block its action. Other compounds interfere with the male sex hormone testosterone, and some chemicals interfere with both systems.

PCB levels in blood of women of reproductive age; percentage of samples exceeding public health guidelines for levels of concern and action.





Experiences from a synthetic estrogen that was used to treat threatening miscarriage in pregnant women (diethylstilbestrol, DES) show that the effects of endocrine disruptors do not always appear in the adults who have been exposed, but may only be seen in the next generation. Often, a fetus in the womb is much more sensitive. In the growing body, the chemicals disturb the fine-tuned interaction of hormones steering the development of the reproductive system, causing irreversible damage.

The picture of endocrine disruption as a toxic mechanism has focused attention on diseases that might be connected with such mechanisms. For men in the western world they include increases in the incidence of testicular cancer, prostate cancer, and possibly also the number of newborn boys with undescended testes or malformed penises. For women, a rise in breast cancer has been discussed in this context, but the connection to contaminants is not very clear.

There are, as yet, no completed studies from the Arctic reporting contaminant effects on reproductive health, but such studies may be appropriate considering the high levels of some contaminants that are known to cause reproductive problems in animals. Recent results from biomarker studies also emphasize the need for further studies. Using cell cultures, it has been possible to look at the hormone-disrupting effect of the actual mixture of contaminants that is present in human blood in the Arctic. Results from East Greenland show that the blood sample, after being stripped of all natural hormones, is able to affect normal hormone processes in cultured human cells. It is too early to say anything about the significance of these findings for health of the Greenlanders in the study areas.

Weakened defenses against disease

The immune system has been increasingly recognized as a sensitive target for environmental contaminants. The cells of the immune system help identify and destroy foreign material such as bacteria and viruses that enters the body. The immune system also plays a role in recognizing cancer cells. An overactive immune system is involved in allergic reactions.

There are a number of contaminants that affect the immune system. In almost all animal species that have been tested, PCBs, dioxins, and furans suppress various components of it. The effects may be more severe in unborn or very young children, when the immune system is still maturing, than later in life. Other contaminants suspected to have such effects are dioxin-like compounds, chlordanes, hexachlorobenzene, PAHs, and possibly also other endocrine disruptors such as DDTs.

Another way the immune system may be disturbed is via vitamin A deficiency. The immune system needs a certain level of vitamin A to function properly. But vitamin A metabolism can be altered by contaminants, specifically by PCBs and dioxins.

In addition to the animal studies, evidence for effects on the immune system comes from studies showing an increased rate of infection among people who have been exposed to organic pollutants. From the Arctic, there is a study from Nunavik that shows a connection between high levels of organochlorine contaminants and increased incidence of ear infections early in life. A recent study of children in Northern Quebec has looked at immune effects of PCBs and DDTs. The preliminary results support the hypothesis that the high incidence of respiratory infections observed in Inuit children is due in part to high prenatal exposure to persistent organic pollutants.

Metals can also be toxic to the immune system. Both mercury and lead have been shown to affect various immune cells. Inorganic mercury can also induce allergies and hypersensitivity. Lead seems to promote hypersensitivity, rashes, and autoimmune response.

Mercury may increase the risk for cardiovascular diseases

There are some indications that mercury can increase the risk for cardiovascular diseases. A Finnish report has noted a correlation in fish-eating Finnish men between high levels of mercury and the risk of coronary heart diseases. The mechanism could be that the mercury promotes the breakdown, or oxidation, of lipids, creating forms that are known to initiate clogged arteries. N-3 fatty acids in combination with selenium and other antioxidants may counteract this effect of mercury. Among Inuit who get large amounts of these nutrients in their traditional diet, death from heart disease is much less common than among other people.

In the Faroe Island study, low-level prenatal mercury exposures have been associated with higher blood pressure in 7-year-old children. This can also be important because high blood

Mechanism behind PCB effects raises concern about other contaminants

One mechanism behind the effects of PCBs on the developing nervous system could be that some of these compounds interfere with thyroid hormones in the body. Thyroid hormones regulate the growth of nerve cells and the way that nerve cells develop different specific functions. In the fetus, the thyroid is essential for growth and for the brain and central nervous system to develop normally. The PCBs as manufactured may not cause detrimental effects themselves. In the body, they are changed into new forms, for example hydroxylated metabolites, or OH-PCBs. The OH-PCBs bind strongly to the special protein that normally transports thyroid hormones from the blood to the brain.

Several compounds that are chemically related to PCBs can also affect the thyroid system. They include dioxins, brominated flame retardants, phthalates, and some pesticides. Phenolic compounds, such as pentachlorophenols, are known to bind strongly to the blood-brain transport protein.

pressure is a risk factor for heart disease later in life. Although insufficient for risk assessment purposes, this evidence suggests that the cardiovascular system is a potential target for mercury and even a slight negative impact could have a major effect on public health.

Cadmium can damage the kidneys

Cadmium accumulates in the kidneys and liver. Even at modest exposure, the kidney can be irreversibly damaged. This leads to the body losing proteins and essential minerals. Recent research has also linked cadmium to the development of osteoporosis (brittle skeleton). Women deficient in iron are especially at risk. The new data from outside the Arctic on cadmium toxicity have led to the conclusion that the guideline for maximum recommended intake is too high to protect against harmful effects.

Cadmium accumulates in the fluid around the egg and can reduce fertility. It has also been related to early menopause, the age when a woman can no longer get pregnant. The growing fetus is partially protected against cadmium. The metal accumulates in the placenta. However, at high enough levels, some of the cadmium passes through this barrier.

For people, the major source of cadmium is tobacco smoke. Significant dietary sources are the kidney and liver from caribou/reindeer and whale. In some areas of the Arctic, such as Greenland, cadmium intake via the diet is higher than dietary guidelines, in addition to exposure from heavy smoking. Dietary intake of iron is also high, which might protect against cadmium from food being absorbed in the body. Nevertheless, there is a need to look more closely at the connection between cadmium intake and the occurrence of effects on the kidneys and skeleton.

Focus on the Kola Peninsula

On the Kola Peninsula of Russia, there has been a fear that pollution from the mining and smelting industry has an adverse effect on health of newborns, especially those born to women working in these industries. To investigate the risks, a study looked closely at the concentrations of nickel and various nutrients in the women of Archangelsk, Nikel, and Monchegorsk in Russia, and Kirkenes, Hammerfest, and Bergen in Norway. Although nickel concentrations were higher among the Russian women, there was no connection to birth weight. However, birth weights overall were lower for the Russian women, and there were signs that insufficient nutrition may play a role.

Another finding was that high levels of lead could cause low birth weight. Lead is also known to be neurotoxic and can affect children's mental development.

Combined effects are difficult to evaluate

Arctic populations are exposed to a mixture of contaminants. Some of them may affect the same sensitive systems in the body, through similar or different mechanisms. A key concern, therefore, is the possibility of interactive effects. If these occur, health risks may be underestimated if the contaminants are looked at one at a time.

There are laboratory studies showing that mixtures of contaminants can cause combined effects. These effects can be additive, where each contaminant adds its effects to the others, or antagonistic, where contaminants actually counteract each other's effects. In a few cases, laboratory studies have shown synergistic effects between contaminants, where the different substances enhance each other's effects. As a further complication, some contaminants may have one effect at low concentrations and completely different effects at higher concentrations.

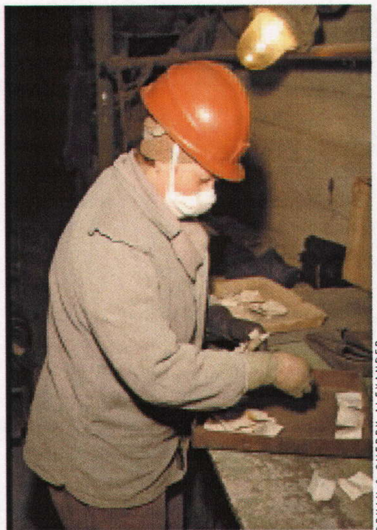
The effects of contaminants are also influenced by the person's general health. Inherited characteristics, nutritional status, and lifestyle factors such as smoking can thus play a major role in sensitivity to contaminants. Age also plays a role, and young children are often more sensitive than adults.

Epidemiological studies can provide information about combined effects that include both contaminants and other factors. This can be the case even when the intention is to study a single contaminant. The overall situation usually varies from one group of people to another, and contradictory findings can sometimes be explained by looking at the situation as a whole.

It may also be too simplistic to look at only one effect of a specific contaminant. The same substance or one of its breakdown products may act on other, even more sensitive systems in the body. Any risk assessment thus has to take into account which system in the body would be most sensitive, along with an evaluation of which individuals in a group would be most sensitive.

At this point, it is impossible to evaluate the combined effects of all contaminants and other factors that influence human health in the Arctic. AMAP's Human Health Program is designed to gather information from a number of different areas to make better assessments of combined effects in the future.

A female worker at the October Mine at Norilsk.



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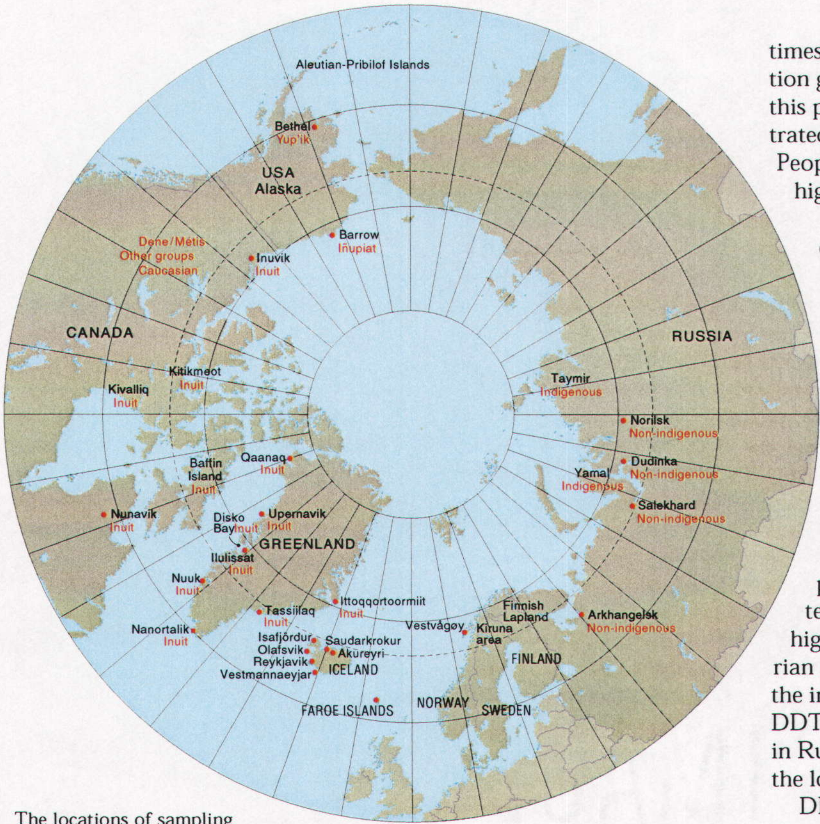
Health check at the Norilsk hospital.



The locations of sampling in AMAP's phase II circumpolar blood monitoring study.

Spatial trends in maternal blood

In 1994, AMAP initiated a circumpolar study of contaminant levels in maternal blood. A few early results were presented in the previous AMAP assessment. In this report these results are combined with new, much more complete data. As they relate to public health guidelines, the data are discussed in the previous section *Contaminants and Human Health*. This section presents geographical trends and their possible explanations.

A general picture that emerges is that levels of persistent organic pollutants and mercury are higher in people who rely heavily on food from marine mammals, such as the Inuit of Greenland and Arctic Canada. In Russia, levels of DDTs and HCHs (hexachlorocyclohexanes) are higher in non-indigenous people, which could indicate that these pesticides are still being used in Russia.

Some pesticide levels reflect current use

Several organochlorine pesticides or their breakdown products are included in the circumpolar survey.

Oxychlordane is a component and breakdown product of technical chlordane. Its levels are higher among Inuit in Canada and Greenland and Aleuts in Alaska compared with the Nordic countries, and highest on the east coast of Greenland. In Canada, levels are 4 to 15 times higher among Inuit than in other population groups. The most likely explanation for this pattern is that oxychlordane is concentrated in traditional marine mammal foods. People who rely heavily on these foods have higher levels.

Using other studies, it is possible to include Russia in the comparison. The results show that levels in the non-indigenous population of the Archangelsk region of Russia are higher than among non-indigenous people of Norway, Iceland, Finland, and Canada. This indicates that chlordanes are used either in the Archangelsk region or in Russian agriculture.

Similar patterns can be seen for DDE, which is a breakdown product of DDT, and for beta-HCH. Beta-HCH is a component of technical HCH. It is very persistent. Levels of DDE and beta-HCH are higher among non-indigenous people in Siberian Russia and in Archangelsk compared with the indigenous groups. It is thus likely that DDT and HCH-based pesticides are still used in Russian agriculture or to control insects in the local environment.

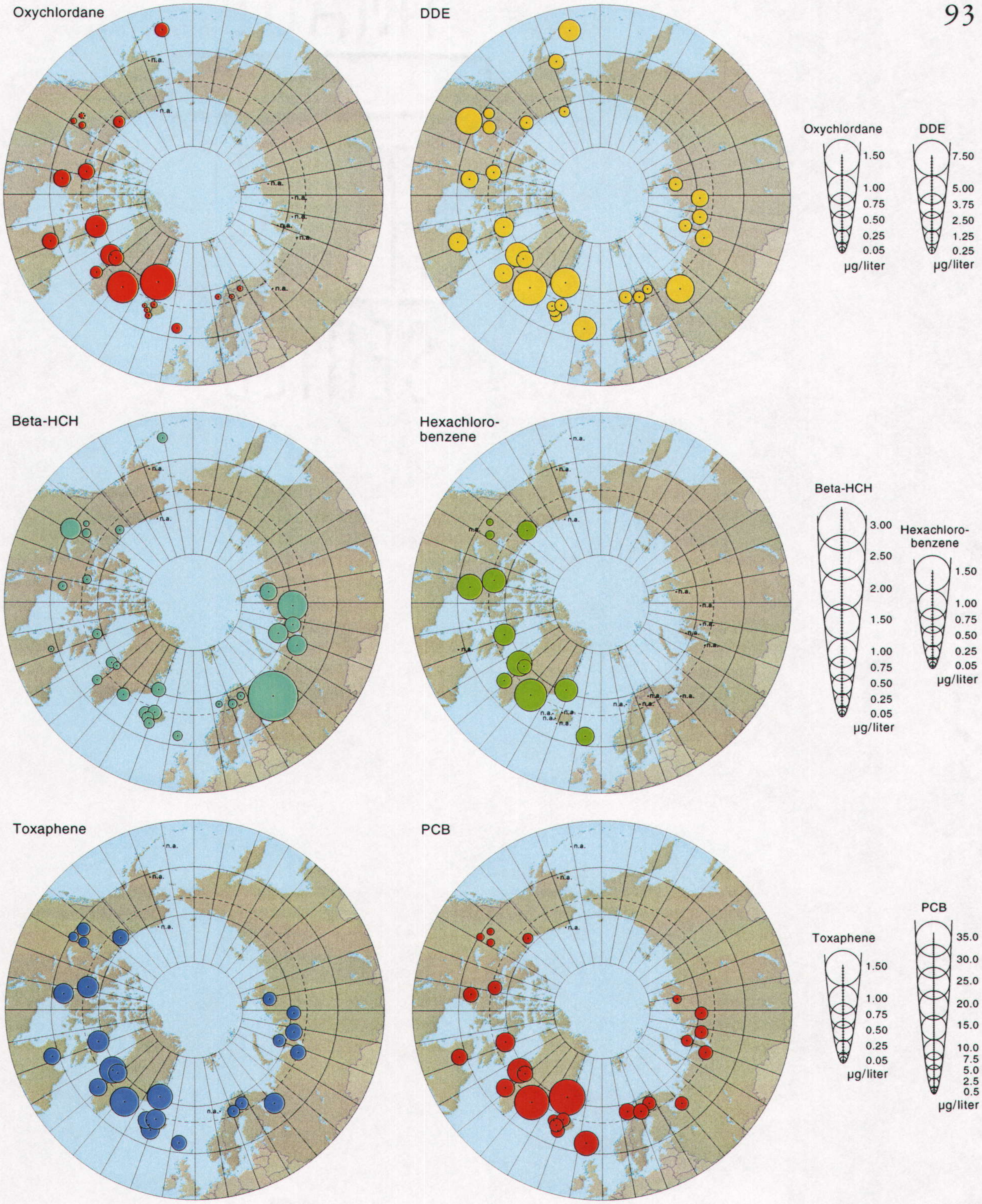
DDT and beta-HCH levels are also 5-12 times higher among people in the category 'other groups' in Canada than in specified groups. The 'other groups' category includes people from Africa and East Asia, regions where these pesticides are still in use. They may have been exposed while living in those areas, or perhaps via food imported directly from their home countries.

Among indigenous peoples, DDT and beta-HCH levels are higher among most Inuit groups in Canada and Greenland than among the Dene/Métis of Canada, who rely more on fish and terrestrial animals, or indigenous peoples of Russia, who rely heavily on reindeer.

A number of other pesticides are included in the AMAP Human Health program, such as toxaphene, mirex, and hexachlorobenzene. The general pattern is that levels are higher among people who rely heavily on marine mammals in their traditional diet.

PCB and mercury levels are connected to marine diet

PCB levels in human blood are best explained by people's food habits. Indigenous people who rely heavily on marine mammals have the highest levels. PCB levels are highest in Greenland, especially in communities on the east coast. Seal consumption is common throughout Greenland but in the northern and eastern regions of Greenland, polar bear is also part of the traditional diet, and the contaminant levels are higher in polar bear than in seals. In southern Greenland and in the bigger towns, people eat

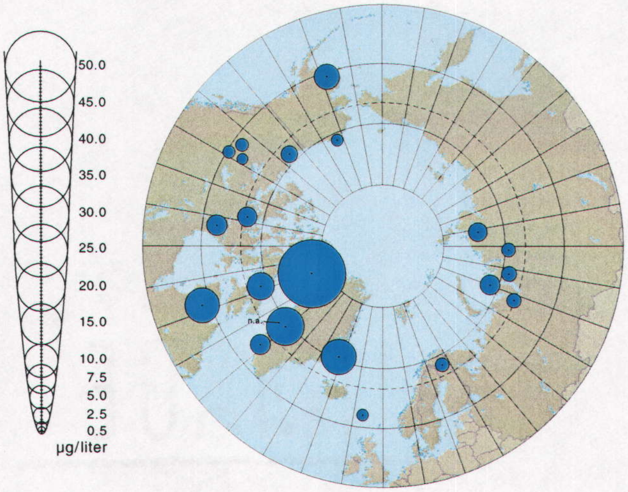


POP concentrations in human blood.
n.a. indicates not available.

relatively more fish and imported foods. In Canada, levels are higher among Inuit living on Baffin Island than among other Inuit groups.

In the Faroe Islands, blubber from pilot whale is the main source of PCBs. Pilot whale consumption has decreased due to public health advice. So far there is very little change in PCB blood levels, however, and the levels are still two to three times higher than in other Nordic countries.

Among non-indigenous populations, the highest levels are in mothers from Norway, Sweden, and Russia. The levels are in the same range as for Inuit from western and northern Canada. The most likely sources are a high intake of PCB-contaminated marine fish and the common commercial food supply.



Mercury concentrations in human blood.

The highest levels of mercury are found in Inuit of Canada and Greenland plus the Yup'ik in western Alaska. For Inuit, the mercury comes mainly from the muscle of marine mammals. In western Alaska, the levels can probably be explained by high intake of northern pike. In the Faroe Islands the major source of mercury is pilot whale.

Other metals

Cadmium levels are higher among Inuit in Canada and Greenland than in other population groups in the Arctic. The most important source of cadmium for people is cigarette smoke, and the high levels can be explained by the high smoking rates along with high cadmium content in Canadian tobacco.

For lead, levels are moderately elevated among some of the Inuit groups and for Dene/Métis compared with other groups in Canada. The most likely source of the lead is lead shot used for hunting. Some Inuit and Dene/Métis in Canada, along with some women in Greenland, exceed the public health action guideline for lead.

In Russia and northern Finland, there has been concern that pollution from the metal smelters could lead to elevated metal levels in people working at these smelters or in their near vicinity. The data in the AMAP survey do not indicate that women living close to the smelters have higher metal levels.

Do contaminants pose a risk to human health?

The previous AMAP assessment raised concern that contaminant levels in some groups of Arctic people were high enough to affect their health. Since then, more data has been gathered and epidemiological studies have provided more knowledge about the potential effects of low-level chronic exposure, as discussed in the previous sections. To summarize the data presented earlier in the chapter, these studies show subtle neurotoxic effects of methylmercury in some regions of the Arctic where meat from marine mammals is an important part of the diet. The severity of the effects is related to the dose the child receives in the womb, before it is born. Exposures to mercury in the Arctic vary widely. In communities where exposures are high enough to cause health concerns, AMAP considers the evidence strong enough to warrant public health strategies to reduce the mercury exposure of women of child-bearing age, especially pregnant women.

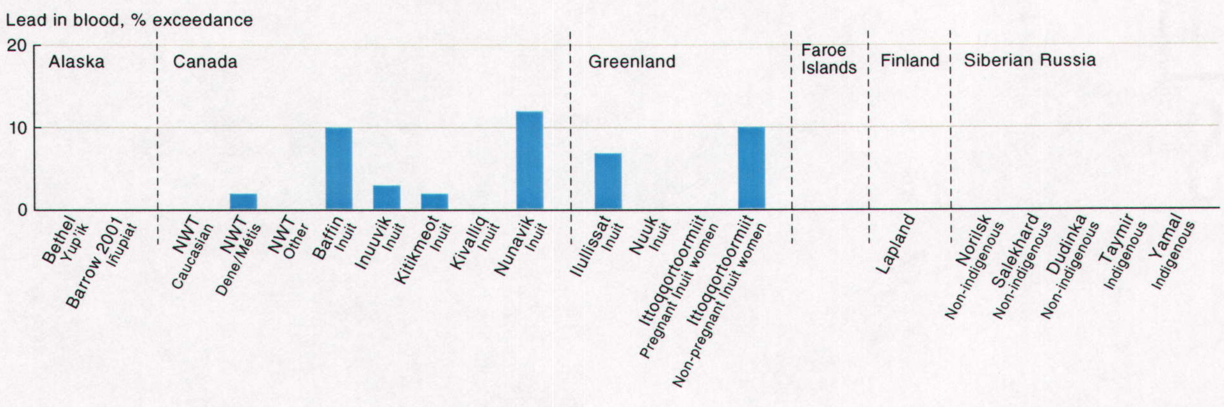
For persistent organic pollutants, emerging epidemiological evidence suggests a negative influence on human health in both Arctic and non-Arctic regions. Again, the main risk is for the child being exposed in its mother's womb.

So far, the major concerns have been for effects on the growing brain. However, it appears that the developing immune system is also sensitive to contaminants. Moreover, there are health effects that have not yet been well investigated but that will be important to look at in the future. They include the role of contaminants in fertility problems, cardiovascular diseases, and osteoporosis.

For contaminants, mercury and PCBs have been in focus. Based on high intake, AMAP concludes that there is also a need to look closely at potential effects of toxaphene, chlordanes, and all substances with dioxin-like effects.

Most health problems are caused by a combination of factors. Compared with the role of lifestyle and inheritance, contaminants alone may play a modest role but are likely to be important in combination with other factors. The only way to reduce exposure to environmental contaminants in the long-term is through national and international controls on emissions and use.

Lead levels in women of reproductive age: percentage of samples exceeding blood guideline action level (100 µg/liter).



Dietary advice may be necessary

Several international conventions and protocols address emissions of POPs and heavy metals. When ratified and implemented, they should reduce new releases of some of the most dangerous POPs to which Arctic populations are exposed. However, these substances are persistent in the environment and it will take in the order of 20 years before there are significant reductions in levels in the fish and wildlife that Arctic people eat. In the meantime, there is a need to consider local risk reduction strategies in the regions of the Arctic where contaminant levels are high enough to cause health concern.

This is not an easy task. The main source of the contaminants is traditional foods, such as marine mammals. These foods provide beneficial nutrients as well as cultural and spiritual identity, and are known to promote health. A switch away from these foods can thus have negative effects on health. On the other hand, the evidence of subtle effects of contaminants in traditional foods is emerging. This underlines the necessity of dietary recommendations that carefully weigh risks against benefits.

In the previous assessment, AMAP concluded that it may be prudent to consider some dietary advice. In communities where exposures are high enough to cause health concerns, the updated scientific assessment confirms the need for balanced dietary advice for young women and pregnant women to help them reduce exposure levels prior to pregnancy. Dietary advice may also be needed for children to limit accumulation of POPs from an early age and for men of reproductive age because of possible effects on male fertility.

A need for local involvement

The specifics of weighing risks and benefits of traditional foods vary between different groups of people. Any dietary advice therefore has to take the local situation into account. In general, risk-benefit discussions have been most fruitful when local public health authorities have worked in concert with the community at risk and also with experts from a variety of disciplines. These local strategies are able to take account of the nature of the problem, the exposure route, the level of education and understanding, and the social and cultural needs of the community.

There are some examples of successful programs to reduce exposure to contaminants. In the Faroe Islands, new knowledge about the effects of mercury and possibly of PCBs on children's development led to new, stricter dietary recommendations in 1998. Previous diet advice, from 1977 and 1989, had some restrictions. Now, adults are recommended not to eat meat or blubber from pilot whales more than once or twice a month. Girls and women are recommended not to eat pilot whale blubber at all until they have given birth to their children, to limit exposure to PCBs, which remain in the body for a long time. Biologically available mercury leaves the blood within a couple of months, and women who plan to become pregnant within three months as well as pregnant and nursing women are recommended to abstain from eating pilot whale meat. People seem to follow the recommendations and levels of mercury in Faroese women have declined approximately 80% in the past nine years. Similar declines have not been seen for PCBs.

Another example of dietary recommendations leading to reduced contaminant levels is from the lower north shore of the St. Lawrence River in Canada, where people traditionally consume seabird eggs. Advice about reducing consumption of seabirds eggs, along with declining contaminant levels in the eggs, have reduced the level of persistent organic pollutants in newborns between 25 and 69% over a seven-year period.

Other communities have chosen not to issue any dietary recommendations. In Canada, high POP levels in marine mammals raised concern and a committee comprised of representatives of northern indigenous groups, government health and research agencies, and national Inuit organizations met to evaluate the options and consider how to best communicate the issues. The result was that the Inuit Tapirisat of Canada coordinated the message to regional leaders with a basic statement that 'So far as we are aware, the risks to public health from continuing to eat beluga and seal blubber are very small and are outweighed by the benefits to you of these foods. However, Inuit must judge for themselves what is acceptable risk for themselves and their families'.

Also in Canada, high mercury levels in waterfowl livers and an initial recommendation by Health Canada to limit consumption of liver of some waterfowl species started a discussion that involved a wide range of organizations. The discussions took into account not only contaminant levels but also information about how often people ate duck livers and the economic, spiritual, cultural, and social benefits of this food. The group made a risk management decision not to issue advice to limit consumption of waterfowl livers, but to update current communication materials and to provide fact sheets discussing the elevated levels of mercury.

Promoting healthy foods is an alternative to restrictive dietary recommendations. In Nunavik, Canada, this approach is currently being evaluated in three communities. The program promotes Arctic char as a fish of choice for pregnant women. Arctic char contains relatively few contaminants and is nutritious. The aim is to reduce intake of mercury.

The health consequences of using lead shot in hunting are an issue in many parts of the Arctic. Current actions to limit exposure range from banning lead shot to discussions with hunter associations as a preparation for future bans. In some places, retailers are asked to provide only steel shot.

Breast feeding should continue

Breast milk can contain almost all of the persistent organic pollutants and there has been concern how this affects children who breast feed. However, breast feeding also has many benefits. They include enhanced bonding between mother and child, providing the baby with nutrients, and boosting the child's immune system. The previous AMAP assessment therefore concluded that breast feeding should continue since the benefits outweighed the currently known risks.

This recommendation to continue breast feeding is re-emphasized in the updated scientific assessment. The health benefits are substantial. Moreover, dietary advice may help women of child-bearing age bring down contaminant levels in the milk. In addition, the epidemilogical studies of effects of contaminants suggest that the health risks for the child are mostly associated with exposure in the womb, rather than through breast milk. This exposure can only be prevented by bringing down the contaminant levels in the environment and by dietary advice to girls and women. Even if restrictions in breast feeding are not currently recommended, this may need to be reevaluated if contaminant levels increase or if other information indicates increased risk.

Summary

From a public health perspective, the environment is the sum of physical, chemical, biological, social and cultural factors that affect people's well being. In the Arctic, the rapid pace of cultural change is having a large impact on human health. On the positive side, infectious diseases and accidents have become less common. But there are less positive aspects, too. As lifestyles become more western, the rates of obesity, cardiovascular diseases, and diabetes have increased. Many people smoke, and high consumption of alcohol is common in many Arctic communities. Suicide is an important cause of death among young men.

Food habits in the Arctic are changing and store-bought food is becoming more important. However, local resources still play an important role, both in supporting cultural and social ties and in providing important nutrients, some of which protect against diseases.

Some traditional foods have high levels of contaminants. The fat of marine mammals and birds contains many persistent organic pollutants, while their meat and that of some predatory freshwater fish can contain high levels of mercury. The kidney and liver of caribou/reindeer and whale can have high levels of cadmium, although cigarette smoke is a more important source of cadmium exposure. Smoking also seems to be connected to levels of POPs in people. Lead is present in birds that are hunted in areas where lead shot has been used in the past or is still being used.

Since the previous AMAP assessment, knowledge about the effects of contaminants on human health has increased in terms of both individual and population-level effects. Moreover, the human health monitoring program has provided information about the levels of contaminants in people, in particular in women giving birth. The main conclusion of this report is that we are even more certain than before that the current exposure of some Arctic populations to the existing mixture of contaminants is inducing some subtle adverse effects.

One of the main concerns is the damage contaminants can do to the developing brain, while a child is still in the womb. Epidemiological studies show that mercury levels in parts of the Arctic are high enough to cause subtle neurobehavioral effects. The people at increased risk live in areas with high intake of marine mammals, such as Inuit in Greenland and Canada, or people with high intake of some fish species. ~~such as Yup'ik in western Alaska.~~ Moreover, PCB levels in blood exceed public health guidelines, indicating a risk for similar neurobehavioral effects in some groups of people in Greenland and Canada. Emerging evidence from Arctic epidemiological studies suggests that PCBs may also decrease resistance to infections in the first year of life.

In addition to the main focus on neurobehavioral and immune effects, contaminants are known to affect hormone systems in the body that are important for sexual development and the ability to have children. A new concern is on the role of mercury in cardiovascular diseases.

For other contaminants, there is a need to look more closely at the potential effects of toxaphene, chlordanes, and all dioxin-like substances, where intake via traditional food is high and in some cases exceeds public health guidelines.

In the long run, international conventions or protocols are the only ways to reduce the contaminant load in Arctic traditional foods and thus in people. However, it will take many years before levels decrease, and in the short-term dietary advice may also be prudent. Such advice has to recognize the importance of traditional foods for people's health and well-being, and to weigh risks against benefit. The advice has to be developed locally and must take into account the needs of the communities involved.

At the international level, the highest priority has to be ratifying and implementing the Stockholm Convention on Persistent Organic Pollutants and the protocols on POPs and heavy metals in the UN ECE Convention on Long-range Transboundary Air Pollution (LRTAP). In addition, the public health threat supports continued work toward a global agreement on mercury.

FINN LARSEN

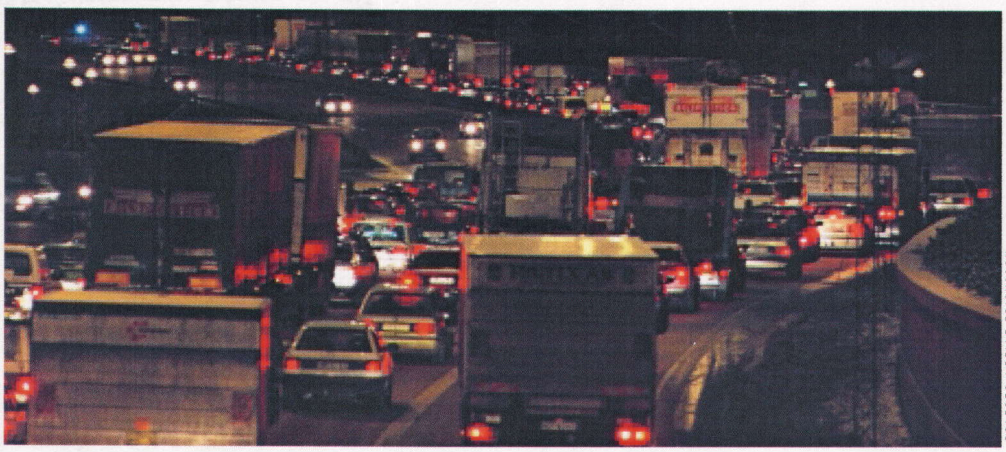
Saqqannguaq Road, Narsaq, Greenland

Changing Pathways

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

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

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



POLFOTO / PELLE ERICHSSON

European Route E4, Stockholm

Climate change in the Arctic

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

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

Global climate change will warm the Arctic

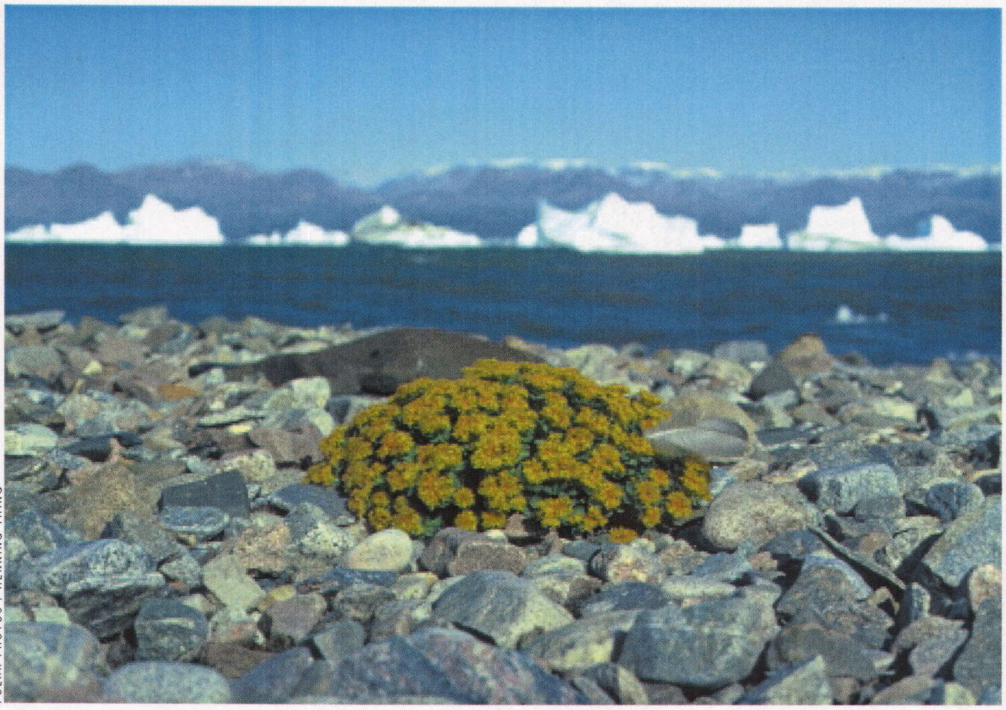
Human activities, such as the burning of fossil fuels, release greenhouse gases to the atmosphere. They affect the Earth's energy balance, which in turn has the potential to influence temperatures and weather patterns. Expert opinion, as expressed by the Intergovernmental Panel on Climate Change, is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

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

Arctic Climate Impact Assessment

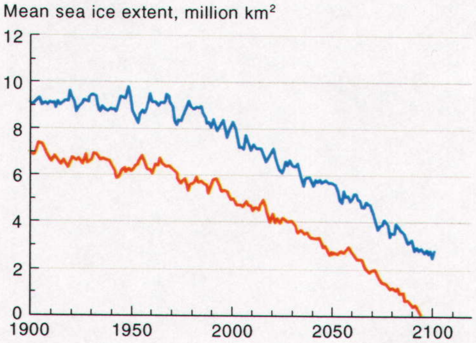
Climate change and variability, and, more recently, notable increases in ultraviolet radiation, have become important issues in the Arctic over the past few decades. Under the auspices of the Arctic Council, a program has been initiated to evaluate and synthesize knowledge about climate variability,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

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



POLAR PHOTOS / HENNING THING

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



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

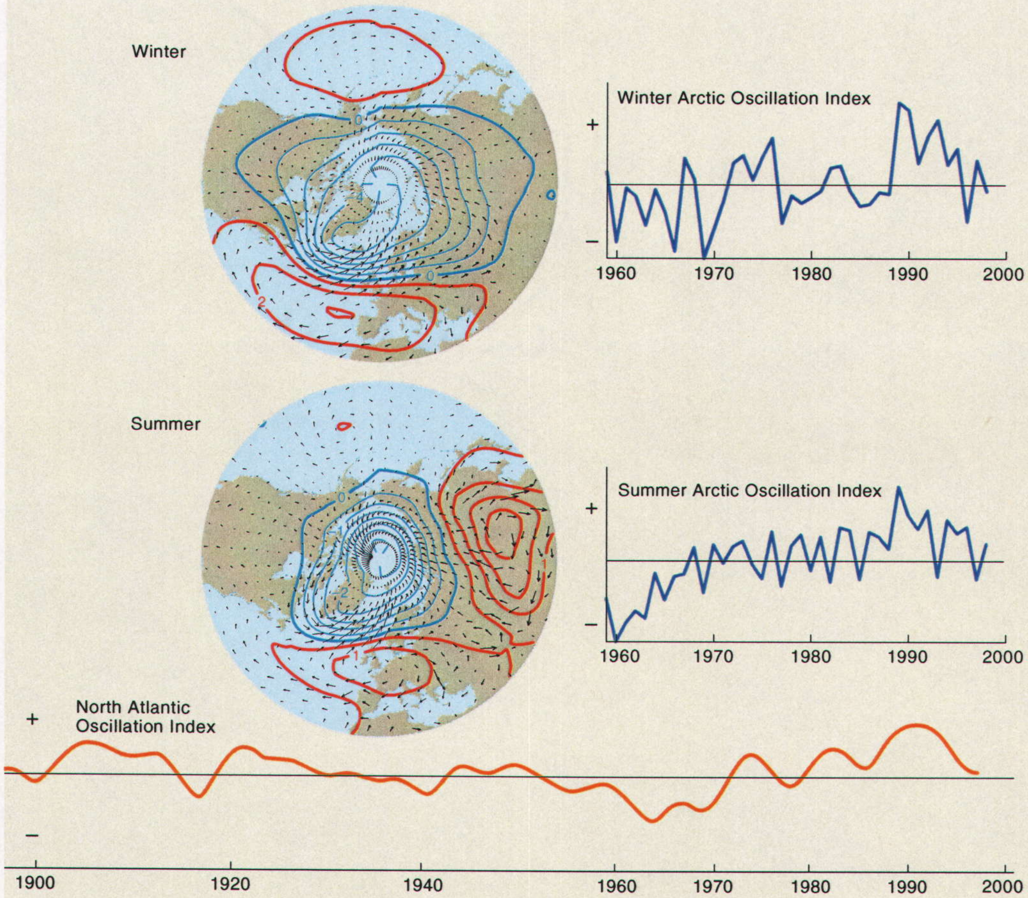
models predict that climate change caused by greenhouse gases might produce an Arctic Ocean that is free of sea ice in the summer.

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

Recent climate trends follow from Arctic Oscillation

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

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

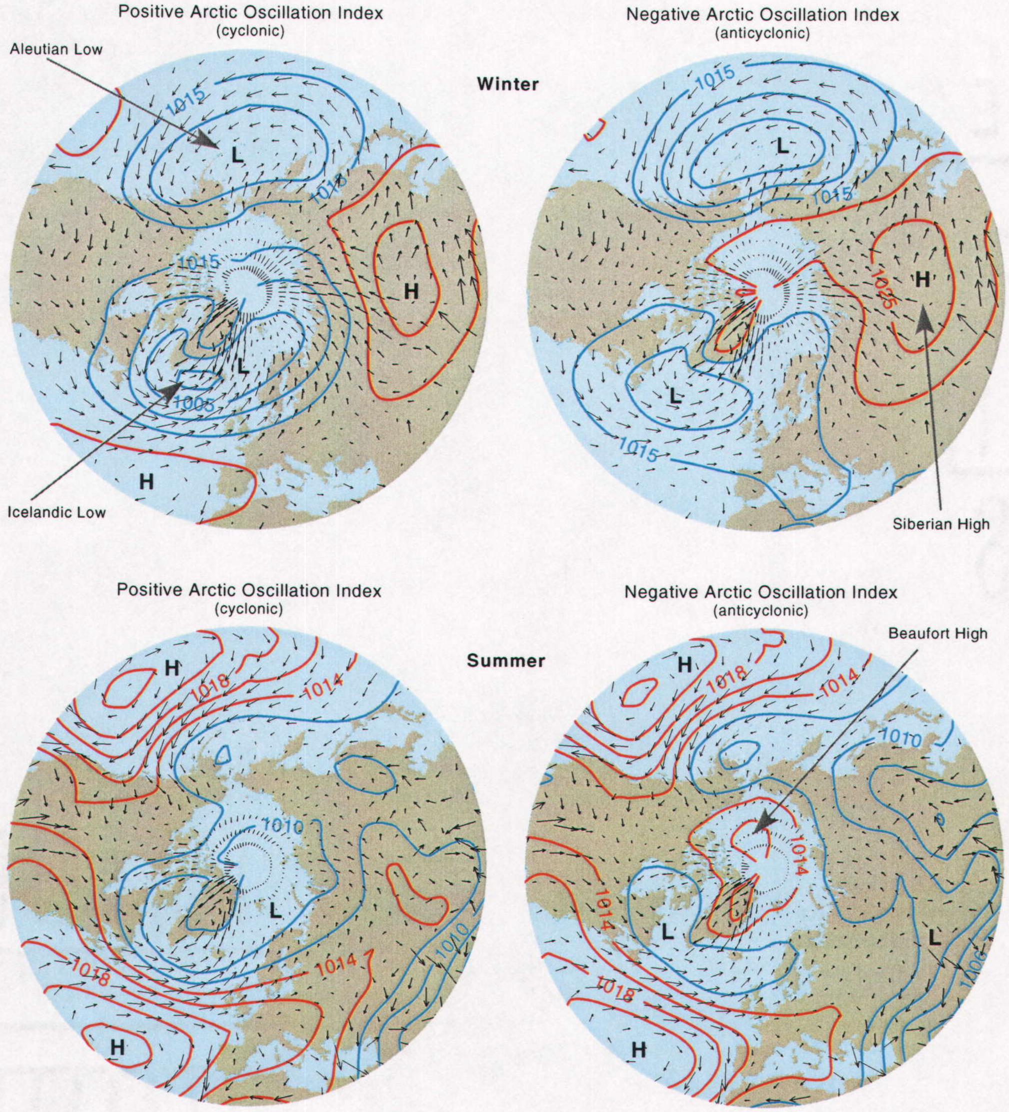


The Arctic Oscillation Index since 1960 and the North Atlantic Oscillation Index since 1900. The maps represent a combination of the Arctic Oscillation Index and atmospheric pressure fields during winter and summer.

The Arctic Oscillation and the North Atlantic Oscillation

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

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



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

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

Winds, precipitation and temperature

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

Wind patterns govern pollution transport

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

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

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

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

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

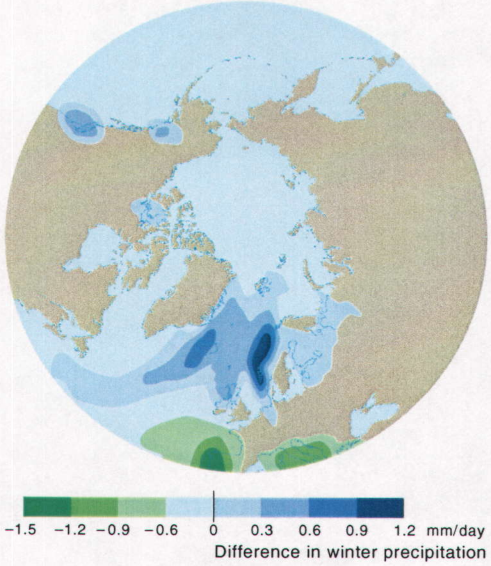
The wind patterns in the Pacific appear to change very little in a shift from a low to a high Arctic Oscillation Index.

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

Precipitation transfers pollutants from the air to slower ocean currents

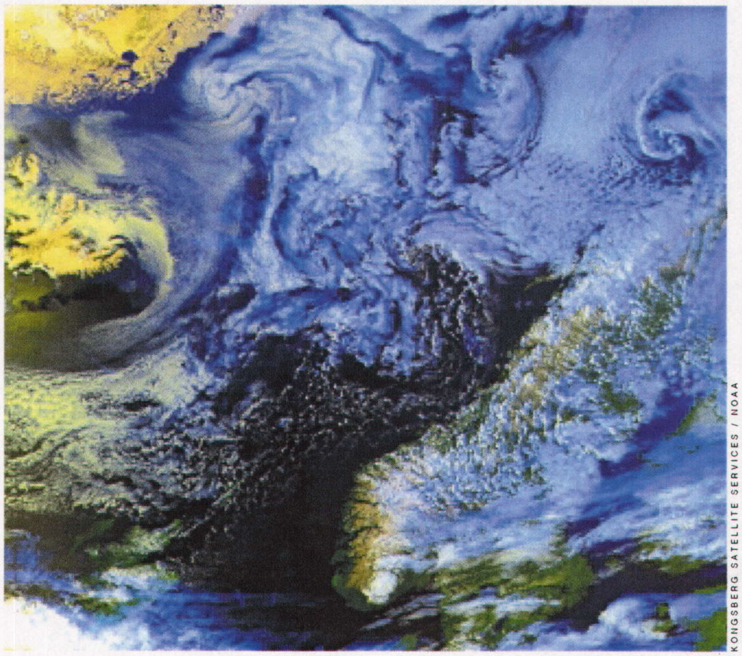
Air transport of particle-associated metals such as lead, cadmium, and zinc will be affected by changing wind patterns. However, these pollutants are scavenged inefficiently within the Arctic and thus tend to stay in the air rather than deposit to the surface. The actual load to land and sea surfaces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

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



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

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



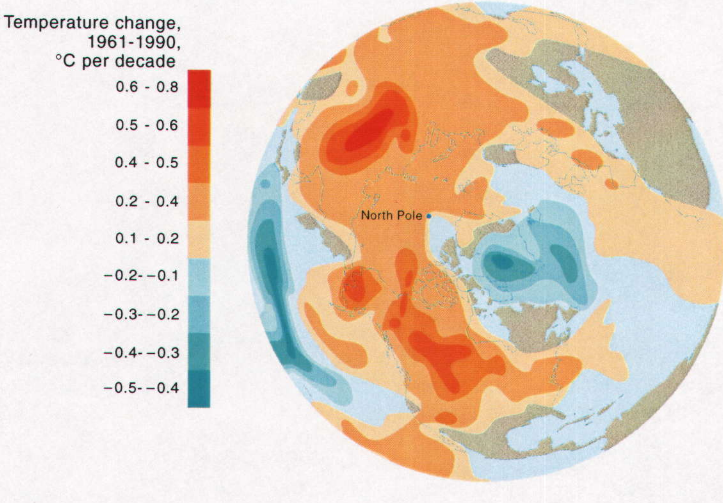
Storm over the Norwegian Sea. Satellite image.

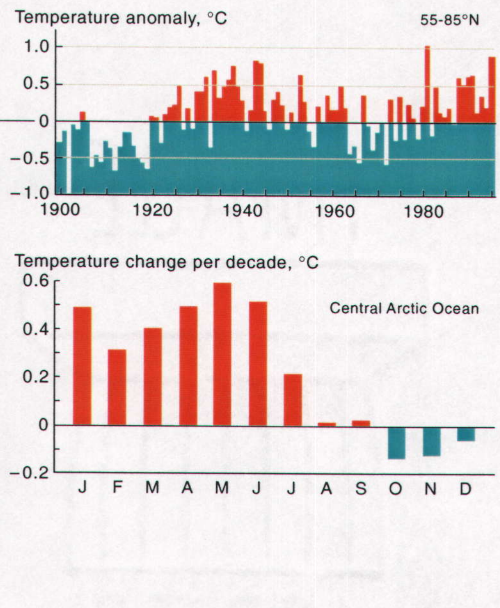
the atmospheric particles that enter the Arctic are thus likely to deposit there.

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

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

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





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

Most of the Arctic has become warmer

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

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

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

Changing water flows in rivers

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

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

Lakes, land, and glaciers

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

Lakes are sensitive to changes

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

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

Permafrost changes may increase mercury cycling and natural radioactivity

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

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

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

POLAR PHOTOS / HENNING THING

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

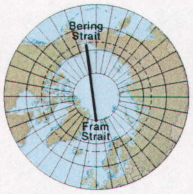
Change in permafrost also has an implication for radon that diffuses out of the ground. This radionuclide is not generally related to anthropogenic activities but comes from soils and bedrock. Radon is trapped in frozen ground in the Arctic, but with warmer temperatures, more radon will diffuse out of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

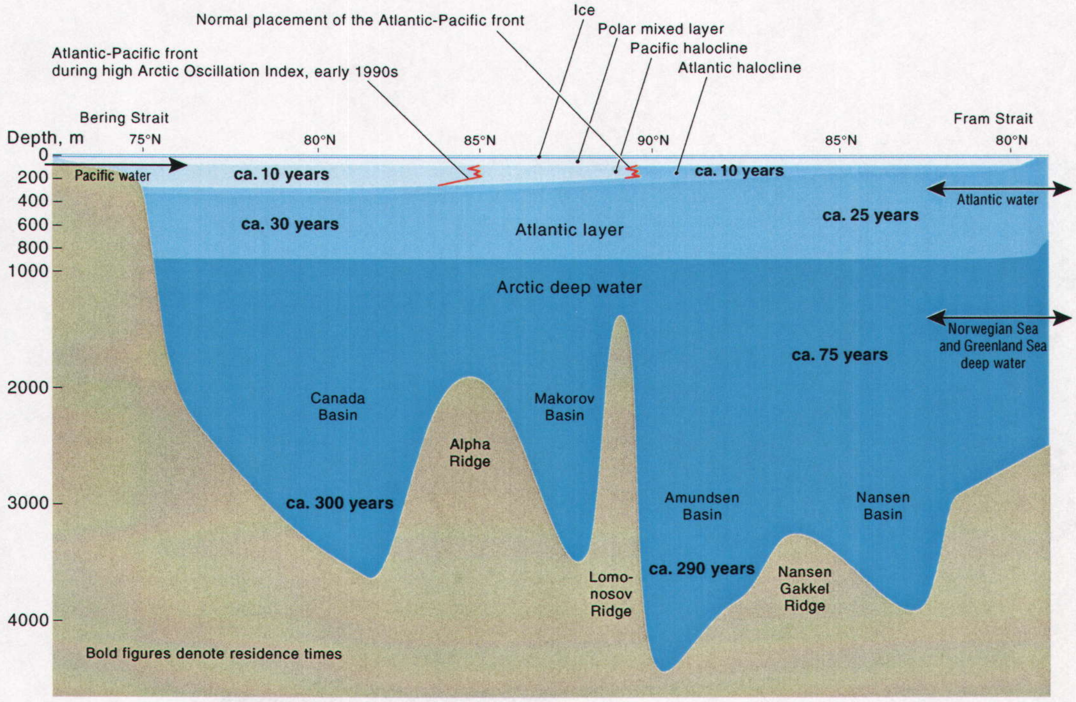
Glaciers could become sources of DDT

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

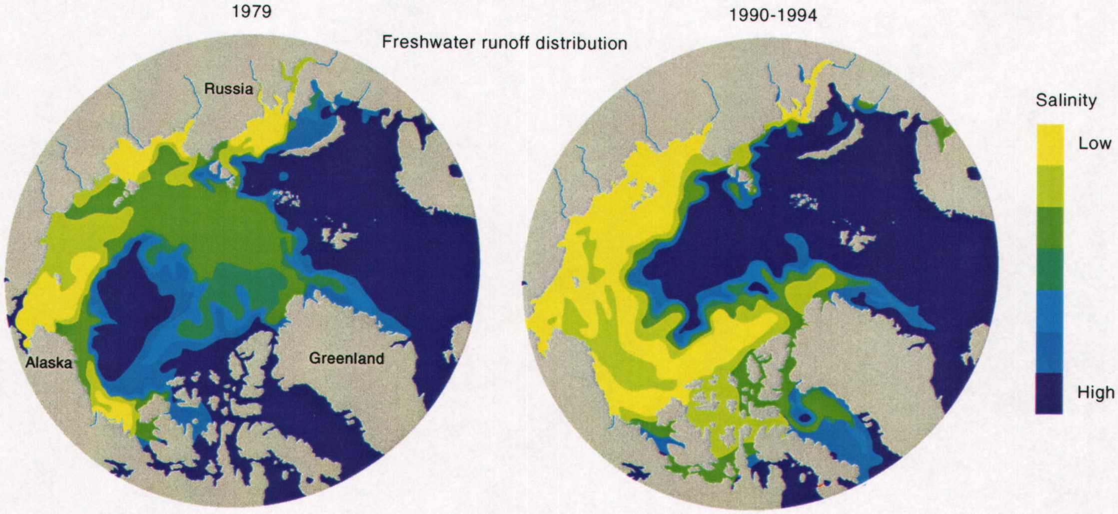
Ocean transport

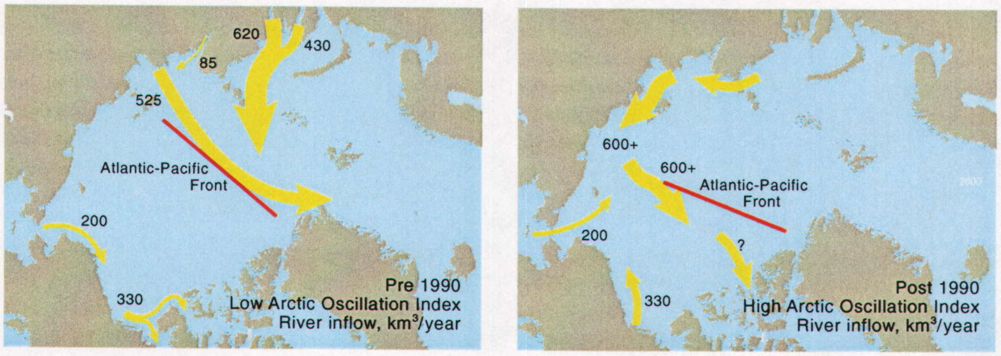
The Arctic Ocean is divided into distinct layers. Below 800 meters is Arctic deep water, with a very long residence time. From 200 to about 800 meters is the Atlantic Layer. At the very top is the Arctic surface water, which is the most important for contaminant transport within the Arctic Basin. Between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





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





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

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

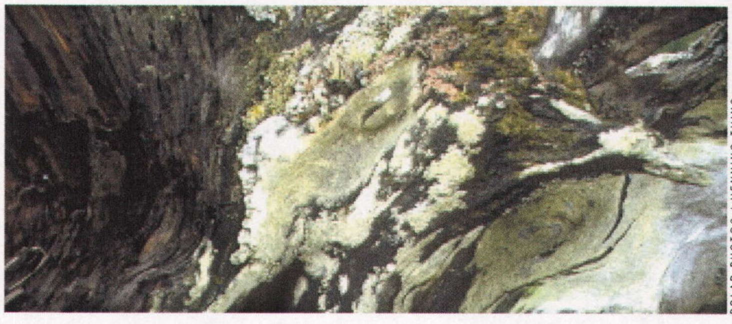
New pathways in the Arctic Ocean surface waters

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

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

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

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



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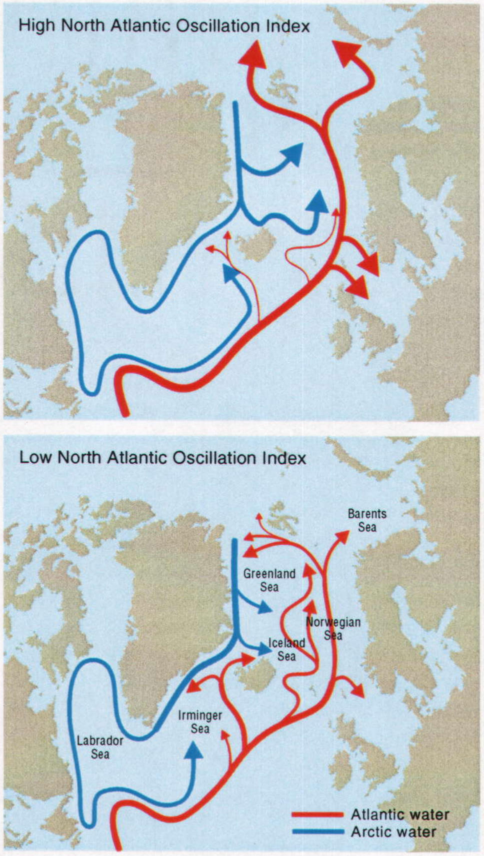


Main features of ocean circulation in the North Atlantic and the Nordic Seas during high and low North Atlantic Oscillation Index.

The Atlantic's increased role leads to declines in cadmium

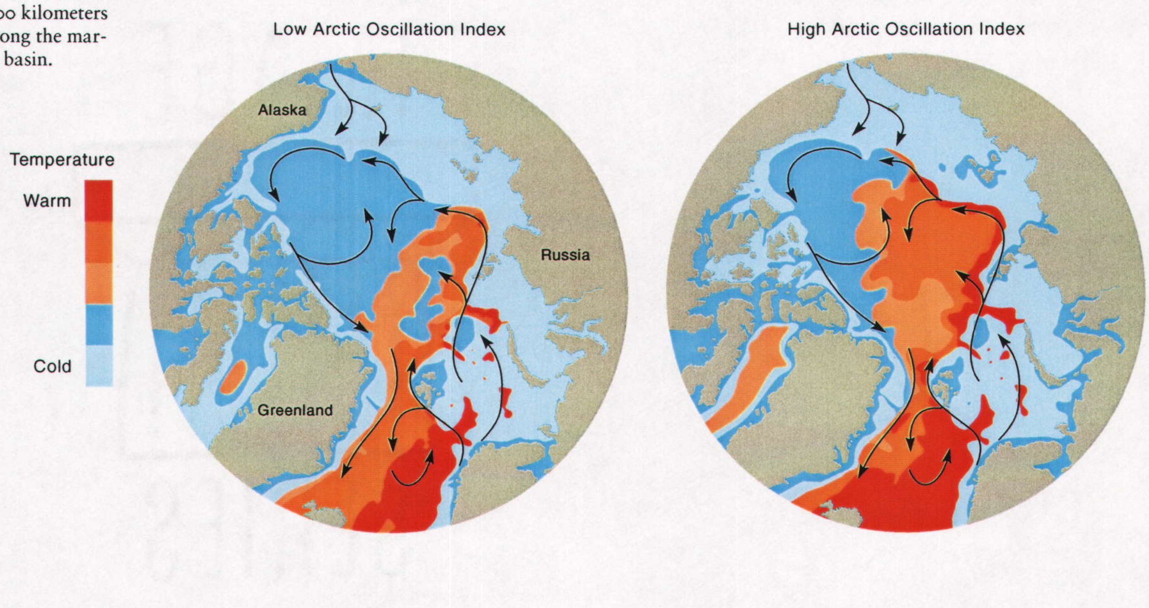
For the Atlantic Layer, the Arctic Oscillation influences the flow of water into and out of the Arctic Ocean. Communication with the Pacific is through Bering Strait, while communication with the Atlantic is through Fram Strait and through the Norwegian and Barents Sea. Important contaminants in the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

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

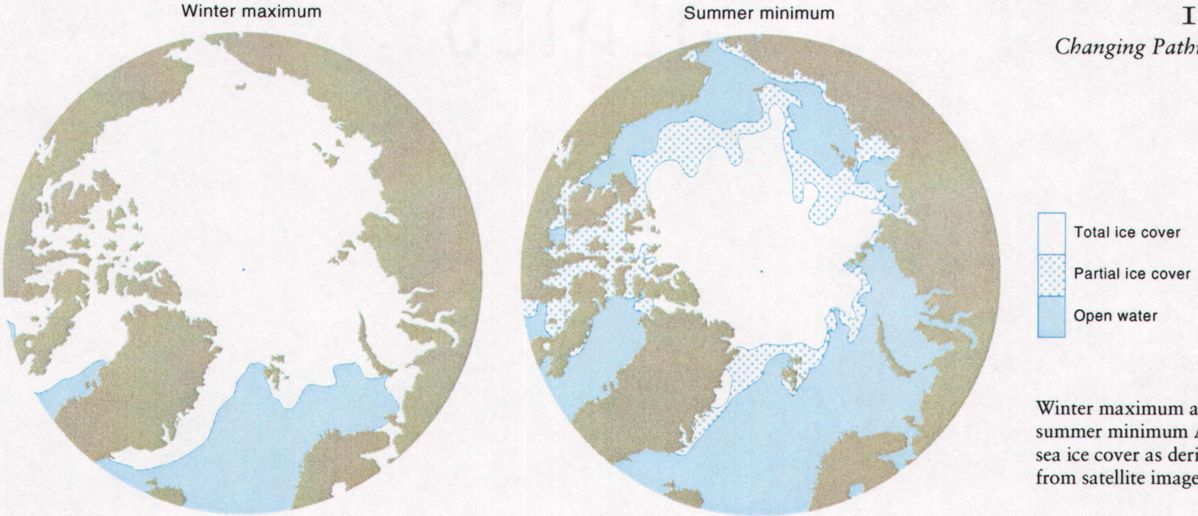
The declining role of Pacific water in the Arctic Ocean has implications for cadmium, a toxic metal that biomagnifies in the marine food web. In the ocean, the distribution of this metal is largely controlled by natural biogeochemical cycles, with the Pacific having higher natural concentrations than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

Sea ice

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



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



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

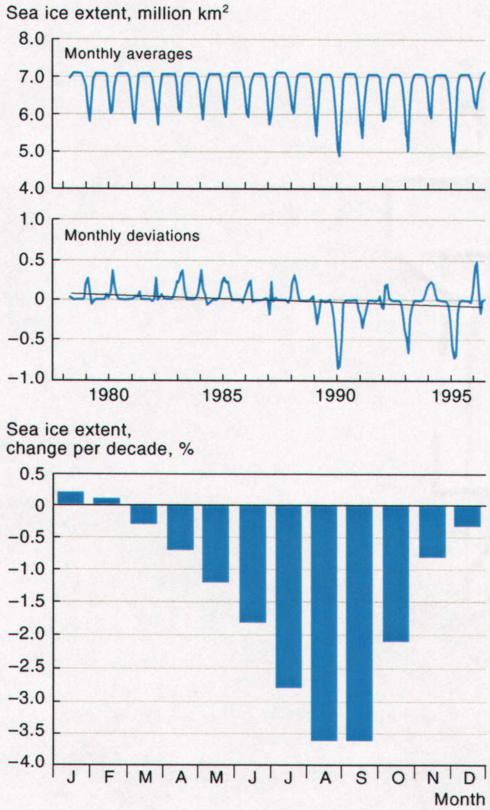
Less ice cover

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

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

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

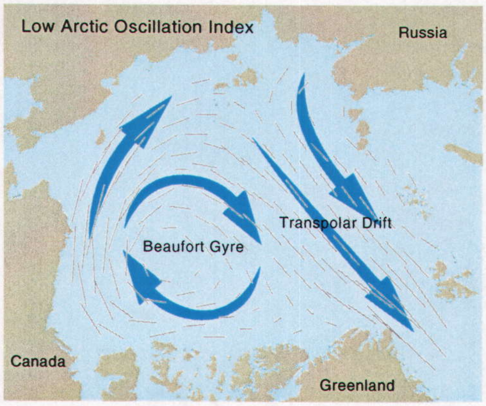
Sudden but temporary changes in ice cover have occurred earlier in Arctic history. Over a century ago, the whaling fleet experienced a dramatic decrease in ice cover in the North American Arctic. In the Barents Sea, about 15 percent of sea ice cover was lost around 1920.

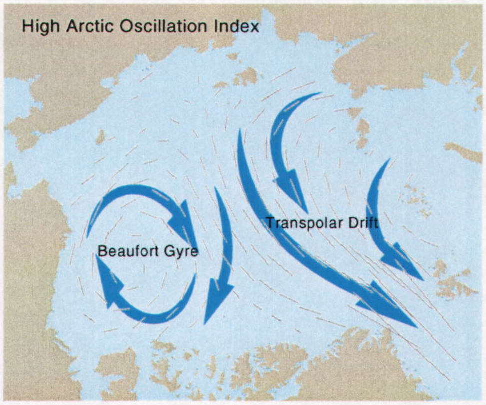


The change in Arctic Ocean sea ice extent from 1979 to 1995 showing the ice loss to be predominantly a late winter–summer phenomenon.

Increased exchange of POPs between sea and air

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





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

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

Ice changes will affect mercury deposition in the Arctic

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

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

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

Shifting routes from drifting sea ice

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

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

Biological impacts

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

Changing plant cover will affect deposition

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

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

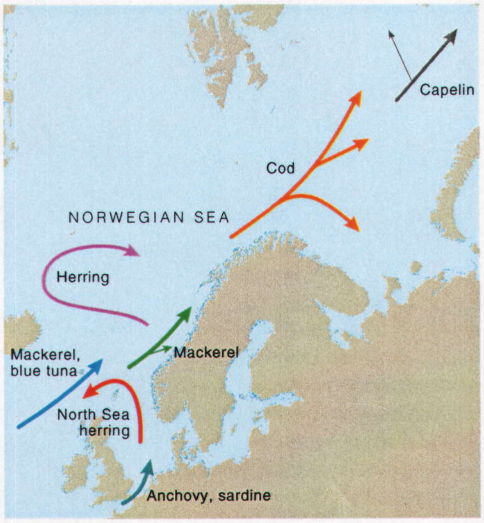
Aquatic ecosystems are sensitive to changes

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

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

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

For marine fish, it is well known that changes in climate or ocean currents can affect the distribution of commercially important stocks, such as Atlantic cod and herring. Water temperatures are important, as are the distribution of prey and predators and the currents that determine the movement of larvae from spawning grounds to their nursery areas. Atlantic cod and its main food item capelin are likely to move northeastwards. Spring-spawning herring may return to the same migration route they followed in the mid-1960s, when the water temperature around Iceland was higher than today. Other more southerly species may become distributed



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

farther north toward and into the Arctic. This will lead to the introduction of new species into the Arctic marine ecosystem. The consequences are difficult to predict but may include changes in the food web and thus in the load of contaminants in biota. Another possibility is changes in migratory routes and contaminants along the route.

Changes in sea ice can alter marine ecosystems

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

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

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

MAGNUS ELANDER

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

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

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

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

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

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

Tourists visiting the North Pole on an icebreaker cruise take the Polar Plunge.

Human activities will increase

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

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

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

Summary

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

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

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

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

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

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

Arctic Pollution 2002

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Supplementary Note to the AMAP report *Arctic Pollution 2002*

In response to questions raised by Gwich'in Council International and Canada, and the USA at the meeting of the Senior Arctic Officials of the Arctic Council, in Inari, October 2002, regarding certain statements made in the AMAP assessment report *Arctic Pollution 2002*, the AMAP lead experts responsible for these parts of the assessment have re-examined these texts.

Based on their re-evaluation and recommendations, the AMAP Working Group has agreed the following statements/changes:

After the *Arctic Pollution 2002* went to print, Canada realized that the data provided to AMAP as a contribution to the figure on **page 76** was in error. New data has now been supplied to AMAP and will be used for the assessment which will appear in the detailed scientific report (*'AMAP Assessment 2002: Radioactivity in the Arctic'*) that will be published in 2003. This data indicates a substantially lower consumption of caribou meat for the Old Crow. Therefore the bar representing cesium-137 intake for Canada should be ignored and the interested reader is referred to the relevant section in the *'AMAP Assessment 2002: Radioactivity in the Arctic'* report.

The sentence in the first column on **page 88** that reads: "*Among the Yup'ik in western Alaska, almost half of the mothers exceeded the stricter US EPA levels.*" is adjusted to read: "*Among the Yup'ik in western Alaska, almost half of the mothers exceeded the stricter US EPA levels, although none exceeded the Canadian guidelines.*"

The sentence on **page 96** that reads: "*The people at increased risk live in areas with high intake of marine mammals, such as Inuit in Greenland and Canada, or people with high intake of some fish species, such as Yup'ik in western Alaska.*"is adjusted to read: "*The people at increased risk live in areas with high intake of marine mammals, such as Inuit in Greenland and Canada, or people with high intake of some fish species.*"

In addition, the following errata should be noted: the y-axis to the figure on **page 24** is mislabelled and should read 'Concentration, µg/g lipid weight' (i.e., units are µg/g and not ng/g).

AMAP
Arctic Monitoring and Assessment Programme