

Arctic Pollution 2009

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Arctic Monitoring and Assessment Programme (AMAP)

AMAP
Arctic Monitoring and
Assessment Programme

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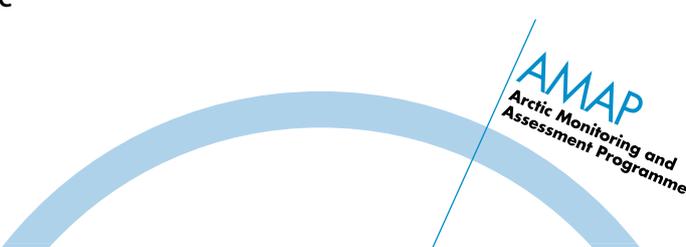
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Preface

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

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

These assessments are delivered to Ministers at appropriate intervals in the form of 'State of the Arctic Environment Reports' on pollution and climate related issues. These reports are intended to be readable and readily comprehensible, and do not contain extensive background data or references to the scientific literature. The complete scientific documentation, including sources for all figures reproduced in this report, is contained in a series of related reports - the AMAP Assessment 2009 reports - or papers specially prepared for publication in the scientific literature, all of which are peer reviewed and fully referenced. For readers interested in the scientific background to the information presented in this report, we recommend that you refer to the AMAP Assessment 2009 reports, or the articles prepared for publication in scientific journals, as listed on page 83 of this report.

This report is the sixth '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 third phase (2002-2008) in relation to three priority areas: persistent organic pollutants, human health, and radioactivity. The assessment described in this report builds upon the previous AMAP assessments that were presented in 1997 and 2002. It updates information presented in the previous assessment reports and addresses new issues and contaminants that were not covered in the earlier assessments.

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

monitoring, have participated in the preparation of this assessment.

AMAP would like to express its appreciation to all of these experts, who have contributed their time, effort, and data; especially those who 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 of the Arctic countries is vital to the success of AMAP. AMAP monitoring work is essentially based on ongoing activities within the Arctic countries, and the countries also provide the necessary support for most of the experts involved in the preparation of the assessments, including the participation of indigenous peoples organizations in the work of AMAP. Canada and Sweden, Canada and Denmark, and Norway and Russia acted as the (co-)lead countries for, respectively, the persistent organic pollutants, human health, and radioactivity components of the assessment. Furthermore, this assessment could not have been delivered without the additional financial support received from Canada and Norway; and from the Nordic Council of Ministers.

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

Tromsø, April 2009



John Calder
AMAP Chair



Lars-Otto Reiersen
AMAP Executive Secretary

Executive Summary

Preamble

The Arctic Monitoring and Assessment Programme (AMAP) was established in 1991 to monitor identified pollution risks and their impacts on Arctic ecosystems. The first AMAP report, Arctic Pollution Issues: A State of the Arctic Environment Report¹ and its update Arctic Pollution 2002² were published in 1997 and 2002, respectively. Three further reports have been published on specific topics: the Arctic Climate Impact Assessment³ (produced by AMAP in cooperation with the Conservation of Arctic Flora and Fauna working group and the International Arctic Science Committee in 2004), and reports on Acidification and Arctic Haze⁴ (2006) and Arctic Oil and Gas⁵ (2008).

These assessments show that the Arctic is closely connected to the rest of the world. The Arctic receives contaminants from sources far outside the Arctic region; Arctic climate influences the global climate and vice versa. The AMAP assessment reports have been welcomed by the Arctic governments, who have 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 and adverse effects of Arctic climate change reported by AMAP.

AMAP information assisted in the establishment, and continues to assist the further evaluation and development of the protocols on persistent organic pollutants (POPs) and heavy metals to the United Nations Economic Commission for Europe's (UN ECE) Convention on Long-range Transboundary Air Pollution (LRTAP Convention) and the Stockholm Convention on Persistent Organic Pollutants. Information from AMAP is useful in documenting trends and in showing whether persistent substances are accumulating in the Arctic, which is relevant with respect to the screening criteria for persistence, long-range transport, and bioaccumulation that are applied to proposals to add substances to the above international agreements.

The Arctic Council's Arctic Contaminants Action Program (ACAP) was established to undertake cooperative actions to

reduce pollution of the Arctic as a direct follow-up to address the concerns raised by AMAP. AMAP information is also used in establishing priorities for the Arctic Council/PAME Regional Programme of Action for the Protection of the Arctic Marine Environment from Land-based Activities (RPA). A number of activities have been initiated to follow-up on the Arctic Climate Impact Assessment.

The current assessment report updates to the information presented in the AMAP 1997 and 2002 assessment reports with respect to three subject areas: persistent organic pollutants, contaminants and human health, and radioactivity. The POPs update has a particular emphasis on 'emerging' and current use POPs. The human health update addresses health effects of POPs, mercury, and lead exposure.

The information presented in the Arctic Pollution 2009 report is based on scientific information compiled for AMAP by scientists and experts, as listed on page 83. The background documents to this assessment have been subject to peer review and are in the process of being published in AMAP scientific assessment reports or scientific journals. All of these documents are made available on the AMAP website, www.amap.no.

This Executive Summary provides the main conclusions and recommendations of the 2009 AMAP assessments.

Persistent Organic Pollutants (POPs)

Legacy POPs

P1. Levels of many POPs have declined in the Arctic environment. This is a consequence of past bans and restrictions on uses and emissions in Arctic and other countries. 'Legacy' POPs that contaminate the Arctic mainly as a result of past use and emissions include PCBs, DDTs, HCB, chlordane, dieldrin, toxaphene, and dioxins.

P2. National policy efforts to reduce the use and emissions of these POPs have been extended regionally and globally through the UN ECE LRTAP POPs Protocol and Stockholm Conven-

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

²AMAP, 2002. Arctic Pollution 2002. Arctic Monitoring and Assessment Programme, Oslo. xii+112 pp

³ACIA, 2004. Impacts of a Warming Arctic. Arctic Climate Impact Assessment. Cambridge University Press. 139 pp

⁴AMAP, 2006. Arctic Pollution 2006: Acidification and Arctic haze. Arctic Monitoring and Assessment Programme, Oslo. xii+112 pp

⁵AMAP, 2008. Arctic Oil and Gas 2007. Arctic Monitoring and Assessment Programme, Oslo. xiii+40 pp

tion, respectively. These initiatives made extensive use of the information presented in AMAP assessments. The Stockholm Convention on POPs explicitly acknowledges that "... Arctic ecosystems and indigenous communities are particularly at risk." The occurrence of chemicals in the Arctic can be evidence of their ability for long-range transport and environmental persistence.

P3. Firm conclusion about the impact of policy decision on environmental levels will require continued monitoring of 'legacy POPs' in both abiotic environments and in key biota. AMAP information on temporal trends in the Arctic has contributed to the evaluation of the 'effectiveness and sufficiency' of the UN ECE LRTAP Convention Protocol on POPs, and the Stockholm Convention.

P4. Additional years of monitoring are needed to increase statistical power of existing time series in order to verify temporal trends. This will allow examination of the response to efforts to reduce global emissions and how this may be affected by climate variability and possible changes in contaminant pathways.

P5. Despite these reductions, concentrations of some legacy POPs, such as PCBs in some top predators in the marine food web, are still high enough to affect the health of wildlife and humans.

Emerging and current-use POPs

P6. Many chemicals in commercial use today have the potential to transport to and accumulate in the Arctic but are not yet regulated by international agreements. Although knowledge about these chemicals in the Arctic remains much more limited than for legacy POPs, new monitoring efforts have extended the information concerning their presence in the Arctic. This information is relevant to ongoing consideration of new chemicals for inclusion under existing national, regional and global agreements to regulate use and emissions of POPs.

P7. Many of these compounds transport over long distances and accumulate in Arctic food webs. New knowledge highlights the potential importance of ocean transport pathways. In contrast to atmospheric pathways ocean currents are slow. This may delay the environmental response to regulations.

P8. Compounds that have some POP characteristics and that are documented in the current AMAP assessment include:

- Brominated flame retardants (BFRs)

The current AMAP assessment includes new information on three groups of chemicals used as flame retardants: polybrominated diphenyl ethers (PBDEs) (including Penta-, Octa- and Deca-BDEs), Hexabromocyclododecane (HCBDD) and tetrabromobisphenol-A (TBBPA). The assessment shows that: Penta-BDE transports over long distances and bioaccumulates in biota. Penta-BDE and Octa-BDEs have been banned/restricted in Europe, parts of North America. They are no longer produced in Russia and use there is very limited. Penta-BDE and Octa-BDEs are under consideration for inclusion under

the international Conventions regulating POPs; Deca-BDEs are now restricted in the EU.

HBCDD is ubiquitous in the Arctic. It undergoes long-range transport and accumulates in animals. It has also been proposed as a candidate for inclusion under international regulations.

There is some evidence that environmental levels of Penta-BDE are now starting to level off or decline due to national regulations and reductions in use and production.

TBBPA is present at low levels in several Arctic animals and plants, but more data are needed to assess its potential to undergo long-range transport.

Some BFRs that are used as substitutes for phased-out substances have been detected in occasional Arctic samples. Their presence in the Arctic is a warning sign that they may have some POP characteristics.

- Fluorinated compounds

Fluorinated compounds reach the Arctic both via the atmosphere and via ocean currents. They are extremely persistent and accumulate in animals that are high in the marine food web.

Production of products containing perfluorooctane sulfonate (PFOS) was substantially reduced in 2001, but PFOS continues to be produced in China. Products that contain PFOS and other fluorinated compounds can still serve as sources to the environment. PFOS and related compounds are currently subject to review for both international and national regulation.

Perfluorooctanoate (PFOA) and other perfluorocarboxylates (PFCAs) continue to be produced. Fluorinated substances can also degrade to PFOA and other PFCAs. Canada is the only Arctic country so far to ban some import and manufacture of several products that are suspected to break down to PFOA and PFCAs.

Precursors of PFOS and PFCAs have been detected in Arctic air and may be a source of PFOS and PFCAs in Arctic wildlife. Concentrations in Arctic air are one order of magnitude lower than in more southern, urban regions.

Time trends of PFOS in wildlife show an initial increase starting in the mid-1980s. In recent years, some studies show a continuing increase while others show a sharp decline. The declines follow reduction in PFOS production.

PFCAs have increased in Arctic wildlife since the 1990s, reflecting continued production of their precursors.

- Polychlorinated naphthalenes

Polychlorinated naphthalenes (PCNs) are no longer manufactured and levels in the environment peaked almost half a

century ago. However, PCNs are still present in the Arctic with indications of further input from a combination of combustion sources and emission from old products. There are no studies to assess their temporal trends in the Arctic. They contribute to dioxin-like toxicity in Arctic animals but are generally much less important than PCBs.

- Endosulfan

Endosulfan is a pesticide that is still in use in many parts of the world. Endosulfan and its breakdown products appear to be persistent in the environment. The presence of endosulfan in the Arctic confirms its ability to transport over long distances. There is clear indication of bioaccumulation in fish but there is no evidence for biomagnification by marine mammals.

Long-term trend analysis of samples taken at Alert (Ellesmere Island, Canada) indicates that endosulfan concentrations have remained unchanged in the remote Arctic atmosphere, unlike most legacy POPs. Calculations based on air and seawater concentrations suggest that endosulfan enters open (i.e. ice-free) waters of the Arctic Ocean.

The limited information available in wildlife indicates that concentrations of endosulfan and its breakdown product endosulfan sulphate in blubber of marine mammals are an order of magnitude lower than those of major legacy POPs such as DDT and chlordane.

Endosulfan is currently under discussion for inclusion under the UN-ECE LRTAP POPs Protocol and the Stockholm Convention.

- Other current-use pesticides

Previous AMAP assessments have highlighted lindane (gamma-hexachlorocyclohexane [HCH]) as a current-use pesticide that is ubiquitously present in the Arctic. Several other current use pesticides (including chlorpyrifos, chlorothalonil, dacthal, diazinon, diclofol, methoxychlor, and trifluralin) have been detected in the Arctic. The levels are often low, but their presence shows that they can transport over long distances and accumulate in the food web.

Biological effects

P9. Recent studies of biological effects of POPs have been able to confirm the causal link between POPs and observations of adverse health effects in Arctic top predators. These controlled experiments on sled-dogs and captive Arctic foxes show effects on hormone, immune and reproductive systems.

P10. The observed effects are mainly due to the breakdown products, indicating that these may be more important than the original POP compounds.

Contaminants and Human Health

Population health and effects of contaminants

H1. In light of current studies, many indigenous populations in the Arctic region have poorer health than national averages. While socioeconomic conditions and lifestyle choices are major determinants of health, contaminants may also have a contributing effect. Toxicological studies show that contaminants, at the levels found in some parts of the Arctic, have the potential for adverse health effects in people. Epidemiological studies, looking at Arctic residents directly, provide evidence for subtle immunological, cardiovascular, and reproductive effects due to contaminants in some Arctic populations. These results indicate that POPs, mercury, and lead can affect health of people and especially children at lower levels of exposure than previously thought. Genetic characteristics of the various Arctic populations also affect their response to contaminants and susceptibility to certain diseases.

H2. A major dietary shift from traditional to store-bought food is underway in most of the Arctic, with important health implications. In addition to environmental concentrations of the contaminants in traditional foods, lifestyle factors and social and cultural practices play a large role in determining human exposure to contaminants in Arctic areas. Despite changes in lifestyle and diet that are resulting in increasing consumption of store-bought foods, traditional foods remain important to Arctic indigenous peoples for social, cultural, nutritional, economic, and spiritual reasons. Store-bought foods are increasingly the main source of dietary energy, but traditional foods provide many nutrients and are still a major contributor to healthy diets in many communities. Some traditional foods can also carry potential risks from contaminants. The combination of high prices for store-bought foods and the work, risks, and costs associated with obtaining traditional foods has made food security a large concern for many Arctic residents.

H3. Recent studies have found a number of mechanisms by which contaminants can affect metabolism. Obesity is associated with an increased risk of cardiovascular disease and of developing diabetes; as in other parts of the world, obesity is increasing in Arctic communities. POPs, even at low concentrations, also increase the risk of diabetes. These new findings emphasize the need to consider the interactions between contaminants and other health conditions.

Trends in exposure and contaminant levels

H4. Human exposure to most legacy POPs and mercury is decreasing in many Arctic populations. This reflects changes in diet, changing levels of environmental contamination, and health advice to critical groups in some areas concerning consumption of certain foods; however, exposure remains high in some popula-

tions. The proportion of women of childbearing age who exceed blood level guidelines for PCBs, mercury, and lead is decreasing. For PCBs and lead, in particular, there is evidence that this reflects the declines in environmental levels of these contaminants.

H5. Marine mammals remain a major dietary source of POPs and mercury, so that people who eat large quantities of marine mammals have higher POPs and mercury levels than those who do not.

H6. Emerging compounds such as brominated flame retardants and fluorinated compounds are a concern for three reasons: they are present in Arctic people and biota, levels globally have increased over the last 15 years, and their toxic effects have not been studied in detail. There is little information on the routes of exposure or trends of these contaminants in Arctic populations.

H7. Reliable interpretation of information on trends and inter-regional differences is critically dependent on an ability to compare data from different studies and different laboratories. Laboratory performance testing procedures initiated by AMAP and others, including the AMAP inter-laboratory comparison programme for analysis of contaminants in human tissue have markedly improved analytical co-operation, data comparability, data reliability and data accuracy in studies using the participating laboratories, and have led to more reliable data on contaminant levels in human tissues. Further improvements can be achieved through continued efforts in this respect.

H8. Increased industrial activity in parts of the Arctic is likely to lead to an increase in local sources of contaminants. Anticipated changes in global and Arctic climate may also result in changes in contaminant transport to the Arctic. Such changes may affect exposure patterns to some contaminants.

Communication

H9. Communicating the results of studies concerning contaminants and people is important in helping Arctic residents make informed food choices. Health advisories issued in response to findings reported in past AMAP assessments have succeeded in reducing exposure to contaminants in some Arctic population groups.

H10. Risk communication must be carried out with great care and respect for culture at a community-level. The involvement of community members and organizations, regional health officials, and indigenous organizations is the key to developing and disseminating messages that are appropriate and relevant.

Radioactivity

R1. Radioactivity in the Arctic is a concern because contamination can persist for long periods in soils and some plants and because pathways in the terrestrial environment can lead to high exposures of people.

Potential sources

R2. In parts of the Arctic, there is a very high density of sources of radionuclides. The risk of accidents combined with the vulnerability of the Arctic environment to radioactive contamination raises a need for continued actions to reduce risks.

R3. Partly as a result of national and international actions addressing concerns highlighted by AMAP, significant progress has been made with respect to actions to reduce risks of radioactive contamination from several of these potential sources. Previous AMAP assessments recommended actions to address potential sources of radioactive contamination of the Arctic including nuclear powered vessels that were poorly maintained or being decommissioned; dumped and stored radioactive wastes, including wastes stored under inadequate conditions; radioisotope thermoelectric generators (RTGs) used as energy sources in northern regions; and nuclear power plants and reprocessing facilities located close to the Arctic. Many of these potential sources are located in northwest Russia. Other issues remain a source of concern:

- As of 2008, 164 of the 198 obsolete nuclear submarines of the Russian northern fleet had been defueled and dismantled; work to safely decommission these vessels continues. Similar plans exist for dealing with nuclear icebreakers and their associated facilities, including the Lapse storage vessel.
- The facilities at Andreeva Bay and Gremikha are used as temporary storage sites for radioactive wastes, spent fuel, and reactors from decommissioned submarines. Progress has been made in improving the physical infrastructure and the legal arrangements to manage these sites. However, much remains to be done, including transport of spent fuel and waste to safer storage sites.
- About half of the radioisotope thermoelectric generators (RTGs) in northern Russia have been removed or will be in the near future.

R4. Some risk reduction has been achieved through significant joint Russian-international action. This includes a regulatory framework for handling the clean-up actions. Moreover, a long-term strategic master plan has been developed, which could become an important tool for further management of radiation risks.

New potential sources

R5. Russian plans for building floating nuclear power plants raise issues about how waste will be handled and about increased marine transport of spent fuel in the Arctic. These power plants would represent new potential sources and may increase risks of radioactive contamination.

R6. Technologically enhanced naturally occurring radioactive material (TENORM) can become a radiation risk in context of mining of uranium and other minerals, phosphate production, oil- and gas extraction, coal mining and the use of geothermal en-

ergy. Several of these activities are likely to increase in the Arctic and more knowledge about waste streams and releases are needed in order to assess human and environmental risks.

Historical contamination

R7. Previous AMAP assessments documented fallout from past nuclear weapons tests, the 1986 Chernobyl accident, and releases from reprocessing plants close to the Arctic as the three major sources of anthropogenic radioactive contamination in the Arctic. Evidence from long-term monitoring in the European Arctic shows that levels of radioactivity in the environment are declining. However, monitoring and mapping activities have decreased in recent years and documentation is therefore lacking for much of the Arctic. Unless environmental pools are re-mobilized, this historical contamination will continue to decrease as sediments are buried and radionuclides decay.

R8. Application of new technology has reduced routine releases of radionuclides to the marine environment from European reprocessing plants, including releases of technetium-99 from Sellafield that were highlighted in the 2002 AMAP assessment.

Climate change and radioactivity

R9. The current assessment identifies the potential of climate change to mobilize radionuclides in the Arctic terrestrial environment and in glaciers. This may also affect radon emission from the ground, which is a major contributor to human exposure to radiation.

R10. Changes in permafrost, erosion, precipitation and extreme weather events may also affect infrastructure related to nuclear activities.

Protecting the environment

R11. Following recommendations of previous AMAP assessments, a framework for protecting Arctic ecosystems from radiation effects has been developed as a complement to the previous focus on protecting human health. It also opens for assessing combined effects with other environmental stressors. There is a need for more data that are relevant for Arctic conditions and organisms to provide the basis for a comprehensive application of this framework.

Recommendations for actions to reduce contaminant levels and effects through international agreements:

- *Encourage countries that have not yet done so to sign and ratify the Stockholm Convention and LRTAP POPs Protocol (P2, H2, H4, H5).*
- *Support the addition of polybrominated compounds and fluorinated compounds to the Stockholm Convention and the regulation of these compounds under other international and*

national mechanisms because they undergo long-range transport and bioaccumulation in human tissues similar to other POPs. (P2, P3, H6)

- *Support the development of a global agreement to limit mercury emissions to complement regional and national efforts that reduce environmental levels and lower human exposure to mercury in the Arctic. (H1)*

Recommendations for actions to promote healthy diets and reduce human exposure to contaminants:

- *Continue to encourage public health officials to recommend breast feeding among Arctic populations as a health practice that optimizes infant growth and development. (H2, H9)*
- *Recommend to health authorities to promote healthy diets through improved access to and consumption of local traditional foods that are high in nutrients but relatively low in contaminants along with improved availability and consumption of store-bought foods with high nutritional value. (H2)*
- *Evaluate past communication efforts in order to improve and refine communication strategies. (H9)*

Recommendations to address potential sources of radioactivity:

- *Continue work to decommission remaining obsolete nuclear vessels, remove remaining RTGs, and to manage spent nuclear fuel and waste at sites in or close to the Arctic. (R3)*
- *Implement additional actions to address continued concerns, especially the storage facilities at Andreeva Bay and Gremikha, and the Lapse storage vessel (R3)*
- *Strengthen plans to ensure safe and secure transport of spent fuel and waste to storage facilities. (R3)*
- *Consider the need to further develop regulatory systems, especially for addressing clean-up operations and improved safety of nuclear facilities. (R4)*
- *Increase attention to technologically enhanced naturally occurring radioactive materials (TENORM) in future assessments, including information from all countries engaged in or planning Arctic oil and gas extraction and uranium and other mining. (R6)*

Recommendations for actions to address gaps in knowledge concerning combined effects:

Monitoring

- *Continue and enhance the geographical coverage of monitoring programs to:*
 - *Document the effectiveness of controls on the use and emissions of POPs (P2, P3, P4)*

X

- Investigate the possible effects of climate change on Arctic contaminants levels, including changes in transport and remobilization (P4, H8, R9, R10)
- Detect health threats related to climate change and contaminants (H8)
- Identify new sources of contaminants and new contaminants that may pose a threat to Arctic residents and the environment (P6, H6, R7)

Research

- Investigate the respective and combined roles of changing contaminant emissions, changing pathways due to climate change, local sources of contamination, and dietary change to determine the causes of changing environmental levels and human exposures. (P4, H8, R9, R10)
- Improve predictive models of contaminant transport and behaviour in the Arctic to better understand the likely impacts of climate change with respect to contaminant levels and human exposures. (P4, H8)
- Conduct further studies to better understand the combined effects of contaminants and other stressors on Arctic wildlife and humans. (P5, P9, H8, R11)
- Include in future assessments the combined effects of POPs, radioactivity, and other stressors on human health and the environment in the Arctic (P5, P9, H8, R11)

Recommendations to address gaps in knowledge concerning POPs:

Monitoring

- Continue monitoring of occurrence and trends of brominated flame retardants (including alternatives being introduced to replace phased-out BFRs) and fluorinated compounds. (P8)
- Increase monitoring of current-use pesticides and their breakdown products in the Arctic environment. (P7)

Research

- Examine the many other chemicals in commerce, such as the cyclic siloxanes for potential Arctic accumulation potential and design programs to search for these chemicals and their breakdown products (to avoid past surprises such as detection of PFOS). (P8)

Recommendations to address gaps in knowledge concerning human health:

Monitoring

- Continue and extend the laboratory intercomparison and testing schemes introduced and promoted by AMAP for laboratories engaged in analysis of Arctic human media to cover emerging POPs. The quality assurance group for the human health program should be provided with adequate resources to ensure quality assurance/quality control on an ongoing basis. Only data that have been approved by this group should be used in AMAP human health assessments. (H7)
- Continue to monitor for trends in legacy POPs, mercury, and lead in human tissues and traditional food items. Dietary assessments should combine contaminant and nutrient analyses in traditional foods as consumed. (H2, H4)
- Conduct further studies combining dietary assessments with contaminant and nutrient analyses in the traditional foods as consumed. (H2)
- Continue and expand monitoring for emerging POPs in human tissues and traditional food items, including development of analytical methods (H6)(H7)
- Continue gathering basic health statistics on a regular basis by all circumpolar jurisdictions at appropriate regional levels, including ones not currently gathered in all areas (e.g., neonatal vs. post-neonatal death rates in Russia).(H2)

Research

- Maintain and expand current human population cohorts in the Arctic in order to provide the information needed to track adverse health outcomes associated with contaminants and changing conditions related to climate change, socio-cultural conditions, and diet. (H1, H2, H3)
- Conduct further research on contaminant effects in humans, including interaction between POPs and mercury and other factors such as genetic susceptibility, diet, and lifestyle, and the resulting health impacts on the cardiovascular, reproductive, neurological or metabolic systems. (H1)(H2)(H3)
- Conduct further studies to determine causes of regional variations and discrepancies in exposure to contaminants (e.g., low mercury levels in Chukotka in contrast with high POPs levels). (H2)(H8)
- Conduct further toxicological studies of POPs mixtures, and emerging compounds where a lack of information is limiting human health risk assessment. (H1)
- Conduct further studies on risk perception, dietary patterns, and determinants of food choice to improve risk communication. (H9)

Recommendations to address gaps in knowledge concerning radioactivity:

Monitoring

- *Improve coverage and implementation of monitoring of radioactivity in the Arctic to meet AMAP objectives and/or to highlight specific regional needs. (R7)*
- *Improve collection and reporting of data relevant to Arctic species and conditions to allow improved radiation protection of Arctic ecosystems. (R11)*

Introduction

This report is the sixth 'State of the Arctic Environment' report addressing environmental contaminants and related matters in the Arctic that has been produced by the Arctic Monitoring and Assessment Programme (AMAP). The first AMAP scientific assessment report, *AMAP Assessment Report: Arctic Pollution Issues*, was published in 1998. An accompanying plain-language summary, *Arctic Pollution Issues: A State of the Arctic Environment Report*, was released the year before. In 2002, AMAP published a series of scientific updates on specific topics (persistent organic pollutants (POPs), heavy metals, radioactivity, human health, and changing pathways), which were also summarized in plain-language format in *Arctic Pollution 2002*. Further scientific assessments were summarized in the reports *Arctic Climate Impact Assessment: Impacts of a Warming Arctic*, *Arctic Pollution 2006: Acidification and Arctic Haze*, and *Arctic Oil and Gas* that were published in 2005, 2006 and 2007, respectively, each expanding what had been one chapter in the first AMAP Assessment.

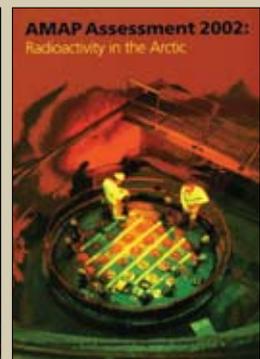
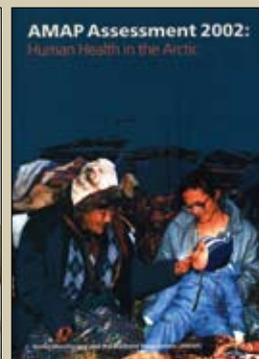
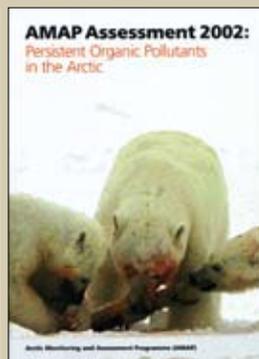
The current report provides new and updated information in three areas: persistent organic

pollutants (POPs), human health, and radioactivity. For these subject areas, new AMAP scientific assessments have been conducted, with results being published in AMAP reports or as papers in the scientific literature. The scientific products and publications upon which this report is based have been subject to rigorous peer review to make sure they are accurate, thorough, and up-to-date. From these materials, this plain-language summary has been written to capture the main messages and make them accessible to general readers. The summary has been reviewed by the authors of the scientific reports, by the members of the AMAP Working Group, and through national review processes in each Arctic country. These reviews have ensured that the summary is an accurate representation of the scientific reports.

Because this sixth assessment is an update and extension of previous assessments (in particular those reported in the 1997 and 2002 AMAP reports), its contents emphasize new material rather than general or introductory descriptions of the topics that are addressed.

Previous AMAP Assessments of POPs, Human Health and Radioactivity

This report updates previous AMAP assessments published in 1997 and 2002.



► During the winter, periods of low precipitation and strong winds contribute to the formation of Arctic haze. Pollution events can also occur at other times of the year as illustrated by these photos from Svalbard showing the results of pollution from agricultural burning in Eastern Europe combined with an extreme weather situation.



Ann-Christine Engvall

For POPs, this assessment provides some updated information about changes in levels in the Arctic environment of persistent organic pollutants that are classified as ‘legacy’ contaminants. The emphasis, however, is on persistent chemicals that are still in use and new chemicals that have been added to the list of substances that may be of environmental concern in the Arctic. They include brominated flame retardants, fluorinated compounds, polychlorinated naphthalenes, and endosulfan along with some discussion of other current-use pesticides and high-volume chemicals. The chapter also provides an update on the implications of POP exposure on effects in Arctic wildlife.

For human health, new information is available about the levels of contaminants in humans and the impacts of contaminants on various aspects of human physiology and disease. The interaction of lifestyle factors with contaminants is an emerging topic of research, as is the potential role of genetic characteristics in determining susceptibility to effects. Risk communication is examined in greater detail than has been done previously.

For radioactivity, this assessment provides an update on sources and potential sources of radioactivity to the Arctic environment, including the results of efforts to reduce the risks associated with waste handling and decommissioning of old nuclear-powered equipment. It also discusses changes

in the range of actual and potential sources and highlights that non-nuclear industrial activities may increase the release of naturally occurring radioactive substances to the environment. While previous assessments have mainly addressed the risks of radioactivity related to human health, this assessment also addresses the impacts on Arctic ecosystems and non-human biota. In addition, it includes a discussion of how climate change may affect radioactive contamination in the environment.

Common to all chapters is that climate change provides a new context for assessing the transport, trends and potential impacts of contaminants in the Arctic. This introduction therefore provides some general comments about contaminant pathways and climate change based on previously published information.

Climate patterns affect contaminant transport

In recent decades, much of the Arctic has experienced a warming trend. In northwestern Canada, central Alaska, and eastern Siberia, the warming has been as much as 3.5°C during winter months. The eastern Canadian Arctic and southern Greenland have seen a modest cooling trend, but the overall pattern in the Arctic has been warming. Permafrost has warmed and even thawed, sea ice has retreated, the treeline has moved northwards, and other ecosystem changes have taken place on land and at sea. The factors driving climate change in the Arctic are the same as those acting globally: greenhouse gases, solar variability, ocean processes, and volcanoes.

Weather in the Arctic varies greatly on short and long time scales. Over the North Pole, there is a permanent wind pattern that creates the Arctic Polar Vortex. Strongest in winter, this circulation pattern produces high pressure areas over Siberia, the Yukon, and Baffin Island, and low pressure areas over the Aleutian Islands and the North Atlantic. These weather systems transport airborne contaminants to the Arctic. Some contaminants are removed from the air by precipitation or deposition. Ocean currents also transport contaminants, though much more slowly than air currents.

The Arctic Oscillation Index reflects the relative air pressure at sea level in the High Arctic compared with the mid-latitude North Atlantic, relative to a 50-year norm. A positive index indicates lower pres-

sure in the Arctic and higher pressure in the North Atlantic. This changes winds and the circulation of seawater and ice in the Arctic Basin. More warm, wet air is carried into the Arctic from the North Atlantic. The waters from Russian rivers are carried towards the Canadian Arctic Archipelago. Contaminants from those rivers thus reach northern Canada under a positive Arctic Oscillation.

When the index is negative, Arctic air is colder, and cold air flows towards the mid-latitudes of North America and Eurasia. Russian river discharge and sea ice are carried towards Fram Strait and the North Atlantic, increasing contaminants exposure in East Greenland. The Arctic Oscillation Index was low and variable from the 1950s through the late 1980s, when it became strongly positive for about a decade. Since 2000, the index has generally returned to its earlier pattern.

Other regional and global climate patterns and events can affect contaminant transport to the Arctic. In the North Atlantic, ocean currents carry warm, salty water northeast across the Atlantic to Scandinavia and the Barents Sea, producing relatively warm weather for the latitude. Water from the North Pacific flows northwards through the Bering Strait, where water temperatures have been rising over the past three decades. Further to the south, upwelling of warm water off the western coast of South America produces an El Niño event. One result of an El Niño is greatly increased wind transport towards Baffin Island, carrying contaminants from southern latitudes to that region.

Projections of future climate change in the Arctic indicate that conditions are likely to resemble

Contaminants transport pathways

Contaminants reach the Arctic via a number of different pathways. Winds provide a fast route for volatile contaminants and for substances that adhere to small particles. Air transport is especially pronounced in the winter. With rain and snow many contaminants are washed from the air and deposit on on the sea ice, open water, or on the ground, where some of them end up in meltwater and rivers. Rivers carry contaminants and process them through sedimentation and resuspension of particles. Lakes, deltas and estuaries can serve as sinks for contaminants in sediment. Ocean currents are slow but important pathways for contaminants that partly dissolve in water. In addition to the physical pathways, migratory animals also play a role for contaminant transport in the Arctic, and locally this pathway can be very important.

a strong positive Arctic Oscillation. The resulting impacts on contaminant levels, trends, and geographical patterns are difficult to predict because many physical, chemical, and biological factors are involved. Human exposure, for example, may be affected by changes in the distribution of species that are hunted, resulting in different pathways of exposure. The release of contaminants from human activity, too, is likely to change, with increases in some contaminants and decreases in others. Furthermore, some effects of climate change will take place quickly, and others slowly. The following are some examples of how climate change may affect contaminant pathways:

Higher temperatures at lower latitudes will increase the volatilization of contaminants. Combined with increased air transport to the Arctic that occurs during strongly positive phases of the Arctic



◀ The island of Bjørnøya (Bear Island) mid-way between the Norwegian mainland and Svalbard receives contaminants transported by winds, ocean currents and by biota.

Oscillation, the delivery of contaminants to the Arctic will increase. If precipitation increases, many contaminants will be taken from the air and deposited on the ground or in the water. Reduced sea ice increases the exchange of contaminants between the ocean and the atmosphere. Deposition of airborne contaminants into the Arctic Ocean could increase, whereas other contaminants that have are currently stored in the ocean water may more readily be emitted from the ocean to the air.

As precipitation increases over land, river flow will increase, resulting in greater delivery of contaminants to coasts. Depending on suspension processes close to the coast some of these will reach the Arctic Ocean. The ocean circulation regime in the Arctic Basin could carry contaminants either through the Canadian Archipelago or via Fram Strait, exposing different parts of the Arctic to the increased contaminant burden.

Climate change may also make contaminants less likely to remain in the Arctic. For examples, higher temperatures and less sea ice can result in more re-emissions of contaminants to the air where they can be transported out of the Arctic more readily than in the past. Changes in the flow of ocean water and sea ice may also increase contaminant transport southwards. The net influence of climate change on contaminant levels cannot therefore be easily predicted.

Biological processes add further complexity. Higher temperature will affect the biological activity but different processes can act in different directions. For example, warmer water and ground will increase microbial activity, which could reduce the lifespan of some substances. However, as Arctic ecosystems become more productive in response to warming, the uptake of contaminants may increase, which could result in higher levels in biota.

Persistent Organic Pollutants

Introduction

When AMAP presented its first major assessment of pollution in the Arctic in 1997/98, available data showed that persistent organic pollutants were ubiquitous throughout the Arctic, also in areas where they had never been used. As the name indicates, persistent organic pollutants (POPs) have chemical properties that make them very long-lived in the environment. The presence of POPs in parts of the Arctic where there are no human activities to explain the contamination showed that the northern polar region served as a sink for pollutants that had been transported over long distances. Many of these chemicals accumulate in wildlife and people, where they can reach levels that are much higher than in the surrounding water or air.

Many POPs are also toxic and can harm both people and wildlife when levels in the environment are high enough. Data in the 1997/98 AMAP assessment showed the levels of POPs in the Arctic were high enough to cause concern for human health among some indigenous populations and for the health of some marine mammals and birds. This general picture was confirmed in AMAP's 2002 assessment, where the authors presented a tentative conclusion that POPs might be affecting the ability of polar bear populations to reproduce. The 2002 assessment also highlighted that levels of POPs were high enough to affect the ability of polar bears to fight infections and influence the reproductive behavior of some seabirds. Concerns for human health were also confirmed, leading to discussions about the need to find ways to reduce the intake of contaminants. However, the only long-term solution to the high levels of POPs in the Arctic is to reduce the emission of POPs into the environment.

The increased knowledge about the POPs in the Arctic has had political impact. The 1997/98 assessment and the data it presented played an important role in negotiations resulting in the Stockholm

Convention on Persistent Organic Pollutants. In fact, the Stockholm Convention highlights the risk that POPs pose to Arctic ecosystems and indigenous people. It also emphasizes the Arctic as a region that can serve as an indicator of chemicals being persistent and able to transport to the Arctic over long distances from more southerly regions. In addition to the Stockholm Convention, the data compiled for the 1997/98 AMAP assessment played an important role for the 1998 POPs Protocol of the United Nations Economic Commission for Europe (UN ECE) Convention on Long-range Transboundary Air Pollution. At a regional level, the Arctic Council Action Plan to Eliminate Pollution of the Arctic was launched and has led to a range of specific activities to address sources in the Arctic. It has since evolved into a working group within the Arctic Council: the Arctic Contaminants Action Program.

For POPs that are classified as legacy contaminants because their use has been mainly in the past, this assessment provides updated information about the levels in the Arctic environment, including some good news about declining levels of substances that have been regulated or banned. However, many persistent chemicals are still in use and new chemi-

▼ Oil drums discarded by the U.S. military on the Melville Peninsula, Nunavut, Canada.



Bryan and Cherry Alexander

► As old BFR-containing products are discarded, wastes may continue to be a source to the environment long after use of specific BFRs in new products has been restricted or banned.

icals have been added to the list of substances that may be of environmental concern. Among these, AMAP's 2002 assessment highlighted brominated chemicals that impart fire resistance and fluorinated compounds that provide stain and water repellency. Other chemicals that raise concern include pesticides that are still in wide-spread use. This chapter provides a thorough assessment of levels and trends in the Arctic of brominated flame retardants, fluorinated compounds, polychlorinated naphthalenes, and endosulfan along with some discussion of other current-use pesticides and of high-volume chemicals. It also provides an update on trends of legacy POPs and a discussion of the implications of POP exposure on effects in Arctic wildlife in the context of other environmental stressors. Major conclusions are presented in a summary at the end of the chapter. Implications for people living in the Arctic are discussed in the chapter Human Health.

Conventions provide policy context

Several global and regional conventions are relevant for POPs. The Stockholm Convention on Persistent Organic Pollutants addresses twelve priority POPs, while the POPs protocol of the UN ECE Convention on Long-range Transboundary Air Pollution (UN ECE LRTAP) covers an additional four. The overall aim is to phase out deliberate production and use and to reduce or eliminate inadvertent emissions from industrial processes. The North-American Commission for Environmental cooperation initiative on the Sound Management of Chemicals is another relevant treaty for international POPs management. For details on these conventions see page 34.

As the production and use of regulated POPs declines, new input into the environment will eventually cease. However, because of their characteristics, POPs will remain in the environment for many decades as a legacy of past use. POPs that have been banned are sometimes referred to as legacy POPs. The previous AMAP reports have thoroughly assessed the distribution and impacts of legacy POPs.

The growing knowledge about POPs and how they behave in the environment have raised concern about several groups of chemical that are still in use but have not been studied for as long as the legacy POPs. The Stockholm Convention and the POPs Protocol of UN ECE LRTAP Convention have defined procedures for adding new substances



into the framework of international regulation. A key concern is to identify those substances that are persistent, can travel far in the environment, accumulate in plants, animals and their ecosystems, and are toxic. Based on past experience and increased knowledge about the physical pathways and behavior of POPs in the environment, the Arctic has been highlighted as an indicator region for the persistence of chemicals and their ability for long-range transport. The presence of chemicals in the Arctic environment is thus a warning signal to policy makers that there is a need for regulation. This chapter highlights several groups of chemicals where new data indicate a need for further action.

Brominated flame retardants

Brominated flame retardants (BFRs) are chemicals used in materials to make them fire resistant. They are organic compounds containing bromine atoms. BFRs have been used in a range of products including polyurethane foam, plastics for electronic equipment, circuit boards and extruded plastic (Styrofoam), textile used for furniture, carpets and curtains, rubber for coating wire, etc. Many countries have legislated high fire safety standards, which has led to an increased use of flame retardants. The different technical products are presented in more detail on the next page.

Similarities to POPs

BFRs have many chemical characteristics that make them behave in ways that are similar to legacy POPs. Some BFRs transport over long distances and accumulate in aquatic food webs. BFR exposure in wildlife can lead to similar as well as different effects compared to legacy POPs, where the effect depends on the chemical structure and which biochemical processes are "disrupted." Monitoring levels in the

environment and possible adverse effects on wildlife have therefore been a high priority and indications of potential problems have led to bans on some BFRs.

The understanding of biological effects of BFRs is not as developed as for legacy POPs. However, for some compounds, studies on laboratory rodents have shown toxic effects. For PBDEs, these include effects on the immune system, neurotoxic effects, and effects on thyroid and sex hormones and reproduction. Other BFRs affect the liver and thyroid hormone systems, and cause neurobehavioral changes (HBCD and TBBPA) or effects on reproduction (TBBPA).

Consumer products are sources to the environment

Most BFRs are added into products during manufacture and are not chemically bound to the material. These may migrate out into the environment. Others react chemically with the material. For these BFRs, the risk of migration into the environment is mainly connected to the chemical reactions not being complete thus leaving a residue that can migrate. BFRs can also enter the environment when the material is destroyed, for example when it is burned as trash or left on dumps where it is exposed to sunlight and other factors that break down plastics. The long life time of products with BFRs will lead to continued release into the environment several decades after the production and use of a certain BFR has ceased. Some BFRs have for example been found at relatively high levels in sewage sludge.

Technical products and their regulatory status

Polybrominated diphenyl ethers: PBDEs

There are three technical PBDE products: PentaBDE, OctaBDE and DecaBDE. The major difference is the number of bromines in the major compounds in the mixture of brominated diphenyl ethers. PentaBDE has been used in polyurethane foams (mattresses, furniture, pillows) and in adhesives, while OctaBDE has been used in hard plastics such as computer casings and monitors. Penta- and OctaBDE were banned in the European Union and in Norway in 2004, including a ban on import and export of products containing these BFRs. The sole manufacturer of Penta/OctaBDE in the United States voluntarily discontinued production at the end of 2005. Both compounds are on a list of chemicals proposed for inclusion in

the Stockholm Convention for consideration in 2009 and the UN ECE POPs Protocol.

DecaBDE is used in plastics such as high impact polystyrene in electrical equipment, in coating for wiring as well as in textile back coating for furniture. In most countries, there are currently no restriction on the production and use of DecaBDE. However, a recent court ruling on the EU directive on the restriction of certain hazardous chemicals has led to its ban within the European Union as of July 2008.

HBCD: Hexabromocyclododecane

Technical HBCD is used in expanded and extruded polystyrene foams (EPS and XPS respectively). Such foams are used for insulation in buildings and in roads to prevent frost-heaving. HBCD is also used in textile back-coating of furniture. As of 2008, there were no restrictions on the production and use of HBCD. A risk assessment is currently being completed within the European Union. HBCD has been proposed for inclusion in the Stockholm Convention but is only at the proposal stage and a risk profile will not be prepared before 2010.

TBBPA: tetrabromobisphenol A

TBBPA is used primarily as a reactive flame retardant in printed circuit boards, and is thus chemically bound to material in electrical and electronic equipment such as TVs, computers, printers, fax machines, cell phones, videos, washing machines etc. It is also increasingly being used as an additive flame retardant in hard plastics, as a replacement for banned BFRs. As of 2008, there were no restrictions on the production or use of TBBPA. A risk assessment has recently been performed within the European Union with the conclusion that, gener-

▼ HBCD is used as a fire retardant in building insulation materials.



ally, no health and environmental risks were identified with TBBPA when used reactively but that there is a need for specific measures to limit risks when TBBPA is used as an additive flame retardant. Moreover, there is a need for further information to determine whether TBBPA can break down by losing bromine atoms and eventually form bisphenol A, which is a hormone-disrupting compound.

Other BFRs

In addition to the brominated compounds that have been subject to policy discussions, a range of other brominated flame retardants have been used or are still in use. Some of them have already been banned. Others are considered possible substitutes for products that are known to have POP characteristics. The following are some examples:

- polybrominated biphenyls (PBB), production has also ceased;
- decabromodiphenyl ethane (DBDPE), considered an alternative to DecaBDE;
- 1,2-Bis(2,4,6-tribromophenoxy)ethane (BTBPE), Hexabromobenzene (HxBBz); Pentabromoethylbenzene (PBEB); Pentabromotoluene (PBT); and 1,2-Dibromo-4-(1,2-dibromoethyl)cyclohexane (TBECH), considered alternatives for Penta- and OctaBDE.

Production, import and export

The United States is the only Arctic country that is currently producing BFRs. An inventory in 2002 of the use of BFRs in the Arctic countries showed that all countries that took part the inventory (all except Iceland) imported BFRs to use in manufacturing of various products. In turn, the Arctic countries exported goods that contained BFRs to other countries. There were many uncertainties in import/export numbers but in general Scandinavian countries and Russia have lower use of BFRs than Canada and the United States. The table below shows the annual world-wide market.

Estimated annual worldwide market demand of BFRs in 2001 by region, and total estimated demand in 2002 and 2003 (metric tonnes).

	PentaBDE	OctaBDE	DecaBDE	TBBPA	HBCD
Americas	7100	1500	24500	18000	2800
Europe	150	610	7600	11600	9500
Asia	150	1500	23000	89400	3900
Total (2001)	7500	3790	56100	119700	16700
Total (2002)	-	-	65700	150600	21400
Total (2003)	-	-	56400	145100	22000

Transport and pathways to the Arctic

The atmosphere provides a route for long-range transport

Knowledge about the transport of BFRs to the Arctic comes mainly from air samples, where information about the levels and how they change over short time spans can be used to model how these compounds move in the atmosphere. Results from such studies show that several BFRs are capable of long-range air transport. In many cases the composition is similar to the technical PBDE products. Models for the transport of PBDEs show that characteristic travel distances in air vary from below 500 to well over 2000 kilometers.

Compared to PCBs, the Penta- and OctaBDEs appear to have slightly less potential to contaminate the Arctic. The reasons are that they degrade more efficiently in sunlight in the atmosphere during their transport. PBDEs are less volatile making them bind to particles. When there are large numbers of particles in Arctic air, which is the case during Arctic haze events, the transport of PBDEs does take place. Therefore, periods of strong winds



Derek Muir

► Open burning is common in Arctic and sub-Arctic communities where municipal waste is not recycled and cannot be placed in controlled landfills or burned in a controlled manner. Such open burning can cause local emission of BFRs from the products that are burned.

and no precipitation may lead to longer transport distances than the models predict for PBDEs. This includes DecaBDE, which is entirely found on particles and may be capable of long-range transport with Arctic haze aerosols. This behavior could possibly explain episodes of higher PBDE levels in air at Alert in northern Canada, but this needs to be further verified. The highest air concentrations of PentaBDE at the Tagish and Alert sites in Canada were associated with local trash burning.

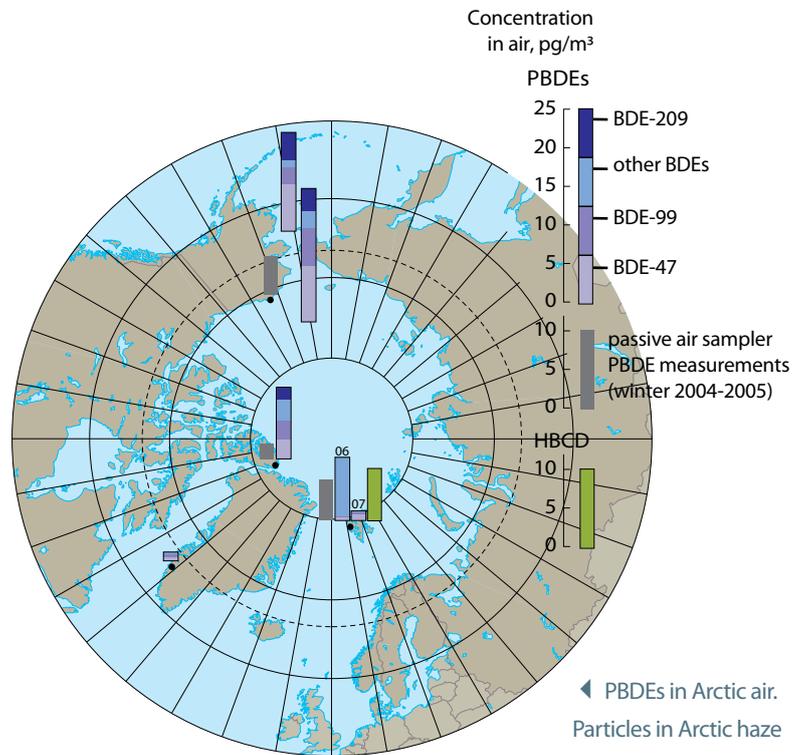
BFRs enter terrestrial food webs

BFRs that are not degraded in the atmosphere will eventually be deposited. PBDEs as well as TBBPA and PBBs have been found in soil and vegetation far from emission sources. The concentrations are quite low compared to legacy POPs. For PBDEs, the composition is similar to the technical PentaBDE product. The presence of these compounds in Arctic vegetation is further evidence that not only the PentaBDEs undergo long-range transport in air but also components of the DecaBDE product, TBBPA and PBB.

BFRs can enter the Arctic food web when animals eat contaminated vegetation. At lower levels in the terrestrial food web, BFRs have been low in the few species that have been studied (frogs, reindeer, grouse, moose and hares from either northern Norway, Sweden or Russia). For PBDEs, the composition is similar to the technical PentaBDE product. Terrestrial mammals that feed on the herbivores (e.g. lynx from Norway) and birds of prey (peregrine falcon from Sweden, Norway and Greenland, golden eagles and merlins from Norway) have higher levels. HBCD, TBBPA, and some PBBs have also been found in birds of prey. The presence of these contaminants in predatory birds shows that BFRs can enter the terrestrial food web.

Lake sediment and freshwater fish provide varied picture

Lakes and rivers can potentially receive BFRs from air as well as from local sources, such as landfills, and from seabird guano. Like most POPs, BFRs tend to associate with particles rather than the water. Measurements of lake sediment show that a few lakes in the remote Arctic have higher concentrations than lakes in industrial areas. A likely explanation for these very elevated concentrations is that these lakes receive BFRs from seabird guano. Generally, however, data



◀ PBDEs in Arctic air. Particles in Arctic haze allow BFRs to transport to the Arctic from more southerly source regions. This may include DecaBDE, which was previously thought not to transport over long distances.

◀ Recent screening studies have found siloxanes in kittiwakes from Svalbard.

▼ Seabirds are responsible for local contamination of some Arctic lakes where contaminants are deposited in seabird guano.



Geir Wing Gabrielsen



Hallvard Strøm/Norwegian Polar Institute

from Arctic lakes showed higher input at more southerly sites in Alaska than in northern Alaska, Canada and Greenland. This may be an effect of the relative proximity to densely populated areas.

The BFR load in lakes is also reflected in freshwater fish, with variations in levels across the Arctic. PBDE concentrations were highest in fish from lakes in the Yukon and much lower in fish from northern Norway and Alaska. Lake Ellasjøen on Bjørnøya is a hot spot for PBDE because of input of seabird guano. High levels have also been found in fish from one site in the Canadian Arctic near an airport. The chemical signature in fish from Canada, Norway, and Alaska confirms technical Penta-BDE as the most likely source.

Lake sediment provides an archive of previous emissions to the environment. Studies of sediment cores from lakes in Arctic Canada and Greenland indicate an increasing input of PBDEs over time. The maximum signal of PentaBDE occurred earlier than the signal for DecaBDE, which was increasing up until the most recent layer (representing the late 1990s).

Rivers are sources to the Arctic Ocean

Rivers are known to be important sources of contaminants to the Arctic Ocean. Measurement of BFRs upstream in the Ob and Yenisey in Russia as well as measurements in their estuaries and further out in the Kara Sea show that BFRs are present in

the river water. The composition indicates technical PentaBDE as the major source. The levels are generally low. The estimated fluxes of sumPBDEs to the Kara Sea were 1.92 kilograms per year from the Yenisey and 1.84 kilograms per year from the Ob. The data confirm suspicions that rivers can serve as sources to the Arctic basin.

Several BFRs have reached the marine environment

Sediment data for the marine environment are available from the Canadian, Norwegian and Russian Arctic. Levels of PentaBDEs range from low at many background sites to higher levels at a site with suspected local contamination at Polyarnyy, Russia. Compared to legacy POPs the background levels are low but higher than in freshwater sediment. HBCD was also detected in sediments outside of Tromsø, Norway (Tromsøflaket) and in the Barents Sea. DecaBDE was found only in the Tromsø area sediments, while levels of TBBPA were below detection limits.

For marine zooplankton, earlier reviews have reported very low levels of BFRs. New results indicate that some invertebrate species that scavenge on dead animals in the water may be exposed to higher concentration, probably because they feed high in the food web. These BFR levels are more similar to mammals and birds high in the marine food web, such as ringed seals and glaucous gulls. The levels in marine zooplankton still are about ten times

The use of BFRs is reflected in the immediate environment. An illustrative example is a study of untreated sewage sludge, marine sediment, invertebrates and fish close to two research stations in Antarctica. At the US base McMurdo, the levels of PentaBDEs in fish were as high as in urbanized areas of North America and decreased with distance from the sewage outfall. Levels at McMurdo were much higher than at a nearby New Zealand base, reflecting the lower use of BFRs in equipment and furnishings at the New Zealand station. Such influence of local use along with measurements showing high levels in sewage sludge indicate that use of material and equipment treated with flame retardants can potentially be a significant local source of BFRs from release of untreated sewage sludge in Arctic communities to local waters. There is no such detailed study for the Arctic but some measurements indicate higher levels closer to settlements.



Lisa Harding, NSF

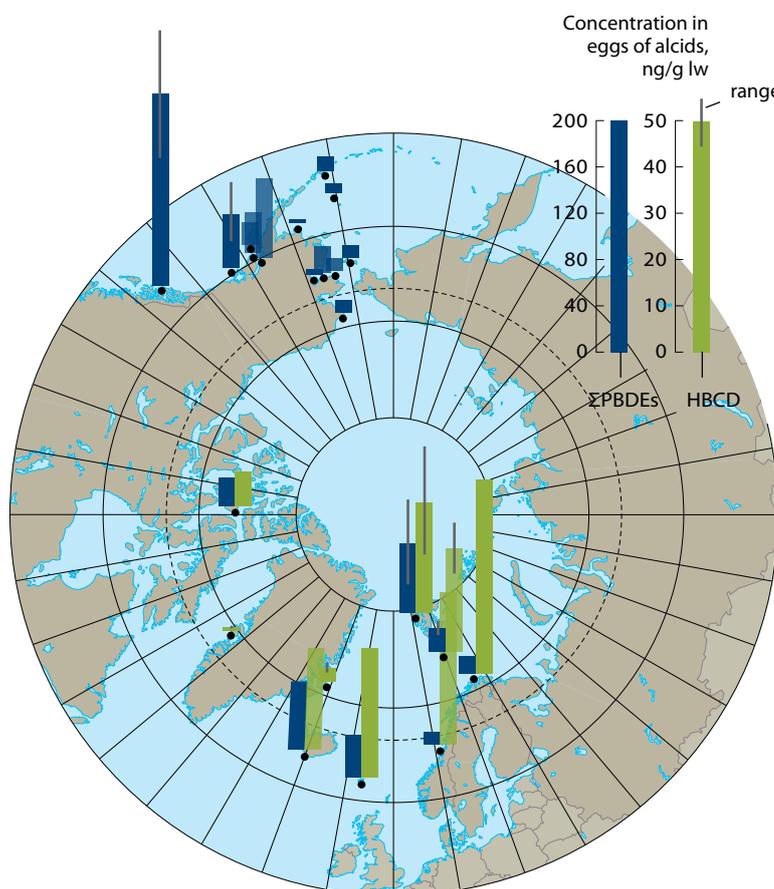
The McMurdo Station waste barn.

lower than PCB concentrations in the same species. Relatively high levels of BFRs have also been found in bottom-dwelling invertebrates as well as in ice-associated amphipods.

BFRs have also been measured in marine fish, including several species of cod, tusk, Greenland halibut, shorthorn sculpin, starry ray, sea-run char, and salmon from different regions. PBDE levels range from 2 to 480 nanogram per gram (lipid weight), which is much lower than for legacy POPs, such as PCBs. Species differences reflect where the fish live and their position in the food web, with the highest levels found in Atlantic cod from southwest Greenland. The low levels in wild salmon were similar to those found in farmed salmon. The composition of BFRs in fish indicates technical PentaBDE as the major source, but there are also some data showing that HBCD and TBBPA have reached marine fish. In a study from Greenland, levels were generally higher near human settlements, indicating they may serve as direct local sources in the Arctic.

Seabird eggs are often used to monitor levels of contaminants in the marine environment. They reflect the contaminants collected by the female birds. Eggs collected from Prince Leopold Island, Lancaster Sound, Canada, show that levels of PBDEs in thick-billed murre and northern fulmar increased rapidly from 1975 to 2003. The highest levels are still an order of magnitude lower than those reported for marine birds in the polluted Baltic Sea in 1999 and may now be decreasing. Levels in eggs collected in Greenland are similar to the Canadian Arctic, while levels in eggs from Svalbard and northern Norway are higher. The highest levels were found in glaucous gulls. Compared to legacy POPs such as PCBs, the PBDE levels in the eggs are much lower, but the presence of PBDEs shows that they have the potential to accumulate in the marine food web. Other BFRs that have been found in Arctic seabirds are PBBs, HBCD, DecaBDE and BTBPE. The Figure above provides an overview of the levels of BFRs in seabirds across the Arctic.

Ringed seals occur across the Arctic and are often used for investigating how levels of contaminants differ geographically in the Arctic marine ecosystems. Most studies have focused on PBDEs. The highest concentrations are found in ringed seals from Svalbard and, slightly lower but in the same order of magnitude, East Greenland. Although these levels are



high in the Arctic context, they are about ten times lower than those found in ringed seals from the Baltic Sea. Compared to East Greenland, levels are much lower in West Greenland where they are similar to the western Canadian Arctic and Alaska. The Alaskan samples also have a different composition of PBDEs in the blubber that probably reflects the long distances from PBDE sources and that some PBDEs degrade during long-range transport.

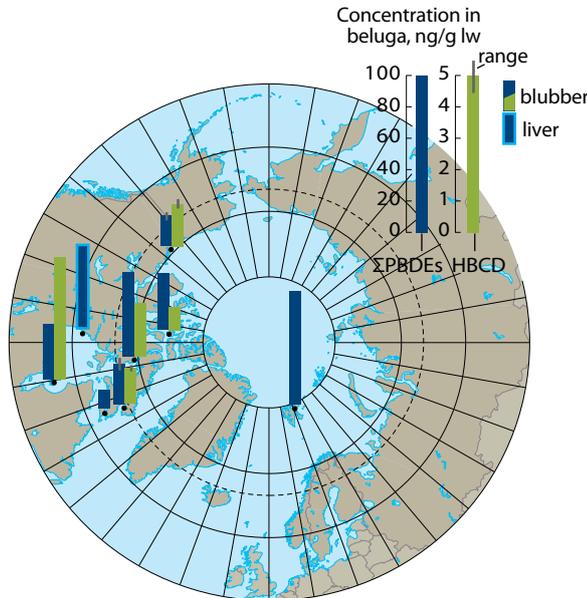
Even in the areas with relatively high PBDE levels, the contamination is much less than for PCBs. For example samples from East Greenland showed 15-60 times lower concentrations of sumPBDEs than sum of ten PCBs in the same sample.

There are fewer measurements of other BFRs compared to the PBDEs and the only compound that has been detected in ringed seals is HBCD. The difference between East and West Greenland that was seen in PBDE levels is also apparent for HBCD but is less pronounced.

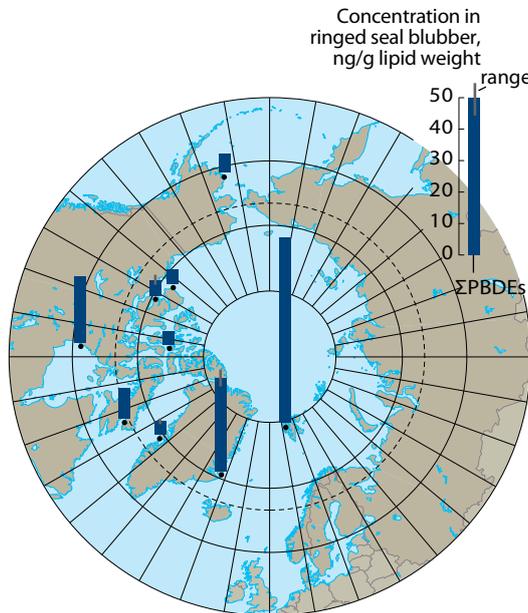
Whales from Alaska, a number of sites in Canada, Greenland, Svalbard, and northern Norway have also been analyzed for BFRs, mainly PBDEs. The species include beluga, narwhal, killer whale and minke

▲ PBDEs and HBCD in seabirds.

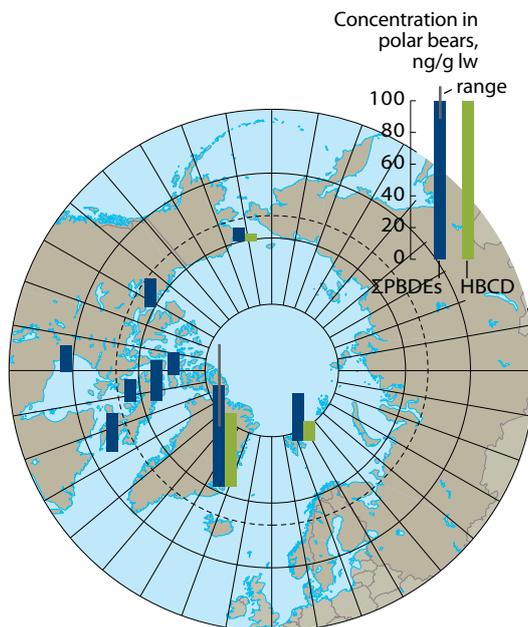
► PBDEs and HBCD in beluga.



► PBDEs in ringed seals.



► PBDEs and HBCD in polar bears.



whale. The levels of PBDEs are highest in populations of off-shore killer whales off the coast of Alaska. These killer whales migrate south to California in the winter. They also feed high in the food web and the combination of these factors exposes them to more contaminants than killer whales that remain in the Arctic or feed lower in the food web. Similarly high concentrations have previously been found in long-finned pilot whales from the Faroe Islands, which is also a migratory species.

Similar to the picture for seals, the PBDE levels in beluga are higher in Norway compared to the Canadian Arctic. Also, the levels of PBDEs in the Arctic beluga are much lower than in locally polluted areas such as the St. Lawrence estuary. Other BFRs found in whales are HBCD, BTBPE and TBECH.

Polar bears are the top predators in the Arctic marine food web. For some legacy POPs (i.e. PCBs), contaminant levels are higher in polar bears than any other species and high enough to affect their health. In contrast to for example PCBs, levels of PBDEs do not increase with the age of the animal.

Measurements of PBDEs in polar bear are available from a range of sites including Alaska, Canada, Greenland, and Svalbard. In general, bears from East Greenland and Svalbard seem to be exposed to higher concentrations compared to bears from North America, which is the same geographical pattern that has been seen in other marine animals and for legacy POPs. Another BFR that has been found in polar bears is HBCD, with the same geographical pattern as for PBDEs.

Spatial trends follow common POP pattern

When looking at data from air, sediment, and several animal species, certain patterns emerge that can give information about source regions for contaminants and how the compounds travel over long distances.

In general, the air concentrations of PBDEs decline from south to north. For example, measurements show higher levels in mid-latitude East Asia compared to the Northern Pacific and even lower levels into the Bering Sea. PBDE concentrations also decline from south to north in lake sediments in Alaska and Canada (excluding hot spots). This shows that the major source regions are south of the Arctic.

The levels in top predators from the marine environment are generally higher than in the terrestrial environment. This difference is most likely due to longer food chains in the marine environment and subsequent increased biomagnification.

For the animals that have been studied, the Arctic region that is most contaminated is the East Greenland-Svalbard area, with lower concentrations in the Russian and Canadian Arctic and the lowest concentrations in Alaska. The same pattern is seen for HBCD although the data are more limited. This is in spite of much higher use of PentaBDE in North America than in Europe. The geographic pattern of PBDE contamination in seabirds and in the marine mammals in the Arctic appear to follow what has previously been shown for PCBs and other legacy POPs. They reflect dominating pathways for these contaminants, where winds and ocean currents from Europe and eastern North America converge in the Eastern Greenland and Svalbard regions.

PBDEs and HBCD biomagnify

The data from marine animals show that PBDEs accumulate in the marine food web and that concentrations magnify between some trophic levels, especially from fish (e.g. polar cod) to fish-eating seal. However, polar bears seem to be able to break down many PBDEs so that biomagnification is low from seals to polar bears, except for hexaBDE. In general, the body burden of marine animals high in the food web consists of PentaBDEs. For example, tissues of polar bears generally contain high proportions of PentaBDEs with no detectable PBDEs higher than hepta-brominated.

Some studies have used models to estimate the biomagnification factors for PentaBDEs. Assuming that the animals cannot break these compounds down, seabirds, marine mammals and terrestrial carnivores have the highest biomagnification factors, almost up to 100. Components of DecaBDE are modeled to biomagnify in marine mammals and terrestrial carnivores with factors up to 8.

For HBCD, the pattern of bioaccumulation/biomagnification is similar to PBDE but the data are too scarce to assign numeric values to the biomagnification potential. It is mainly the alpha-isomer that biomagnifies. In a food-web study in Arctic Canada, the overall rank order of HBCD concentrations

were narwhal > redfish \approx clams > shrimp > beluga > zooplankton > walrus > arctic cod.

In conclusion, although there are differences in the magnitude of biomagnification of single PBDE congeners, both PBDEs and HBCDs have considerable potential to biomagnify in both marine and terrestrial environments.

Time trends with mixed messages

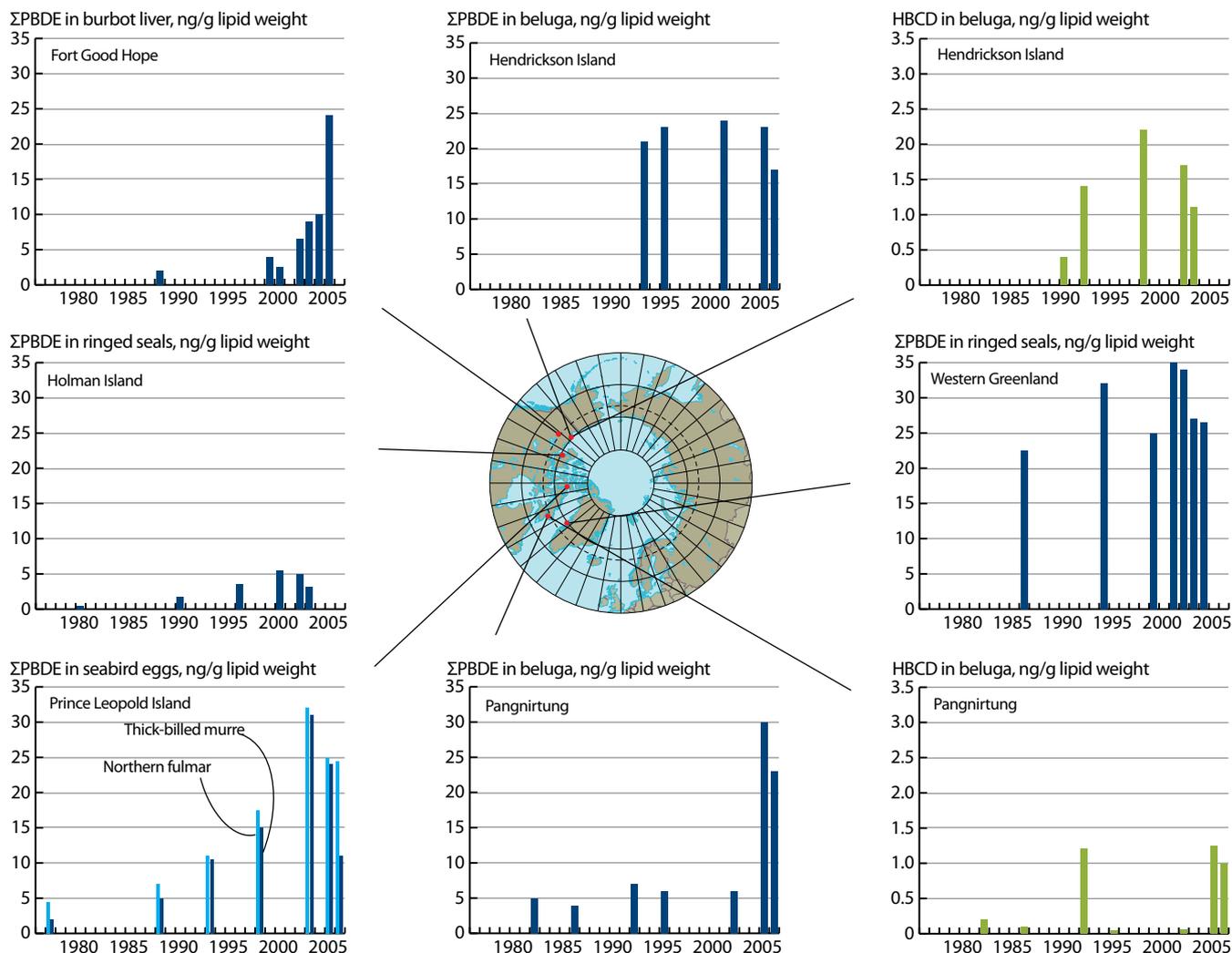
Are BFR levels increasing or declining? This simple question does not currently have a simple answer.

Air samples from Alert, Nunavut, from 2002 to 2004 show that the levels for eight different PBDE congeners were increasing. PBDEs were still found to be increasing in 2005 at Alert.

Sediments generally cover a much longer time period. Sediment from Lake Ellasjøen on Bjørnøya shows that PBDEs are present in the sediment layer representing the years 1946-1959. Signals of HexaBDE only appears in the surface sediment (1987-2001). The summed concentrations represent a more than five-fold increase in PBDE levels over the past 50 years.

This historic increasing trend in sediment is reflected in some animals from which there are time trends available. These include Arctic char, lake trout, burbot, seabird eggs, ringed seal, and beluga from Canada, ringed seal from Greenland, cod from the Barents Sea, and seabird eggs from Svalbard. However, the picture that emerges for more recent years is more complicated. Most studies report increases of PBDEs in the Arctic, but in some studies the most recent data points are below previous maximum concentrations. This may be an early indication that PBDE concentrations have stagnated or declined in the past two to five years.

An example of the uncertainty in recent trends is that studies of ringed seal in eastern and western Canada and East Greenland and northern fulmar in Canada indicate a recent decline, while PBDE levels in ringed seal from Hudson Bay and West Greenland have continued to increase. Another example of mixed messages is that land-locked char from Resolute Bay in the Canadian Arctic showed a marked increase in 2006 while samples from Char Lake from 1999 to 2005 show constant concentrations and results from Lake Amituk show an increase from 2005 to 2007 but at lower levels than for the years 2001-2003. In the marine environment, levels in ivory gull eggs from Seymour Island



▲ Time series of PBDEs and HBCD in Arctic wildlife.

in the Canadian Arctic indicate a steady increase in PBDE from 1976 to 2004, while concentrations of HBCD decreased during the same period. In ringed seals from western Hudson Bay and the central Canadian archipelago both PBDEs and HBCD increased from 1992 to 2005.

In summary, environmental levels of PBDEs and HBCDs have followed the production and use of BFRs with increasing levels up until the early 2000s. They may now be starting to level off or decline, at least in some areas.

Conclusions for brominated flame retardants

The accumulating evidence from air samples and measurements in vegetation and animals shows that Penta- Octa- and DecaBDE can transport over long distances and accumulate in Arctic biota. Similar to the PBDEs, it is now clear that HBCD is ubiquitous in the Arctic, that it undergoes long-range transport, that it accumulates in animals and that some components biomagnify.

Environmental levels of PBDEs and HBCDs have followed the production and use of BFRs with increasing levels up until the early 2000s, which are now starting to level off or decline, at least in some areas.

For TBBPA more data are needed to assess its potential to undergo long-range transport, but it does show up in Arctic wildlife at very low levels. PBB is only included in a few studies. It may be prevalent but the methods for measuring it make it difficult to separate this technical product from one of the PBDE congeners.

Other BFRs that have been detected in occasional samples include BTBPE, HxBBz, PBEB and PBT. The scarce measurements that are available indicate that they may reach the Arctic and accumulate in animals high in the food web. This is a warning sign that they also undergo long-range transport and that levels in the environment may increase over time. However, more data are needed to assess whether they qualify as POPs.

Fluorinated compounds

Poly- and perfluorinated compounds (PFCs) are organic molecules with fluorine atoms attached. They have gained attention as potential POPs only recently, although they were commercialized over 40 years ago. Environmental concerns were initially raised when one of the major compounds – perfluorooctane sulfonate (PFOS) – was detected at relatively high levels in wildlife in 2001. Since then, PFOS and the related compounds have been detected globally, even in remote regions such as the Arctic.

The recognition of fluorinated compounds as Arctic contaminants was the result of advances in chemical analysis in the late 1990s. Studies of archived wildlife samples and sediment cores have since then shown that these substances have been present in the Arctic since at least the 1970s and possibly earlier. Many fluorinated compounds are extremely persistent in the environment.

Use and production

There are two major production processes for manufacturing fluorinated compounds. One came into use in 1949 and has mainly been used by the 3M Company. The other process has been

used by various companies since the 1970s to make fluorotelomer-based chemicals. The bulk of products from these processes have been used in the manufacture of fluoropolymers, which are used for making materials repel oil, stains, grease, and water, and as non-stick surfaces on cookware.

The major fluorinated compounds that have been measured in the environment are the perfluorinated sulfonates, of which PFOS is the best known, and the perfluorinated carboxylates (PFCA), of which PFOA (perfluorooctanoic acid) is a well known example.

PFOS and other perfluorinated sulfonates (PFSAs)

From the 1950s to 2002, the 3M Company was the main manufacturer of perfluorooctane sulfonate (PFOS) and some related compounds. Manufacturing of PFOS has continued in China, which is believed to be the world's leading producer. The primary use of PFOS was as a surfactant in fire fighting foams. However, PFOS represented only a small amount of the compounds manufactured in the chemical process that 3M used. The bulk of the products were used in the manufacture of stain repellents in carpets, textiles, and food packaging.

The chemical terminology of fluorinated compounds

The fluorinated compounds are named based on the lengths of the carbon chain and the functional group that has been attached.

One common class of fluorinated compounds is the perfluorinated sulfonates (PFSAs) which are signified by "S" in the final letter of the acronym (e.g. PFHxS, PFOS, PFDS). PFOS – which is the major perfluorinated sulfonate – is built on an eight-carbon skeleton with a sulfonate group at one end and fluorine atoms at all other carbon bonds. Fully fluorinated compounds such as PFOS are referred to as perfluorinated. Other perfluorinated sulfonates have longer or shorter carbon chains, e.g. perfluorohexane sulfonate (PFHxS, with 6 carbons) and perfluoroheptane sulfonate (PFHpS, with 7 carbons).

There are several additional perfluorinated compounds that have a similar structure but have other functional groups. These include the perfluorinated sulfonamides (acronym = FOSA) and the sulfonamide alcohols (acronym = FOSE).

Another group of compounds are the perfluorocarboxylates (PFCAs). Examples are PFOA, PFNA, PFDA. Analogous to the sulfonates, the third letter indicates the length of the carbon chain (octa/eight, nano/nine and deca/ten carbons respectively). The last letter – A – signifies that the compound has a carboxylic acid functional group.

A third group of compounds is the fluorotelomer alcohols (abbreviated FTOHs). As the name implies, these compounds have an alcohol functional group. The FTOHs are known to degrade in the atmosphere, microbially, and in animals to the PFCAs.

PFOS can directly enter the environment through impurities in commercial products and as emissions during the manufacturing process. Further, PFOS can be formed through the degradation of other fluorinated compounds in the atmosphere and by wildlife and humans.

Despite the recent reductions in production, PFOS is the most common of the perfluorinated sulfonates in the environment. In addition to the eight-carbon PFOS, low concentrations of 6-carbon and 10-carbon fluorinated sulfonates are occasionally found. The precursor compounds are prominent in the atmosphere and have been detected in a small number of wildlife samples.

At the end of the 1990s, the US Environmental Protection Agency started investigating the need to regulate PFOS based on the fact that it was present in human blood samples from the general population. In addition, there were concerns about its persistence, bioaccumulation, and potential toxicity. In 2001, the 3M Company announced a voluntary phase out of its PFOS-based chemicals. The 3M Company has been using compounds based on a four-carbon chain as a replacement to the previous chemistry based on eight carbons. However, since 2003 China has been manufacturing PFOS in increasing amounts.

PFOA and other perfluorocarboxylates (PFCAs)

Perfluorinated carboxylates (PFCA) are a class of fluorinated compounds with a carboxylate functional group, of which PFOA is the best known. PFOA and the related compound perfluorononanoate (PFNA) are produced in large quantities. They are used as aids in the production of some fluoropolymers (e.g. Teflon®). Several other compounds from the same chemical process are incorporated into commercial products, such as stain repellents, from which they may be released to the environment.

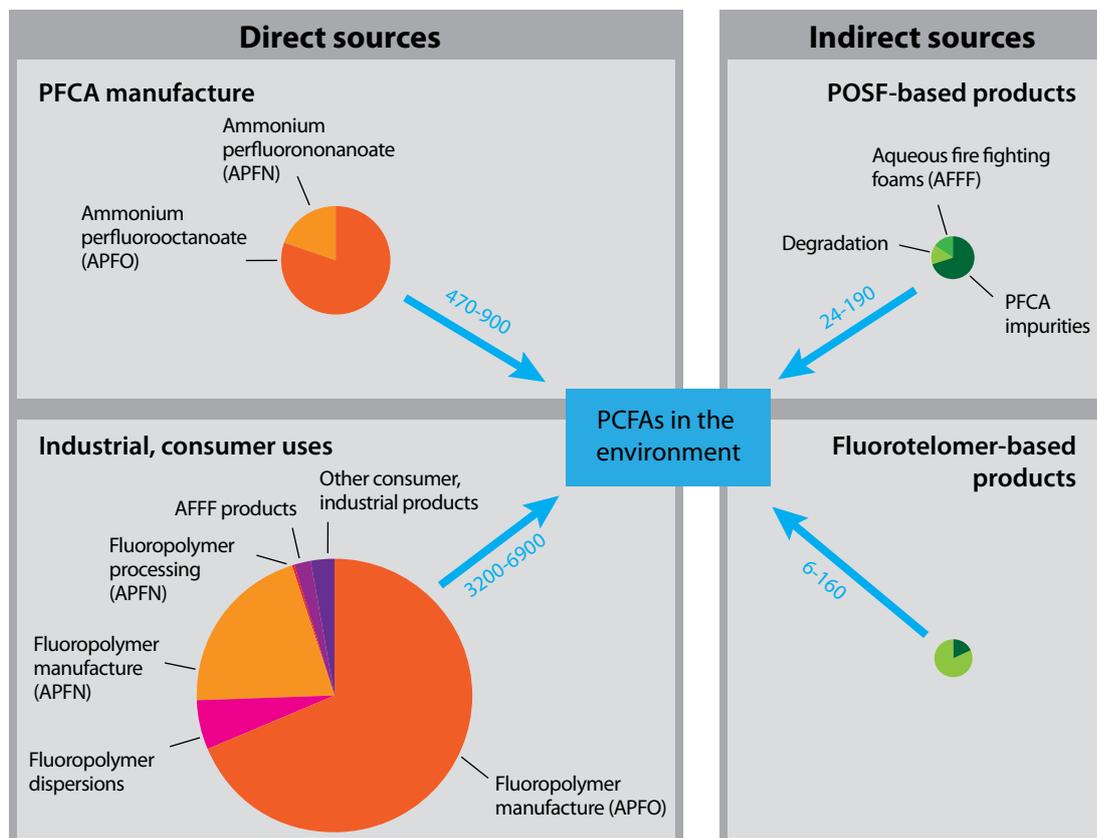
The PFCAs in the environment have two sources: the direct production and the degradation (atmospheric or biological) of other fluorinated chemicals that are released from the products in which they are used (e.g. from treated carpets).

The PFCA that has received most attention is the eight-carbon PFOA. PFOA is detected in only very low levels in Arctic wildlife. In general, it is the longer-chain PFCAs – 9 to 11 carbons – that dominate.

National and international regulations are discussed

Regulation of fluorinated compounds is being discussed in both international and national contexts. PFOS has recently been nominated as a candidate

► Sources of PCFAs in the environment. Pies represent relative magnitudes of different sources; values are in tonnes.



POP to the Stockholm Convention and to the LRTAP POPs Protocol. In 2006, the European Union decided to restrict the use of PFOS as well as products that can degrade to PFOS, starting June 2008. However many uses are exempted, and discussions are on-going about how these exemptions are to be phased out.

Since 2004, Environment Canada has banned the import and manufacture of four products that are suspected to break down to PFOA and other PFCAs. In January 2006, the US Environmental Protection Agency and the eight major companies in the industry created the 2010/15 PFOA Stewardship Program. The companies committed to reduce facility emissions and product content of PFOA and related chemicals by 95 percent by 2010, and to work toward eliminating emissions and product content by 2015.

As alternatives to PFOS, the industry is currently producing fluorinated compounds with shorter carbon chains. The goal is to make the compounds less persistent in the environment. This assessment includes measurement of some of new products, which have been found in the Arctic, and also discusses their role as possible sources of PFOS and PFOA in the environment.

Properties in the environment and accumulation in wildlife

The chemical bond between carbon and fluorine is among the strongest chemical bonds known, making fully fluorinated organic compounds extremely persistent in the environment. PFCAs and PFOS are not known to degrade in the environment. However, several “precursor” compounds that are used in the production process and in commercial applications do degrade readily in the environment, ultimately forming the persistent PFSAs and PFCAs. There is clear evidence that PFSAs and PFCAs are globally distributed, including in the Arctic. In fact, polar bears from the Arctic contain some of the highest PFC levels measured in wildlife.

Studies on laboratory animals show that PFSAs and PFCAs can be taken up by the digestive system and are not broken down. They accumulate in the blood, liver and the kidney, with liver concentrations typically being the highest. This is different from most other POPs, which accumulate in fatty tissues. They have also been found in human blood from people in the Arctic, although studies are very limited.

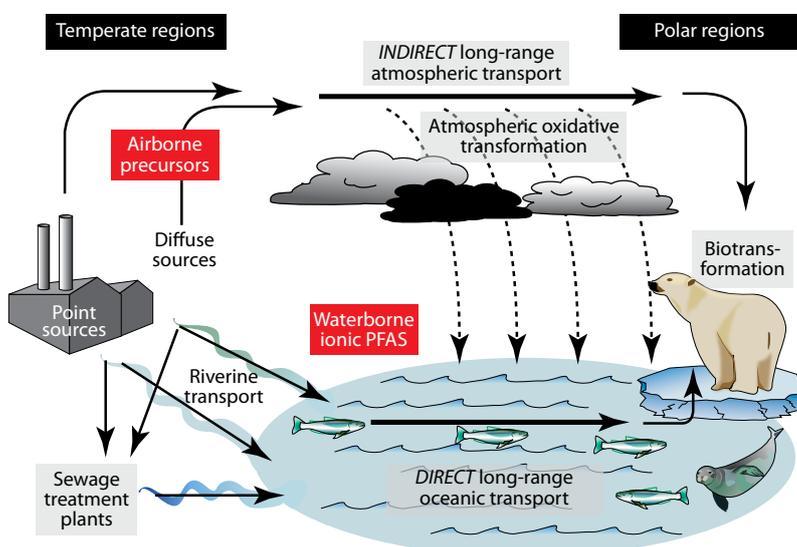
The effects of PFCs on the health of Arctic wildlife are not known. Generally, PFCAs and PFSAs do not appear to be acutely toxic, but high concentrations can cause a “wasting” syndrome because the chemicals disrupt lipid metabolism and cause enlargement of the liver. PFCAs can cause developmental and other adverse effects in laboratory animals. They appear to remain in the human body for a long time, which has raised concerns about potential risks for human health if more PFCAs are released into the environment.

Studies of the Arctic marine environment show that fluorinated compounds accumulate in species at the top of the food web. This is particularly true for PFOS and some long-chain PFCAs. Some studies indicate biomagnification of PFOS, i.e. that the compound is enriched with increasing trophic level, e.g. from zooplankton to Arctic cod and from Arctic cod to fish-eating whales and seabirds. There are as yet no relevant food web studies of Arctic terrestrial or freshwater environments.

How do fluorinated contaminants reach the Arctic?

Unlike other POPs, the two main classes of fluorinated compounds detected in the environment are not volatile. However, their appearance in Arctic animals indicates that they can be transported over long distances. Therefore their transport pathways have generated considerable scientific interest. Since the 2002 AMAP assessment, two major pathways have been proposed. One pathway focuses on volatile precursors that have been detected in the Arctic atmosphere and shown to degrade to PFCAs in the atmosphere.

▼ Transport pathways for fluorinated compounds.



The second pathway is aquatic and involves emissions from the manufacturing of fluorochemicals, degradation of fluoropolymers in sewage treatment plants, and direct leakage from domestic and industrial use to the environment. In the environment, PFOS and PFCAs are very water soluble and such emissions would eventually reach the Arctic via rivers and ocean currents.

For PFOA and the other PFCAs in the Arctic marine environment, modeling studies suggest that ocean transport is one to two orders of magnitude more important than atmospheric transport. PFOA-precursors released to the atmosphere could also be degraded and deposited in the oceans near where they are emitted and then transported via the ocean currents. In either case, changes in seawater concentrations in the Arctic Ocean would be slow and response to declining emissions delayed due to slow transport via ocean currents. No models have yet been developed for the other, more predominant PFCAs.

For PFOS-related compounds, there is currently a lack of modeling studies that address the role of different pathways. However, the same processes of indirect transport via precursors and ocean transport are thought to apply. The PFOS precursors have

sufficient atmospheric lifetimes to permit long-range transport and have been detected in the Arctic atmosphere. Moreover, degradation products have been detected on atmospheric particles. PFOS and some PFCAs have been found in snow cores from ice caps that are mainly influenced by atmospheric deposition. Changes in levels in some Arctic wildlife also point to fairly fast delivery pathways, which is more consistent with atmospheric transport.

Some measurements from Resolute Lake (Canadian Arctic) also point to the possibility of local Arctic sources. In this case the contamination may have come from runoff from a local airport. Such local sources are not well investigated and it is unclear to what extent they contribute to the more general contamination of the Arctic environment.

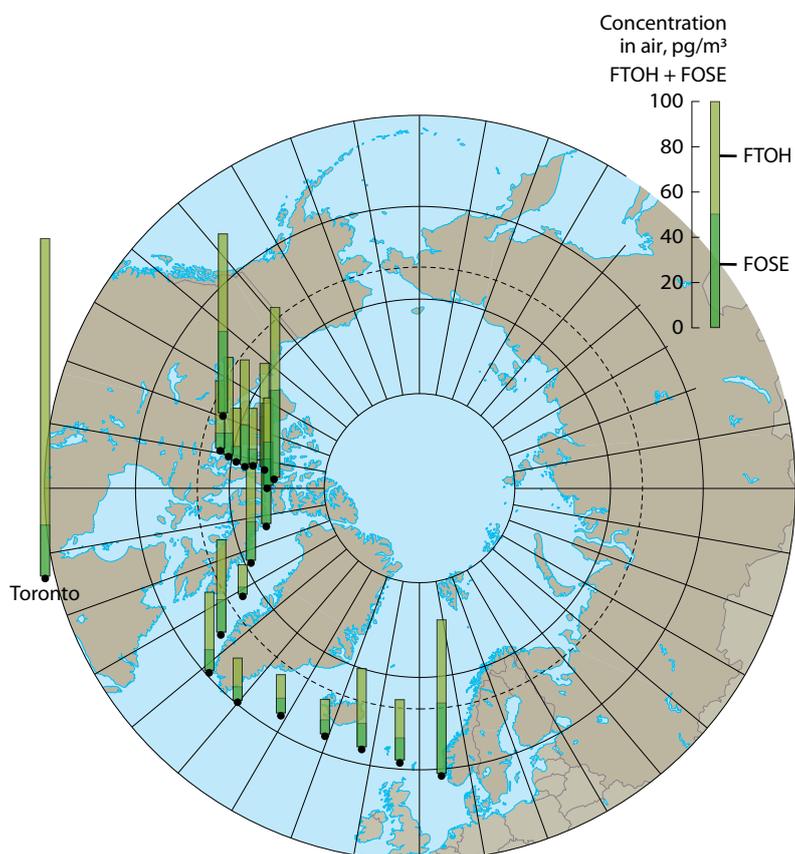
Geographic patterns and source regions

Data on fluorinated compounds in air, water and other compartments of the Arctic environment can be used for understanding geographic variation in levels across the Arctic and assessing where the contaminants originate. The Figure (left) shows air concentrations. In general there are very limited data from the abiotic environment, with the majority of measurements from the Canadian Archipelago and the North Atlantic. Current studies show that precursors are ubiquitous in the Arctic atmosphere. They confirm that these compounds are subject to long-range transport and are therefore potential sources of PFCAs and PFOS-related compounds to the Arctic environment. Moreover, these compounds have been found on atmospheric particles. This supports theories that precursors in the atmosphere can be a source of these compounds in the Arctic.

The concentrations of the precursors in Arctic air are one order of magnitude lower than in air collected in more southern, urban regions. These urban regions are likely sources to the Arctic. There is variation in the relative abundance of the various compounds across the Arctic, which may be a consequence of differences in emission patterns between North America and Europe, but the data are too limited to draw definite conclusions.

There are as yet few measurements in precipitation, seawater, lakes and sediment, and not enough data to reliably assess geographic variation. In general, levels are low compared to similar measurements in more southern environments. Levels in

▼ Total air concentrations of fluorinated compounds, fluorote-
lomer alcohols (FTOH) and perfluorooctane
sulfonamido alcohols (FOSE).



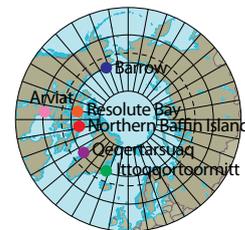
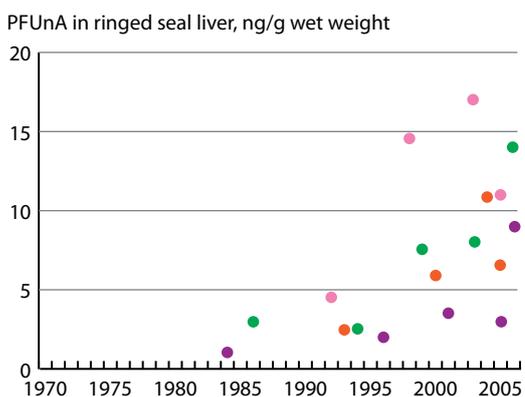
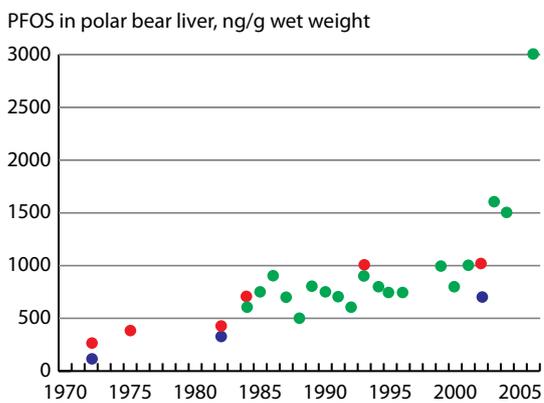
seawater confirm that ocean transport to the Arctic occurs, although the importance of this transport pathway is still unknown. Time trend data from the Canadian Devon Island ice cap show increasing PFCA and declining PFOS levels.

Also for wildlife, there is a paucity of information about the geographic distribution of fluorinated compounds in the circumpolar Arctic, and the few studies that exist only cover the marine environment. Studies from Greenland looking at fish, birds and mammals show higher PFOS levels in East Greenland than West Greenland. A study of polar bears, covering a range of populations from Alaska to Svalbard, showed higher levels in East Greenland and Hudson Bay as compared to the western North American Arctic. In Norway some studies suggest higher concentrations in seabirds in more southern locations than further north, possibly mirroring proximity to source regions in Europe. Studies from North America show some differences between populations but with no apparent explanations. However, ringed seal populations show higher PFCA and PFOS levels at locations with greater freshwater influence. Because the fluorinated compounds have different transport pathways and different biological properties than other POPs, it is also difficult to draw conclusions from their spatial distribution.

In general there are not enough data to interpret circumpolar spatial trends. In particular almost nothing is known about levels in the Russian Arctic.

Time trends show initial increase and some recent declines

An increasing number of temporal trend studies in wildlife have been published in the past five years. So far they have focused almost exclusively on the marine food web, using measurements from mammals and seabirds. Most measurements come from the North American Arctic, Greenland, and Norway. In general, time trend studies show an initial increase in fluorinated compounds from the early data in the mid 1980s. For more recent developments the picture is less consistent. Some studies show a continuous or accelerating increase. They include ringed seals from East and West Greenland and East Greenland polar bear. In contrast, declining levels of PFOS have been noted in sea otter from Alaska and in ringed seal and beluga from the Canadian Arctic. These trends are consistent with the known trend of increasing



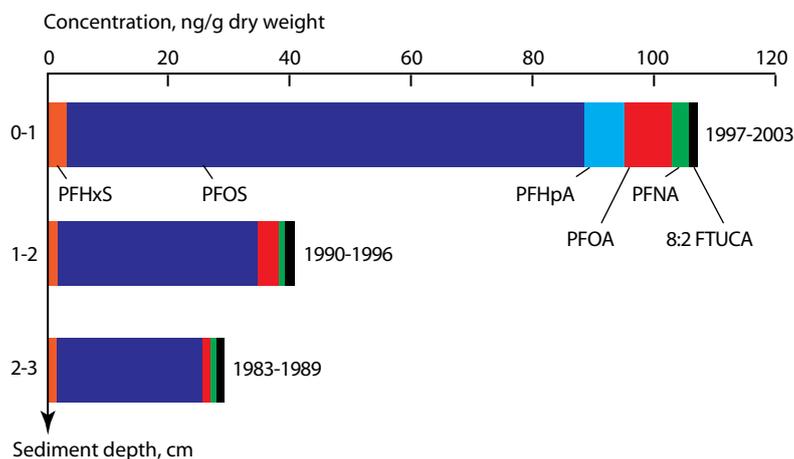
Temporal trends of fluorinated compounds in marine mammals.

production of PFCA precursors and the decline in PFOS-based chemicals.

The explanation for the geographic differences in time trends might be that Greenland and the Canadian Arctic are influenced by air and ocean currents from different source regions. For example, surface water in the Canadian Arctic archipelago and northern Hudson Bay originate from the Pacific whereas the European Arctic is influenced by Atlantic Ocean water.

Studies in seabirds from northern Norway show different time trends depending on the specific compound. There are very few data from the abiotic environment, but sediment cores from lakes in the Canadian Arctic show a general increase in levels over the past 50 years.

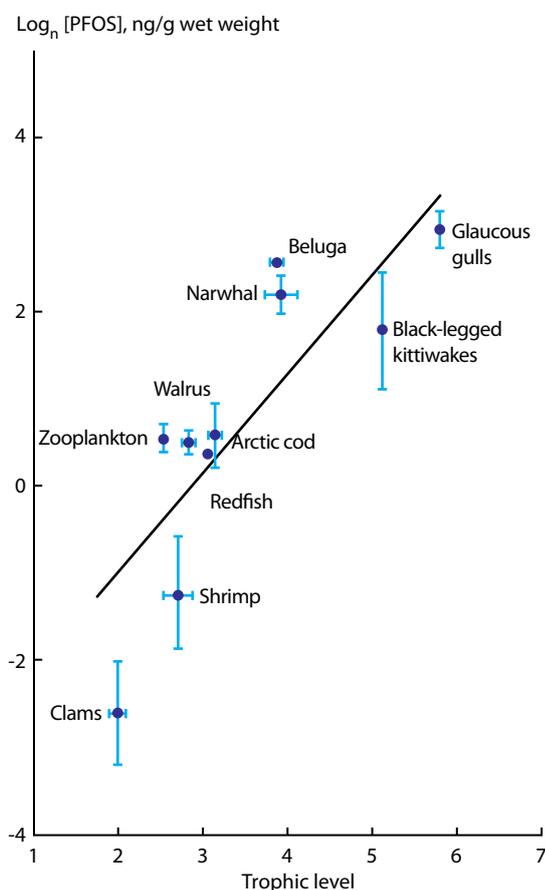
Fluorinated compounds in sediments from Resolute lake, Canada.



Conclusions for fluorinated compounds

In general, the knowledge about fluorinated compounds in the Arctic is based on relatively few studies compared to legacy POPs. Since these compounds have only recently been recognized as Arctic contaminants, the data sets are expected to grow rapidly. Most of the present studies are from the marine environment and cover only some of the potential problem chemicals. Transport pathways and bioaccumulation are different from the legacy POPs, but it is clear that they reach the Arctic both via the atmosphere and via ocean currents. Some fluorinated compounds accumulate in animals that are high in the marine food web and levels in polar bears are among the highest concentrations measured. Although production of the major technical product – PFOS and PFOS-based compounds – has been dramatically reduced there are current sources that may contribute to continued input into the environment. They include products from which these chemicals can migrate, environmental degradation of compounds that are still in use, and emissions from manufacturing of various fluorinated compounds. The fluorinated compounds are currently subject to review for both international and national regulation.

► PFOS
biomagnification in the eastern Canadian Arctic marine foodweb.



Polychlorinated naphthalenes (PCNs)

Polychlorinated naphthalenes (PCNs) are a group of persistent chemicals that were produced as industrial compounds and also released in combustion processes. They were first patented as flame retardants and dielectric fluids in the early 1900s but have since found uses in a wide range of industrial applications, including fungicides in wood, textile and paper industries, plasticizers, oil additives, casting material for alloys, and lubricants for graphite electrodes. They also occur as trace contaminants in commercial PCBs.

Production and sources to the environment

Production figures for PCNs are not well known, but are estimated to be about 10 percent of global PCB production tonnages. The largest PCN manufacturer ceased production in the late 1970s and they are supposedly no longer made. However, illegal import of PCNs into Japan has been reported after 2000. Although use has declined, in most countries PCNs are not banned.

Sources to the environment include combustion as well as evaporation from products that contain PCNs. According to a study of sources in Europe, about 80 percent of the estimated PCN emissions came from combustion. The PCNs originate from waste that is being burned or from *de novo* synthesis in the combustion process. Another study, from Toronto, pointed to evaporation as the major source of PCNs in air within the downtown area while combustion also contributed to PCN levels in suburban air. A third study looking at patterns that were representative of a range of specific sources pointed to technical PCB mixtures as a significant source.

PCNs are chemically similar to PCBs and are thought to be toxic via a similar mechanism to dioxins and dioxin-like PCBs.

PCNs are currently not covered by the Stockholm Convention or the UN ECE LRTAP POPs protocol. However, The UN ECE Task force on POPs has supported that PCNs be considered a POP in context of this convention.

Levels in air highlight importance of Eurasian sources

Like other persistent organic pollutants, PCNs are spread around the globe. Investigations of PCNs in the Arctic are few but have increased in recent years.

The Figure (right) shows levels in Arctic air. The most pronounced spatial pattern is that PCN levels are much higher at most European Arctic and subarctic locations than in Siberia, Iceland, Alaska and the Canadian Arctic. High concentrations in the Barents Sea have been connected to parcels of air that have travelled from Europe, while the lowest levels could be traced to air masses that had originated over the open ocean, northern Scandinavia or Greenland. Levels of PCNs at Dunai (Siberia) were correlated with air coming from eastern and western Russia and at Alert from the North Atlantic and Europe.

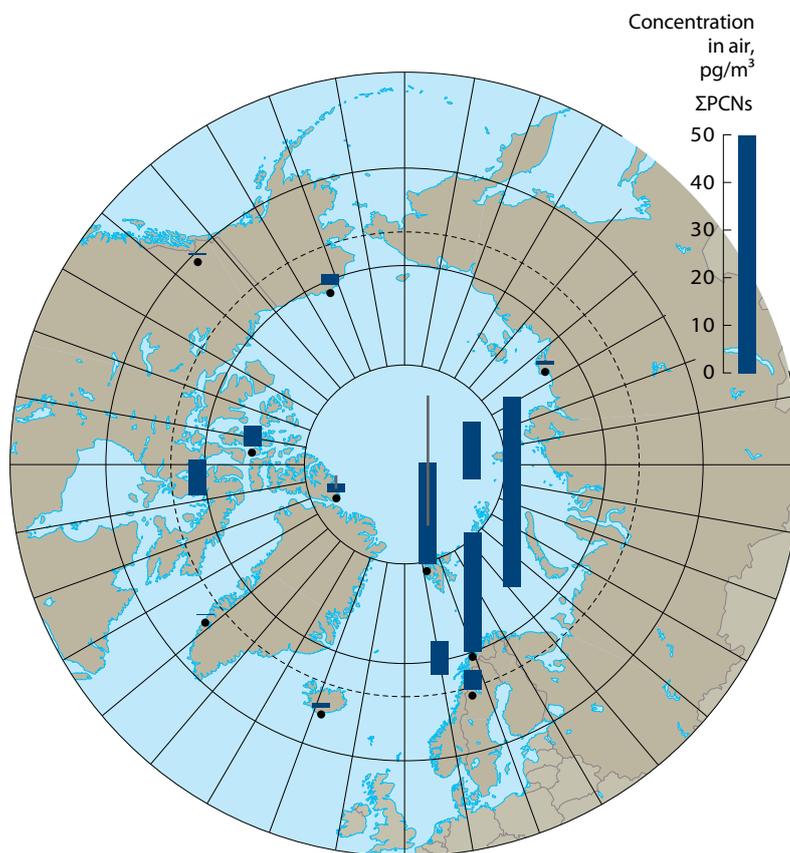
Attempts to identify the sources indicate that PCNs at Alert (Canada) come from PCN-containing products while combustion influence was more apparent at Ny Ålesund, Svalbard. One study notes that PCN levels at Siberian and high Canadian Arctic stations tend to follow the trend for Arctic haze, which is well known to carry combustion pollutants from Eurasia into the high Arctic in winter-spring.

The contribution of dioxin-like toxicity from PCNs varies depending on location and sample type. At Arctic-subarctic sites where air studies have been conducted, PCNs accounted for 13-98 percent of the toxic potential of PCNs and dioxin-like PCBs combined, with a generally higher contribution from PCNs during winters.

Levels in biota are lower than for PCBs

In Arctic and subarctic animals, PCNs are found in invertebrates, fish, marine mammals, and seabirds. However, the database is small, especially for the Arctic Ocean, and for whales and polar bear. The available data suggest that among marine mammals, the concentrations follow the order: harbor seals ~ pilot whales > ringed seals ~ Weddell seals (from Antarctica). The levels in birds vary over two orders of magnitude with the highest concentrations in glaucous gull from Bjørnøya and northern fulmar from the eastern Canadian Arctic. The lowest concentrations were in glaucous gulls from Svalbard and black-backed gulls from the Faroe Islands.

Measured as toxic equivalents, the PCN levels in seals, polar bear and seabirds are much lower than for PCBs, generally less than a few tenths of a percent although up to 9 percent in some harbor seals. Whales appear to be an exception, where PCNs can contribute up to 10-20 percent of the toxic equivalents.

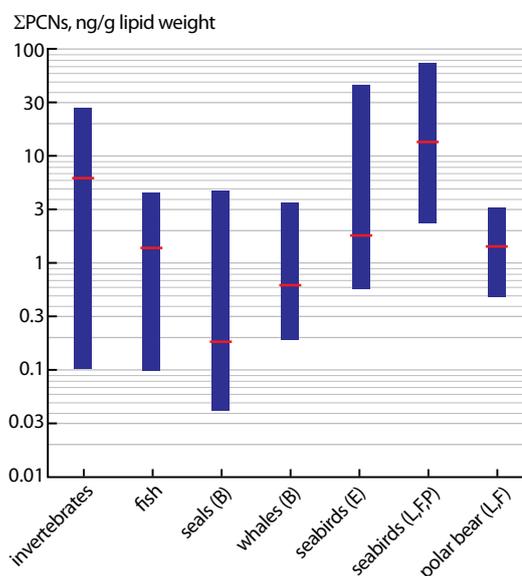


PCNs do not biomagnify much in the aquatic food chains in which they have been studied, with the exception of marine birds where some congeners appear to biomagnify. Some animals appear to be able to break down certain congeners.

▲ Concentrations of total PCNs in air of Arctic and subarctic regions.

Poor picture of patterns and trends

The data on PCNs in Arctic animals are too scarce to determine any spatial patterns of how this pollutant is spread throughout the circumpolar region. The data on PCNs in the Arctic are also too scarce to



◀ Range of arithmetic mean concentrations of total PCNs in biota of Arctic, subarctic and Antarctic regions. B = blubber, F = fat, L = liver, E = eggs, P = plasma. Red lines indicate geometric means.

determine any time trends. However, sediment cores from lakes outside the Arctic, including the United Kingdom, Switzerland and Japan, indicate that PCN levels in the environment peaked around 1960.

Conclusion for polychlorinated naphthalenes

Although PCNs are no longer produced and levels in the environment of temperate regions peaked almost half a century ago, PCNs are still present in the Arctic with indications of further input from a combination of combustion sources and emissions from old products. However there are no studies to assess their temporal trends in the Arctic. PCNs contribute to dioxin-like toxicity in Arctic animals, particularly whales but for other animals PCNs are generally less important than dioxin-like PCBs.

High-volume chemicals with POP characteristics

The POPs that have been regulated by international conventions or have been considered for policy action represent only a small fraction of the chemical substances that have been registered for commercial use. Some of the lessons learned about POP characteristics are also relevant for assessing chemicals that have been in use for a long time but are currently not regulated.

In the 1970s and early 1980s, legislation in Europe, the USA and Japan and some smaller economies required registration of all chemicals produced above certain production thresholds. Chemicals that had been produced prior to that time were often registered with little or no additional requirements for information on their physical and chemical properties or toxicity. Separate pesticide legislation in the same countries required more detailed information when a chemical was applied as a pesticide and banned many older, chlorinated insecticides. Virtually all of the organic chemicals currently detected in the Arctic were already in use in the 1970s.

Scientific understanding of the properties of chemicals that influence their accumulation in the Arctic has improved in the past 30 years and models have been developed to predict long-range transport and bioaccumulation potential. It is now accepted that the combination of ability to exchange between water and air, and between air and soil or plant surfaces, combined with the presence of multiple chlorine, fluorine or bromines on the molecule are the basic characteristics that make some chemicals POPs.

Since the previous AMAP assessment of POPs in the Arctic, a number of peer reviewed scientific papers have focused specifically on the Arctic accumulation potential of chemicals in commerce. A recent report identified 120 high-production-volume (>1000 tonnes per year) industrial organic chemicals and pesticides with POP characteristics, i.e. potential to undergo long-range atmospheric transport, along with predicted persistence and bioaccumulation. Of these, about 65 were predicted to have the ability to biomagnify into the Arctic indigenous peoples' traditional food supply, i.e. marine mammals. The same study noted that about 4300 organic chemicals, most with low or unknown production, had Arctic accumulation properties based on the similar structure to known POPs or predicted physical-chemical properties and biomagnification. The study did not take into account the potential for metabolism of the chemicals in animals, i.e. it assumed no biodegradation.

A recent alert about high-volume chemicals concerns siloxane, see details in box (next page).

Endosulfan and other current use pesticides

Endosulfan is a pesticide that has been used since the 1950s and is still in use in many parts of the world. It is effective against a broad number of insects and mites and is applied to many crops, including cotton, cereals, fruit trees, tea, and coffee. Major producers are India and the United States. Endosulfan is acutely toxic and in other parts of the world it has been responsible for killing people and fish when used incorrectly. For the Arctic, it is a concern because it has some POP characteristics. Unlike many other organochlorine pesticides, the levels of endosulfan in the environment are not declining, probably because of its continued use.

Transport over long distances

Endosulfan is semi-volatile and persistent enough to enable it to transport over long distances, with physical-chemical properties similar to other organochlorine pesticides such as chlordanes. Despite its reputation for being less persistent than conventional POPs, it occurs ubiquitously in the environment. Previous studies, using tree bark to survey the distribution of endosulfan, indicated that long-range transport of endosulfan would be limited compared to more volatile chemicals. However, a more recent global survey

Siloxane

Cyclic siloxanes are chemicals with POP-like characteristics that have come into increasing use during the past 20 years to enhance the qualities of other products. They are used in a number of applications, such as personal care products, fuel additives, car polish, cleaners, and anti foaming agents. Cyclic siloxanes are also formed during thermal degradation of silicone polymers. Large quantities are produced globally ($>4.1 \times 10^5$ tonnes per year in the United States and >1000 tonnes per year in the European Union). The cyclic siloxanes have been identified as possible persistent and bioaccumulative and toxic chemicals in a number of chemical screening studies in Canada and Europe because of their ability to bioconcentrate in fish and predictions of long atmospheric persistence. There are only a few studies that have investigated the levels of cyclic siloxanes in free ranging animals. Cyclic siloxanes have been detected outside the Arctic in marine fish (Denmark and Norway), freshwater fish (Finland and Norway), and marine mammals (Denmark). In the Arctic, siloxanes have been detected in marine mammals from Faroe Islands and in glaucous gulls from Svalbard and Bjørnøya. No measurements have been made in the rest of the Arctic. The concentrations in liver samples from Bjørnøya ranged from 32 to 69 nanogram per gram wet weight, which is comparable to concentrations of some brominated flame retardants. This level is 3-4 times lower than the level detected in liver samples from cod collected in the Oslo fjord. The presence in remote environments was unexpected because they were anticipated to degrade in the atmosphere and not be able to accumulate in warm blooded animals.

using passive air sampling devices showed endosulfan to be the most abundant organochlorine pesticide in the global atmosphere. Furthermore, long-term air monitoring in the Canadian Arctic reveals that endosulfan is one of the most abundant organochlorine pesticides in the remote atmosphere, after hexachlorobenzene and the hexachlorocyclohexanes (HCHs).

Levels of total endosulfan in air are highest closest to source regions and generally the levels in the Arctic are one order of magnitude lower. However alpha-endosulfan the major component of the technical endosulfan product, appears to travel easily and concentrate in higher elevations. Thus, regional atmospheric levels of alpha-endosulfan are comparable to those near sources, which indicates a potential for regional or medium-range transport. In the Arctic, levels of alpha-endosulfan are about ten times higher than beta-endosulfan. Long-term trend analysis reveals that endosulfan is not declining in the remote Arctic atmosphere, unlike some of the legacy pesticides; presumably reflecting ongoing use of this pesticide.

Accumulation in water bodies and sediment

Endosulfan is nominated for possible regulation under the Stockholm Convention and in the UNECE LRTAP POPs protocol. Within the expert committee under the Stockholm Convention, a decision has been made to prepare a risk profile for 2009. To qualify for consideration as a POP under these conventions, it must be shown to be persist-

ent and able to transport over long distances. In addition, there has to be evidence that it accumulates in the environment and biota and possesses toxic characteristics, with the potential to adversely affect human health and/or the environment. In the review process under the Stockholm Convention, degradation products are also considered. This section assesses endosulfan's potential to accumulate in soil, water and sediment and discusses the implications for its potential toxic effect and environmental impact. Like other organochlorine pesticides with similar properties, the highest levels of endosulfan are usually found in sediments within freshwater systems and in soil. The semi-volatile nature of endosulfan allows it to volatilize from soil and other surfaces into the overlying atmosphere during the warmer parts of the year. Therefore, endosulfan has the right combination of physical properties to enable it to be atmospherically transported to and deposited to remote regions such as the Arctic.-

Given the physical-chemical properties of endosulfan, it will adhere to organic particles and over time most likely end up in the sediment. Riverine transport of sediment may thus be source of endosulfan to coastal areas. For the Arctic Ocean, direct deposition from the atmosphere to the water appears to be a more important pathway. This is because suspended particle levels are low in regions of open cold water. A recent review of endosulfan in Arctic seawater demonstrated the widespread distri-

bution of this chemical in surface waters. However, the concentrations in surface water were lower than those for lindane, which is another current use organochlorine pesticide.

Though data on the flux of endosulfan between air and water are scarce, it has been demonstrated that over areas of ice-free open water, endosulfan is still loading into marine waters. This is in contrast to some of the legacy organochlorine pesticides that are now re-volatilizing out of Arctic Ocean water due to declining levels in the atmosphere.

With direct deposition from air to water as a major pathway to the marine environment, seasonal climate fluctuations affecting the sea ice cover becomes a major factor for the fate of endosulfan in Arctic seas. This raises concerns that in a warmer Arctic there will be increased loading of endosulfan from the atmosphere to ice-free ocean surfaces.

Degradation products may be toxic to water insects

Even if endosulfan is considered persistent, it can degrade once it is in the environment due to a combination of biological and physical processes. The main product of this degradation is endosulfan sulfate. Endosulfan sulfate is in itself persistent and has been shown to remain in soil for many months. It generally shows a lower acute toxicity in laboratory studies than the alpha- and beta-endosulfans, but its longer lifetime results in a notably higher chronic exposure. One study suggests that it can contribute to changes in population densities of water insects.

Endosulfan's potential to biomagnify

Many legacy POPs become toxic to Arctic biota because they biomagnify. This means that animals cannot break down the compound very well and that the chemical therefore passes between each level in the food web and reaches high concentrations in top predators. For endosulfan, the data on food web uptake is limited because of analytical uncertainties, but there is sufficient evidence from both Arctic and temperate freshwater studies to show that alpha-endosulfan can bioaccumulate in the lower food web, with bioaccumulation factors akin to other legacy POPs. Moreover, the data show that residues of endosulfan (and sulfate) are present in higher trophic level organisms (such as marine mammals). It appears that such higher level organisms can break down endosulfan, which reduces the potential for biomagnifica-

tions to top predators. However, there is variability between similar food webs and therefore greater uncertainty about some biomagnification steps, e.g. from fish to mammals.

Additional data on bioaccumulation (uptake and storage in biota) come from outside the Arctic and partly from areas with intensive use of endosulfan. They suggest some but limited bioaccumulation potential. Overall, in terms of enrichment in biota, endosulfan partly shows POPs characteristics. However, there is a shortage of data, especially on the major degradation product endosulfan sulfate which has been detected in selected marine mammals such as the beluga. The maximum body concentrations of endosulfan in various species of animals in the Arctic display a wide range in values but these are considerably less than toxicity thresholds observed in laboratory studies.

Conclusion: Endosulfan partly fulfills POPs criteria

The classification of POPs is based on toxicity, the tendency to undergo long-range transport, persistence, bioaccumulation characteristics and the presence in remote environments. Endosulfan partly fulfills these criteria due to its persistence, bioaccumulation tendency, toxicity and occurrence in remote environments. In particular, the occurrence of endosulfan in the Arctic, as well as in remote mountain regions, confirms its ability to transport over long distances. The parent compound and the degradation products appear to mainly be persistent in soils. There is some evidence of bioaccumulation in field studies conducted in remote regions, but there is still uncertainty regarding endosulfan's ability to biomagnify.

Nevertheless, the actual problem compound may be the breakdown product endosulfan sulfate. Its slow degradation may result in high chronic exposure. Moreover, it enriches in remote aqueous environment, where it may pose a substantial hazard to water-living organisms. However, the shortage of data on endosulfan sulfate does not allow for definitive recommendations.

Other current use pesticides

Many current use pesticides have been introduced to replace legacy POPs. They are designed to be less persistent in the environment. However, some persistence is necessary for their function in agriculture

Current use pesticides

Chlorpyrifos is an organophosphate insecticide that is also marketed as *Dursban* and *Lorsban*. It has been found in fish samples in Alaskan parks, in surface water, ice and fog from the Bering and Chukchi seas, snow samples from Alaska, in air in the eastern Canadian archipelago, and in subarctic and Arctic lakes in Canada.

Dacthal is an organochlorine herbicide. It is also called DCPA or chlorthalidimethyl. It has been found in snow from the Alaskan coast, in air, seawater and invertebrates from the Canadian Arctic, in subarctic and Arctic lakes in Canada, and in Russian river sediment. It has also been found in fish and seals from the Canadian Arctic and in fish from Alaskan parks.

Diazinon is an organophosphate insecticide (also called Spectricide and Sarolox). It has been found in subarctic and Arctic lakes in Canada.

Dicofol is an organochlorine pesticide (also called Kelthane, Carbax and Decofol). Dicofol has been detected in Arctic air samples and a chemical signature of DDT contamination indicates dicofol products from China as the source.

Methoxychlor is an organochlorine insecticide (also called methoxide, dimethoxy-DDT and methoxy-DDT). It has been detected in air samples from several stations, in Russian rivers, in fish from Alaskan parks, in a range of terrestrial, freshwater and marine biota from Greenland, and in seabirds from Svalbard.

Trifluralin is a dinitroaniline herbicide (also called Treflan). It is a candidate POP for the UN ECE LRTAP Convention. It has been detected in air samples from several sites, and in sediment, zooplankton and Arctic char from Bjørnøya.

Chlorthalonil is an organochlorine fungicide, also marketed as Nopocide and Daconil. It has been found in water and air in the eastern Canadian archipelago and in subarctic and Arctic lakes in Canada.

Other current use pesticides that have been detected at low concentrations in subarctic and Arctic lakes and snow are atrazine, desethylatrazine (degradation product), alachlor, disulfoton, flutrafol, terbufos, fenitrothion, metolachlor, and methyl parathion.

and they are known to deposit in regions removed from the site of application. Moreover, many of these chemicals are used in large quantities and there is some concern that they will still transport over long distances and end up in remote environments such as the Arctic.

Previous AMAP assessments have highlighted lindane (gamma-HCH) as a current use pesticide that is ubiquitously present in the Arctic. Several other current use pesticides have been detected in Arctic air, soil, water or animals. The levels are often low, sometimes too low to quantify, but the presence of these chemicals in environments where they have never been used nevertheless shows that they can transport over long distances. In addition to gamma-HCH mentioned above and endosulfan, which has been discussed separately, the current-use pesticides that have been reported as detected in the Arctic are listed in the box above.

A study of an ice core from the Austfonna ice cap in Svalbard found about 20 current use pesticides that had been deposited in snow since 1970 to about 2000. These included the organophosphate insecticides and herbicides that are widely used in cultivation of corn (maize). Maximum concentrations were typically in the most recent

snow/ice horizons but deposition in the 1960s was apparent for some chemicals. The likely source regions for these agricultural chemicals were northern Europe and Russia because of their proximity to Svalbard and the frequent movement of air masses from continental Europe to this area.

In addition to the current use pesticides that have been detected in the Arctic, the screening of potential POP chemicals discussed in the previous section predicts that several other current-use pesticides may reach the Arctic.

▼ Farmer spraying pesticide on rice field.



Legacy POPs

Legacy POPs is a term applied to chemicals that are banned or restricted. However, because they are persistent, they remain in the environment and may do so for a long time. Monitoring the levels of legacy POPs in the Arctic is of interest because it provides information about environmental degradation and fate and the impact of policy decisions. It may also give an indication of how other factors, including climate change, may influence the levels in the environment. Moreover, information about legacy POPs is important in assessing the combined effects of different pollutants on wildlife and human health. Legacy POPs have been reviewed in detail in previous AMAP assessments. This report focuses on how the levels of legacy POPs have changed over time. It also presents an update on biological effects. The main compounds of concern are presented in the box on the next page.

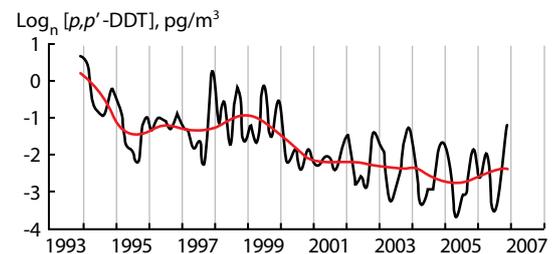
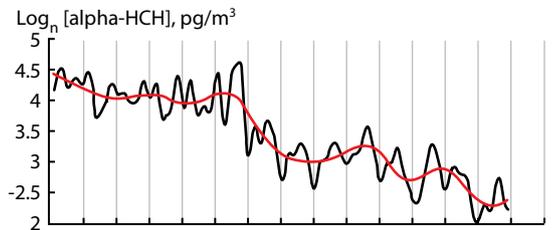
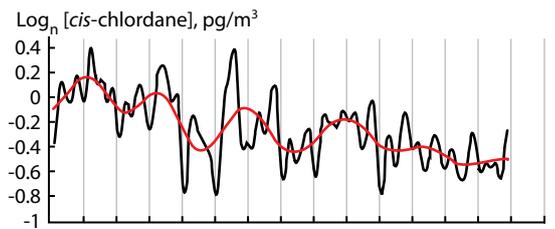
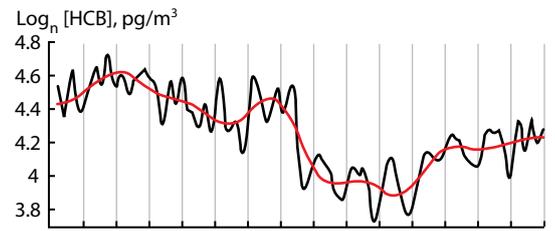
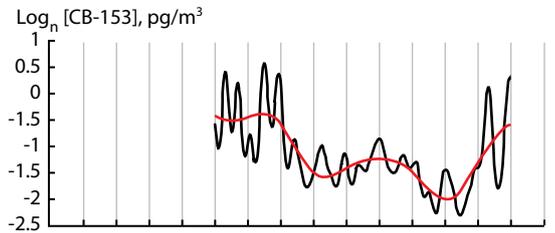
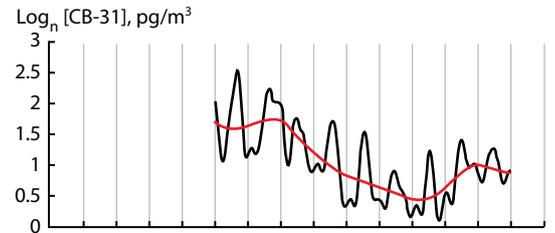
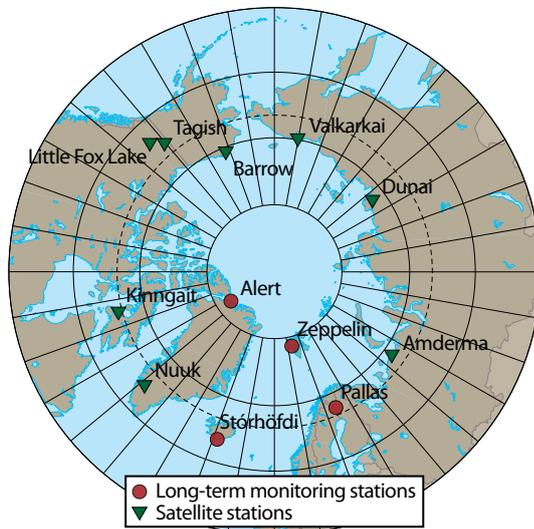
Levels in air and time trends

Air is a rapid long-range transport route for POPs from the areas where they are used to the Arctic. Polluted air masses only take a few days to travel several thousand kilometers. They reach even the most remote parts of the Arctic and provide a major pathway for pollution into the region. Since the early 1990s, AMAP has systematically monitored levels of pollutants in Arctic air. The data are used for evaluating time trends. These results have contributed to effectiveness and sufficiency evaluations of the Stockholm Convention and the UN ECE LRTAP POPs Protocol. They are also used to validate models of air transport that can help

identify where the pollutants come from. Of the 12 POPs that were initially identified in the Stockholm Convention, continuous monitoring data are only available for PCBs, HCB and DDT. Three stations also report data for chlordane.

As might be expected from their discontinued use, levels of legacy POPs in air are generally declining. The apparent half-lives (indicating the rate of decline) vary for different compounds and different

► POPs have been monitored at several locations around the Arctic; however, long-term monitoring has only been conducted at a few sites. The graphs show examples of trends of legacy POPs in air over time from the Zeppelin station on Svalbard.



Legacy POPs

PCBs

Polychlorinated biphenyls (PCBs) are a group of chemicals that have been used in a number of applications including transformer and capacitor oils, hydraulic and heat-exchange fluids, lubricating and cutting oils, and as plasticizers and joint sealants. The manufacture and use of PCBs are banned under the Stockholm Convention but they are still present in some existing products, such as old electrical equipment. Countries have until 2025 to take action to phase out use of existing equipment with PCBs and have to eliminate or treat the recovered PCBs by 2028. The Convention also requires that countries take steps to limit emission of PCBs with the aim to eventually eliminate releases into the environment. PCBs have a range of toxic effects. The most significant is that they affect the immune system and disturb behavior and reproduction in birds, fish and mammals. In the Arctic, they affect the polar bear population in particular. As one of the most ubiquitous pollutants, they also play a major role in impact of POPs on human health.

DDT and DDE

DDT has been used widely to kill insects and is still used against mosquitoes to control malaria in some parts of the world. The Stockholm Convention limits the production and use of DDT to controlling disease. It also allows DDT as an intermediate in production of the pesticide dicofol in countries that have registered this exemption. Measurements often refer to DDE which is a toxic and persistent breakdown product of DDT. DDT-DDE affects sex hormones and thus reproduction. It has been identified as the major cause of egg-shell thinning and decline of populations of predatory birds such as the peregrine falcon. The decreasing levels in the environment have been important for the recovery of bird populations although the previous AMAP assessment (2002) concluded that egg-shell thinning was still a concern for several bird populations. This assessment includes reports on 7-17 percent eggshell thinning in ivory gulls in four colonies in Svalbard and Russia compared to pre-DDT levels. This is approaching a degree of eggshell thinning that is known to cause declines in bird populations.

Chlordane

Chlordane is used to control termites and is also used as a broad-spectrum insecticide for agricultural crops. The Stockholm Convention limits the production and use to narrowly prescribed purposes and to countries that have registered for exemptions. Chlordane affects reproduction and the immune system.

HCB

Hexachlorobenzene (HCB) is a past-use fungicide and has also been emitted to the environment as a by-product from the production of chlorinated pesticides, incineration, and metallurgical processes. The Stockholm Convention limits the production and use to narrowly prescribed purposes and to countries that have registered for exemptions.

HCHs

Hexachlorocyclohexane (HCH) comes in several different chemical forms (isomers). The gamma-isomer (γ -HCH) is the same as the insecticide lindane. Mixtures containing the alpha (α -) and beta (β -) isomers were banned or its use was phased-out in the 1980s. Use of lindane has declined from the 1980s and 1990s. Canada, a major North American user, deregistered use of lindane in agriculture in 2004. Lindane has a range of toxic effects including effects on the nervous system, reproduction, and the immune system.

Dioxins and furans

Dioxins and furans are created as by-products in high-temperature processes, such as waste burning and metallurgical industries, and as trace contaminants in some herbicides and in PCB mixtures. The Stockholm Convention and the UN ECE LRTAP POPs Protocol regulate emissions. The toxic mechanism is the same as for dioxin-like PCBs and includes effects on reproduction, the immune system and increased risk of cancer.

Toxaphene

Toxaphene is an insecticide that was widely used until the 1990s. It is regulated by the Stockholm Convention and the UN ECE LRTAP POPs Protocol.

Mirex

Mirex was used as insecticide and fire retardant until 1978. It is regulated by the Stockholm Convention and the UN ECE LRTAP POPs Protocol.

stations. However, most PCBs decline with a half-life of less than 10 years. Some intermediate weight PCB congeners show longer half-lives (~20 years) at some locations in the Arctic. This mirrors the historical decline rates of PCB emission estimates derived from production and consumption data of PCBs from 1930 to 2000. The emission of lighter and heavier PCB congeners declines faster than intermediate congeners in the polar region. This indicates that the rates of decline in air concentrations of PCBs were mostly driven by declines in primary emission. A modeling study indicates that when primary emission stops, soil becomes the major global PCB reservoir and the rate of decline in air will depend solely on that in soil.

The half-lives of organochlorine pesticides (i.e. DDT, HCHs, chlordane) in Arctic air generally range from 3 to 16 years. Trans- and cis-nonachlor (minor components of the technical chlordane formula), which have extremely low air concentrations, have very long half-lives at Zeppelin, 26 and 94 years respectively. This indicates that their concentrations are leveling off at this location. The figures on page 26 give some examples of time trends.

Climate change may affect time trends

For some POPs, there are local variations in patterns over time which may have important policy implications. The most significant finding, and in contrast to the general declining trends, is that the levels of PCB, HCB and DDT have *increased* at the Zeppelin station during the last four years of the time series (2002-2006). A possible explanation is that climate change, along with changes in ocean currents, has led to declining ice cover and an ice-free western coast of Spitsbergen (Svalbard, Norway) during the winters of 2003 to 2006. The open water has possibly allowed POPs that have previously been trapped in the ocean water to escape to the air. For some POPs, the Arctic Ocean has been a sink for global emissions. If, or when, the sea ice disappears, this store of old POPs may become an important source to the atmosphere long after direct releases into the environment have ceased. This is suspected to be happening for alpha-HCH, which shows higher levels in Arctic air when the ice breaks up. Its chemical signature confirms that the “extra” alpha came from the sea, not from long-range transport. Climate change may thus delay the impact in the environment of policy actions against POPs.

Another anomaly is episodes of increased levels of PCBs in air at Zeppelin in July 2004 and spring 2006. These were possibly caused by boreal forest fires in Yukon/Alaska and agricultural fires in Eastern Europe, respectively, where the biomass burning enhanced volatilization of previously deposited organic chemicals, such as PCBs, from soil. Similarly, episodes of chlordane and DDE were observed at Alert and Zeppelin in 2004, which may also be the result of biomass burning. Thus, changes in local climate regimes, such as that at Zeppelin (Svalbard), may already be affecting temporal trends. Increased frequencies of forest fire events at northern latitudes due to climate change may also result in enhanced input of pollutants to the Arctic.

The general message in terms of temporal trends is that the legacy POPs are declining in air but that this decline may be complicated by climate change via e.g. decreasing sea-ice coverage and an increase in forest fire events. Change in pesticide use, such as an increase of use of chlorothalonil and quintozene which are contaminated with HCB (a legacy POP), may be another complicating factor.

Levels in wildlife are declining

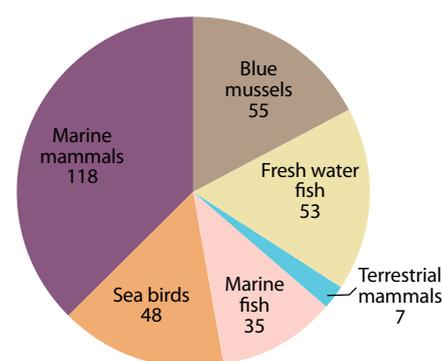
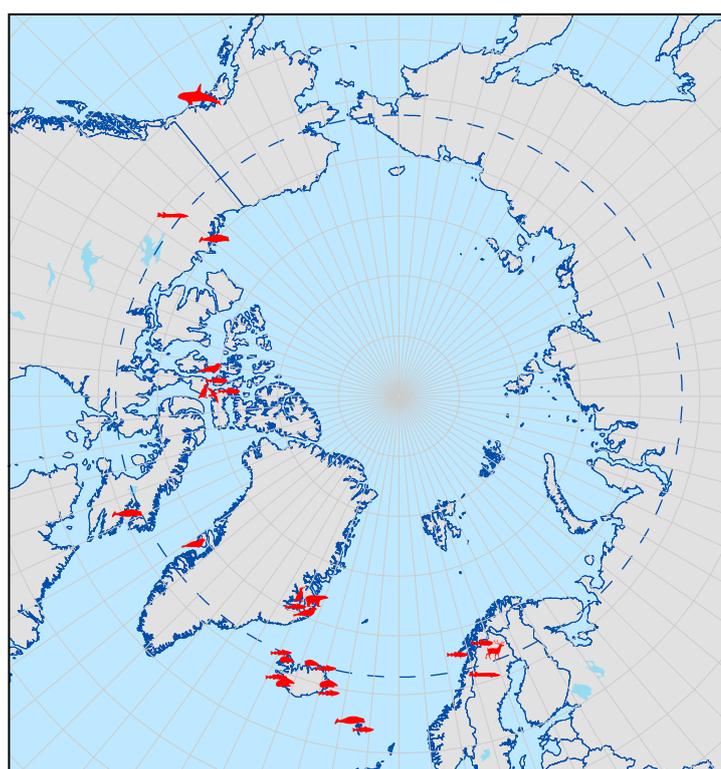
Legacy POPs in air and water are likely to end up in wildlife, but the levels in various animals reflect more factors than the concentrations in the surrounding environment. Factors such as changing feeding habits and the age of the animals have to be considered when trying to elucidate time trends. To draw reliable conclusions, there is a need to assess a number of different studies covering different regions and different species and to do so in a statistically robust manner. For this assessment, a time trend analysis was performed based on 319 different time series of legacy POPs. Only time series with at least six years of data and having years both before and after 2000 included. The figure on the next page shows the distribution of species and countries where the individual studies were conducted.

In addition, literature for the past four to five years dealing with time trend analysis was reviewed. The conclusions from this time trend assessment are summarized on the next page.

More time series data are needed

Statistically significant conclusions from time series require data from a certain number of years, especially in situations with large variation between

PCBs	Many time trend analyses (40% of the time series analysed) show a significantly decreasing trend of PCB-153. This is found throughout the western Arctic species belonging to both terrestrial, freshwater and marine ecosystems (no time series for the Russian Arctic were available). A literature review of the recent publications supports the decreasing trend of PCBs in Arctic biota. The mean of 40 time series was an annual decrease of 1.4%. The studies pointed to very few increasing trends.
α -HCH	Many time trend analyses show a significant decreasing trend of α -HCH, especially in freshwater fish, seabirds and marine mammals. No significantly increasing trends were found. The mean of 32 time series was an annual decrease of 7.4%, the highest found among legacy POPs.
β -HCH	While there are consistent decreasing trends in marine biota from Greenland and Iceland, the picture for Canada is more complicated with many time series showing no trend and some showing increasing trends in marine mammals and sea-birds. The mean of 21 time series was an annual decrease of 2.9%.
γ -HCH	Most time series from Canada and Greenland (including freshwater and marine fish, seabirds and marine mammals) show decreasing trends, and none a significant increasing trend. The mean of 11 time series was an annual decrease of 7.3%.
DDE and DDTs	Many time trend analyses show a significant decreasing trend of DDE and DDTs all over the Arctic, especially in seabirds and marine mammals. Also the majority of recently published temporal trend studies report decreasing trends. The mean of all time series was an annual decrease of 1.9 and 4.4% for DDE and DDTs, respectively.
HCB	Decreasing trends are observed in many countries. However, the trend in marine mammal populations was less apparent than for other legacy POPs. The mean of 40 HCB time series was an annual decrease of 2.5%.
Chlordane and trans-nonachlor	Decreasing trends are observed from many Arctic countries. However, in seabirds and marine mammals from Canada the trend is less apparent and there are only few reports of significant decreases. The mean of 17 chlordane and 29 trans-nonachlor time series was an annual decrease of 1.8 and 1.0%, respectively.
Heptachlor epoxide	No firm conclusion can be drawn because of the limited number of time series available that only cover Canada. The mean of 6 time series, all from Canada, was an annual decrease of 0.7%.
Dieldrin	Decreasing trends are observed from Canada and Greenland. No or very limited knowledge exist in other parts of the Arctic. The mean of 11 time series deriving from Canada and Greenland was an annual decrease of 2.1%.
Mirex	No firm conclusion can be given as both increasing and decreasing trends were found in Canada and time series outside Canada were very limited. The mean of 12 time series from Canada and Faroe Island was an annual decrease of 1.6%.
Toxaphene	Decreasing trends are found in one freshwater fish population in Canada and one seabird population in Greenland. The mean of 10 time series (freshwater fish, seabirds and marine mammals) deriving from Canada, Greenland and Faroe Island was an annual decrease of 0.8%.
Dioxin, furans, and dioxinlike PCBs	Levels of dioxins, furans and dioxin-like PCBs are often reported as toxic equivalents: TEQs. Decreasing trends are found in Canada and Greenland. No knowledge is available from other Arctic countries. Only two time series were available; both of seabirds from Canada, with an annual decrease of approximately 4%.



-  Killer whale
-  Fulmar / kittiwake
-  Murre / guillemot
-  Polar bear
-  Beluga / pilot whale
-  Cod / sculpin
-  Mussels
-  Ringed seal
-  Pike / burbot
-  Char
-  Reindeer

◀ Available time-series of legacy POPs in Arctic biota. These time-series generally show decreasing trends over the past two- to three-decades.

different years. In these temporal trend analyses only few studies (less than 10) fulfilled the statistical requirements. To draw firmer conclusions in the future will therefore require continued monitoring of legacy POPs in key biota. This is especially important for time series that will obtain sufficient statistical power in the near future as additional years of data are added.

Effects in Arctic wildlife

Since the 2002 AMAP assessment, knowledge about the effect of POPs on mammals and birds at the top of the Arctic marine food web has increased substantially. This includes better understanding of how POPs influence the animals. Moreover, controlled experiments have been able to confirm that current levels of POPs in the Arctic affect the health of top predators, such as polar bears.

A major challenge for understanding the impacts of POPs in wildlife is to link the effects seen in the animals to a specific cause, such as the load of contaminants. Many studies rely on correlations between high loads of contaminants and effects, along with the use of biomarkers. Biomarkers are changes

in the animals' physiology or anatomy that can be measured and are known to be affected by specific POPs. Examples are changes in liver enzymes.

A weakness of such studies is that the researchers often have limited knowledge of the life history and general condition of randomly-captured animals. There are always many factors that affect the health on an animal, for example infections, predation, climate change and food scarcity. This makes it very difficult to prove cause-effect relationships for one specific stressor.

Biological effects on polar bears have been confirmed

Polar bear feed on top of the Arctic marine food web and are exposed to high levels of several legacy POPs. Previous AMAP assessments have concluded that this exposure put the health of polar bears at risk because it affected their ability to fight infections and to reproduce. Moreover, there were some signs that contaminants affected the vitality of the polar bear populations around Svalbard.

One way to confirm that these effects are actually caused by POPs is experiments where the animals are fed contaminated food, which is neither practi-

► Animals such as polar bears are exposed to a number of stressors that can lead to adverse health effects.



cally feasible, nor ethically justifiable. An alternative to experiments on wild animals is to use a surrogate species that can be studied in captivity and/or under more controlled conditions. Recently studies have been published where sled dogs and Arctic foxes have been used as potential surrogates for polar bears and other Arctic top predators. In the sled dog study, juvenile dogs in West Greenland were fed either blubber from minke whale (including its environmental load of contaminants) or pork fat for two years. The West Greenland minke whale has a similar load of contaminants as ringed seals and was considered representative of the diet of polar bears.

Compared to the control animals (on a diet of pork fat), the sled dogs who were fed blubber had altered liver and kidney functions, reduced immune response and impaired cellular immunity. These toxicological effects are similar to those that have recently been reported in East Greenland polar bears.

A similar study has been done on farmed Norwegian Arctic foxes. Like the sled dogs, they were fed minke whale blubber or pork fat. For one group of animals, the researchers simulated starvation of polar bears by reducing the food to the fox, so that POPs that had been stored in the foxes' fat were released to the blood where it can expose sensitive organs. The results show that especially the cells in the kidneys have changes in size and shape, which may cause changes in the function of the kidneys. Some changes were also apparent in the thyroid, which is important for the animal's temperature control and for brain development and reproduction.

Looking at the mechanism behind the effects, they appear to be linked to changes in liver enzymes that can transform POPs such as PCBs and PBDEs into break-down products. Based on these studies of polar bears and on studies of glaucous gulls in the Canadian High Arctic, Eastern Greenland and Bjørnøya, biotransformation into these break-down products may be more important for the toxic effect than the levels of the original compound.

New observations have been made on effects in polar bears in East Greenland, where reduced size of reproductive organs has been documented in both male and female bears. However, previous observations on pseudohermaphroditism (female animals with male characteristics) in a few female polar bears from Svalbard were not verified. The polar bears in East Greenland also had changes in their livers and



Maja Kirkegaard

◀ Sled dogs have been used as surrogates for polar bears in studies looking into the effects on wildlife of dietary exposure to contaminants.

kidneys that could be linked to POPs. Studies of the skeletal system in East Greenland polar bears showed reduction in bone mineral connected to POP exposure. However, they did not see any changes in immunological organs such as lymph nodes, spleen, thymus and thyroid gland.

Taken together, these observations and controlled experiments show that POP-contaminated food causes similar changes in polar bears, Arctic foxes and sled dogs.

Whales and seals

The levels of POPs in whales depend on the eating habits of different species. Bowhead and gray whales, which are low in the food web, have low levels of contaminants. Recent studies have confirmed the very low POP levels in blubber of these species, with no signs of effects on the biology on the animals.

Beluga feed at a higher level in the food web and populations in the highly polluted St. Lawrence estuary are known to show adverse effects, including impacts on the immune system and tumors. Arctic beluga are less contaminated. At present, it is not known whether they may show more subtle effects, but a previous AMAP assessment that made comparison to known effect levels in other animals concluded that levels of PCBs in toothed whales are high enough to raise concerns. Further studies of biological impacts on beluga would therefore be warranted.

Seals present a similar picture to beluga with well documented toxic effects on highly exposed

population outside the Arctic, in this case the Baltic Sea. There are no new studies of biological effects on seals in the Arctic, but based on comparisons to known effect levels in other species, the previous AMAP assessment concluded that contaminant levels at some sites were high enough to raise concerns about effects on the immune system, on their levels of vitamin A, and reproduction.

Marine birds

Some species of Arctic seabirds feeding at the top of the marine food web are exposed to high levels of POPs. Previous AMAP assessments have concluded that levels were high enough to cause concern for a number of physiological and ecological effects. At Bjørnøya, observations were made in the early 1970s that breeding glaucous gulls behaved strangely and also had alarmingly high levels of PCBs and DDE. Since then, dead or dying glaucous gulls have also been recorded sporadically. This island is a known hot spot for PCBs as well as numerous other POPs. New studies have confirmed or established a link between specific POPs and effects on the liver enzymes, hormones and the immune system and that these changes are linked to survival and reproduction. For example, some POPs affect how the birds regulate their body temperature and transfer heat to the eggs, which in turn influence how they tend the nest.

Observations of glaucous gulls at Bjørnøya and great black-backed gulls from the northern Norwegian coast have shown that the effects of some POPs are worse when the birds are exposed to additional stressors such as infections, predation, climate change and/or food scarcity. This suggests that a changing environment with an increased stress on birds may change (e.g., increase) the impact of pollutants. POPs may also affect the health of Arctic marine bird at other locations in the Arctic, such as the highly contaminated ivory gull and skua at Svalbard, Franz Josef Land (Russia), the Faroe Islands, Iceland, and northern Norway.

Fish

In general, the POP levels in fish are low enough to not raise concerns about biological effects. There are some exceptions among long-lived fat marine fish (e.g. Greenland shark) and populations of freshwater fish that live at local hot spots. For Arctic char, there is new evidence of biological effects at Lake Ellasjøen on Bjørnøya. This lake receives a high load

of contaminants from guano from a nearby seabird colony and the POP levels are much higher than in another lake on the island. The effects that have been observed in Lake Ellasjøen char include indications that the liver is affected as well as hormones related to stress reactions.

In addition to these observations, there are experiments showing that environmentally relevant levels of POPs can affect the immune system and hormone systems of Arctic char.

Summary of biological effects

New studies and observation confirm that POPs cause biological effects in some Arctic species in some areas. Polar bears with high levels of contaminants are particularly at risk for effects on their reproduction and their defense against infections. Regions of special concern are East Greenland, Svalbard and the Kara Sea area. Some glaucous gulls and ivory gulls that are highly exposed to POPs are also at risk for effects on their reproduction, especially in the context of various other environmental stressors.

Breakdown products of POPs may be more important for the toxic effect on animals than the original compound. New evidence shows that the effect of POPs on the health of Arctic seabirds can be enhanced by other stressors.

Chapter summary

Recent years have seen increased international policy efforts to reduce the use and emission of a number of persistent organic pollutants and many of the most persistent and toxic chemicals have been banned. The levels of many such legacy POPs are now declining in the Arctic environment. This includes levels of PCBs, DDTs, HCHs, HCB, chlordane, dieldrin, toxaphene, and substances with dioxin-like toxicity. However, concentrations of POPs in some wildlife are still high enough to affect the health of several groups of animals, especially top predators in the marine food web. There are also some signs that climate change may affect contaminant pathways and distribution in the future, for example turn the Arctic Ocean into a source to the atmosphere or increase forest fires that can remobilize POPs in the soil. The database for time trends is growing but remains limited and firmer conclusions about the impact of policy decisions on environmental levels will require continued monitoring of legacy POPs in

both the abiotic environment and in key biota.

Since the previous AMAP assessment, new information has become available about several classes of man-made chemicals that are not yet regulated by international agreements. Similar to the legacy POPs, they are also present in Arctic environments where most have never been used, which indicate that they can transport over long distances and may accumulate in food webs that are remote from the source regions. They include brominated flame retardants, fluorinated compounds, polychlorinated naphthalenes and some current use pesticides, such as endosulfan. Based on assessments presented in this report, the following conclusions can be drawn.

The brominated compounds in the technical products Penta-, Octa- and DecaBDE (PBDEs) can transport over long distances and accumulate in biota. They therefore have POP characteristics. Similar to these PBDEs, it is also clear that HBCD is ubiquitous in the Arctic, that it undergoes long-range transport, that it accumulates in animals and that some components biomagnify. National regulations and changes in use and production appear to have had some effect. At least in some areas, environmental levels of PBDEs and HBCDs are now starting to level off or decline. TBBPA has been measured at low levels in several animals, but more data are needed to assess its potential to undergo long-range transport. Other brominated flame retardants that have been detected in occasional samples are PBB, BTBPE, HxBBz, PBEB and PBT. These latter four are used as substitutes for PBDEs and their presence in the Arctic is a warning sign that they also undergo long-range transport and that levels in the environment may increase over time.

The knowledge about fluorinated compounds in the Arctic is based on limited data but available information shows that the fluorinated compounds reach the Arctic both via the atmosphere and via

ocean currents. They accumulate in animals that are high in the food web in the marine environment. Although production of the major technical product – PFOS – has declined sharply, products that contain PFOS and other fluorinated compounds can still serve as sources to the environment. The fluorinated compounds are currently subject to review for both international and national regulation.

Polychlorinated naphthalenes (PCNs) are no longer produced and levels in the environment peaked almost half a century ago. However, PCNs are still present in the Arctic with indications of further input from a combination of combustion sources and emissions from old products. They contribute to dioxin-like toxicity in Arctic animals but are generally less important than PCBs.

The pesticide endosulfan partly fulfils the criteria of a POP due to its toxicity and its occurrence in remote environments. Its presence in the Arctic confirms its ability to transport over long distances. Endosulfan and its degradation products appear to persist, yet there is no clear indication of significant bioaccumulation or biomagnification. The actual problem compound is the breakdown product endosulfan sulfate. Its slow degradation results in potential for high chronic toxicity. Moreover, it enriches in aquatic environments, where it may pose a hazard to water-living organisms. The data on other current use pesticides are very limited, but several compounds have been found in the Arctic.

Screening of high volume chemicals indicate that many current-use organic compounds have chemical characteristics that make them similar to POPs and thus potential to transport to the Arctic. Characteristics that signal potential environmental concerns are ability to exchange between water and air, and between air and soil or plant surfaces, combined with the presence of multiple chlorine, fluorine or bromines on the molecule.

International treaties and actions to limit the use and emission of POPs and heavy metals

Under the auspices of the United Nations Environmental Programme (UNEP), the Stockholm Convention is the major international, legally binding instrument for managing POPs on a global scale. Signed in 2001, it came into force in May 2004, and by March 2008 had been ratified by 153 countries. Among Arctic countries, only the United States and Russia have yet to ratify the convention. At present, twelve POPs are governed by the convention, but eleven more have been proposed for addition to that list. Of those eleven, nine have been found to meet the definition of 'persistent organic pollutant'. Risk management evaluations have been completed for five of these, which have been recommended for addition to the convention's list.

The Aarhus Convention on the Long-Range Transport of Air Pollutants, under the auspices of the United Nations Economic Commission for Europe developed two protocols in the mid-1990s – the POPs and Heavy Metals protocols. The POPs protocol addresses sixteen chemicals and the Heavy Metals Protocol covers three heavy metals – mercury, lead and cad-

mium. The protocols identify bans and restrictions, some emission limits, and codes of best practice related to POPs and metals. Both were signed in 1998 and came into force in 2003. Each has been ratified by 29 countries, though both Russia and the United States have yet to ratify them.

Under environmental cooperation related to the North American Free Trade Agreement, Canada, Mexico, and the United States have successfully eliminated the use of all twelve chemicals in the original list of the Stockholm Convention. In addition, they have developed a North American environmental monitoring and assessment plan. In 2006, the initiative was reoriented to foster tri-national collaboration on chemicals of concern, to provide consistent data to decision makers, and to increase monitoring and assessment capacity.

The European Union has introduced a number of measures targeting harmful chemicals in the environment. Important measures adopted in recent years include legislation concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH; EC/1907/2006), which

	Type of chemical	Stockholm Convention	UN ECE Protocols on POPs (UN ECE, 2008a)	Addressed by North American Regional Action Plan
Aldrin	Pesticide	Listed under Annexes as of 2008	No production or use permitted	Not in use in NA
Chlordane	Pesticide	Listed under Annexes as of 2008	No production or use permitted	Production and use eliminated
Dieldrin	Pesticide	Listed under Annexes as of 2008	No production or use permitted	Production and use eliminated
Endrin	Pesticide	Listed under Annexes as of 2008	No production or use permitted	Not in use in NA
Heptachlor	Pesticide	Listed under Annexes as of 2008	No production or use permitted	Not in use in NA
Hexachlorobenzene (HCB)	Pesticide Industrial chemical	Listed under Annexes as of 2008	No production or use permitted; limits on emissions	Not in use in NA
Mirex	Pesticide	Listed under Annexes as of 2008	No production or use permitted	Not in use in NA
Toxaphene	Pesticide	Listed under Annexes as of 2008	No production or use permitted	Not in use in NA
Dichloro-diphenyltrichloroethane (DDT)	Pesticide	Listed under Annexes as of 2008	No production or use permitted	Production and use eliminated
Polychlorinated biphenyls (PCB)	Industrial chemical	Listed under Annexes as of 2008	No production or use permitted	Production ended, no new uses, phase-out and destruction
Polychlorinated dibenzo- <i>p</i> -dioxin (PCDD)	Industrial by-product	Listed under Annexes as of 2008	Limits on emissions	Best practices and waste management
Polychlorinated dibenzofuran (PCDF)	Industrial by-product	Listed under Annexes as of 2008	Limits on emissions	Best practices and waste management
Polyaromatic hydrocarbons	Industrial by-product		Limits on emissions	
Chlordecone	Pesticide	Considered a POP and risk management evaluation complete	No production or use permitted	
Hexabromobiphenyl (HBB)	Industrial chemical	Considered a POP and risk management evaluation complete	No production or use permitted	
Lindane (gamma-hexachlorocyclohexane)	Pesticide	Considered a POP and risk management evaluation complete	Restrictions on use	Production and use eliminated
Perfluorooctane sulfonate (PFOS)	Industrial chemical	Considered a POP and risk management evaluation complete	Considered a POP and undergoing assessment of management options	

requires manufacturers and importers to identify the dangers from their substances, assess potential risks and stipulate measures to rule out any damage to health and the environment; the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS; 2002/95/EC); and legislation on waste electrical and electronic equipment (WEEE; 2002/96/EC).

UNEP established its 'mercury programme' in 2003. In 2005 UNEP's Governing Council called for the development of a report on supply, trade and demand for mercury on the global market and facilitated the establishment of partnerships between governments and other stakeholders as one approach to reducing risks to human health and the environment from mercury. In 2007, UNEP's Governing Council requested further reports on mercury emissions to the atmosphere and options for reducing mercury releases to the environment. Following review of this information, in 2009, UNEP's Governing Council decided to begin negotiations aimed at developing a legally-binding instrument on mercury by 2013.

Russia has undertaken several domestic steps to reduce pollution, centered on a national policy that entails over fifteen federal laws and codes. It has also participated in the development of five international agreements, though has only ratified one of them to date.

AMAP assessments have extensively used in the development and implementation of the Stockholm Convention and the UN ECE LRTAP Protocols on Heavy Metals and POPs, and continue to be used in evaluating the 'effectiveness and sufficiency' of these instruments and as an important source of information on new candidate substances. The Arctic regional monitoring strategy has contributed to the development of UNEP global monitoring programme for POPs. AMAP's 2002 recommendations on the need for action on mercury were taken up by the UNEP Governing Council in initiating its mercury programme.

In addition to ensuring implementation of global and regional agreements, further monitoring is required to determine whether national, regional, and international actions are achieving the desired goals of reducing contaminant levels in the environment and in humans.

	Type of chemical	Stockholm Convention	UN ECE Protocols on POPs (UN ECE, 2008a)	Addressed by North American Regional Action Plan
Hexabromocyclododecane (HBCD)	Industrial chemical	Proposed for inclusion; risk profile will not be prepared until 2010	Under consideration	
Pentabromodiphenylether (PentaBDE)	Industrial chemical	Considered a POP and risk management evaluation complete	Considered a POP and undergoing assessment of management options	
Octabromodiphenyl ether (OctaBDE)	Industrial chemical	Considered a POP and risk management evaluation underway	Considered a POP and undergoing assessment of management options	
Pentachlorobenzene (PeCB)	Industrial chemical	Considered a POP and risk management evaluation complete	Restrictions on use	
Short chain chlorinated paraffins (SCCP)	Industrial chemical	Under consideration	Considered a POP and undergoing assessment of management options	
alpha-hexachlorocyclohexane (alpha-HCH)	Pesticide	Considered a POP and risk management evaluation underway	Restrictions on use	Not in use in NA
beta-hexachlorocyclohexane (beta-HCH)	Pesticide	Considered a POP and risk management evaluation underway	Restrictions on use	Not in use in NA
Endosulfan	Pesticide	Under consideration	Under consideration	
Polychlorinated naphthalenes (PCNs)	Industrial chemical and byproduct		UN-ECE Task force on POPs has supported that PCNs be considered a POP	
Hexachlorobutadiene (HCBD)	Industrial Chemical and byproduct		Considered a POP and undergoing assessment of management options	
Trifluralin	Pesticide		Considered a POP and undergoing assessment of management options	
Pentachlorophenol	Pesticide		Considered a POP and undergoing assessment of management options	
Dicofol	Pesticide		Considered a POP and undergoing assessment of management options	

Contaminants and Human Health

Factors Influencing Human Exposure to Contaminants

Many factors influence human exposure to contaminants. The release of contaminants into the environment is just the starting point. As described in the Introduction, air circulation, ocean currents, and rivers carry contaminants from their sources throughout the world. Contaminants move from one part of the environment to another, and are taken up in the food web. Most human exposure is through diet, so the human position in the food web is crucial. This section describes two aspects of exposure that have received less attention in the past: human activity within the Arctic and social and cultural influences. International agreements affect contaminant emissions and, ultimately, exposure. Major agreements relevant to the Arctic are summarized here.

Global and regional treaties help reduce contaminant emissions

The main international agreements limiting use and emissions of POPs and heavy metals are listed on pages 34-35. The Stockholm Convention is the major international, legally binding instrument for managing POPs. Signed in 2001, it came into force in May 2004, and by March 2008 had been ratified by 153 countries. Among Arctic countries, only the United States and Russia have yet to ratify the convention. At present, twelve POPs are governed by the convention, but eleven more have been proposed for addition to that list. Of those eleven, nine have been found to meet the definition of “persistent organic pollutant.” Risk management evaluations have been completed for five of these, which have been recommended for addition to the convention’s list.

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Russia has undertaken several domestic steps to reduce pollution, centered on a national policy that entails over fifteen federal laws and codes. It has also participated in the development of five international agreements, though has only ratified one of them to date.

The development and implementation of global and regional agreements is a promising step, but further monitoring is required to determine whether they are achieving the desired goals of reducing contaminant levels in the environment and in humans.

▼ Mother breast-feeding infant at summer camp, Qaanaaq, northwest Greenland.



Bryan and Cheryl Alexander

► Discarded transformer at old DEW Line site on the Melville Peninsula, Nunavut, Canada.

Industrial activity in the Arctic may become a larger local source

Mining has taken place in the Arctic for over a century. In some areas of northern Russia, particularly the Kola Peninsula and the Norilsk region, local impacts of pollution have been severe. In Canada, mining activity is increasing for many minerals, but no smelting takes place and only localized environmental impacts been found. The situation is similar in Alaska, where large-scale mining consists of one coal mine and one open-pit lead-zinc mine, in addition to many small gold mines. Testing to date has revealed no health problems associated with mining pollution. Mining is expected to increase in Greenland, too, in the near future.

Oil and gas activity has been underway in many parts of the Arctic for decades. Current practices appear to pose relatively little threat to human health through the release of contaminants. Petroleum exploration and production are expected to increase in coming years, likely leading to increased releases of petroleum hydrocarbons, but even a large oil spill is not expected to add substantially to POPs and heavy metals levels in the Arctic. The social impacts of oil and gas activity include increased income as well as social disruption from immigration and other causes. These can lead to both positive and negative impacts on human health, potentially affecting health outcomes related to contaminants.

There are many waste sites in the Arctic that have the potential to become sources of contaminants, particularly as permafrost thaws. The Distant Early Warning (DEW) Line sites across northern North America have considerable amounts of hazardous chemicals, including PCBs, paints, and oil. The costs of clean up are made higher by the remoteness

▼ Raw sewage being dumped into the sewage lagoon on Igloodik Island, Nunavut, Canada.



Bryan and Cherry Alexander

of the sites. Other military sites pose similar threats. The containment of municipal waste and sewage in rural Alaska often relies on permafrost. As permafrost thaws, pathogens and contaminants are more likely to be released to the surrounding environment. So far, however, no systematic evaluation of this potential problem has been undertaken.

In Russia, one estimate indicates that as many as 12 million drums of waste were left in the Arctic at the end of the Soviet era. The contents of these drums are not known, but likely include waste oils, lubricants, contaminated water, and other substances. Many are located near communities and may be major sources of local pollution. Remediation efforts are underway, led by indigenous communities in cooperation with the Arctic Council. Another effort has inventoried and safely disposed of over 1300 tonnes of obsolete pesticides in the Russian Arctic.

Social and cultural practices influence contaminant exposure

Among Arctic indigenous peoples, eating traditional foods is seen as healthful, both physically and spiritually. Sharing of food has great cultural significance, also generating a sense of individual and community well-being. Sharing ensures that families and individuals are provided for in times of need, and also influences the type and amount of food that people eat. Traditional foods are also an important source of many nutrients. At the same time, traditional foods are the main avenue for exposure to contaminants. Social factors that

influence dietary and other lifestyle choices are thus important influences on contaminant burdens.

In addition to food consumption, smoking and breast feeding are both subject to social and cultural influences and are routes of human exposure to environmental contaminants. In the case of breast feeding, the benefits to mother and infant are well documented, though many contaminants are carried in breast milk. Smoking, on the other hand, carries no known health benefit, though it may be undertaken as a social activity in some settings. Tobacco smoke carries cadmium and other contaminants.

Food, Diet, Nutrition, and Contaminants

Exposure to contaminants in the Arctic is largely through food. Since food also provides energy and nutrients, contaminants must be considered in light of the whole dietary system. Harvesting, sharing, and eating traditional foods provide many benefits to Arctic peoples. This section describes the relationships between traditional foods, nutrition, and exposure to contaminants.

Traditional food is important for many reasons

Indigenous peoples of the Arctic recognize many health benefits from traditional food. Its use is often important to identity. Sharing of food maintains interpersonal relationships and community cohesion. Traditional food is often cheaper to obtain than store-bought food (i.e., food produced outside the Arctic), which is important where costs of living are high. Traditional food nourishes the body and the spirit, both through consumption and also through spending time on the land and sea to obtain those foods.

Today, many other factors influence consumption levels of traditional foods as well as overall well-being of Arctic peoples. The influence of non-indigenous society, industrial development, and the availability

of store-bought foods all contribute to a shifting diet. Overall, studies of food choice in Arctic Canada have shown that accessibility, convenience, and personal preference are the main factors determining the extent of traditional food consumption.

Contaminants appear to play a lesser, but often important, role in food choice. In some studies, respondents indicated that information about contaminants did not affect the decision to eat traditional foods. In another study, 40% of women surveyed in western Canada indicated that concern about contaminants led them to serve traditional foods less often.

Access to traditional food often depends on social networks. In strong networks with active hunters and fishermen, traditional foods are commonly shared and thus readily accessible. Within such a network, most individuals follow the general dietary pattern of the group. These results indicate that health advice to change diets may not be effective because traditional food freely available through sharing networks is likely to remain more attractive than expensive food from a store, despite the health implications. Developing other choices that are culturally appropriate but carry fewer contaminants is likely to be more effective.

Further studies are needed for regions other than the Canadian Arctic to determine if similar patterns are found elsewhere in the circumpolar North.

Most dietary energy comes from store-bought food

Several studies of food consumption have been carried out around the Arctic. Except for some areas of northern Russia, most dietary energy comes from store-bought foods. In the Canadian Arctic, for example, traditional food contributed 11.4-29.9% of dietary energy for women and 16.0-28.5% for men



Rane Willerslev



Rane Willerslev

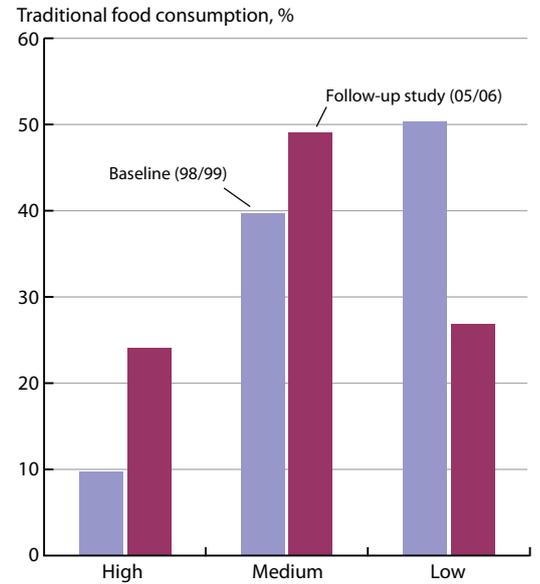
◀ Shifts from traditional to store-bought foods may reduce exposure to contaminants, but at the same time it reduces intake of some nutrients that are beneficial to a healthy diet.

► Comparison of traditional food consumption in Inuvik, Canada in 1998/1999 and 2005/2006.

among Dene/Métis adults surveyed in 1997. In the same region, children age 10-12 surveyed in 2001 were found to obtain less than 5% of their dietary energy from traditional foods. Studies of mothers in the Inuvialuit region showed an increase in traditional food consumption between the periods 1997-2000 and 2003-2006. This increase may be the result of differences between surveys, but it also may reflect health advice to continue eating traditional foods.

In Uummannaq, Greenland, the contribution of dietary energy from traditional food declined from 41% in 1976 to 13.4% in 2004. Another study in Greenland found that increasing age and economic status were more closely linked with obesity (being overweight to the point of affecting one's health) than the composition of an individual's diet. In Norway, younger coastal Saami eat few local fish, unlike older persons and those living inland. Inland Saami continue to consume reindeer, whereas Norwegians in the same area eat mostly store-bought foods. In Alaska, several studies have found that traditional foods contribute 15-22% of dietary energy, though this appears to be lower for younger people.

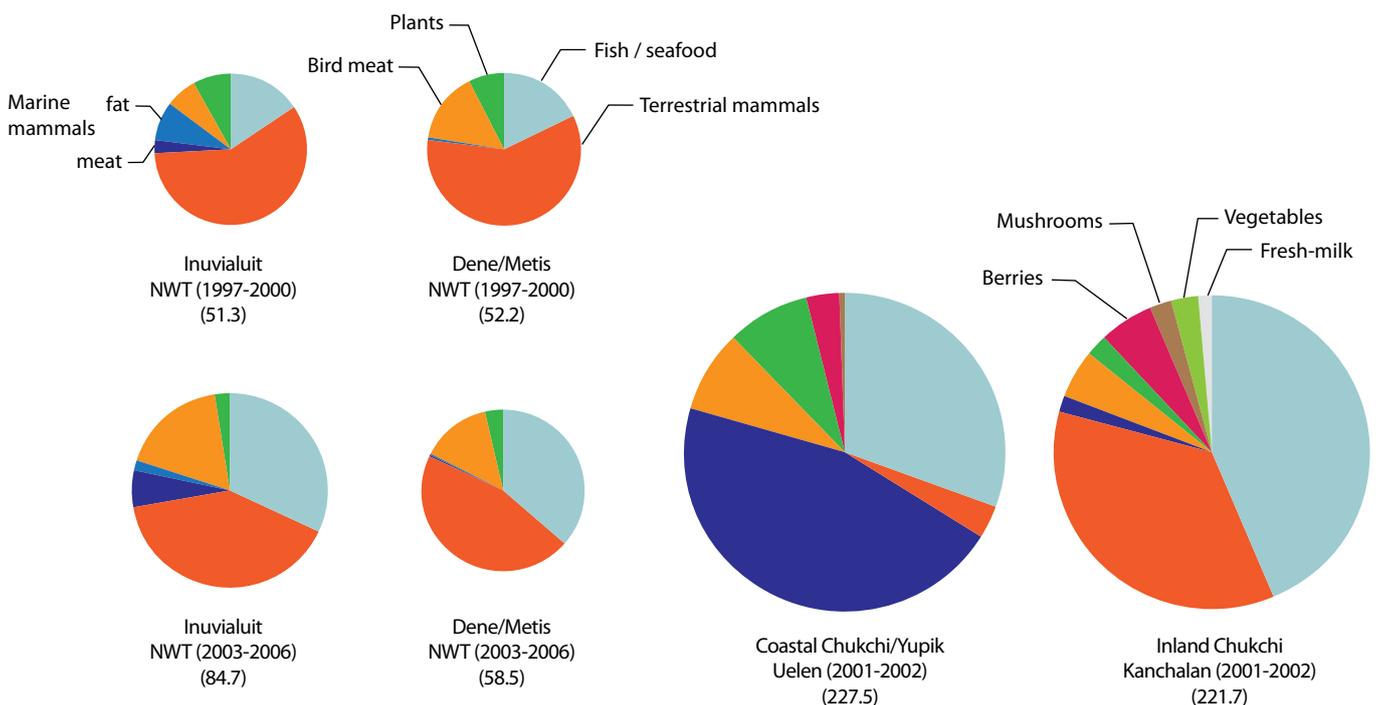
In all regions, the contribution of many nutrients from traditional foods is higher than the energy contribution. For younger persons eating less traditional food, overall nutrient intake is typically lower, too. The prevalence of obesity appears to be rising in Greenland, Canada, and Alaska. Although still associated with chronic health problems, obesity



among Inuit may carry lower risk than it does for Caucasians. For example, cholesterol levels among Inuit of all body types were lower than among corresponding southern Canadians and Europeans.

Russia is an exception to the general trend, particularly after the end of the Soviet Union and the consequent decline of government services and support in remote areas. Fish and land mammals, primarily reindeer, are the main components of local diets. Between 1985 and 2000 in Chukotka, the contribution of traditional foods to meat intake increased from 55% to 89%. Furthermore, younger people were more likely to prefer traditional food than older people who grew up during the Soviet era.

▼ Traditional food consumption among Inuvialuit and Dene/Métis in Canada in 2003-2006 compared with that in 1997-2000; and traditional food consumptions in two communities in Chukotka, Russia in 2001-2002 (numbers are amounts in kg/person/year).



Traditional foods provide many nutrients

While most dietary energy comes from store-bought foods, nutrients are another matter. Traditional foods are the main sources nutrients associated with meat and fish: protein, fat, most minerals, vitamin D, and long chain omega-3 fatty acids. Store-bought foods, on the other hand, provide most of the carbohydrates, water-soluble vitamins, vitamin A, and calcium. The diversity of traditional foods and the wide range of consumption levels, however, make generalizations difficult. Comparisons of specific nutrients and also of specific locations provide more details. Seasonal variation in diets means that nutrient intake can vary considerably during the year. Further research is needed to understand the significance of such variation.

Omega-3 fatty acids are found in marine foods and provide health benefits. Not surprisingly, their consumption is higher among coastal people, particularly those with higher consumption of traditional foods. Unfortunately, the same traditional foods that provide many nutrients often also carry contaminants, a dilemma addressed in more detail later in this report. Because traditional foods are high in some nutrients and low in others, a dietary shift towards store-bought foods can have some nutritional benefit while also creating deficits. Many of the store-bought foods that are eaten, however, are high in sugars and fats and thus do not contribute to a healthy overall diet. Because younger people tend to eat fewer traditional foods, and also eat high-sugar store-bought foods, nutrient deficits are a big concern for children and youth. Alcohol consumption, too, is often high in the Arctic, leading to nutritional and other health and social problems.

Intake of contaminants reflects environmental levels, dietary patterns

As with nutritional data, comparisons of dietary exposure to contaminants must take many factors into account. Geographic variability in contaminant levels in the environment mean that the same eating patterns in different areas may produce very different contaminant burdens. Of course, eating patterns tend to vary greatly from place to place, which must also be taken into account. Existing studies of dietary exposure have used different approaches and methods, so that direct comparisons must be treated with caution. Nonetheless, some patterns are apparent. Public



Rane Willerslev



Rane Willerslev



Rane Willerslev

▲ Traditional food consumption, and all the activities that are associated with it, remains important to indigenous communities throughout the Arctic.

Average daily intakes of key contaminants (micrograms/day) compared with tolerable daily intake (TDI) values from studies undertaken in different countries. Information on the proportion of the study populations that exceed blood level guidelines is given on pages 48 and 49.

		PCB Arochlor-1260	DDTs	Chlordanes	Hg
	Tolerable daily intake ^a , micrograms/day ▶	60	1200	3	12.2
	▼ Study group, year				
Canada	Whitehorse, Yukon (1998)	-	0.36	0.06	-
Finland	4 cities, 4000 persons (1998)	1.2	-	-	-
Greenland ^b	Uummannaq, NW Greenland (1976)	36.8	22.5	9.4	83.8
	Uummannaq, NW Greenland (2004)	12.1	8.8	7.1	33.6
	Narsaq, SW Greenland, (2006)	5.4	1.8	1.3	8.6
Sweden	4 cities, 4000 persons (1998)	0.62	0.52	0.12	-

^a - Not available; ^bBased upon TDI microgram/kg bodyweight/day PCB=1.0; DDT =20, chlordanes =0.05; ^cThe three sample years represented different compositions and percentages of local food.

health advice needs to reflect local patterns and habits, but can draw on data from around the Arctic.

In Greenland, marine mammal consumption was the main source of POPs and mercury. Intake levels in Uummannaq were lower in 2004 than in 1976, though much of the difference is a result of lower consumption of traditional foods. Lead and total PCBs showed real declines in concentrations in food, whereas DDT, mercury, and chlordane were unchanged. Hexachlorobenzene, mirex, and toxaphene had all increased significantly. Interestingly, blood plasma levels of POPs in smokers were up to double those of non-smokers with similar diets. Since tobacco smoke is not a source of POPs, it must create another physiological response that affects metabolism to increase uptake. In a study in

southwestern Greenland, intakes of PCBs, chlordane, and toxaphene were found to be higher than recommended.

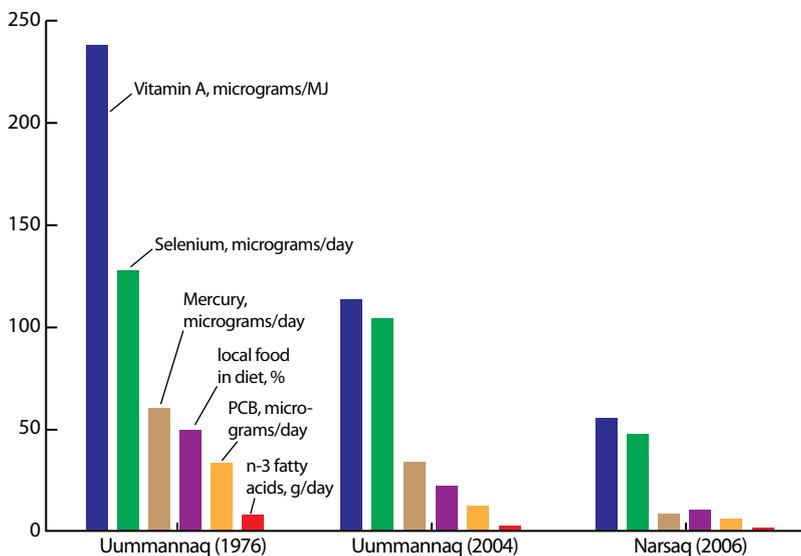
In Canada, no trends were apparent for mercury intake or environmental level. POPs, on the other hand, were generally decreasing in the environment. Chlorobenzene, endosulfan, and PBDEs, however, have been increasing substantially since the 1980s. As in Greenland, marine mammals appear to be a major route of exposure. Inuit had levels of most POP pesticides that were eight to ten times higher than those of Dene, Métis, and Caucasians. Inuit exceeded dietary intake guidelines for several POPs and for mercury. Intake levels for most POPs declined from the late 1980s to the late 1990s, though toxaphene increased five-fold in that period.

A study in northern Alaska found that bowhead and beluga whale blubber had the highest levels of POPs of foods examined. Daily intake was recommended to be no higher than 300g of bowhead maktak (skin and blubber) and 78g of beluga maktak. The same study found that some store-bought foods, such as sardines, salmon, and beef tongue, had higher levels of POPs than some local foods, such as whitefish and Arctic char. The study did not examine actual consumption levels, so it is not clear whether intake guidelines were exceeded or not. For mercury, another study found that people who ate fish had higher levels of mercury, but only northern pike were found to exceed action levels for human consumption.

Compared with official food safety limits in Russia, POP levels were generally low, though DDT and HCH exceeded the limits slightly in marine mammal

▼ Local food percentage, contaminant and nutrient content measured in duplicate meal portions from Uummannaq 1976 and 2004 and Narsaq 2006.

Local food, contaminant and nutrient content of diet



blubber. Food prepared indoors, however, was found to have higher levels of POPs than the same food tested when it was harvested or prepared outdoors. This phenomenon has not been observed in other Arctic countries, but appears to reflect indoor sources of pollutants such as DDT and PCBs. Pesticide use and chemicals used to treat building materials are the likely sources. In Chukotka, food prepared by extended burial in the ground was often contaminated by contact with polluted soils.

Unlike POPs, metals in the Russian Arctic exceeded food safety limits for many species and tissues. Fish and reindeer meat were below the limits, but reindeer kidney and liver were high in mercury and cadmium. Waterfowl exceeded the limits for mercury by a factor of two or three. Seals had higher levels of mercury than terrestrial mammals, birds, and fish. Seal meat exceeded the limits by 3-10 times, kidney by 10 times, and liver by 20-100 times. Whales and walrus meat were below the limit, but walrus kidney and liver were two to four times higher. Cadmium was double the limit in reindeer meat, kidney, and liver. In marine mammals, meat had levels of cadmium lower than the limit, but liver of all marine mammals exceeded the limit.

In Finland and Sweden, fish were the major sources of POPs for the general population. Analyses of typical “market baskets” of food showed that contaminant levels were generally below levels of concern, though 10% of the Swedish population exceeded total toxic equivalent intakes for combined POPs. Mercury intake in Finland, on the other hand, was only about 15% of the recommended maximum intake.

In Norway, gull eggs were found to be high in POPs. A 60 kilogram adult eating eight eggs per year would exceed the intake levels. A 20 kilogram child would need to eat only three gull eggs per year to exceed intake levels. Fulmar eggs are part of the traditional Faroese diet, and are high in POPs. Overall fulmar egg consumption is well below one egg per person, but for those who do eat eggs and fulmar meat, the resulting exposure to PCBs can be noteworthy.

Food security is a concern for many Arctic residents

“Food security” refers to confidence that food is available, accessible, safe, and nutritious. There are many reasons for concern about food security, ranging from

inability to buy food, to shortages of food supplies, to poor quality of the food itself. Concern about contaminants can undermine food security if people feel the food is not safe to eat. In the Arctic, there is also a cultural dimension in that traditional foods are closely associated with cultural continuity and vitality. Loss of traditional foods or an unwillingness to eat those that are available may contribute to food insecurity even if store-bought foods are widely available. Food safety and hygiene are rising concerns in the Arctic, stemming from food-borne illnesses and diseases spread from animals to humans.

Few studies have been done of food security in the Arctic, mostly in Canada and Alaska. Isolated communities in northern Canada report that 40-83% of residents are insecure about food, compared with 9% among non-indigenous persons. Among Alaska Natives and Native Americans, the figure is 30%, twice the national average. The high costs of both store-bought food and of going hunting were major factors in food insecurity in northern Canada. The lack of a hunter in the family also tended to increase food insecurity.

Arctic animals can carry parasites. *Trichinella* is found in bears, walrus, and other animals (including domesticated pigs), and can cause the parasitic disease trichinosis in humans unless the meat is thoroughly cooked or deep frozen. In Greenland, the risk of trichinella exposure is higher in hunting districts and with higher consumption of traditional foods, especially polar bear. In Nunavik, Canada, public health measures, including communication and also free testing of walrus meat, have helped reduce the incidence of trichinosis. In West Siberia, over half of some human populations carry the helminth parasite, spread through certain types of fish.

▼ The parasitic worm, *trichinella*.



► Changes over time in levels of legacy POPs and metals in blood of pregnant women from three communities in Greenland and Canada.

Levels and Trends

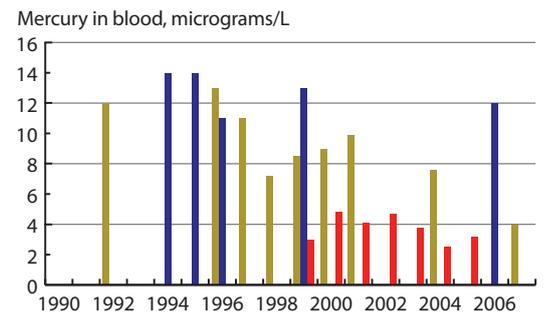
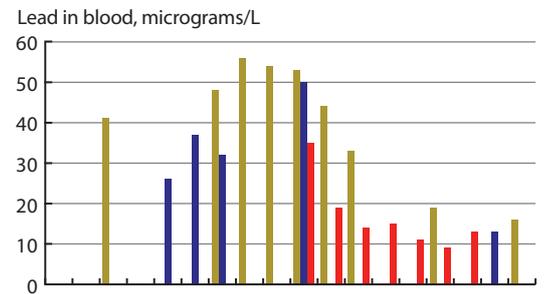
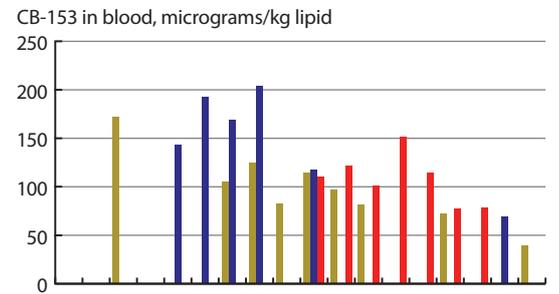
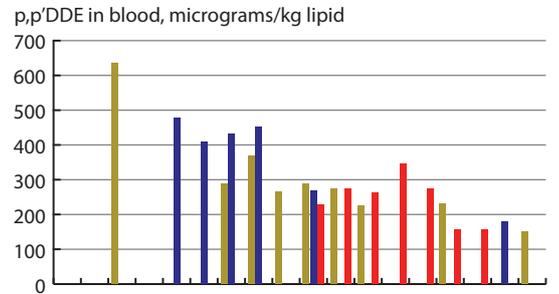
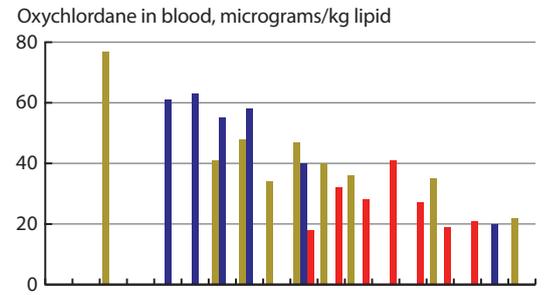
POPs and metals levels in humans in the Arctic have been monitored for more than a decade. Most studies have looked at maternal blood levels, but there are also data for adults in many areas. These studies show trends over time in contaminant levels, geographical patterns, and also the effects of changing diets and lifestyles. This section provides a circumpolar overview of contaminant levels, including the first-ever examination of trends. The comparisons are made possible by rigorous quality-assurance/quality-control standards in the laboratory analyses used here (see QA/QC Box).

Levels of legacy POPs and metals are generally decreasing in humans

Where data are available, levels of nearly all POPs and metals are decreasing in mothers in the Arctic. Most of the results are from Arctic Canada and Greenland, where studies have been conducted in the 1990s and again the following decade. But most other studies elsewhere in the Arctic show similar declines. One exception is Nuuk, Greenland, where levels of mercury and oxychlordan have been more variable. This community, however, was not as dependent on traditional foods as the other Greenland communities, where marked decreases in contaminant levels were seen. Slight increases and modest declines in contaminant levels are within the range of analytical error, and so may not actually indicate true changes. For many contaminants, however, the declines have been dramatic, almost certainly showing a real change in exposure and body burden.

In the Inuvik region of Canada's Northwest Territories, a comparison of results from 1998 with those from 2005-06 shows a decline in all six contaminants analyzed in three population groups (Dene-Métis, Inuvialuit, Caucasian). Because the study examined pregnant women or new mothers, different individuals took part in the two studies. The details should thus be treated with some caution, but the overall results are clear.

Declines in environmental levels may be the cause of declines in some contaminants, whereas changes in diets may be responsible for others. Public health advice to eat traditional foods with lower contaminant burdens are one reason for dietary change. One surprise in these findings is that mercury levels decreased, despite higher consumption of foods expected to carry more mercury. Further studies of actual mercury levels



■ Nuuk, Greenland (Inuit) ■ Disko Bay, Greenland (Inuit) ■ Nunavik, Canada (Inuit)

in prepared foods are needed to shed more light on this apparent anomaly.

In the Baffin Island region of Nunavut, maternal blood levels of the same contaminants also declined over the same time period. Studies in Nunavik, Quebec, from 1992 to 2007 show the same trends. The Inuit Health Survey conducted in Canada and

Quality Assurance/Quality Control

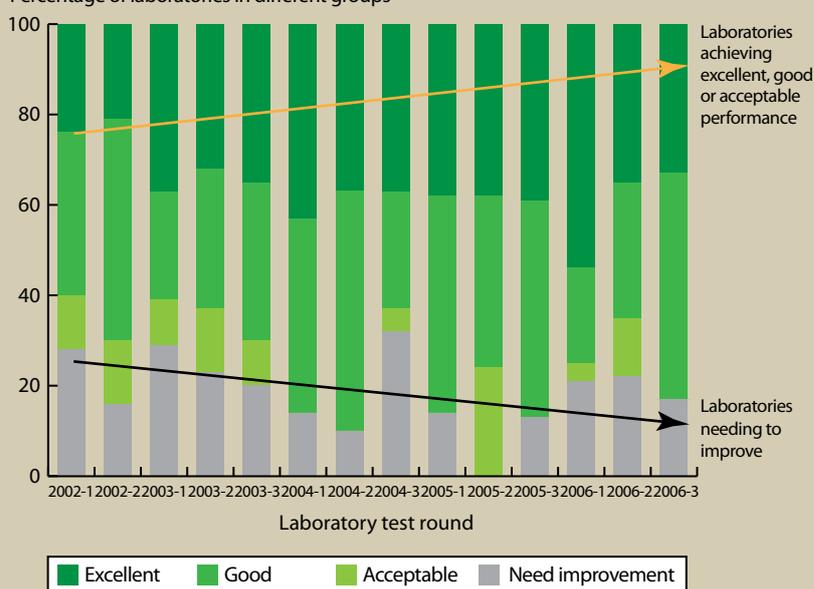
Environmental contaminants are typically found in minute quantities. Careful laboratory analyses are required to detect concentrations in the parts per million or parts per billion. A small error can give an inaccurate impression of risk, or misleading information about trends over time. Rigorous testing of the laboratories involved is the only way to determine if reported results are reliable. The most reliable approach is intercomparison, in which various laboratories analyze identical samples. The results are then compared to assess quality of results and to determine if there are any systematic errors.

For heavy metals, several national and international intercomparison procedures exist, providing a high degree of confidence in the results from laboratories that participate in these exercises. In this case, AMAP should continue to require that metals data come from laboratories that participate in one or more intercomparisons.

For POPs in human tissues, AMAP has instituted an intercomparison since 2001, known as the AMAP Ring Test. With 28 labs participating, the Ring Test involves analyses of 32 compounds. The results of the test have been good, with general improvement over time. The test data have been examined in several ways, providing a high degree of confidence that trends in analytical data do indeed reflect trends in the real world. One important finding is that gravimetric methods for lipid analysis were not as reliable as enzymatic methods, which has important implications for future contaminant analyses. Because the Ring Test is the only one of its kind for human tissues, its continuation is important for AMAP and those who use AMAP results.

Emerging compounds present a new challenge. Levels in animals are typically extremely low, near the detection limits of current analytical techniques. Many laboratories lack the equipment needed to analyze some substances, such as PFOS. A lack of reference materials for testing and the expense of doing so are among the obstacles to conducting laboratory intercomparisons for many of these chemicals. With growing concern about these compounds, however, evaluating the reliability of laboratory results is a priority.

Percentage of laboratories in different groups



Greenland from 2004 to 2008 examined Inuit men in Nunavik and found the same declines as were seen in pregnant Inuit women.

In Greenland, maternal contaminant levels in the Disko Bay region declined sharply, similar to Canada. In Nuuk, however, while levels were much lower than in Disko Bay, there was no trend over time except for lead. The difference in overall levels reflects much higher marine mammal consumption in Disko Bay, where the declines in contaminants may be related to changes in diet. In Nuuk, the diet may not have changed as much, resulting in lesser or no change in contaminant levels. Another study examined contaminants in about 600 women 20-50 years old and adult men in eight districts in Greenland. Levels of POPs and mercury were highest in Qaanaaq, in

the northernmost district, likely the result of higher consumption of traditional foods and possibly higher localized contaminant levels.

Certain POPs have been monitored in maternal blood in Iceland in 1995, 1999, and 2004. Study participants were all pregnant women in their third trimester. The 1995 study included only Reykjavik, but follow-up studies took place in other areas as well. In all areas, levels of PCB 153 and DDE declined over time. Oxychlorane did not change, but was low to start with. A dietary study in 2002 found that fish consumption had declined about 30% since 1992. This seems the most likely explanation for the decline in contaminant levels in maternal blood.

Similar results appear in monitoring studies from northern Norway. Maternal blood samples collected

in Kirkenes in 1996 had higher levels of POPs than samples taken in Bodø in 2004. These results should be treated as preliminary, since there are only two points in time, and the communities were different. A larger maternal blood monitoring study is underway, and should be able to confirm or reject the apparent decrease in contaminant levels.

In Sweden, much the same trend was found in maternal blood studies in Kiruna in 1996 and 2007. In addition to showing sharp declines in DDE and PCB 153, the Kiruna studies included mercury and lead. Levels of both metals went down, mercury by nearly half and lead by more than half.

Monitoring in Finland has used breast milk instead of maternal blood. Studies in southern and central Finland were conducted in 1987, 1993-94, 2000, and 2005. Over that time, PCB 153 levels dropped dramatically in both regions. The study in 2005 included mothers from northern Finland as well. Of the three regions, the highest levels of most POPs were found in southern Finland, perhaps because of higher consumption of fish from the Baltic Sea.

In Russia, too, data to assess changes in contaminant levels is available for breast milk from ethnic Russian women from Murmansk and Arkhangelsk. The former was studied in 1993 and 2000, and the latter in 1996 and 2000. The short time span and relatively low sample size in Murmansk especially means that any changes should be interpreted with caution. Nonetheless, the results show declines in oxychlordane, DDE, and PCB 153. This apparent trend may be the result of lower levels of contaminants in Russian food products, or perhaps lower use of the chemicals in the two areas.

Time trend data in Alaska are available for metals and POPs among the Yupik of the Yukon-Kuskokwim Delta, based on studies in 1999-2003 and 2004-2006. Mercury, lead, and cadmium levels declined, with lead declining more than 90%. The differences may reflect seasonal variations in diets, if the blood was drawn at different times of the year. This factor and possible differences in dietary habits among the participants in the two studies have yet to be analyzed. The change in POPs levels between these two time points is much more variable. Some contaminants such as oxychlordane and DDE have decreased, whereas others such as transnonachlor and HCB have increased. This variability may be due to the short time span between these two time points and the persistence of many of these POPs.

POPs levels are higher in those who eat marine mammals

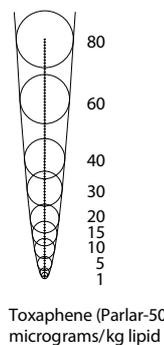
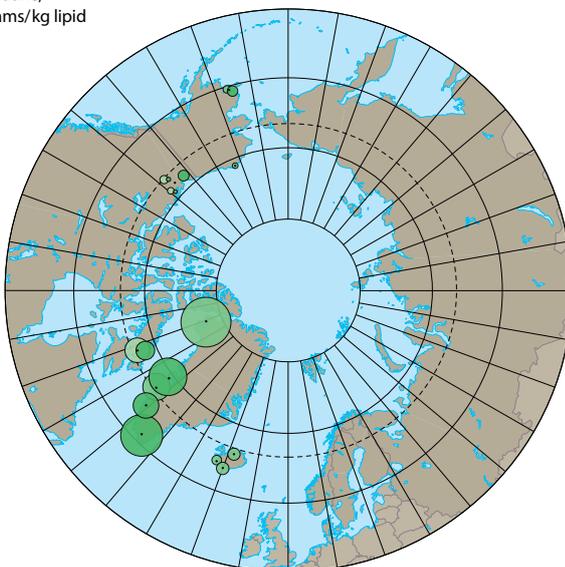
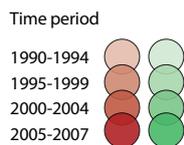
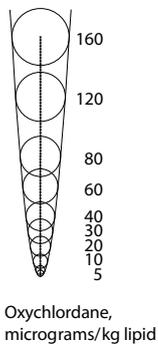
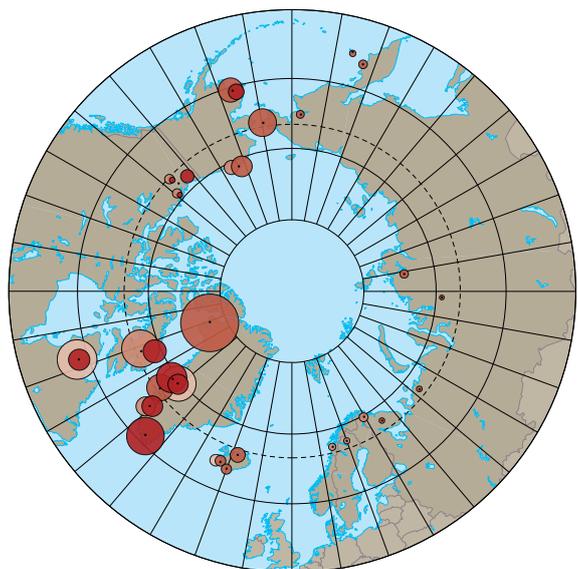
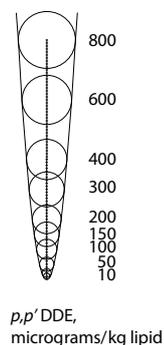
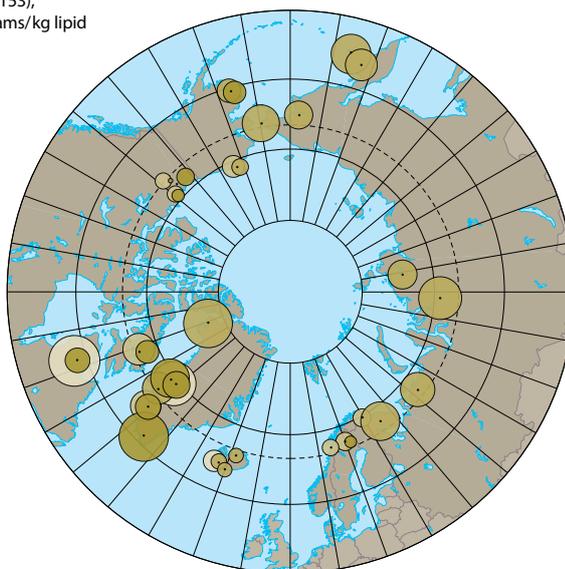
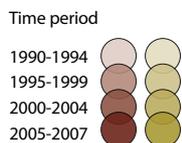
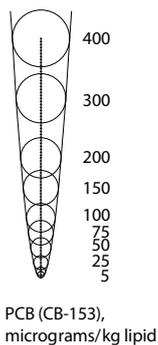
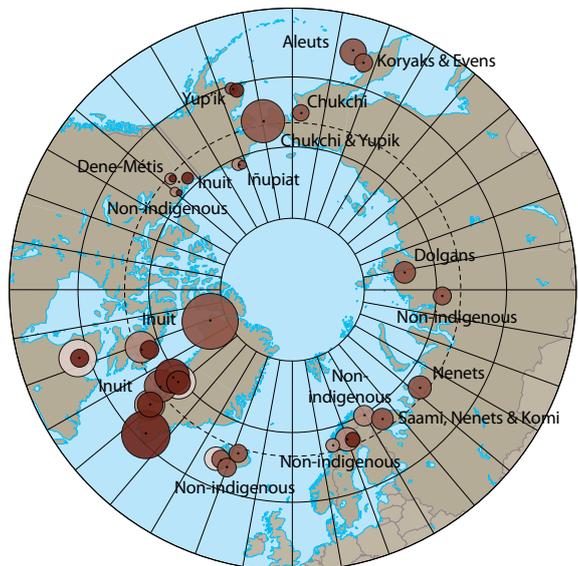
The available data on contaminant levels also show regional patterns, both within countries and also among the circumpolar nations. For POPs, the highest levels tend to be found among groups that consume marine mammals. Among men in Greenland, for example, those in the northern municipality of Qaanaaq had the highest levels of all POPs studied. Women of reproductive age from the same district had the highest levels of all POPs except DDE, which was slightly higher in the southern municipality of Narsaq. Qaanaaq is a hunting district, with high harvests of marine mammals.

In the Inuvik region of Canada, a similar difference can be seen in POPs levels between Inuvialuit, who hunt seals and beluga whales, and both Dene/Métis and Caucasians, who generally do not. Inuit from Baffin Island and Nunavik had still higher levels. In Alaska, Yupik have higher POPs levels than Iñupiat. While Iñupiat have high consumption rates for marine mammals, this is dominated by bowhead whale, which feeds at a lower trophic level than seals and belugas and thus has lower POPs levels. The Yupik, in addition to consuming relatively more seals, also eat more fish and fewer caribou than the Iñupiat. In Russia, coastal residents of Chukotka had much higher levels of chlordane, HCH, and PCBs than were found in other regions. These residents also consume far more marine mammals than people in the other regions that were studied. Some contamination of foods may also result from burial of meats in contaminated soils. In some cases, barrels and other containers that previously held various chemicals may be used to store or prepare food, brew alcohol, or hold drinking water.

Another pattern was seen in Russia as well. Levels of DDT and DDE were high for all regions and ethnic groups, with the highest levels found in pregnant women of Russian ethnicity from the Norilsk region. These levels are likely to be the result of agricultural use of DDT, which then enters the food supply system, or residential use as pest control. The ratio of DDE to DDT is an indicator of local use versus long-range transport. The ratio in Russia suggests local uses and sources, which in some regions may reflect availability of pesticides imported from China.

Although recent levels of some POPs are highest in Russia, the levels seen there are nonetheless

◀ PCB, DDE, oxychlordan and toxaphene-concentrations in blood plasma (Alaska: serum) of mothers, pregnant women and women of child-bearing age during different time periods.

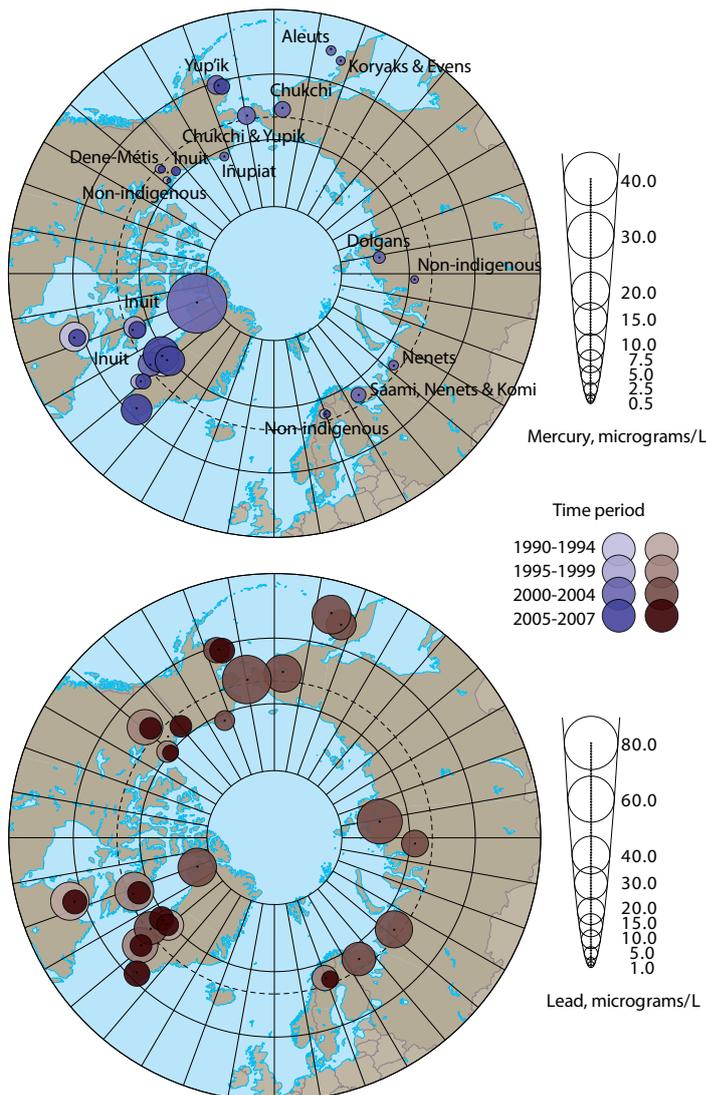


Toxaphene (Parlar-50), micrograms/kg lipid

similar to or lower than the levels recorded in the eastern Canadian Arctic and in Greenland in the 1990s. The ability to make comparisons across both time and space is a major advance made possible by coordination of research and by rigorous quality assurance/quality control standards.

Mercury levels remain highest among Inuit in eastern Canada and Greenland, though recent declines are encouraging. The fact that mercury levels are low among groups in Russia that have high POPs levels indicates that further dietary and related research is needed to explain the divergence between the mercury-POPs ratio in wildlife and the corresponding ratio in humans. Lead levels remain relatively high, particularly in Russia, where the source is not clear. The use of lead shot in some regions of the Arctic is likely to remain a substantial source, though steel shot is becoming more common.

▼ Mercury and lead concentrations in blood of mothers, pregnant women and women of child-bearing age during different time periods.



Fewer women are exceeding blood level guidelines for PCBs, mercury, and lead

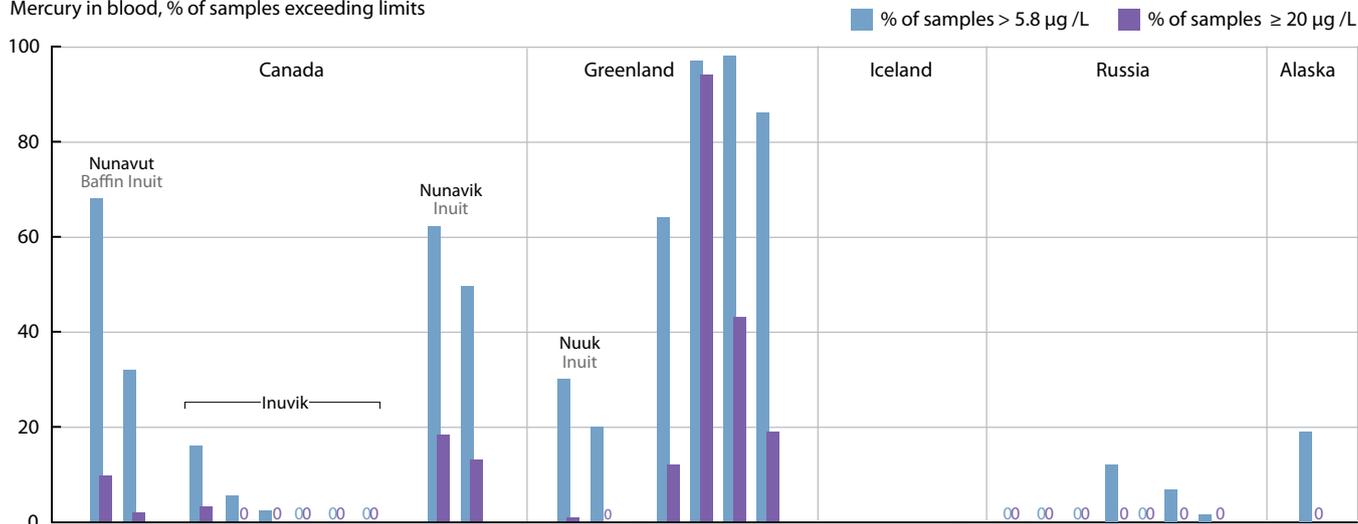
Monitoring results for certain contaminants have also been compared with established health guidelines. Canada and the United States have published levels of concerns or action levels for various contaminants. Examining levels found in Arctic women of reproductive age against these guidelines shows that some women in some regions exceed the guidelines, but the percentage of those who do appears to be declining over time. This finding is consistent with the overall decline in most contaminants described earlier.

For PCBs, there are two guideline levels in Canada. The Canadian Action Level is 100 micrograms per liter. The Canadian Level of Concern for pregnant women is 5 micrograms per liter. No women in Canada, Iceland, or Russia exceeded the Action Level. In Greenland, 8% of women exceeded this level. Except among Saami women in the Kola Peninsula of Russia, some women exceeded the Level of Concern in all regions studied. Nonetheless, a comparison with results from earlier studies shows that the percentage of women exceeding either level is declining.

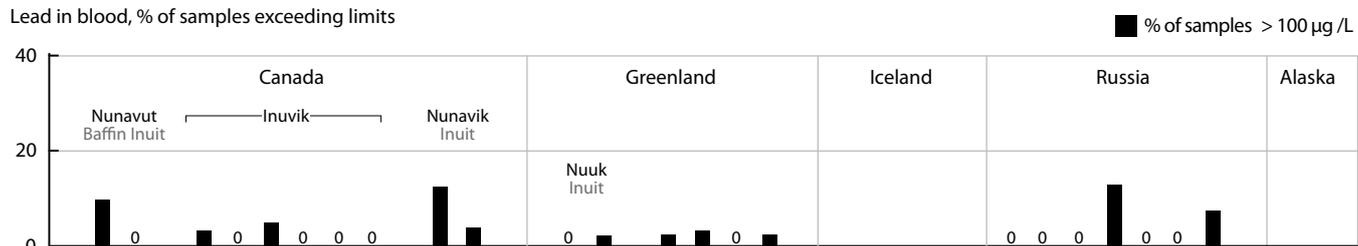
Mercury shows a similar pattern, with Greenland having the highest percentages of women exceeding the various guideline levels. More than three-quarters of Greenlandic women exceeded the US evaluation level of 5.8 micrograms per liter, and over a third exceeded the Canadian increasing risk range threshold of 20 micrograms per liter. The percentages were considerably lower in Canada, though Nunavik and Baffin Island had higher proportions than did Inuvik. In Russia, none of the women exceeded the Canadian level. On the Taimyr Peninsula, 12% of women exceeded the US evaluation level, which was the highest percentage of any of the Russian regions.

For lead, the regions with the highest percentages above the current US and Canadian guideline level of 100 micrograms per liter were the coastal areas of Chukotka and the Taimyr Peninsula. (The guideline levels are currently under review.) No other areas in Russia had any results above the guideline, as was also the case in Canada. In Greenland, relatively few women exceeded the guideline, and only in some regions.

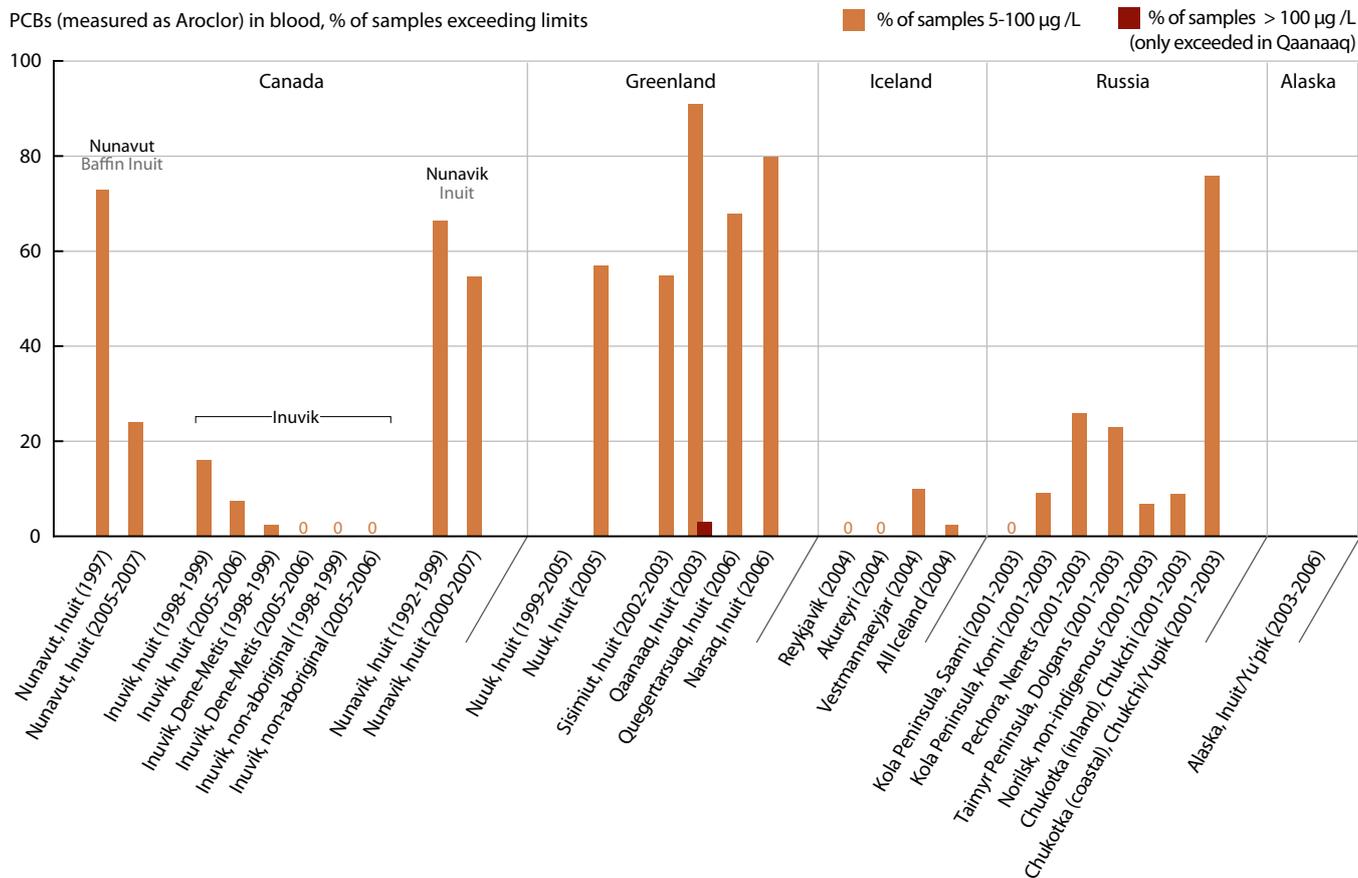
Mercury in blood, % of samples exceeding limits



Lead in blood, % of samples exceeding limits



PCBs (measured as Aroclor) in blood, % of samples exceeding limits



▲ Exceedance of blood guideline values for mercury, lead and PCBs in mothers and women of child-bearing age in different populations in Canada, Greenland, Iceland, Russia and the United States (Alaska).

Emerging compounds are a growing concern in the Arctic

The “traditional” POPs have been monitored for many years in the Arctic, as described above. But many more compounds are made, released, and later found in the environment around the world (see the POPs chapter for descriptions of these chemicals). Some of these compounds have been examined in samples from Arctic residents. While traditional POPs are largely declining, many emerging compounds give new reasons for concern about human health impacts. Monitoring in the Arctic can shed light on the persistence of these chemicals as well as the threat they pose in the region itself.

▼ PBDEs (sum of BDE-47, -99, -100 and -153) and PFOS in blood plasma (Alaska: serum) of mothers and women of child-bearing age.

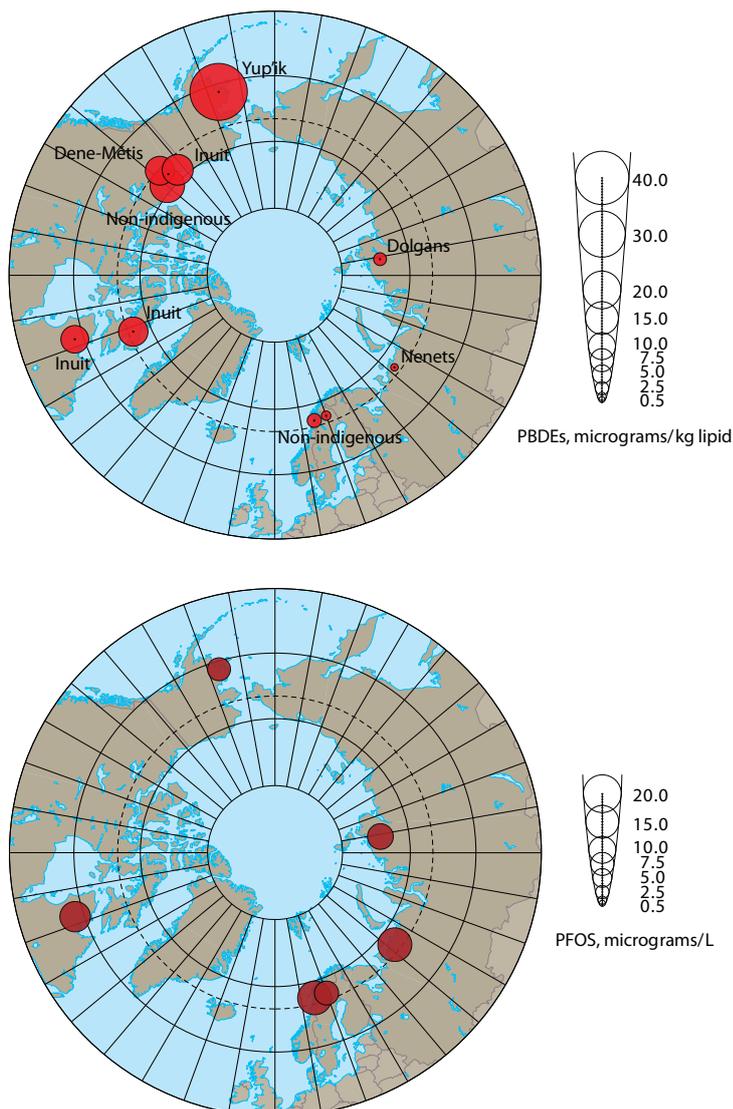
Brominated fire retardants are used on some clothes and many other household materials to reduce risks from fire. Some of these compounds have the characteristics of POPs, in terms of persistence and long-range distribution. Their levels in

humans have not been addressed in previous AMAP assessments. The highest levels of brominated fire retardants found in the Arctic are in Yupik from Alaska, whereas other regions report relatively low levels. These high concentrations in Yupik mothers are similar to values elsewhere in the U.S., which are higher than concentrations elsewhere in the world due to the widespread use of brominated fire retardants in the U.S. There are no firm data to determine time trends in the Arctic, but some compounds are decreasing in southern Sweden and Norway, which is likely related to the earlier phase out of various brominated compounds in these countries. Different compounds in this class need to be studied, as their use and longevity vary. Some longer-lived compounds may become relatively more significant in future years in the Arctic, particularly those that are more likely to accumulate in the food web and expose humans through diet.

Fluorinated compounds are resistant to stains and to sticking. They are used to coat cooking equipment and some cloth products. They are also very difficult to analyze. One of these compounds, PFOS, has been found in slightly higher levels in blood plasma in men from Nunavik than elsewhere in the Arctic. There remain many uncertainties about PFOS, including the pathways by which it reaches humans. The lack of standard analytical methods makes comparisons of data difficult. There is not enough data on PFOS to allow any firm conclusions on trends. There are also limited data on another chemical in this class, PFOA, but levels appear high enough to warrant further study. Both PFOS and PFOA need to be included in future monitoring of arctic populations.

Halogenated phenolic compounds include PCP and metabolites of PCBs. At present, there are no certified reference materials or laboratory intercomparisons to determine the reliability of data for this class. Further assessment is needed to confirm initial results indicating concern in some regions, such as coastal areas of the Chukotka Peninsula.

Short-chain chlorinated paraffins and siloxanes are among the additional classes for which no Arctic data are available. All appear to have the characteristics needed to be present in the Arctic, including high production volumes. Screening of these substances is needed to assess their presence and potential harm in the Arctic.



Contaminants and Metabolism

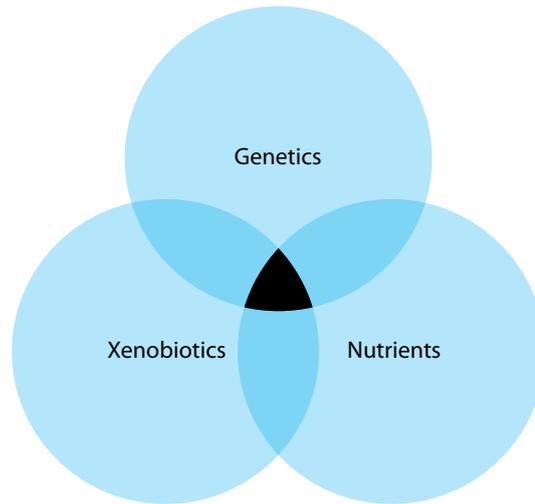
The prevalence of obesity is increasing around the globe. With obesity come several other health problems, including metabolic syndrome, diabetes, and cardiovascular disease. As discussed earlier, these trends are apparent in the Arctic, too. Changes in diet and lifestyle are usually blamed, but may not be the whole story. Interactions between lifestyle factors and contaminants is a new area of research. If effects are additive, contaminants exposure thought to be “safe” may in fact contribute to disease. Contaminants and lifestyle factors are thus inseparable, scientifically and in terms of public health. This section describes the ways in which even low levels of contaminants can contribute to metabolic disturbance.

Fat, protein, and carbohydrates provide energy and also regulate metabolism

Fats are a normal component of diet. Polyunsaturated fatty acids are essential nutrients, producing metabolites that the body cannot synthesize in other ways. Some metabolites are needed for development of the retina and central nervous system. The fatty acids also help produce key hormones, regulating blood pressure, blood coagulation, and inflammatory responses of the immune system. They also play vital roles in regulating metabolism, including the deposition and burning of body fat.

Body fat does more than store energy. It is also an endocrine organ, producing some compounds that have anti-inflammatory effects and others that have pro-inflammatory effects. The balance between these effects depends in part on the ratio between omega-3 and omega-6 polyunsaturated fatty acids. Omega-3 fatty acids are typically found in fish and marine mammals, so Arctic coastal peoples generally have a comparatively high intake of this class of fatty acids. A higher proportion of omega-3 fatty acids appears to be related to a stronger anti-inflammatory effect.

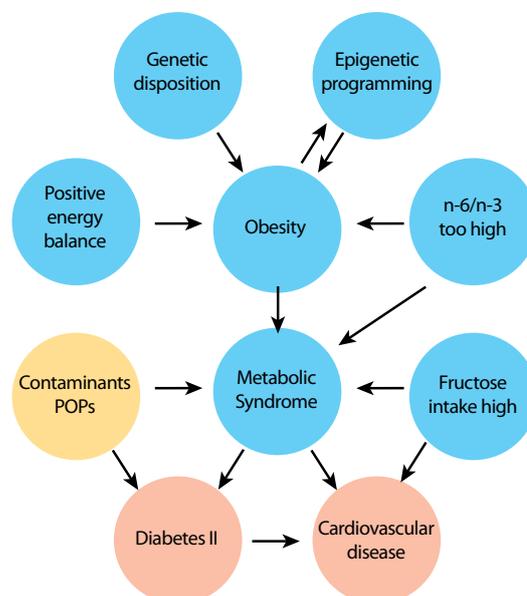
Although much dietary advice has focused on the total amount of fat that is eaten, the quality of the fat is a more important factor. Diets high in saturated fats are more likely to produce metabolic disorders, whereas polyunsaturated fats (particularly omega-3s) are both necessary and have a number of health benefits. Recent dietary advice



◀ Genes, macronutrients, and contaminants may have synergistic effects on the development of diseases. The probability for illness is increased when several predisposing factors are simultaneously present in the same individual.

suggests a higher proportion of energy from fat, but less than 10% from saturated fats.

Dietary advice has also recommended reducing the intake of simple carbohydrates such as refined sugars. In particular, high consumption of fructose, a sugar found in fruits and products such as corn syrup, can cause a number of metabolic problems. Fructose produces a number of health effects, from high levels of triglycerides in blood to hypertension and insulin resistance. These conditions lead to diabetes and cardiovascular disease. Contaminants may exacerbate the bodily processes that lead to such effects. The role of fructose is especially worrisome because it is a common manufactured sweetener in many foods such as sodas, which in turn are consumed in large quantities in many Arctic regions.



◀ Genetic and environmental factors increase in concert the susceptibility of an individual for public health problems such as, type2 diabetes and metabolic syndrome. All these conditions may have complications involving the cardiovascular system.

► Effect of mercury and dioxin-like compounds on the pathogenesis of diabetes and its complications. (HDL: high density lipoprotein. LDL: low density lipoprotein. TNF- α : tumor necrosis factor. NF- κ B: nuclear factor, PON-1: paraoxonase-1.

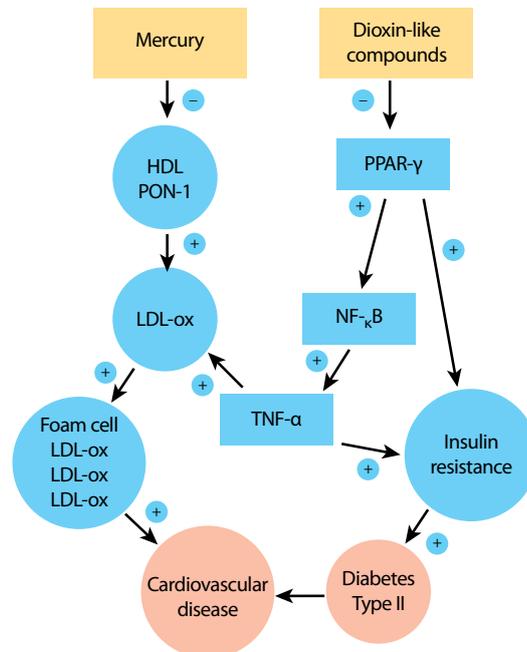
Contaminants can disturb the metabolism in several ways

Several POPs cause oxidation in the body. Oxidation reactions can produce free radicals (an atom or molecule with an unpaired electron, making it especially chemically reactive) that can lead to a series of reactions that cause damage to cells. Among other things, oxidation can lead to an inflammatory response. Some PCBs, for example, produce oxidative stress in cells. Anti-oxidants such as Vitamins C and E, however, can counteract that effect. Among Inuit, some evidence of oxidation from contaminants was found, but at a modest level, probably because a relatively high intake of omega-3 fatty acids provided some protection.

Methylmercury is also an oxidant and affects calcium regulation. It can therefore act together with PCBs, which is a problem because both contaminants are often found in the same foods. The increase in oxidation from contaminants can be compounded by some aspects of the non-traditional diet, such as the reduction of omega-3 fatty acid intake.

PCBs also affect the body's ability to metabolize fat. One result is an increase in triglyceride levels in the blood, which is associated with increased risk of cardiovascular disease. Another is an increase in the inflammatory response. The role of PCBs in this regard may exacerbate similar effects from consumption of saturated and trans-fatty acids prevalent in foods imported to the Arctic. In addition, some PCBs interfere with the enzymes that metabolize the PCBs themselves, thus inhibiting the body's ability to react to the very compound causing the disruption.

Dioxins and similar compounds can increase the risk of diabetes, although the long-term effects of



low levels of exposure are unclear. These and other POPs can also affect the balance of sex hormones, though this too requires further study as some compounds strengthen sex hormone effects and some weaken them. The exact combination of contaminants, including industrial compounds that are ignored in many studies, will have a major effect on the net impacts to sex hormones.

Of primary concern, in the context of increasing obesity rates in the Arctic and around the world, are effects that can increase risks associated with obesity. The fact that some POPs increase the risk of diabetes is particularly worrisome, since obesity is also associated with increased diabetes risk. The interactions of POPs and obesity with regard to diabetes and other diseases are not yet fully understood and are a priority for research.

Effects and Public Health

Determining the effects of contaminants on public health in the Arctic requires three strands of information. First, basic information about human populations in the region. Second, an understanding of the toxicological effects of different contaminants, separately and in combination, at the levels found in humans. Third, analysis of whether those effects can be detected in human populations in the Arctic. This section presents the available information on all three strands, including descriptions for emerging compounds that have not been addressed in previous AMAP reports on human health.

▼ A woman having her lung function tested at the hospital in Norilsk, western Siberia, Russia.



Demographic data show different patterns for many Arctic populations

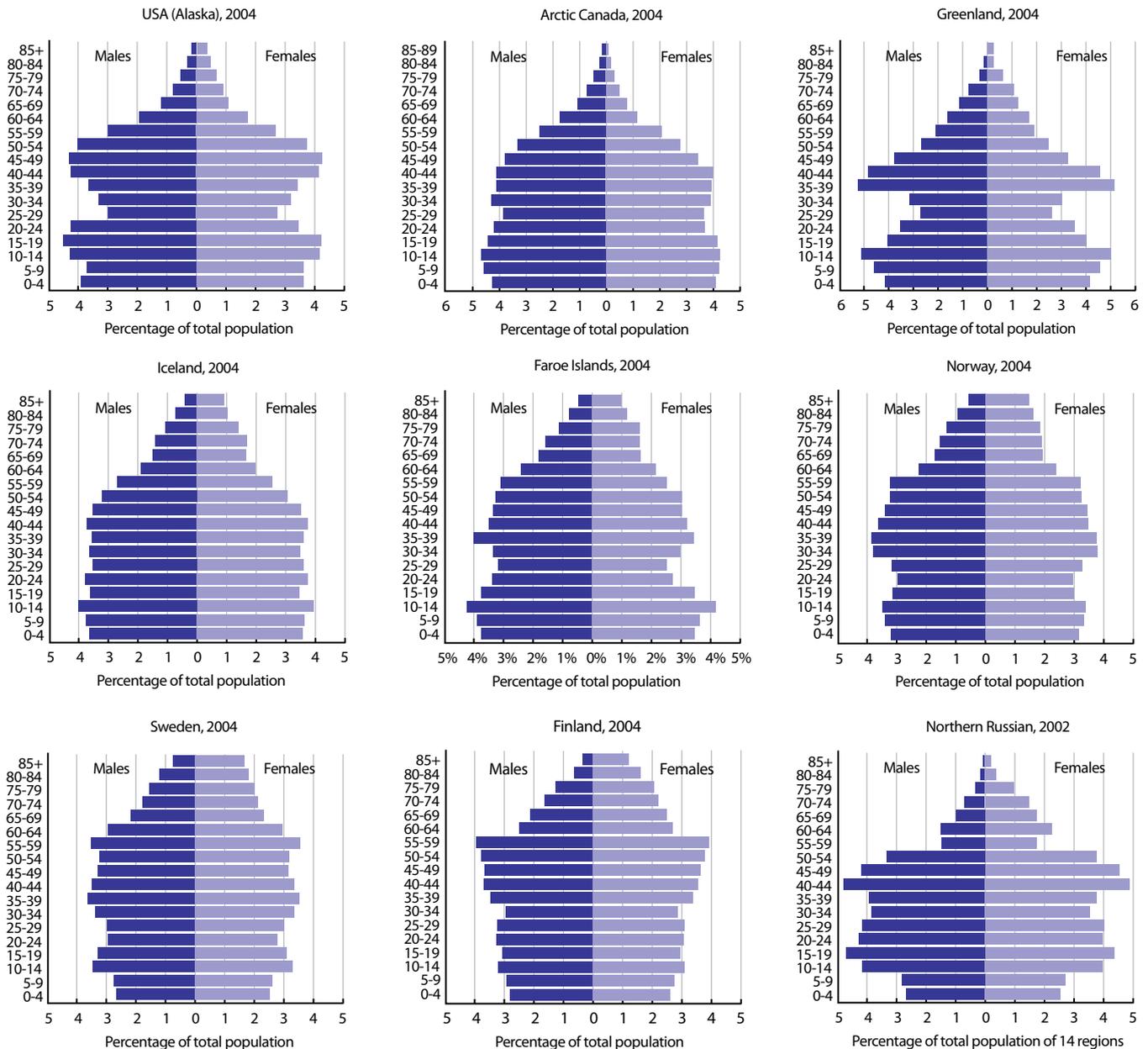
At the most basic level, demographic data indicate broad patterns of overall health and well-being. Several indicators can be used, including life expectancy, birth rate, death rate, infant mortality, and fertility rate. The relative proportions of males and females in a population, as well as the age distribution of a population, can indicate disruptions to “normal” patterns from various causes. In many countries, data on indigenous people are not available to support comparisons with national or non-indigenous Arctic populations.

The age distribution of Iceland’s population, for example, indicates high infant survival and long life

expectancy, with few disruptions over time. The Russian Arctic, by contrast, has seen relatively few births in the past decade, high mortality among adults, low survival into old age, and a relatively low life expectancy. Economic and other impacts in the Russian Arctic undoubtedly contribute to the shape of the age distribution, with many people having moved away from the region following the end of the Soviet Union, and associated losses of services and reduction of standard of living. The apparent absence of young adults in Alaska and Greenland may be the result of temporary migration away from Arctic areas, for example to seek education or employment opportunities, with individuals returning later in life.

Birth rates in the Arctic are not high relative to global patterns. Nunavut has by far the highest birth

▼ Population structure in Arctic countries and regions.



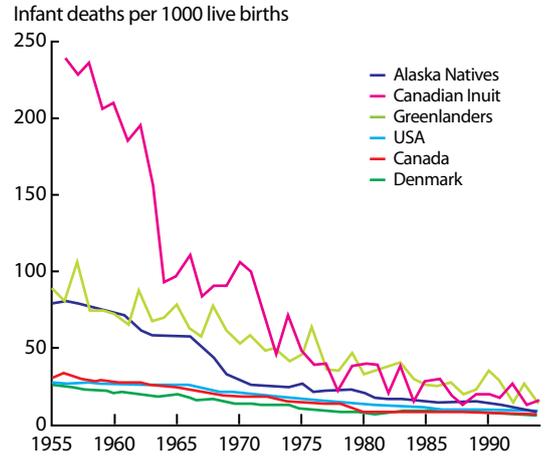
► Trends in infant mortality rate of Greenlanders, NWT Inuit and Alaska Natives compared to Denmark, Canada and USA.

rate in the Arctic, followed by other parts of northern North America and the North Atlantic islands. A few regions of the Russian Arctic approach the same ranges. Northern Sweden and Finland and northwestern Russia are the areas with the lowest birth rates in the Arctic.

Life expectancy in the Arctic is generally lower than for the overall population of each country. But there are exceptions, such as women in Alaska and the Oulu region of Finland, and both men and women in the Nordland region of Norway, as well as the Yamal-Nenets and Khanty-Mansi regions of Russia. The Nordic countries have long life expectancy, with the exception of Greenland, though northern regions of Norway, Sweden, and Finland are slightly lower than the countries as a whole. Russia has the lowest life expectancy, as well as the greatest discrepancies between men and women. Iceland, with the longest life expectancy, also has the lowest difference between men and women in this regard. Regions with higher proportions of indigenous residents also have lower average life expectancies.

▼ Life expectancy at birth in Arctic countries and regions (2000-2004).

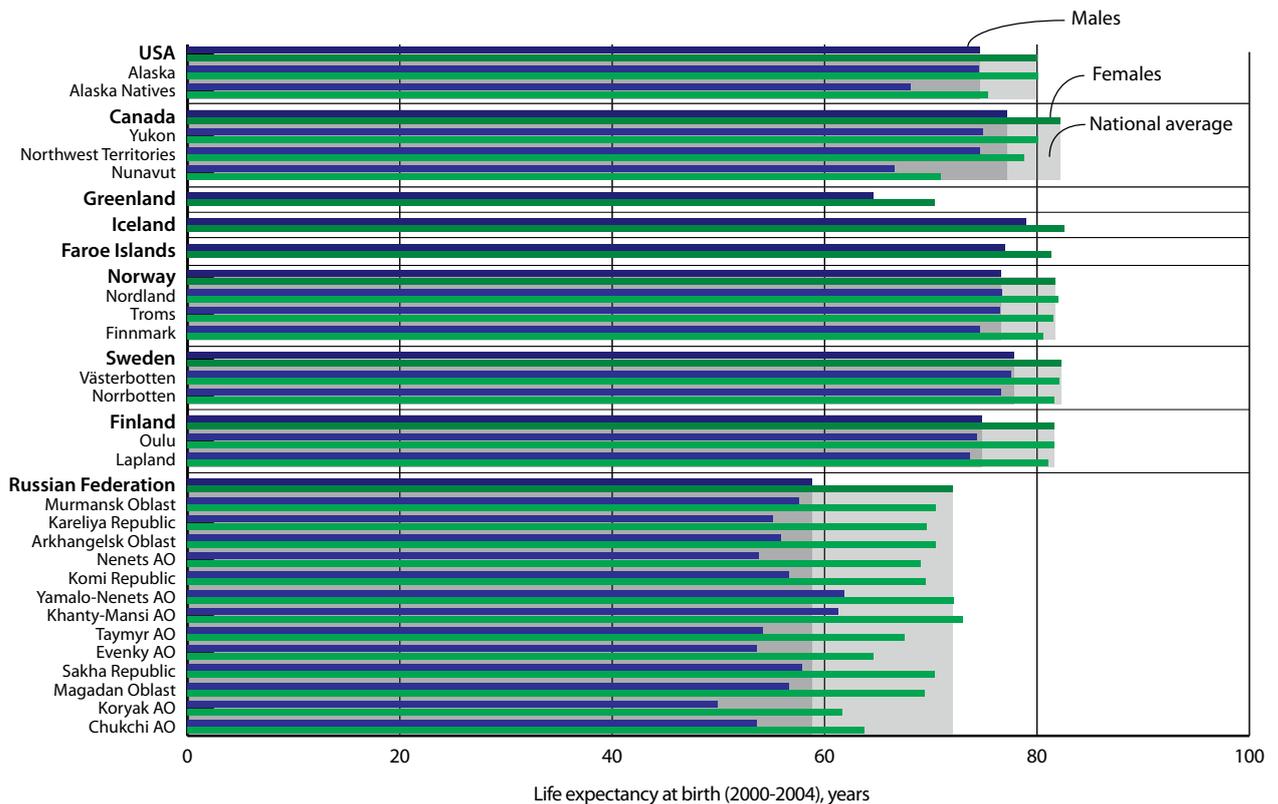
Infant mortality rates shed light on overall living conditions and well-being, in addition to basic health. Dramatic evidence for improved living conditions in the North American Arctic can be seen in the trend of infant mortality over the second half of the twentieth century. Among Canadian Inuit in particular, the



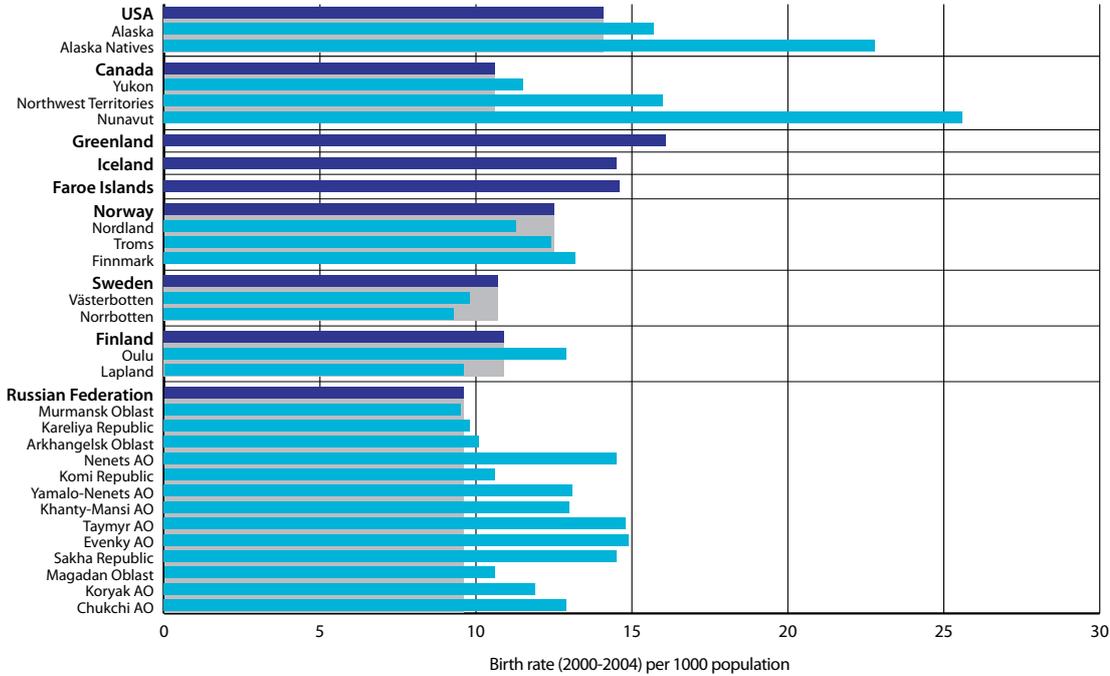
death rate fell from nearly one in four live births to fewer than one in fifty.

Despite this improvement, infant mortality rates in Arctic regions remain higher than national averages. In Nunavut, the rate of 15.3 deaths per 1000 live births is almost three times the national average. The highest rate in the Arctic is in the Chukotka region of Russia, at 28.9 deaths per 1000 live births. The great variation in infant mortality rates across the Russian Arctic likely reflects differences in socio-economic conditions and provision of health care services. The Nordic countries are among the top ten countries worldwide in terms of lowest infant mortality, but Greenland's rate more closely matches that of Nunavut.

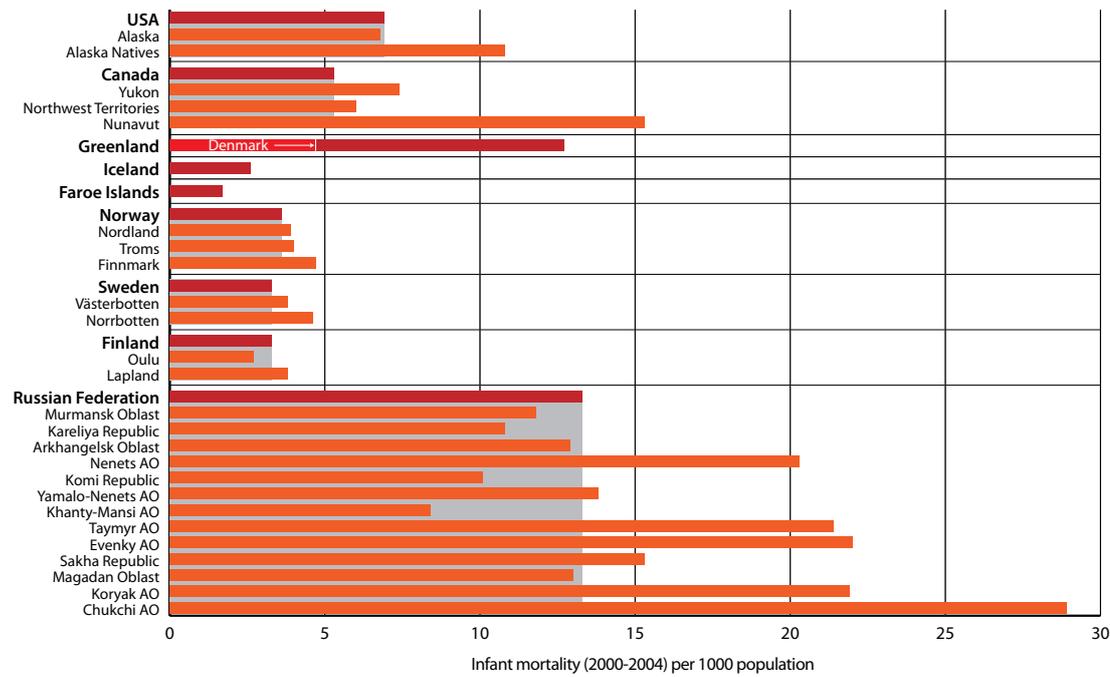
In Alaska, the overall infant mortality rate is com-



◀ Birth rate in Arctic countries and regions (2000-2004) per 1000 population.



◀ Infant mortality in Arctic countries and regions (2000-2004) per 1000 population.



parable to the national average, which likely masks a substantial difference between largely non-indigenous urban populations and largely indigenous rural populations.

Overall death rates offer some insight into health and living conditions, too. In Arctic North America, crude death rates are substantially lower than national averages, likely reflecting a dearth of older people in the populations, as seen in the age distribution discussed earlier. Causes of death provide further details

of trends in health. Among Arctic indigenous peoples, deaths from suicide and injuries remain far more common than for general populations of Arctic countries. At the same time, deaths from chronic illnesses such as heart disease and cancer are rising to become more like national averages. The two-pronged challenge has major impacts. In Greenland, for example, if suicides and tobacco-related deaths are removed from the statistics, life expectancy increases by eight years for men and six years for women.

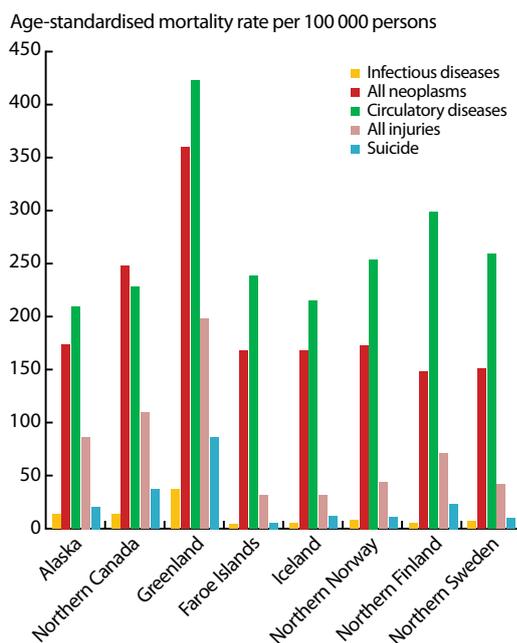
Most Arctic indigenous peoples are less healthy than national populations

There are many distinct indigenous peoples in the Arctic. Combining them all into one category to assess health status may conceal many specific differences and patterns. Nonetheless, most if not all indigenous groups have experienced economic and social marginalization, rapid cultural change, and major shifts from traditional ways of life. Some of these changes have led to advances such as the sharp reduction in infant mortality. Others have resulted in exposure to new diseases, especially sexually transmitted diseases.

Overall, indicators of health among most Arctic indigenous peoples point to lower health status than for national populations. Life expectancy is lower, infant mortality is higher, certain infectious diseases are more common, and injury and suicide rates are much higher. At the same time, lifestyle patterns such as tobacco use, poor diets, and lack of physical activity are increasingly common among the same groups. The Saami are one exception to the general pattern found elsewhere in the Arctic.

In Alaska, Arctic Canada, and Greenland, the gap between indigenous health indicators and those of the general population has been decreasing over time. Nonetheless, substantial deficits still exist, especially for deaths from suicide and injuries. Among Alaska Natives, the overall mortality rate is higher than for non-Natives, and is higher for many causes such as cancer, heart disease, and violent deaths.

► Age-standardized mortality rates for selected causes.



In Russia, indigenous peoples in northern regions have far lower life expectancy than the general Russian population. Indigenous men can expect to live only 45 years, compared with 58.8 years for all Russians. Among women the difference is even greater, 55 years versus 72.1 years. Violent deaths are much higher, too, with alcohol involved in a quarter to a half of all suicides among northern indigenous peoples.

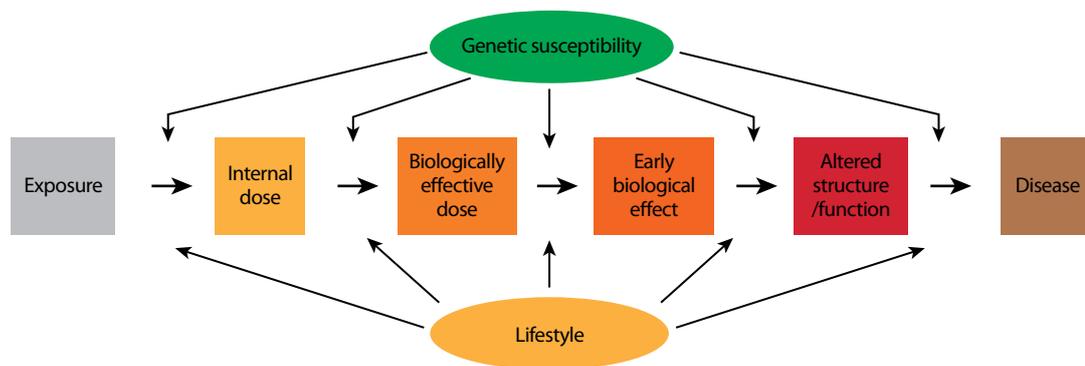
Assessing the health status of Saami is made difficult by the lack of statistics that distinguish ethnicity in Finland, Sweden, and Norway. Nonetheless, some recent studies have focused on Saami health in comparison with the rest of the population. In Finland, Saami men had lower mortality from disease than Finnish men, perhaps due to diet, lifestyle, or genetics. This was offset, however, by a higher death rate from causes such as suicide. In northern Norway, mental health among children and youth was similar among Saami and non-Saami. The prevalence of various types of cancer showed a different pattern among Saami compared with general populations, and even among various Saami groups. Different dietary and lifestyle habits may be at least part of the reason. The more thorough integration of Saami into national populations, together with a high standard of living in those countries, may help explain why Saami show few health deficits compared with other indigenous peoples.

Toxicological studies show the potential for effects at levels found in the Arctic

Toxicological studies are experiments designed to determine whether compounds cause effects and at what levels, typically using animals or human tissue samples. Epidemiological studies, described later, are observational studies designed to assess whether such effects are seen in a human population. Because effects may be subtle at low levels of contaminants, and because experiments using humans are rarely possible, toxicology and epidemiology are often used together to evaluate whether effects are occurring in people.

Biomarkers are indicators of response to contaminants. They are typically a first sign of response, found before broader health effects would appear in a population. Biomarkers can be found at various stages in the pathway from exposure to

◀ Different types of biomarkers in the pathogenic sequence between exposure and disease.



disease. Cytochrome P450 enzymes, for example, are involved in transforming various chemicals that enter the body. A study in the Faroe Islands found that the activity of one of these enzymes changed in relation to levels of PCBs and other POPs. In Nunavik, on the other hand, POPs levels among women did not appear to alter the activity of this enzyme, whereas smoking did.

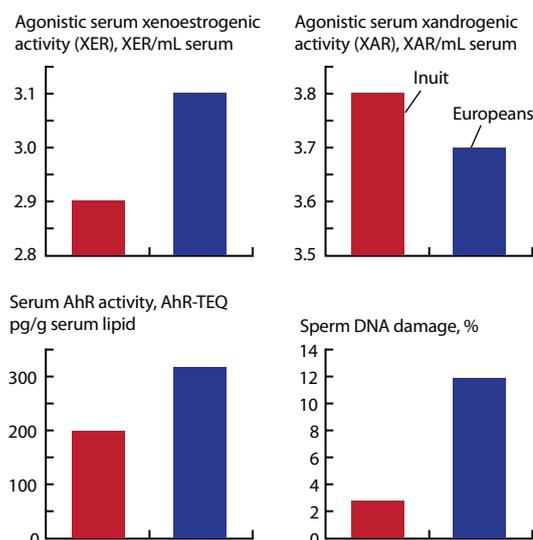
Another study in Nunavik found that the activity level of Paraoxonase 1, an enzyme that appears to help prevent heart disease, was lower in Inuit who had high levels of methylmercury. Conversely, Inuit with high levels of selenium had higher activity levels of the enzyme. Further study is needed to determine if these biomarkers also indicate changes in disease outcomes. Similarly, POPs may cause genetic effects that are linked with cancer and other health impacts. This, too, requires further study in Arctic populations.

Another type of toxicology research examines the effects of mixtures of compounds in addition to individual contaminants. Arctic peoples are exposed to a variety of chemicals at various levels. These compounds include some that are the result of transformation in the body or the food chain, in addition to the original contaminants that were transported to or released in the region. In piglets, a mixture of contaminants similar to that seen in the Arctic led to reduced immune system function. The same mixture harmed the reproductive and neurological systems of rats. Together, the results show that mixtures of contaminants may be more harmful than assessment of individual contaminants would suggest.

To assess potential impacts on humans, laboratory research has examined POPs mixtures taken from human blood samples. The mixtures from

Inuit blood samples elicited hormonal effects that were different from the effects produced by mixtures from European blood samples. Genetic factors may influence the actual effects of exposure in two ways. First, the uptake and metabolism of contaminants may be affected, so that individuals with the same exposure have different mixtures of contaminants in their blood. Second, the effects of contaminants on genetic and physiological systems may vary by individual, resulting in different outcomes from the same blood levels. Further research is needed to examine the interactions among contaminant mixtures, genetic characteristics, and other influences such as lifestyle and diet that may differ between individuals and populations (see Genetics Box on next page).

In addition to studying “traditional” POPs and metals, some recent toxicology studies have examined emerging compounds such as brominated fire retardants and fluorinated compounds. Results to date do not indicate a risk of human health effects, but further monitoring is required.



◀ Serum biomarkers respond differently in Inuit and European populations, likely due to differences in genetic or lifestyle factors. Differences in contaminant mixtures may also play a role.

Genetics and Contaminants

Different human groups have different genetic patterns. Most of these differences are thought to be random and neutral, in the sense that they provide no advantage or disadvantage. Some differences, however, are the product of selective pressures. In other words, they confer some advantage with respect to environmental or other factors that have influenced one group of people more than another.

Genetic diversity in a population is an important form of resilience. Groups with a greater variety of genes are more likely to have one that is adaptive to a given stress. A disaster or catastrophe that kills off a high percentage of a population can leave the survivors with lower overall genetic diversity. Even though the population may recover in overall number of persons, the genetic diversity will remain low.

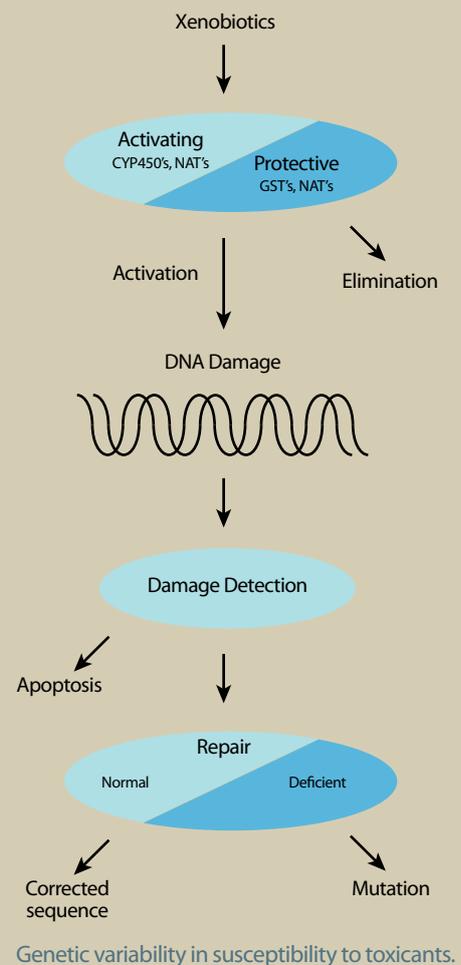
Chemicals, including many environmental contaminants, can cause genetic mutations. Some genetic mutations can affect an individual's health or reproductive ability. If not fatal, such mutations may be passed on to subsequent generations.

In the Arctic, few genetic studies have been published. Among the limited work that has taken place, the genetics of Inuit have been studied far more than other indigenous peoples. Some of their genetic patterns show connections with populations in Asia, where Inuit and other New World peoples are believed to have originated. Other patterns may reflect adaptations to the Arctic climate, including the ability to thrive on a diet comprised mainly of protein and fat. Like most non-European peoples, Inuit lack the ability to digest milk, which is linked to a specific gene. A tendency for alcohol abuse may also have a genetic basis.

Genetic characteristics can affect the uptake and impacts of contaminants, too. For example, one study found that the toxic equivalence of dioxin-like activity in persons from West Greenland was linked to the consumption of dairy products. Either the dairy products carry dioxin and related contaminants, or they increase the toxicity of dioxins from other sources. Those who are lactose intolerant are less likely to suffer this effect because they are less likely to consume dairy products.

Other genetic patterns can reduce susceptibility to different diseases. For example, Inuit and many Asian populations are less likely to get prostate cancer. The same genetic pattern may make Inuit and others less susceptible to lower sperm counts resulting from exposure to contaminants, although the link is speculative at this point. Genetic factors can also affect the uptake, fate, and toxic effects of contaminants in the human body.

The degree to which genetic patterns are relevant to contaminants exposure and health outcomes requires further study. Examining other Arctic populations may help identify common characteristics or other factors. Health advice, including dietary recommendations, may best be tailored to the specific genetic patterns of a given group of people.



Epidemiological studies reveal effects in the Arctic

Epidemiology seeks patterns and correlations among observed health phenomena. Many such patterns are only apparent when large numbers of individuals can be studied. In the Arctic, low population size makes it difficult to find large enough groups with shared characteristics, such as lifestyle, ethnicity, or diet. In addition, the mixture of contaminants found in the Arctic makes it harder to distinguish effects from one or more compounds, especially when those effects may be combined. Nutrients, too, can reduce the impacts

of some contaminants, and other factors such as lifestyle, access to health care, and genetics may affect responses to contaminants as well.

Despite these obstacles, some contaminants effects have been found in Arctic populations. The growing fetus and newborn children are particularly vulnerable to the toxic effects of many contaminants found in the environment. Studies in Russia have found that high POPs levels were associated with an increase in general health deficits among newborns, including low birth weight, premature births, and stillbirths. The sex ratio of newborns

(boys to girls) may also be affected, but this finding requires confirmation. Mercury may be associated with increased risk of spontaneous abortion. Nickel, however, was not associated with any health deficits, despite high levels of exposure in mining districts in the Russian Arctic.

Little epidemiological work has been done to date in the Arctic on reproductive function and contaminants. There are some suggestions of changes in proportions of X and Y chromosomes in sperm from Greenlandic and Scandinavian men, but more research is needed.

Neurotoxicity, by contrast, has been studied in relation to PCBs, mercury, lead, and nutrients. In Nunavik and the Faroe Islands, prenatal exposure to PCBs is associated with a specific set of cognitive deficits, resulting among other things in slightly lower performance on IQ tests. Methylmercury exposure reduced verbal ability, hand-eye coordination, and attention span in the Faroes, similar to results from other parts of the world. Despite health guidelines implying a lowest-effects level for lead, recent studies have found that there may be no safe exposure level. Even low levels of lead exposure in infants and children were found in Nunavik to result in behavioral and motor skill deficits.

Studies of selenium and fatty acids were designed to determine the extent to which these nutrients counteracted the effects of contaminants. Selenium is known through experiments to bind with mercury and render it biologically harmless. Its effect on methylmercury has been unclear, but recent studies in Greenland and Nunavik indicate that selenium offers little protection against chronic exposure to methylmercury, as is typical in many Arctic diets.

To the contrary, a study of selenium in Nunavik found that the trace metal was associated with negative impacts to the vision system. Selenium, although a necessary nutrient, can be toxic in high levels. Indeed, levels in Nunavik were found to be higher than guidelines for adults, though less is known about selenium toxicity in children. Omega-3 fatty acids were associated with improved mental function, but were not found to offset negative impacts from contaminants. While nutrients need to be studied in conjunction with contaminants, the evidence so far suggests that there are no simple ways to prevent negative impacts from contaminants exposure.

The immune, cardiovascular, and metabolic systems can also be affected

Several studies in Nunavik have examined contaminants and infectious diseases among children. The results, consistent with other studies elsewhere, show that higher exposure to POPs leads to higher rates of infections such as middle ear infections and lower respiratory infections. Although the studies were not always able to control for all factors, the results have been consistent and show a clear correlation between level of exposure and frequency of infection. Vitamin A deficiency may play a role, but requires further study. A study in the Faroes found that prenatal exposure to PCBs lowered a child's immune response to tetanus and diphtheria vaccines.

Cardiovascular disease is increasing among Arctic populations, as noted earlier. Studies elsewhere in the world have found links between POPs and heart

▼ The hospital at Norilsk, western Siberia, Russia.



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disease. A study in Nunavik found no clear connection between contaminants and cardiovascular disease, although the links are complex and affected by nutrients in diet, lifestyle, and other factors that may mask the role of contaminants.

Mercury appears to cause higher blood pressure. Although other factors may be involved, studies comparing adults in Greenland and Denmark found that higher mercury levels were associated with higher pulse pressure (the difference between systolic and diastolic pressure). Children in the Faroes were found to have higher blood pressure with higher methylmercury levels. These and other results indicate that methylmercury is likely to cause cardiovascular disease. This outcome of mercury exposure may be more significant, from a public health standpoint, than neurological effects that have been found.

Diabetes, too, is a serious and increasing public health concern for Arctic indigenous peoples. Although lifestyle and dietary factors are usually recognized as the causes of diabetes and related metabolic dysfunction, the role of POPs has received more attention in recent years. This link is discussed in more detail in the next section.

If these preliminary findings are confirmed regarding contaminants and various diseases, the effects attributable to POPs and metals in the Arctic may increase substantially. Particularly for common diseases, a small increase in risk can lead to a larger increase in the number of individuals affected.

Risk Communication

Assessments of human health and contaminants in the Arctic have generated a great deal of information and knowledge. Communicating results to Arctic residents, however, is another matter. A major complication is the “Arctic dilemma,” which is that people are generally exposed to contaminants through traditional foods, which are also culturally, nutritionally, economically, spiritually, and socially vital. Thus, the message is complex. Effects and risks also vary by region, age, sex, and other factors. This section describes the need for a sound communication strategy, with messages designed for specific audiences in each country, region, or area.

Communication involves many factors and poor communication can increase anxiety

Communication requires the involvement of at least two people. There are many opportunities, on both ends, for misunderstanding to develop. When the subject is complex, the difficulty becomes larger as too much information may be overwhelming but too little can omit crucial knowledge. If the subject involves people’s well being, emotions may run high, perhaps magnifying the perception of risk. When many individuals from various backgrounds are involved on all sides, the challenge becomes greater still. Each person may understand the information differently, may talk a little differently, or may bring his or her own biases to the discussion.

► Nenets children working out in the school fitness room, Yamal, north western Siberia, Russia.



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Communicating about contaminants and human health in the Arctic has all of these features and more. Getting the message out is important but not simple. Merely mentioning contaminants can cause stress and anxiety. Miscommunication can exacerbate the situation, leading people to change their behavior in ways that may be worse than the original risk. If people learn that traditional foods are contaminated, they may stop hunting and fishing. This may undermine community cohesion that develops through sharing and working together and may lead to poorer dietary habits through decreased consumption of traditional foods. Poor risk communication may cost community members more money if people buy food at the store instead of providing their own. These changes may harm health. If those impacts are blamed on having followed scientific advice, distrust of research and researchers may result.

There have been many attempts around the Arctic to communicate information about contaminants and associated risks to human health, as discussed below. One common challenge is understanding how risks will be perceived by members of the target audience. That perception of risk is influenced by individual characteristics, such as age, sex, level of education, and culture. It is also influenced by whether the risk is voluntary, when the effects are likely to be seen, the degree of uncertainty about the risks, and other factors. Another key factor is the degree to which people feel they can take action to avoid the risks, in contrast to feeling helpless or without alternatives.

In the Arctic, discussing traditional foods in connection with health risks is a great challenge. Many people may feel they have few good alternatives to traditional food, particularly if part of the public health message is that store-bought foods also carry considerable risks. A sense of trust between the person providing information and those receiving it is also crucial to addressing differences in risk perception so that the risk is neither over- nor under-estimated. In other words, the full context of communication must be considered, not just the wording of a report or layout of a poster.

Communication efforts to date have had mixed results

In the Faroe Islands, in contrast, risk communication appears to have been largely effective with respect to consumption of pilot whales. In the

1970s, Faroese first became aware of the high levels of mercury found in pilot whales. Subsequent studies have found neurological deficits in children from mercury and also, to a lesser extent, from PCBs. Recommendations to eat less pilot whale, and for women to avoid it until after they had had children, went against cultural practices and also a renewed local importance given to whaling in response to international pressure to stop hunting pilot whales.

Fortunately, pilot whales were the main route of contaminant exposure on the Faroes. Islanders eat a lot of fish, but the fish had comparatively low levels of mercury and PCBs and were not considered a threat. In addition, fish confer many health benefits, so a dietary adjustment posed no nutritional dilemmas. Follow-up studies have shown that pilot whale consumption has indeed declined considerably, especially among young women. The fact that the health advice focused on one food, and that many Faroese had already been involved in the studies examining effects from mercury and PCBs in pilot whale, helped make the communication effort simpler.

In Canada, considerable attention has been given to communicating the results of the Northern Contaminants Program to residents of Arctic communities. There have also been follow-up studies to determine how well that information has been understood. The results indicate that Northerners are generally familiar with the idea of contaminants, but that the full message does not reach many people. Consumption of traditional foods remains high in most areas, with some people saying that they will not change their diets in response to contaminants. In part, this appears to stem both from cultural attachment to traditional foods and from an expectation that unsafe foods would be visibly affected.

Knowledge of specific contaminants was lowest among young women and girls, which is a matter of some concern since women of childbearing age are one of the main targets of much public health advice. A likely cause of this knowledge gap is a lack of understanding among researchers and health professionals of the individual and collective characteristics of young women in the region in relation to risk perception.

Contaminants tend to rank low on lists of health concerns among Canadian Northerners. Other environmental concerns, such as garbage, rank higher. Personal behaviors, such as smoking

and alcohol consumption, are also recognized as major health risks. In one study of four communities, residents' responses showed an understanding of the basic message of the risks associated with environmental contaminants. Nonetheless, few reported having modified their behavior in response. This may be due to a perceived lack of alternatives, to an acceptance of the risk in light of social and other benefits of traditional foods, or to the message not being fully accepted despite the information having been conveyed.

Other countries are developing communications programs

Contaminants have already produced negative health effects in Greenland. Health experts there have recommended that contaminants be addressed as part of an overall health policy. This is particularly important with rising obesity, since obesity and contaminants can compound the effects of each. The recommendations for a health policy with regard to contaminants include international action to reduce the release of contaminants, increased attention to identifying healthful foods available in Greenland, increased physical activity to help combat obesity, and avoidance of foods with the highest contaminant levels.

Russia has considerable quantities of contaminants in waste sites and polluted areas across its

Arctic territory. New legislation is needed to reflect a growing awareness of the importance of proper waste management and recycling. Many Arctic residents are also increasingly aware of their role in disposing of garbage in environmentally sound ways. Once the legislation is in place, then communications and other strategies can be developed to promote human health and other goals.

In Norway, health communications are typically handled through local public health officers or through the media. The media is clearly a more powerful vehicle, but messages in an official report may not be the same as those in the media story about that report. Expert panels convened by the government to assess a particular health topic may issue a plain-language report for public and media consumption, but most publicity will be via media rather than directly from the report.

A more consistent and rigorous approach is needed for risk communication

To date, AMAP has conducted three assessments of human health and environmental contaminants in the Arctic. Each has been characterized by careful data collection, analysis, and interpretation. A great deal of attention has been given to topics such as quality assurance/quality control for laboratory analyses to ensure that trends and patterns are real.

▼ Dietary advice on consumption of traditional foods for communities in Chukotka, Arctic Russia.

Зелёный цвет Потребление не ограничено	<i>Нерпа</i> 	<i>Лахтак</i> 	<i>Морж</i> 	<i>Кит</i> 	<i>Олень</i> 
	Мясо	Мясо	Мясо	Мясо	Мясо
	Жир	Жир	Жир	Жир	Жир
	Печень	Печень	Печень	Печень	Печень
Жёлтый цвет Потребление лучше сократить до 300-400 г/сутки	Почки	Почки	Почки	Почки	Почки
	<i>Заяц</i> 	<i>Рыба лососевая</i> 	<i>Рыба морская</i> 	<i>Утки уся</i> 	<i>Тунбровые птицы</i> 
	Мясо	Мясо	Мясо	Мясо	Мясо
	Жир	Жир	Жир	Жир	Жир
Розовый цвет Потребление лучше сократить до 100 г/сутки	Печень	Печень	Печень	Печень	Печень
	Почки				
	Красный цвет Этот продукт лучше заменить другой пищей				

Studies of effects have looked at obvious and subtle physiological disruptions to see what contaminants are doing to people. Comparatively less attention has been given to the effective communication of the result of these extensive and intensive research and monitoring programs.

The various communications efforts around the Arctic have one thing in common: they have not relied upon communications professionals. Despite some successes, such as in the Faroes, no clear strategies have been developed for a communication program. It is not even clear whether the intended audience is the general public, health officials, or others. Each group has different characteristics, as do the residents of different countries, members of different ethnic groups, and so on.

In the future, a communication strategy should be developed to address these and other challenges. It should identify various target audiences, develop clear terminology, and define its goals. In addition, the communication effort should be evaluated carefully to determine how well it is working and what can be improved. Because contaminants come largely from outside the Arctic, the communication strategy should also identify how best to reach decision-makers who can influence the production and release of contaminants around the world. For example, Arctic findings can be used in international negotiations concerning contaminants. This was done successfully in the creation of the Stockholm Convention, where Arctic data continue to provide justification for adding new chemicals under the convention.

Chapter summary

The transport of contaminants to the Arctic is affected by climate patterns. Anticipated changes in global and Arctic climate are likely to result in increased contaminant transport to and from the Arctic. International actions such as global and regional treaties lead to reduced emissions, which in turn result in decreases in contaminant levels in the Arctic. Increased industrial activity in the Arctic, however, would lead to an increase in local sources. In terms of human exposure to contaminants, social and cultural practices play a large role, in addition to environmental concentrations of the contaminants themselves.

Traditional foods are very important to Arctic indigenous peoples for social, cultural, nutritional,

economic, and spiritual reasons. A major dietary shift is underway across much of the Arctic. Most dietary energy now comes from store-bought foods, although traditional foods provide many nutrients and are a major contributor to healthy diets in many communities. Some traditional foods can also carry risks from contaminants. The intake of contaminants is determined by environmental levels and dietary patterns of individuals and communities. The combination of high prices for store-bought foods and the work, risks, and costs associated with obtaining traditional foods has made food security a large concern for many Arctic residents.

The levels of mercury, lead, and most POPs are decreasing in most parts of the Arctic. Marine mammals remain a major source of POPs, so that people who eat marine mammals have higher POPs levels than those who do not. Reflecting the declines in environmental levels of many contaminants, the proportion of women of childbearing age who exceed blood level guidelines for PCBs, mercury, and lead is decreasing. At the same time, emerging compounds such as brominated flame retardants and fluorinated compounds are a concern in the Arctic because levels have increased over the last 15 years and their toxicology has not been studied in detail. Careful laboratory procedures, including rigorous quality control and quality assurance, provide analytical results with high levels of confidence, supporting the assessment of trends over time and space. Testing procedures initiated by AMAP and others have led to more reliable data, and continued efforts will result in further improvements.

Recent studies have found a number of mechanisms by which contaminants can affect metabolism. Obesity is increasing worldwide due to lifestyle changes and dietary shifts, and the Arctic is no exception. Obesity is associated with an increased risk of cardiovascular disease and of developing diabetes. POPs, even at low concentrations, also increase the risk of diabetes. These new findings indicate that future studies need to consider the interactions between contaminants and other health conditions.

The characteristics of different Arctic populations vary in many respects. In general, indigenous populations in the region are less healthy than national averages. While socioeconomic conditions and lifestyle choices are major determinants of health, contaminants may also have a contributing effect.

Toxicological studies show that contaminants, at the levels found in some parts of the Arctic, have the potential for adverse health effects in people. Epidemiological studies, looking at Arctic residents directly, provide evidence for subtle immunological, cardiovascular, and reproductive effects due to contaminants in some Arctic populations. Genetic characteristics of the various Arctic populations may also affect their response to contaminants and susceptibility to certain diseases, a topic requiring further investigation.

Communicating the results of studies concerning contaminants and people is important. A chief goal

of sharing such information is to help Arctic residents make informed choices regarding the benefits and risks associated with dietary choices. Messages concerning contaminants are often complex, with many factors shaping how they are given and received. Communication efforts to date have had mixed results. Effective approaches have involved communities in the development of communication materials, which helps avoid messages that are unclear, appear contradictory, or do not reach the intended audience. Rigorous evaluation of communication efforts can help identify problems and successes, leading to better strategies and approaches.

Radioactivity

Introduction

Previous AMAP assessments of radioactivity in the Arctic have highlighted that the Arctic terrestrial environment is more vulnerable to radioactive contamination than many other parts of the world. Moreover, they have shown that past sources such as fallout from nuclear testing in the 1950s and 1960s and the 1986 accident at the Chernobyl nuclear power plant still contribute to human exposure. The 2002 assessment also highlighted continued releases to the marine environment from European reprocessing of nuclear waste and the risks associated with handling spent nuclear fuel and radioactive waste in northwest Russia.

This assessment provides an update of sources of radioactivity to the Arctic environment, including the results of efforts to reduce the risks associated with waste handling and decommissioning of old nuclear-powered equipment. It also discusses changes in the range of actual and potential sources and highlights that non-nuclear industrial activities may increase the release of naturally occurring radioactive substances to the environment. While previous assessments have mainly addressed the risks of radioactivity related to human health, this assessment also addresses the impacts on non-human biota due to the vulnerability of Arctic ecosystems. In addition, it includes a discussion of how climate change may affect radioactive contamination in the environment.

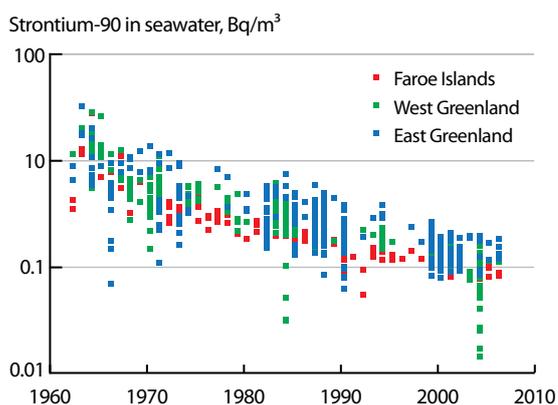
Sources: Update based on actions and climate change

The sources of radioactive contamination in the Arctic can be divided into past contamination sources and potential future sources. This section provides an update of different sources of radioactivity to the Arctic, including their role for human and ecosystem exposure. It addresses the impact of actions to reduce risks as well as other changes to sources since the previous assessment. In addition, it addresses how climate change may impact the risks linked to these sources.

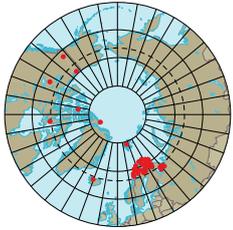
Past fallout remains in the terrestrial environment

From a circumpolar perspective, fallout from past nuclear weapons testing has historically been the most important source of human and environmental exposure to anthropogenic radioactive contamination. Other past significant emissions include fallout from the 1986 accident in the Chernobyl nuclear power plant, which affected the European Arctic. Although the fallout spread all over the globe, the Arctic is particularly vulnerable because Arctic vegetation has very efficient uptake of radionuclides.

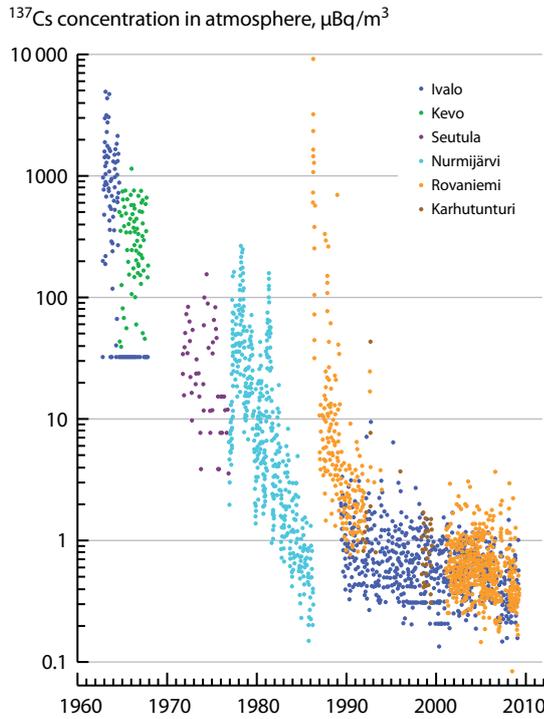
Monitoring of radionuclides in the atmosphere in Finland and ocean water near Greenland and the Faroe Islands shows that traces of atmospheric weapons tests in the 1950s and '60s are still detected but with declining levels over time. Air monitoring data from Canada highlight how some of the fallout that has been incorporated in vegetation can be re-released into the environment in connection with forest fires, where cesium levels exceeding the detection limit coincide with summer forest fires. Other data show that in spite of the peak of weapons testing being over 50 years ago, the radiocesium from the fallout remains in the top layer of the soil, the reason being that processes that would normally favor mobility are slower in colder environments. Past fallout is thus likely to remain a source of radioactive contamination for grazing wildlife and for people.



◀ Strontium-90 measurements in seawater demonstrate the decline in contamination from fallout from historical nuclear weapons testing.



► Atmospheric monitoring for radioactivity is conducted at sites around the Arctic. The graph shows measurements at some Finnish stations. The generally decreasing levels increased again in 1986 as a result of the Chernobyl accident.



The legacy of Chernobyl will remain for a long time

In the European Arctic, fallout from the 1986 accident in the Chernobyl nuclear power plant added further radicesium to the environment, even if the fallout in the Arctic was much less than further south in Fennoscandia and close to Chernobyl. The additional contamination is observable as small peaks in the atmospheric record (see figure above) as well as in the monitoring records of deposition and levels in vegetation and food products such as milk and meat.

Monitoring data have been used to understand the effective ecological half-lives of radionuclides in different environments and food webs. An example is studies of deposition, grass and lamb meat from

▼► Levels of cesium-137 in Canadian caribou reflect deposition which has declined since its peak in the 1960s.

► Levels of cesium-137 in the air can increase when forest fires release cesium that was taken up by trees following fallout from atmospheric nuclear weapons testing and the Chernobyl accident.



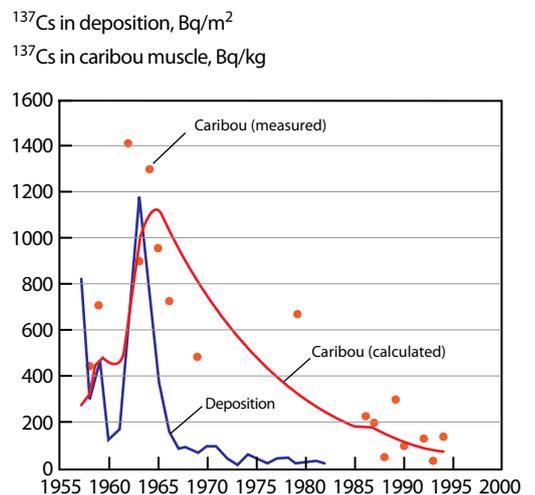
Ecological half-life

Ecological half-life is a parameter that tells how long it takes radioactive contamination to leave a specific system during a specific time period. It depends on the chemical properties of the radionuclide, how radionuclides interact with the soil and vegetation, and how the land is managed (e.g. plowing).

Effective ecological half-life combines ecological half-life with the physical half-life of the radionuclide in question.

the Faroe Islands, which found ecological half-lives for cesium-137 of up to 21 years in soil, up to 16 years in grass, and up to almost ten years in lamb meat. In Finland similar studies have been done with the soil→grass→milk food chain where the ecological half-life of cesium-137 in milk after the Chernobyl accident was about 2.2 years, increasing to 11 years for the period 1993-2008.

A food chain of major importance in the Arctic is lichen→reindeer/caribou→people. It has been studied extensively as it has been a major source of radionuclide intake to people. Lichen effectively absorb nutrients and contaminants from the air, including radioactive fallout, and were thus more contaminated than green plants after the atmospheric tests and the Chernobyl accident. Long-term studies in Scandinavia after the Chernobyl accident show that the effective ecological half-life is about three years. Previous AMAP assessments have presented overviews of contamination in reindeer and caribou with details for Russia, Norway and Iceland. The figure below shows some recent data from Canada and Greenland with falling levels since a peak in the



1960s. The effective ecological half-life is calculated at about six years, and levels are now less than 100 becquerels per kilogram of meat. A major difference compared to the data from Norway, Russia and Iceland is that Canada and Greenland were much less affected by fallout from the Chernobyl accident. The levels are similar to areas of northern Finland that were only slightly affected by Chernobyl fallout. In northern Finland, the effective ecological half-lives in the post-Chernobyl period are slightly longer than in Canada ranging from 8 to 9.5 years in different areas. In Chernobyl-affected areas in Norway and Sweden the current effective ecological half-life has been estimated at approaching 30 years.

Lessons about the ecological behavior of radionuclides

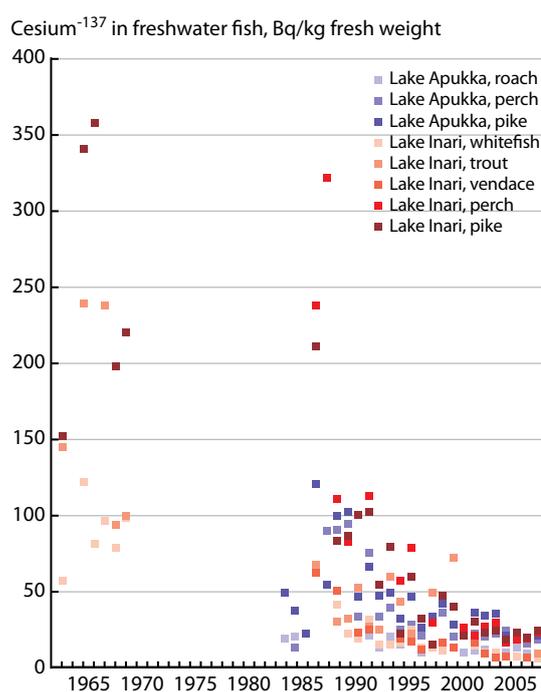
A general conclusion from the behavior of radio-cesium in the environment after Chernobyl is that lichen are more contaminated than green plants immediately following a fallout event but that cesium remains for a longer time in green plants than in lichen. Following the Chernobyl accident, this led to seasonal differences in levels in reindeer meat, with higher levels in late winter after the reindeer had fed mainly on lichen than during summer and in the fall after the reindeer had fed on green plants. The difference was enhanced by slower metabolism of the reindeer in the winter. With time, these seasonal differences have diminished.

For berries and mushrooms, the levels and ecological half-lives can vary greatly depending on the species. For example, for the fungi of the genus *Lecaninum* there has been no significant change in the cesium levels in the past 20 years, and in the species *Suillus luteus*, levels have increased rather than decreased, contrary to other *Suillus* species. For years with high abundance of mushrooms on the pastures, mushrooms can be an important source of radiocesium for reindeer and other grazing animals. Measurement of wild berries in Finland show much higher levels in cloudberries (a typical Arctic species) than in bilberry, lingonberries and cranberries. The activity levels for all berries are, however, below international recommendations.

The levels in freshwater fish depend on the ecosystem in which they live and their food habits. Directly after the Chernobyl accident the highest levels were found in predatory fish, such as pike

and to some extent in perch and trout, compared to non-predatory fish, such as whitefish and roach. In the first eight years after the accident, the effective ecological half-lives were similar in two different lakes that were studied in Finland, one clear lake with low nutrient levels and one eutrophic lake with high nutrient levels. Since then, the half-lives in the eutrophic lake have increased and are now close to the physical half-life of cesium-137, probably because cesium from the surroundings follows the flow of nutrients into the lake. In both lakes, the levels in fish are much lower now than they were in the 1960s when they were most affected by nuclear fallout.

The declining levels of radioactivity in the environment are also reflected in people. However, the levels in people in Chernobyl-affected areas who consume large quantities of reindeer meat and other products from the wild, than in other parts of Fennoscandia. For example, in the year 2000, the mean body content was ten times higher in a group of Finnish consumers of wild products than in the general Finnish population. In central Sweden and Norway, there is still a need for actions to limit the intake of cesium-137 by reindeer herders. Using stricter countermeasures, the levels in these groups could have been comparable to levels in the general population. However, these were not implemented because the changes in lifestyle that those countermeasures would have required was so great that the total consequences were assessed to be negative.



Marine discharges from spent fuel reprocessing have declined

In the Arctic marine environment, discharges to the sea from reprocessing of spent nuclear fuel at Sellafield (United Kingdom) and Cap de la Hague (France) have historically been a major source of radioactive contamination, especially cesium-137 but also other radionuclides. These contaminants can be transported over long distances and follow the Atlantic current to the Norwegian Sea and further along the Norwegian coastline into the Barents Sea on a route that takes four to five years. These contaminants will eventually reach the Arctic Ocean. Routine releases from the European reprocessing plants declined drastically in the 1970s. However, the previous AMAP assessment reported increasing levels of technetium-99 and iodine-129 and raised discussion about the need for new assessments of potential impacts of these releases.

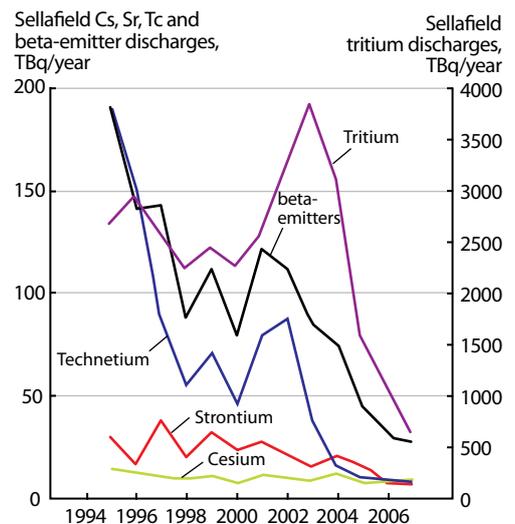
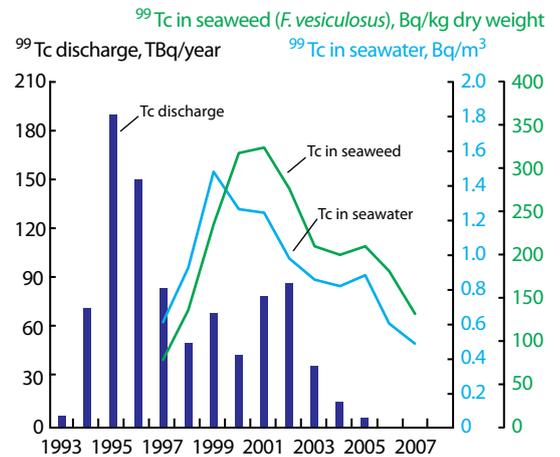
Since a peak in 1995, the discharges of technetium-99 have dropped considerably. The increase in discharges from Sellafield was associated with a new facility for treating a backlog of stored medium-level radioactive waste. This was designed to remove some contaminants (mainly actinides), however some radionuclides, including technetium-99 remained in the discharges to the Irish Sea. This explains the increased levels reported in the previous AMAP assessment. In 2004, a new purification technology was implemented at Sellafield, designed to extract technetium-99. Discharges to the Irish Sea of technetium-99 have since dropped considerably.

Because of the wide dispersion and massive dilution of these contaminants in the water, the result-

ing exposure of people in the Arctic has nevertheless been relatively low.

Today, the main concern in relation to Sellafield is the tanks on land for temporary storage of Highly Active Liquor. There are currently 21 large tanks, with a total storage volume of 2360 cubic meters. In 2004, they held 1000-1500 cubic meters of waste with a very large inventory of cesium-137, stron-

► Seaweed is an excellent bioindicator for technetium-99 in the marine environment. Seaweed accumulates technetium from the seawater and is easily accessible in most coastal areas. It has therefore been used for routine monitoring. The figure shows a peak in technetium-99 in 2000-2001 in brown algae from Hillesøy near Tromsø in northern Norway about five years after the peak in discharge of this radionuclide from Sellafield in 1995. In seawater, the activity peaked in 1999 at Hillesøy.



Climate change may release contaminants stored in the environment

Low mobility of radionuclides in the cold environment in combination with high content of organic matter has made the Arctic tundra a large sink for both anthropogenic and naturally occurring radionuclides. When the climate changes - with warmer temperatures, changes in precipitation and shifts in the presence of snow, ice and water - these contaminants may become more mobile. For example, radionuclides are often associated with dissolved organic matter. In recent years, elevated levels of dissolved organic matter, which makes the water brownish in color, have been observed in a number of countries and this is generally regarded as a climate-related phenomenon.

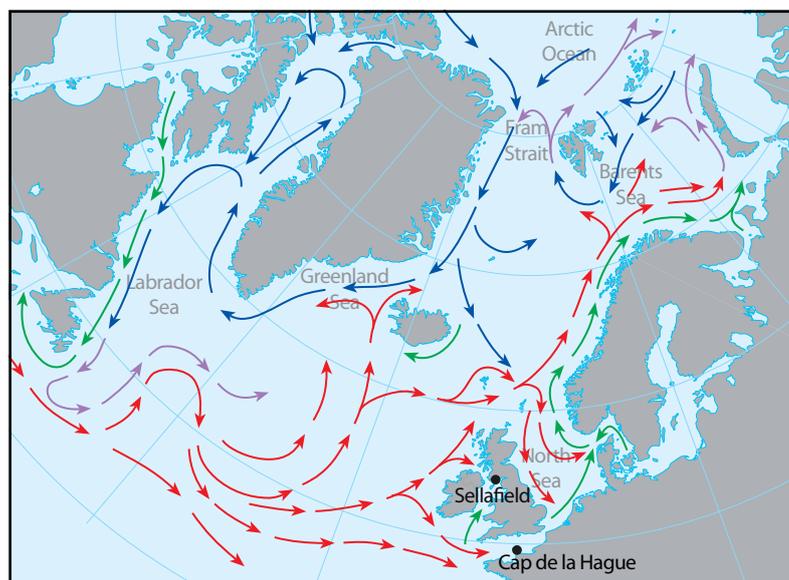
Glaciers have also served as sinks for fallout from nuclear weapons testing. Glaciers grow or shrink depending on the amount of precipitation and the temperature. With climate change, Arctic glaciers are currently shrinking, and their ice, including its load of contaminants, is released via meltwater and calving. Calculation based on the two glaciers and fjords on Svalbard show that the inventory of radioactive contamination in glaciers can serve as a significant source for local contamination. However, the impacts are neither well understood nor have they been subject to enough research to make any assessment of risks to ecosystems or people.

tium-90 and other radionuclides. The UK Nuclear Installation Inspectorate has required Sellafield to reduce the amount of stored High Active Liquor but until that is done the storage tanks remain a potential source to the Arctic environment. If they were to fail, they could release a considerable amount of radioactive substances to the marine environment and eventually to the Barents Sea. A rise in cesium-137 would be apparent after two to three years with a peak that would be far beyond the highest levels of the 1980s. Even after 20 years, the cesium concentration would be well above today's levels.

Climate change is likely to affect marine pathways

Climate change is likely to affect the transport of contaminants in the marine environment. For example, movement both into and out of the Barents Sea may become more rapid than today. We may also expect an increased exchange of water (including its load of contaminants) between the surface layer of the ocean and the so-called Atlantic layer below. The circulation in the Atlantic layer is slower than the surface water and the consequence would be that contaminants that enter the Arctic marine environment may stay in the Arctic longer than they do today. These processes would affect radionuclide transport from the European reprocessing plants and also outflow from the Baltic Sea, which carries contaminants from the Chernobyl accident to the Arctic marine environment.

Changes in the sea ice may also affect contaminant



— Arctic Water — Mixed Arctic and Atlantic Water
— Atlantic Water — Coastal Water

transport in the Arctic. With declining multi-year ice, it is less likely that contaminated sediment carried by sea ice from the Russian coast and continental shelf will reach Fram Strait where it would otherwise melt and release its load. Instead, the sediment is more likely to be released on the continental shelf, where it can be reincorporated in ice during the next winter.

▲ Main current systems in the North Sea, Norwegian Sea, Greenland Sea and Barents Sea area.

Changes in temperature may affect how radionuclides are taken up and retained by animals in the water. The knowledge base is too poor to make any new assessments of risks, but in general, changes in temperature may lead to changes in turnover rates of contaminants in cold-blooded animals such as fish.

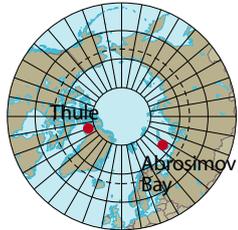
Iodine-129 is used for mapping ocean transport

Iodine-129 has an extremely long half-life (16 million years). It has been released from nuclear facilities, mainly from nuclear fuel reprocessing plants, and has been used as a tracer of long-term ocean circulation patterns. Between 1990 and 2000, annual discharges from Cap de la Hague and Sellafield increased drastically. The 'leading edge' of the contamination associated with this increase has now entered the Labrador Sea, with a transit time of about seven to nine years. After first entering the North Sea, it flowed northward along the Norwegian coast towards Spitzbergen. From there, it flowed into the Arctic Ocean via the Fram Strait and the Barents Sea. It also circulated counterclockwise around the Greenland Sea passing southward along the east coast of Greenland. It entered the Labrador Sea at depths of 3000 meters with Denmark Strait Overflow water. The levels of iodine-129 are too low to be of health or environmental concern but they show that radionuclides and other contaminants that enter the North Atlantic can quickly spread over large areas.



Iodine-129 discharges from the Cap de la Hague reprocessing plant, France.

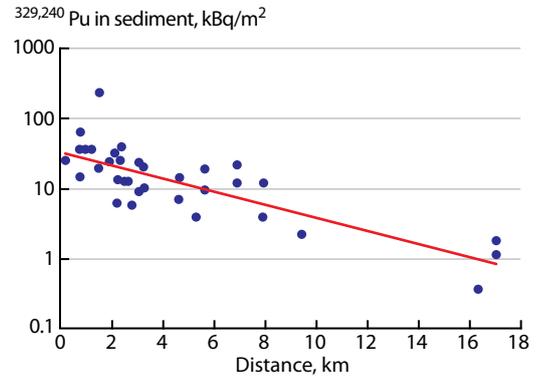
► Declining levels of plutonium-239,240 in marine sediments at Thule, with distance from the crash site.



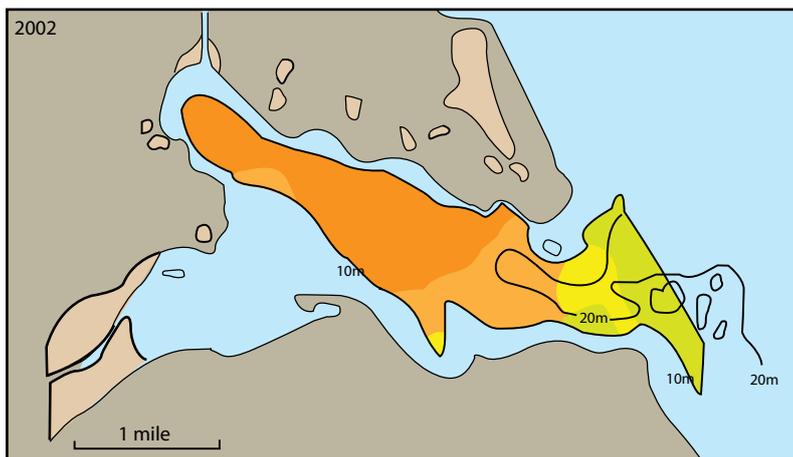
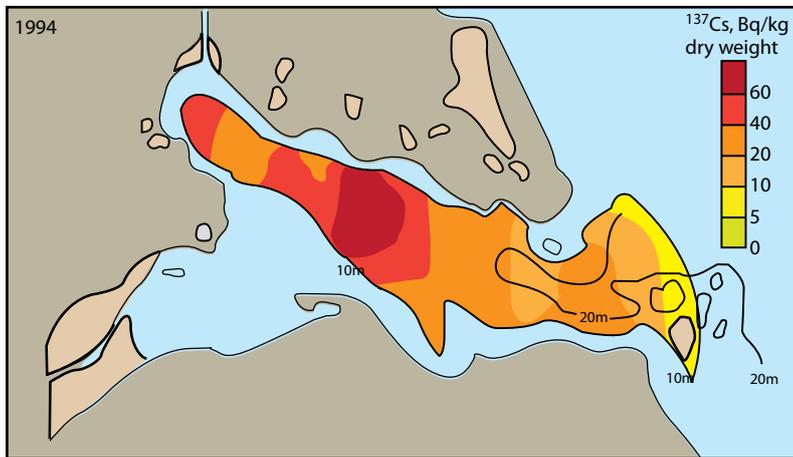
▼ Distributions of cesium-137 in Abrosimov Bay surface sediments in 1994 and 2002.

Updates on radioactive material in Abrosimov Bay and Thule

Previous AMAP assessments have addressed the issue of radioactive waste dumped at the bottom of the sea in the Russian north, with the conclusion that the major risks are long term and connected to the corrosion of the containment. A 1994 survey of Abrosimov Bay concluded that there was a need to monitor the situation. In 1998, the International Atomic Agency (IAEA) concluded that the dumping sites should be monitored on a regular basis. Unfortunately, there have been no joint Russian/Norwegian expeditions to the dump sites in the Kara Sea since 1994. However, there has been a joint Russian/Norwegian programme with yearly measurement in the open Barents Sea and along the coast of Finnmark and the Kola starting in 2002. The new data show decreasing inputs from remote sources such as global fallout, European reprocessing plants and the Chernobyl accident. The data also show that in the Barents Sea, so far, there is no signal of radioactive leakage from the submerged objects.



Information concerning the crash of an American B-52 at the Thule airbase in northeast Greenland in 1968 was reported in both previous AMAP assessments. The latest investigation of this site was conducted in 2003. It showed that plutonium from the nuclear weapons that were on the American B-52 persists in the environment. The highest concentrations are in the sediment under the location where the plane crashed on the ice. The distribution is very uneven and associated with “hot” particles. The new data (with an estimated inventory of 2.9×10^{12} becquerels of plutonium) support the 1997 AMAP conclusion that earlier investigations may have underestimated the inventory on the seabed. Concentrations of plutonium in surface sediments are generally elevated due to biological mixing with deeper more contaminated layers. Concentrations in seawater, seaweed and bottom-dwelling animals are low but above the background level. The radioactive material does not present a risk to human health, even if people were to eat shellfish with the highest concentrations. Plutonium from the accident has also created elevated activity levels in soil around Narssarsuk. For people visiting the site, this could constitute a small risk if radioactive particles were resuspended and inhaled.



Dealing with obsolete submarines, spent fuel and radioactive waste

The previous AMAP assessment highlighted the poor situation surrounding decommissioning of submarines of the Russian Northern fleet and storage of spent fuel and radioactive waste from these submarines and other nuclear-powered vessels. These storage sites pose a major potential risk to the local and regional environment. Although some activities had been initiated to improve the situation, the previous assessment concluded that much remained to be done.

Dismantling and decommissioning of submarines successful

A total of 198 Russian nuclear submarines have been taken out of service by the Russian navy. As of March 2008, 164 are decommissioned. This is a result of comprehensive efforts by Russia and contributions by donor countries, especially from G8 countries following the 2002 Kananaskis G8 Global Partnership commitments. Of the remaining 34 nuclear submarines, 11 are under decommissioning and 20 are waiting to be decommissioned (9 in northwest and 11 in the far east of Russia).

Operations to remove spent fuel from liquid metal reactors, previously identified as a major issue, have begun. Other activities are the processing of several hundred tonnes of low-level radioactive waste and preparing casks for transport and storage of spent nuclear fuel.

Further activities are in advanced stages of planning. They include defueling and decommissioning of the *Lepse* Floating Maintenance Base, which has been used for storing spent fuel and radioactive waste and which is in a very poor condition. Plans also include defueling of a Papa Class nuclear powered submarine with management of spent fuel and radioactive waste. In addition, enhanced radiation monitoring and emergency response in the Archangelsk region has been commissioned.

Dismantling of submarines is not a risk free activity. The Norwegian-Russian efforts have been well documented and include improved environmental monitoring and impact assessments. In general, these efforts have been successful without radiological incidents or accidents.

There are not many submarines left to be dismantled. The spent nuclear fuel from the decommissioned submarines has been successfully transported to a dedicated facility at the Mayak reprocessing plant. If left unattended, it would have posed a potential threat to people and the environment. The remaining submarines are mainly of specific types that are more difficult and expensive to dismantle. A majority of these are expected to be dismantled by funding from the Russian federal budget by 2010.

Poor conditions at Andreeva Bay and Gremikha are slowly improving

In the 1960s, the Soviet Navy developed bases at Andreeva Bay and Gremikha on the Kola Peninsula

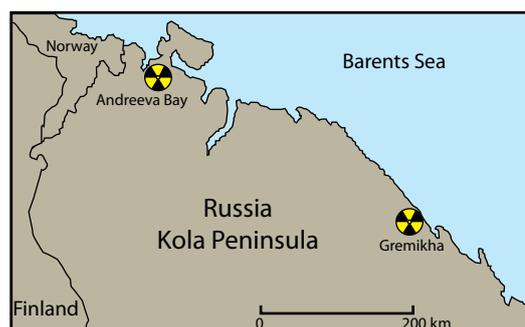


Norwegian Radiation Protection Authority

to service nuclear submarines and to store nuclear waste. They were used intensively in the late 1980s and early 1990s. Since then support has ceased and the sites have become temporary storage sites. Maintenance was not kept up according to plan and the facilities have degraded. In 1982, failure in the containment in one building of Andreeva Bay resulted in leakage of radioactive water and forced the relocation of the spent fuel. There are currently 3000 containers of spent nuclear fuel in Andreeva Bay holding 1.3×10^{17} becquerel, in addition to large amounts of solid and liquid radioactive waste, comprising 6.0×10^{14} becquerels and 2.2×10^{12} becquerels, respectively. Gremikha was mainly used for reactors from decommissioned submarines but also holds control rods and extracted parts from old submarines. It holds about 1.3×10^{16} becquerel of spent fuel and 3.3×10^{13} becquerels of radioactive waste.

In addition to both sites having areas containing highly radioactive material, parts of the sites are severely contaminated. Doses exceed 1 millisievert per hour in some places (compared to recommended limits of

▲ Building #1 at Andreeva Bay, used for dry storage for spent nuclear fuel, was demolished in 2008.



◀ The location of the Andreeva Bay and Gremikha nuclear waste handling and storage sites on the Kola Peninsula.



▲ Improvements to buildings and infrastructure at Andreeva Bay have increased the security and reduced the risks of releases of radioactive activity at this storage facility.

1 millisievert per year for exposure of the public from nuclear activities/contamination and 20 millisieverts per year for people working with radiation). Monitoring of the coastal strip indicates that radionuclides can move from the contaminated sites to the surrounding environment via groundwater flow. There have also been discussions about the possibility that the stored waste would set off a spontaneous nuclear chain reaction. Current assessments show that, even though conditions are worse than expected, a chain reaction could not be initiated without an external influence. There remains uncertainty about what the consequences of such an accident would be for the nearby area and surrounding region.

In 2002, a Russian federal enterprise was established to manage the Andreeva Bay and Gremikha sites and some work has been carried out with assistance from the international community (Norway, United Kingdom, Sweden, Italy and France). It includes constructing equipment and infrastructure for removing spent nuclear fuel, building roofs to prevent rainwater from entering the building, decontamination of buildings and material, and securing the area. The present plan suggests that transport of spent nuclear fuel and radioactive waste from Andreeva Bay can start in 2013-2014. For Gremikha, feasibility studies have started and some urgent action has been taken to secure infrastructure and to prepare for transport of spent nuclear fuel. The removal of fuel to the Russian reprocessing plant in Mayak was scheduled to start at the end of 2008.

Possible climate change impacts on facilities

Climate change may pose new challenges regarding Andreeva Bay and Gremikha. The impact of weather

and climate on infrastructure is well known for Andreeva Bay, where freeze-thaw actions contributed to loss of integrity of the fuel storage facility and extensive contamination of the Andreeva Bay site. Further degradation combined with precipitation has contributed to radioactive material being washed out into the marine environment. A number of factors other than climate contribute to the degradation, but assessing the impact of climate change, in similar ways as has been done for nuclear infrastructure outside the Arctic, is nevertheless warranted.

Mayak update

Mayak is a facility that was built in 1948 for producing weapons-grade plutonium. Since 1987 it has been used mainly for reprocessing of spent nuclear fuel and for producing MOX fuel from weapons-grade plutonium. The facility has generated large amounts of radioactive waste. The environmental risks of Mayak for the Arctic were assessed in 1997 and further discussed in the 2002 AMAP assessment. The conclusion was that major risks concern potential accidents and leakage into tributaries to the river Ob, but that even worst-case scenarios pose little hazard to the Arctic environment. The current assessment provides an update on levels in the rivers Irtysh (a tributary to Ob) and Tobol (a tributary to Irtysh). Measurements show that the concentrations of strontium-90 are greater in the Tobol by an order of magnitude compared to background levels for Russian rivers while they are close to background in Irtysh. The elevated levels were below intervention levels for drinking water.

Data from the Ob estuary are contradictory regarding the importance of Mayak as a source of contamination. One study points to atmospheric fallout as the main source of plutonium whereas a study of water in the Ob River, Ob estuary and the Kara Sea points to the Mayak facility as a key source. The new data do not change previous assessments that Mayak is currently not a major source for radioactive contamination of the Arctic. Nevertheless, climate change could influence the transport of radionuclides from Mayak to the Arctic areas. Further studies are needed to assess this. The risk of accidents is still a concern, especially any releases to the air. Previous assessments indicate that leakage into the river system from failure of current containment would only lead to very low doses to humans in the Arctic from exposures via the marine environment.

New strategic plan aims for long-term management

In addition to the specific ongoing activities to reduce risks from potential sources in Russia, a long-term strategic plan has been developed by the Russian Ministry for Atomic Energy jointly with the Northern Dimension Environmental Partnership Support Fund. It is a step towards the implementation of the Global Partnership Programme approved by the G8 leaders in Canada in 2002 and will serve as a reference point for further work, including needs for environmental monitoring.

The strategic program covers the majority of facilities in northwest Russia related to scrapped military and civilian nuclear naval vessels together with their supporting infrastructure. It will span the time interval necessary to decommission and remediate all facilities, which is longer than for previous short-term 5-10 year programs. Since March 2008 the plan has been managed by the Centre for Nuclear and Radiation Safety of Rosatom.

A major challenge identified in the strategic plan is the need for improved storage facilities for radioactive waste. A new facility for long-term interim storage of reactor compartments has been developed at Sayda Bay, while a repair workshop is under construction and will be complete by April 2009. The current storage facility will soon be extended. In addition, the design of a long-term storage site has started.

Coordinated with Russian-led activities, Norway has an action plan for cooperation on nuclear safety and radiation protection in relation to nuclear activities in northwest Russia. The plan includes technical support and regulatory cooperation, such as development of norms for monitoring and workers' safety, the practice of improved inspection procedures, improved emergency preparedness and response, and enhanced safety culture.

A general conclusion from the on-going work on improving nuclear safety in the Russian northwest is that the regulatory framework has improved, as have communication and coordination between authorities in different countries. This includes arrangement for emergency preparedness and response and better supervision of remediation activities. Continued national and international efforts are however required to assure that the work will proceed in a timely and safe manner.

Radioisotope thermoelectric generators: thefts and decommissioning

Radioisotope thermoelectric generators (RTGs) use radioactive decay to produce heat that is then used for producing electricity. They are self-contained devices with a long service life and have been used for powering various devices, such as lighthouses, in remote areas of the Arctic. RTGs pose a threat to human health if the casing is breached. The radioactive fuel is in the form of hockey-puck sized pieces of ceramic material. If handled directly, the very high radiation dose rates would result in the death of those concerned after only a short period of exposure. The half-life of the commonly used radioactive source, strontium-90, is 29 years and the fuel sources remain dangerously radioactive for hundreds of years. As of February 1, 2008, 519 RTGs were in operation in Russia.

Most RTGs have no form of security, like fences or warning signs, and there have been thefts and break-ins. The previous AMAP assessment raised concern about RTGs because some devices had been dropped during helicopter transport or vandalized. In the wrong hands, RTGs could potentially be used as "dirty bombs" where conventional explosives are used for spreading radioactive material. The following list of incidents in the Arctic has been compiled by the Norwegian Radiation Protection Authority:

- During the summer of 2001, four people were brought to the hospital after being exposed to radiation when trying to disassemble the beacon light near Kandalaksha in the Murmansk area.



Norwegian Radiation Protection Authority

◀ Radioisotope thermoelectric generator.

- In September 2003, supervision personnel from the Northern fleet stopped an attempted theft of an RTG beacon light at the Golets Island in the White Sea. The beacon light had a particularly strong RTG with six strontium cores.
- In November 2003, two beacon lights from the Kola Bay were found disassembled and everything except the strontium cores were taken. A third theft was discovered south of the mouth of Nerpa.
- In addition to previous incidents of dropped RTGs outside the Arctic, two accidental RTG drops from helicopters happened in September 2004, where the RTGs dropped onto rocks from an altitude of 100 meters. No release of radioactive strontium was registered.

So far, thieves have been interested in the metal shielding rather than the radioactive fuel but the thefts show how easily such material may go astray. The number of incidents has led to joint Russian-international efforts to safely decommission RTGs along the Russian coastline. For example, in 2007 the last RTG was removed from the Murmansk region. By the end of 2008, 169 of 180 RTGs around

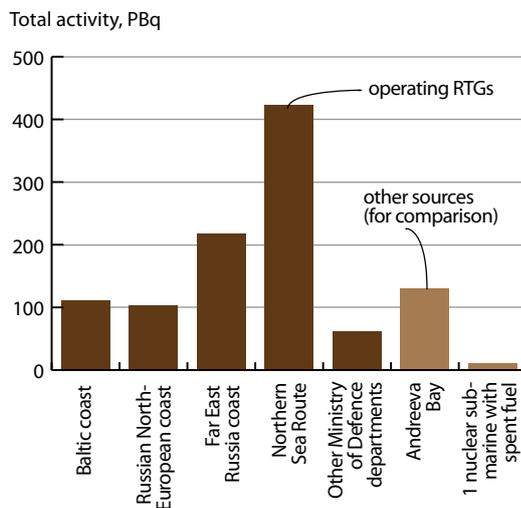
the Barents Sea were removed as part of a bilateral agreement between Norway and Russia. The remaining 11 devices, located in the Archangelsk and Nenets regions, will be removed in 2009. The RTGs are replaced by solar panels. Discussions are also on-going for Finland and France to contribute to removing RTGs and creating safe storage of the radioactive material. The United States, with contributions also from Canada, funds a support program that has recovered 87 RTGs along the Northern Sea Route and will recover the remaining 10 devices along the Northern Sea Route and 11 devices in the far east of Russia. Moreover, by the end of 2008, 24 RTGs were recovered from Bilibino. The program also includes enhanced regulatory processes with better safety supervision during decommissioning and transport.

Nuclear power plants: climate change and floating nuclear power plants raise new concerns

As reported in earlier AMAP assessments, there are two nuclear power plants situated within the Arctic, the Kola power plant on the Kola Peninsula and the Bilibino power plant in northeastern Russia. The concerns that have been raised previously related to potential accidents, with calls for effective emergency preparedness and response systems. A new concern, especially relating to the Bilibino power plant, is climate change. Bilibino is situated in a permafrost area where the thawing of this permafrost is likely to cause ground movements, which can threaten the structural stability of buildings. Previous incidents from other nuclear facilities, e.g. Andreeva Bay, show that such freeze-thaw actions can contribute to structural instability that can lead to release of radioactive material to the surrounding environment. There is thus a need to conduct risk assessments also for Bilibino that take climate change, including changes in the permafrost, into account.

A major new development regarding nuclear power plants is Russia's intention of developing floating nuclear power plants for use in the Arctic region. Russia's nuclear industry has undergone and continues to undergo a major restructuring in connection with large-scale expansion of nuclear power. In 1991, there was a competition for the best design of low capacity nuclear power plants. The winning design was a floating nuclear power plant. In 1996, a report announced the inten-

▶ Radioactivity associated with RTG sources in different parts of northern Russia is being reduced as these sources are decommissioned and replaced.



▶ Radioactive energy sources in lighthouses along the Murmansk coast have been replaced by solar cells.



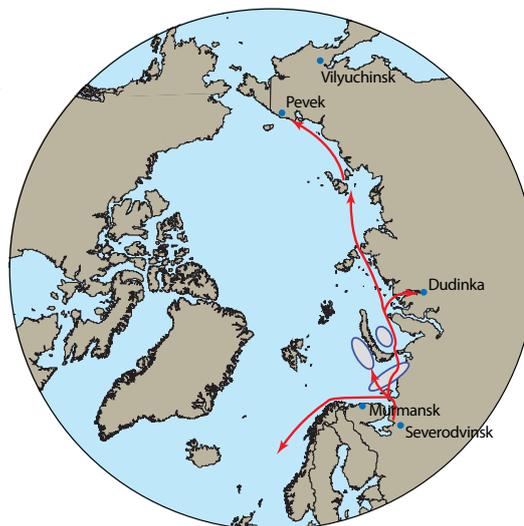
County Governor of Finnmark

tion of locating floating nuclear power plants in a number of places in the Russian North. In April 2008, the keel of the floating nuclear power plant *Academician Lomonosov* was laid in the Sevmash shipyard at Severodvinsk, and the plant is due to be completed by 2010.

The floating power plants are developed at least partly as commercial products and estimates of planned units are difficult to make. They range from one per year to 15 over an unspecified period of time. The power plants are marketed internationally and there are indications that other countries, such as China, are interested in the project. The locations that have been discussed for Russian plants include 33 towns in the Russian far north and far east. Russia has also indicated that such plants could be used to supply energy for oil and gas extraction in the Barents Sea. It is probable that the infrastructure for construction, fuelling and servicing such plants would be built around the Kola Peninsula/Archangelsk region. Should the plans proceed, there will be more nuclear power plants in the Arctic and also increases in the transport of fresh as well as spent nuclear fuel and radioactive waste.

Climate change will affect exposure to natural radioactivity

Radioactive elements are found naturally everywhere in the environment. Some radionuclides, called primordial radionuclides, are extremely long-lived and have been present on Earth since it was formed. Others are formed from the decay of the primordial radionuclides. For example,



◀ Potential locations of floating nuclear power plants in the Arctic. Grey shaded areas indicate locations of oil or gas exploration areas where they may be employed as power sources. Arrows indicate potential routes from an assumed manufacturing/servicing centre in the Arkhangelsk region to international customers or Russian locations outside of the Arctic.

uranium-238 will, through several steps, decay to radon gas, radon-222 with a half-life of only 3.8 days. Because of its inert chemical properties, radon can escape relatively easily from the matrix in which it is formed and reach the open air where it can be inhaled by people. Radon, with its short lived radioactive decay products, is the main contributor to radiation dose to people.

Climate change is likely to affect both the release of radon and the behavior of its decay products in the environment. Currently permafrost acts as a barrier to radon release from the ground. When the permafrost thaws, emissions of radon are likely to increase, potentially increasing indoor radon levels by up to two orders of magnitude. The impact on human exposure is however difficult to assess as a number of different factors affect the behavior of radon decay products. Building practices, dwelling design and ventilation are also important.

Potential marine transport of spent fuel

In Norway, public concerns have been raised about the possibility of sea transport of spent nuclear fuel to the Russian north and along the Norwegian coastline as climate change reduces the ice cover in the Arctic. In Norway, large economic and cultural interests are connected to production and export of marine food products, and past experiences have shown that only rumors of radioactive contamination of sea-food can have economic consequences for producers. In 2007, a report estimated the radioecological consequences of potential accidents during transport of spent nuclear fuel along Norway's coastline, based on a worst-case scenario. This scenario involved a ship loaded with 100 fuel packages of standard fuel assembly sinking at an accident location that was particularly vulnerable for radioactive contamination and where the consequences of the accident would be highest.

In spite of the very unlikely worst case assumptions, the assessed dose to the most highly exposed individual humans would not be higher than 1 millisievert per year. Health consequences due to the elevated radiation doses to humans would thus be of minor concern. Results did indicate however, that concentrations of radionuclides in some marine organisms exceeded guideline levels for sea food. Elevated levels of radionuclides in marine food products may have economic consequences in a market that is very sensitive to reports of contamination. Potential impacts on the environment were not assessed.

► The risk of radioactive contamination of the marine environment along Norway's coast has raised concern mainly due to the financial risk to food producers if their products are perceived as contaminated.



Carey Arnold

Although most of the dose from natural radiation comes from inhaling radon and its decay products, some of the dose is ingested via food and thus reaches people via the food webs on which they rely. Arctic terrestrial food webs are especially efficient in concentrating radionuclides, which explains the high exposure of some Arctic populations. Some of this natural radiation comes from long-range transport via air that has crossed continents, while some emanates from the local ground. There is often a build-up of radon in the snow cover during winter, which is rapidly released during snow melt in the spring. If the soil is frozen for a shorter period because of climate change, and if the depth of the snow cover changes, the flux of natural radioactivity from the rocks and soils within the Arctic is likely to change. However, there is not sufficient knowledge at this stage about the relative roles of long-range transport and internal Arctic emission to assess how human and environmental exposure in the Arctic will change over time.

Extraction of fossil fuels and mining can enhance natural radioactivity

Industrial activities can enhance exposure to natural radioactivity. This happens in mining and processing of ores that contain natural radioactivity and in the extraction of oil and gas. These processes often involve the extraction and movement of large amounts of material. Even if the concentrations of radionuclides in these materials are very low compared to nuclear fuel or waste from nuclear

activities, these and other industrial activities can potentially contribute to the dose that affects people's health. This can occur, for example, where materials containing natural radioactivity are used in building construction and fertilisers. Therefore, this assessment includes an initial survey of non-nuclear technical activities that may enhance the naturally occurring radioactivity, the so-called TENORM (Technologically Enhanced Naturally Occurring Radioactive Materials) industries.

Uranium mining

Uranium mining is one of the most important TENORM activities. During mining operations, large amounts of waste rock are generated, with higher levels of uranium compared to other types of rock. Waste rock can cause radiological problems if radionuclides are leached into the surrounding environment, because of the dust created, and because it emanates radon. In addition, the uranium ore is milled and treated to extract the uranium from the ore. After most of the uranium has been extracted, about 85 percent of the activity is still left in the so-called mill tailings. These tailings are often disposed of in ponds or piles where they can contaminate the surrounding water and also serve as a local source of gamma radiation, dust and radon emanation.

Canada has a long history of uranium mining, including at sites in the Arctic. Although the mining activity has ceased, renewed interest in nuclear power may lead to renewed interest in exploiting this resource in Arctic Canada as well as elsewhere in the Arctic.

Historic Canadian uranium mining has resulted in local contamination problems that have been addressed in recent years. One such site is Port Radium on the east shore of Great Bear Lake in the Northwest Territories of Canada. This site was used for extracting radium, uranium, and silver during different periods from 1932 to 1982, after which the site was covered with waste rock. An environmental survey conducted by the Canadian government in partnership with the Déline First Nation from 2001 to 2004 showed some elevation of background radiation levels resulting in a recommendation to remediate the site. Transport of ore from Port Radium along waterways and land has also led to contamination in connection with spills during loading and reloading of the material. These sites are also to be remediated. Indigenous people working in these industries have raised concerns about the health risks from handling ore. As part of the joint plan, the doses to 35 of these workers have been reconstructed. The cumulative doses during the period of employment ranged from 27 to 3015 millisieverts. The numbers can be placed in relation to 20 millisieverts, which is the internationally recommended annual dose limit for people working with radioactivity, and 2.4 millisieverts as an average annual dose to the public from natural radiation.

Another historic Canadian mining site is the Rayrock mine, 145 kilometers northwest of Yellowknife. It operated from 1957 to 1959. Radioactive tailings were deposited on land and partly flowed into three small lakes. Measurements from 1985 showed mildly elevated levels of radioactivity but below Canadian drinking water guidelines. In 1996 and 1997, the mine was sealed and the dumped material was relocated and capped with silt clay. The monitoring program that was put in place has since showed that fish and caribou from the area are safe to eat, that the water quality meets drinking water standards, and that there is very little risk to humans from radionuclide exposure.

Mining for other minerals

Mining for other resources can also enhance natural radioactivity, especially if the ore is enriched in uranium or thorium that can enter the processing industries. The content of natural radioactivity varies greatly in different ore type, with examples ranging from iron ore with less than 5 becquerels uranium per kilogram to pyrochlor (a mineral rich in the rare metal

niobium) with 1000 becquerels uranium-238 and 80000 becquerels thorium-232 per kilogram. Other metal ores that are relatively rich in natural radioactivity include tin, ilmenite (titanium), rutile (titanium) and bauxite (aluminium). Radionuclides can escape from waste and by-products such as tailings, mine water, scale and slag. With chemical and heat treatments, they can also be emitted to the air.

Phosphate extraction

Another example of technologically enhanced natural radioactivity is phosphate mining and processing. The radioactive content is not as high in the igneous phosphate ores that are common in the Arctic as they are in sedimentary rock. However, there is still concern about the large amount of radium-226 that is incorporated in phosphogypsum, and other radionuclides in phosphoric acid from the production process. The concern with phosphogypsum includes radon emanation and leaching of radionuclides into the groundwater.

Fossil fuels and other energy production

Extraction of fossil fuels is another potential source of technologically enhanced naturally occurring radioactive material. For coal, the radioactive material ends up in the ash when the coal is burnt, especially in fly ash that can result in emissions to the air. The radiological hazard from emissions to the air have been evaluated in a number of studies from the 1970s and 1980s with the conclusion that emissions from coal burning contribute only a small amount to the radiological dose to people living close to coal-fired power plants (1-5 percent above normal background levels.)

During oil and gas production, large volumes of water are co-extracted with the hydrocarbons from the reservoirs. This produced water is a potential source of TENORM in the Arctic. Produced water has been shown to have elevated concentrations of radium isotopes in particular, with activity concentrations from less than one to several hundred becquerels per liter. If discharged to the sea, this activity will be rapidly diluted, although some material can precipitate and end up in the nearby sediments.

Another concern is that radium may co-precipitate with other metals inside pipes and valves, where it becomes incorporated in so-called scale. The activity concentration in scale can vary from very low to several hundred thousand becquerels



▲ Exposure to naturally occurring radioactivity can be enhanced as a result of TENORM industries, including oil and gas development. Scale on the inside of pipes can reach high levels and pose a hazard to workers.

per kilogram. Procedures are commonly in place for protection of workers. Controls for the management of the waste arising, e.g. from pipe-cleaning operations, are necessary to protect the environment from contamination.

Geothermal energy is minor in most countries except Iceland. In the production of geothermal energy hot water and steam is pumped from deep boreholes to the surface. Radium-containing scale can form in pipes, production equipment and ponds. It can also be released to the atmosphere with locally elevated radon levels. The potential risks depend on the local geology. Current knowledge does not allow any quantification of the risks. Experience from drilling for water in Norway, where the bedrock typically has high level of natural radioactive substances, suggest that it may be a major contributor to elevated radon levels in houses, at least if the water comes into contact with the indoor air.

Protection of the Arctic environment

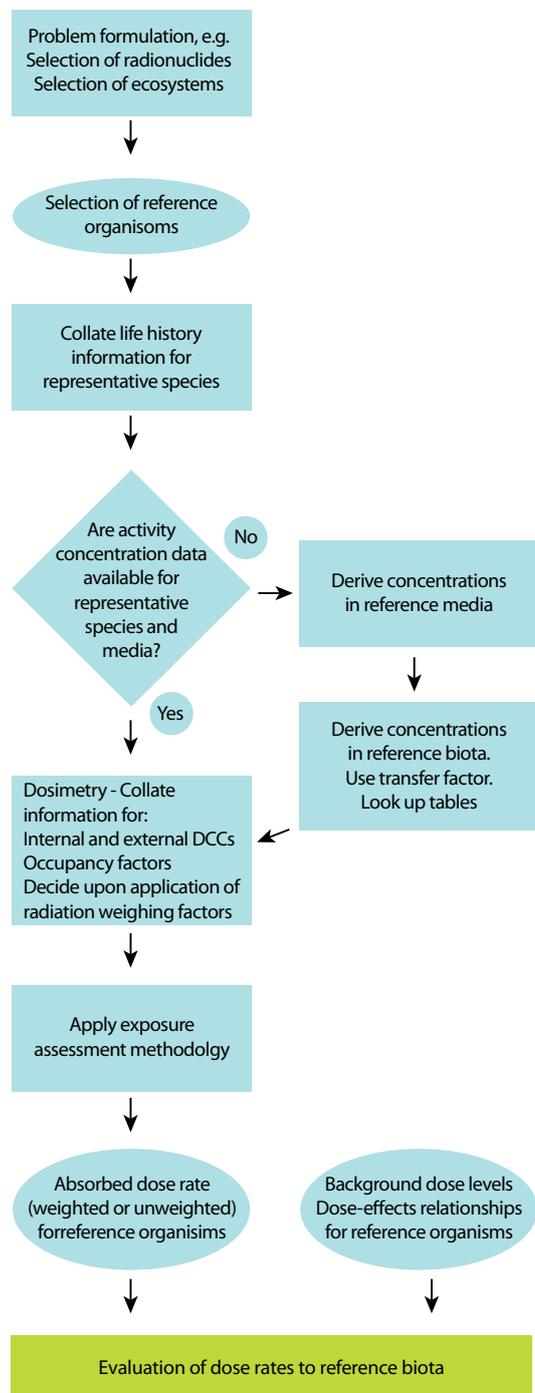
AMAP's assessments of radioactivity as well as radiological protection frameworks in general have traditionally only focused on human health and environmental issues of direct relevance to human health. Inspired by the environmental focus for other contaminants, e.g. persistent organic pollutants, the AMAP radioactivity group has played an important role in initiating international efforts to assess the environmental impact of radioactive contamination. They include formulating a framework for making environmental assessments by estimating the exposure of plants and animals to radioac-

tivity and comparing this to dose rates known to have specific biological effects, in order to judge the increased risks.

At the international level, the initial work on developing methods for the assessments has been carried out in two European collaborative projects: Framework for Assessment of Environmental Impact (FASSET) and Environmental Protection from Ionizing Contaminants in the Arctic (EPIC). These studies have been superseded by the project Environmental Risks from Ionizing Contaminants: Assessment and Management (ERICA). In addition, the International Commission of Radiological Protection (ICRP) has begun to formulate a framework for protecting the environment, which is to be harmonized with approaches to protect human health. The suggested environmental impact assessment for the Arctic environment follows a flow from problem formulation (e.g. selecting the radionuclides and the regions of interest) to collecting information on relevant species to assessing the exposure and evaluating possibly increased risks.

So far, the EPIC environmental assessment has focused on 13 radionuclides that broadly represent routine releases from power plants and reprocessing facilities, accidental releases, and naturally occurring or technologically enhanced naturally occurring radionuclides (TENORM). In addition, a number of reference organisms have been identified that are typical or representative of the environments of interest. The next step involves estimating the exposure to radionuclides, including calculating the transfer of radionuclides from the surrounding environment into the organism in question, either directly or via food. The estimates are based on information available in the scientific literature, but often data are lacking for a particular organism. Such cases are managed by a systematic approach choosing *inter alia* data from other organisms as a surrogate and making the choices transparent for the assessor.

The current approach has some built in limitation. For example, it assumes that organisms come into instant equilibrium with their surrounding environment, whereas in reality organisms will retain radionuclides in their bodies and return them to the surrounding over timescales that can range from days to years. Here, knowledge about biological half-lives provides additional information.



The next step is to calculate the radiation exposure of different organisms. The dose rate is expressed in microgray per hour and is the sum of internal and external dose rates. The calculations currently do not take into consideration the type of radiation, although provisional weighting factors have been applied. In making dose estimates for humans, a weighing factor is often used to account for the larger damage by alpha particles compared to beta- and gamma-radiation, but these weighing factors are likely to vary depending on the organisms and endpoints in question.

Estimated dose rates for a specific organism are related to dose rates of known biological effects and natural background radiation.

The effects of concern in environmental assessment may be different from assessments of risks to people. For people, the increased risk for cancer has guided dose limits. For other species and ecosystems, effects on reproduction and mortality are important as are ecological effects such as impact on biodiversity and predator-prey relationships. Changes in hormone signals or in the immune system may be important for survival and reproduction. An additional end point is adaptation effects, i.e. changes in response to conditions of chronic irradiation. Reproduction is a particularly important endpoint as it may affect not only the individual organism but the long-term survival of a population. There are now databases available pertaining to radiation effects in wild organisms that includes data from field studies in northern Russia as well as Chernobyl-contaminated areas. A preliminary scale that illustrates observed biological effects is presented in the table below. In general, the threshold

◀ The stages in the EPIC assessment methodology, an approach that is now being used to assess environmental impacts of radioactive contamination.

Relationship between absorbed dose rates and effects.

Absorbed dose rate, Gray/day	Effect
10^{-6} — 10^{-5}	Natural radiation background for Arctic/northern organisms.
0.0001 — 0.0005	Minor cytogenetic effects. Stimulation of the most sensitive species.
0.0005 — 0.001	Threshold for minor effects on morbidity in sensitive vertebrate animals.
0.002 — 0.005	Threshold for effects on reproductive organs of vertebrate animals, decrease of embryo's survival.
0.005 — 0.01	Threshold for life shortening of vertebrate animals. Threshold for effects in invertebrate animals. Threshold for effects on growth of coniferous plants.
0.01 — 0.1	Life shortening of vertebrate animals; chronic radiation sickness. Considerable damage to coniferous trees.
0.1 — 1	Acute radiation sickness of vertebrate animals. Death of coniferous plants. Considerable damage to eggs and larva of invertebrate animals.
>1	Acute radiation sickness of vertebrate animals, lethal dose received within several days. Increased mortality of eggs and larva of invertebrate animals. Death of coniferous plants, damage to deciduous plants.

for deterministic effects in wildlife lies somewhere in the range of 0.5-1 milligray per day for chronic low-dose radiation.

A major challenge is to extrapolate data on individual organisms to higher levels of biological organisation, e.g. effects on the populations. For example, animal populations with high reproductive rate such as mice and ubiquitous fish species may be still viable at dose rates in the order of 10 milligray per day, even if there are effects on the health of individual animals. The dose limit will therefore depend on the type of organism that needs protection and the type of protection that is desirable, i.e. protection of populations versus protection of individuals.

Based on the data that have been gathered so far, there are now computer software tools for making environmental assessments. For selected scenarios, these tools can also be applied to Arctic environments but there is also a need for more data that better reflect Arctic reference organisms.

Is the Arctic different?

Only some of the data that have been gathered for environmental assessments of radiation come from the Arctic. Questions have therefore been raised about whether Arctic ecosystems and animals may be more vulnerable to radioactive contamination than their non-Arctic relatives. One reason for such added vulnerability could be the natural environmental stress that is caused by harsh climatic conditions and the low biodiversity in many Arctic ecosystems.

At the species level, cold-blooded and hibernating animals may have different sensitivities in the Arctic than in temperate environments because radiation effects develop more slowly at low temperatures. In this case, climate change with increasing ambient temperatures might make Arctic animals more vulnerable. However, repair of the damage is also less effective in cold conditions. Sometimes, the lesions in cold-blooded and hibernating organisms may not appear during the winter period but manifest themselves intensively during the summer.

Eggs and fish in early developmental stages are more sensitive to radiation than adult animals. In some Arctic fish species the roe takes longer to develop and is thus exposed to radiation for a longer period of time than in temperate climates,

which could make these populations more vulnerable. Long-lived species, which are common in the Arctic, may also receive a higher total dose. In the event of elevated exposure, this could also damage their reproductive cells, which could decrease fertility or pass on damage to the next generation. Many Arctic animals use fat as an energy reserve. The high concentration of fat could increase sensitivity to radiation because the radiation affecting fats produce toxic lipid peroxides.

Many Arctic animals are under stress from other contaminants, such as heavy metals and organic pollutants, which raises the issue of potential combined effects that could make Arctic animals more vulnerable. Unfortunately research on combined effects of environmental pollutants and radiation are rare. A review of such effects in people has concluded that there is little evidence for this at levels typically encountered in the environment. At the same time, there are studies of interactions that indicate that action of one agent can be influenced by simultaneous exposure to other agents, at least at high exposure. Future studies of combined effects need to take a range of issues into account, including the types of exposure and their sequence and timing. They need to consider how the different contaminants affect the behavior of each other in the bodies of animals and how they might modify the biological effects.

A general conclusion about the methodology for assessing radiation effects on vegetation, animals and ecosystems is that the hypothesis that the Arctic could be more sensitive than other environments has not yet been adequately tested. Moreover, the collection of relevant data lags behind for the Arctic compared to temperate regions, and the data that do exist do not always lend themselves to the systematic approaches that have been used in the wider context. Even if the conceptual frameworks that have been developed are a step forward, some basic work still remains to be done before it is possible to assess the impact of radiation on Arctic biota and ecosystems in a robust manner.

Chapter summary

In areas from which there are monitoring data, the levels of radioactivity in the Arctic environment are declining. A major source of contamination is still fallout from atmospheric testing of nuclear weapons in the 1950s and 1960s. In the European

Arctic, fallout from the 1986 Chernobyl accident is still present in the environment. After rapid initial declines, radioactive contamination persists in soil and some plants.

Routine releases of radionuclides to the marine environment from European reprocessing plants have decreased thanks to the application of new technology.

Previous AMAP assessments have highlighted risks associated with potential sources in north-west Russia and recommended actions to improve safety surrounding nuclear installations and waste handling. This assessment reports significant joint Russian-international action to reduce the risks. An example is that about half of the radioisotope thermoelectric generators (RTGs) have been removed or will be so in the near future. Another example is that 164 of 198 obsolete nuclear submarines have been defueled and dismantled and that this work continues. Substantial progress has also been made in improving the physical and legal infrastructure to manage spent nuclear fuel and radioactive waste at sites in the Arctic, notably Andreeva Bay and Gremikha. Plans for dealing with nuclear icebreakers and their associated facilities are in place, where the very poor condition of the *Lepse* storage vessel remains a major problem. As part of the international effort, Russia has decided on a strategic plan that spans the time necessary to decommission and remediate all facilities.

New potential risks include Russian plans for building floating nuclear power plants and the possibility of increased marine transport of radioactive material in the Arctic.

The scope of this assessment is wider than previous AMAP assessments of radioactivity in the Arctic. New issues include an initial review of technologically enhanced naturally occurring radioactive material (TENORM) in the Arctic. TENORM can become concentrated in connection with the mining of uranium and other minerals, phosphate production, oil- and gas extraction, coal mining and the use of geothermal energy. Several of these activities are likely to increase in the Arctic. The current and potential impacts have not yet been fully assessed.

Another new issue is climate change, where there are major uncertainties about how this will affect radiation exposure conditions in the Arctic. Identified potential impacts include mobilization of natural and artificial radioactivity in the Arctic tundra environment and in glaciers. Climate change is likely to affect radon emission from the ground, which is the major contributor of exposure of people to radiation. Changes in permafrost, erosion, precipitation and extreme weather events may affect infrastructure related to nuclear activities and will require further assessments. Changes in ocean circulation and in the sea ice may affect the pathways of contaminants in the marine environment.

Previous radioactivity assessments have focused on human health. This assessment also describes a framework for assessing the impact of radiation on vegetation, animals and ecosystems, to be used in the larger context of environmental protection and management. Work on protection of the environment from radioactive substances is in progress and highlights the need for more data that are relevant for Arctic conditions and species.

Background scientific documentation for this report

Persistent Organic Pollutants:

The following review articles, constituting the 2009 AMAP assessment of Persistent Organic Pollutants in the Arctic are being submitted for publication in a Special Issue of the Science of the Total Environment:

Bidleman, T.F., P.A. Helm, B. Braune and G.W. Gabrielsen. Polychlorinated Naphthalenes in Polar Environments - A Review.

Butt, C.M., U. Berger, R. Bossi and G.T. Tomy. Levels and Trends of Perfluorinated Compounds in the Arctic Environment.

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Sources of photography in this report

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Rune Dietz (rdi@dmu.dk) – cover.

Polar bears tranquilized during tagging operations in East Greenland, 2008.

Lisa Harding, National Science Foundation (<http://photolibrary.usap.gov>) – page 10.

The waste barn at McMurdo Station is where the station's refuse is collected, sorted and prepared for shipment off the continent. The US Antarctic Program recycles approximately 65% of its waste.

Maja Kirkegaard (mki@dmu.dk) – page 31.

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Open-burning of rubbish at Resolute, Arctic Canada.

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