UNDERSTANDING ARCTIC MARINE POLLUTION[1]

By

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[1] [1] The content of this paper is the responsibility of the author(s) and does not necessarily represent the views of the PAME Working Group as a whole, or it's member countries.

Preface

This document has been prepared as an informal contribution to the Arctic Council's *Workshop in Support of the Preparation of the Arctic Marine Strategic Plan, Reykjavik, October, 2003.*

It has been produced at the request of the AMAP Board, and with the assistance of Canada. The AMAP Board would like to acknowledge, with appreciation, the work of Jason Stow (DIAND, Canada) in drafting this document.

The document itself is based mainly on the information presented in the 1997 and 2002 AMAP assessments of the State of the Arctic Environment with respect to pollution issues. The documented is intended to accurately reflect the findings of the AMAP assessments, but is not a product of the AMAP Working Group and does not, therefore, necessarily reflect the views of the AMAP Working Group.

Introduction

The state of the Arctic environment is influenced by contaminants that are transported from sources outside the Arctic and to a lesser extent within the circumpolar region. Of particular concern is evidence of elevated levels of exposure in humans through the consumption of marine mammals as part of a traditional diet. The purpose of this background paper is to describe where the contaminants of concern are coming from (sources); how they get into and behave in the Arctic marine environment (pathways); how contaminants behave in Arctic marine ecosystems and what effects they have on biota; the levels of contaminants that Arctic peoples are being exposed to and the potential health risks; and finally, how climate variability and global climate change might affect contaminant pathways in the future.

Background

Contaminants in the Arctic generally fall into one of the following categories:

- Persistent Organic Pollutants (POPs) including pesticides, industrial chemicals, byproducts of incineration and byproducts of chemical processes;
- Heavy metals of which the highest priority is placed on mercury, cadmium and lead;
- Artificial radionuclides that have been released to the environment through nuclear weapons testing, nuclear fuel reprocessing, radioactive waste disposal and accidents; and,
- Polycyclic aromatic hydrocarbons (PAHs) including components of petroleum and byproducts of combustion.

Most of these contaminants originate in agricultural and industrial regions of the planet where they are emitted/discharged from various sources onto the ground surface, to the air, or to water. Once released into the local environment they eventually make their way into the atmosphere, rivers and oceans. As a result atmospheric and ocean currents that carry air and water around the world also carry a burden of contaminants that were picked up along the way. As these global currents of air and water move into the Arctic they bring with them their burden of contaminants to which Arctic ecosystems are exposed. In essence, much Arctic contamination is a reflection of worldwide contaminant emissions into the global atmospheric and ocean reservoirs.

The information contained in this paper has been drawn from: AMAP assessment reports (AMAP 1998, 2002, 2003a, 2003b; and, Macdonald *et al*., 2003); Contaminants in the Arctic Marine Environment by Macdonald and Bewers (1996); and, Canadian Arctic Contaminants Assessment Reports (Jenson *et al*., 1997; Bidleman *et al*., 2003; and Fisk *et al*., 2003).

Contaminant Sources

Heavy metals

Fossil fuel combustion is the main source of anthropogenic mercury emissions accounting for approximately two thirds of the global budget. Fortunately these sources of mercury can be controlled with cleaner-burning power plants, emissions controls, and the use of fuels other than coal that contain less mercury. These types of measures have been taken in North America and Europe resulting in significant reductions in mercury emissions from these regions, however, expanding economies and power requirements in developing regions such as southeast Asia have resulted in increased use of coal. Consequently Asia now accounts for half of global mercury emissions, and half of that comes from China. Large Eurasian rivers, in particular the Ob, Lena, and Yenisey, have also been shown to be efficient carriers of mercury released in industrial effluent making them a minor (relative to the atmosphere) but still significant regional source to the Russian Arctic seas.

The majority of anthropogenic cadmium emitted to the atmosphere comes from the production of non ferrous metals such as zinc. Other sources include coal combustion, iron production, cement production, waste disposal and waste incineration. Anthropogenic sources of lead are similar to those of cadmium, however, the main source during the second half of the 20th century was the combustion of leaded gasoline. Fortunately a widespread ban of the additive tetraethyl lead has resulted in drastic reductions in lead emissions since the early 1980s. Leaded gasoline is, however, still used in some countries, including Russia. Lead and cadmium from industrial activity is either emitted to the atmosphere or released in wastewater. Large rivers can represent a significant source of industrially derived metal contamination to the Arctic marine environment. Another source of localized lead contamination comes from the use of lead shot, which accumulates in aquatic environments and is subsequently ingested by waterfowl. Most Arctic countries have banned the use of lead shot and are promoting the use of safer alternatives such as steel. Mining of lead rich deposits in the Arctic also results in the increased release of lead to the environment as indicated by elevated levels in local aquatic environments.

Heavy metals are naturally occurring elements in the Earth's crust and not all of what is measured in the environment is anthropogenically released. The majority of cadmium circulating in the Arctic seawater is considered to be natural. The largest source to the Arctic marine environment is derived from Pacific seawater that, due to natural geochemical distribution and processes, has cadmium levels that are five times those in the Atlantic. Mercury is also a naturally occurring metal whose concentrations in environmental media vary from place to place based on local geology. Natural biological processes have the ability to mobilize both cadmium and mercury thereby making it difficult to identify anthropogenic influences. Although an accurate estimate is difficult to make with much certainty, global budgets suggest that over half of the Hg presently cycling in the atmosphere and upper ocean derives from anthropogenic sources.

Persistent organic pollutants

Global inventories of POPs production, use and emissions, have recently been estimated with refined accuracy and have assisted with the identification of global source areas. To date global inventories have been created for PCBs, á- and â-HCH (Figure 1), DDT and to a certain extent, toxaphene all of which are either banned or have had their uses severely restricted. Even as these substances are gradually removed from use and production, however, soil residues from past applications have been shown to persist as active sources long after applications cease. It is estimated that soil residues were responsible for the emission of approximately 320t of toxaphene from US agricultural land in 2000, nearly 20 years after the substance had been banned. These inventories provide direct evidence of diminishing sources of previously-used POPs and also provide information on potential lingering sources. Many of the most prominently measured pesticides in the Arctic marine environment have now been largely banned, however, current-use pesticides are also being measured. The most commonly measured of these in-use pesticides are endosulfan and lindane (ã-HCH).

Some POPs, including polychlorinated dibenzo-p-dioxins and furans (PCDD/Fs) and hexachlorobenzene (HCB), as well as PAHs are produced as industrial by-products. PCDD/Fs are produced during waste incineration and other combustion processes, metallurgical industries and chlorine bleaching in pulp and paper production. Hexachlorobenzene is a common biproduct in the production of chlorine and chlorinated organic chemicals such as pesticides. A recent review of emissions by UNEP found that between Japan, Canada, the USA and northern Europe, Japan and the USA were the largest producers of PCDD/Fs accounting for several kilograms of TEQ (a toxicity weighted measure of concentration for this mixture of chemicals). These incidental emissions can be reduced through optimizing combustion efficiencies and treatment of flue gasses. These same mitigative interventions will also result in reduced PAH emissions which are also produced during combustion processes.

Two relatively new classes of compounds, brominated flame retardants (BFRs) and perflourinated alkanes (PFAs), have widespread applications in many synthetic materials. Many plastics and foams contain BFRs to make them flame retardant, whereas PFOS, a well known PFA, was used in synthetic materials to make them stain resistant. Consequently these substances have made their way into homes, offices and vehicles worldwide. Since they were introduced to the commercial market, BFRs and PFAs have also found their way into the environment and have been repeatedly measured in Arctic media. While it is relatively easy too identify where these chemicals are produced, and in what quantities, identifying which products contain BFRs and what the actual sources to the environment are is significantly more difficult. The disposal and potential incineration of materials containing these contaminants are potential sources to aquatic ecosystems and the atmosphere. An additional concern associated with incineration is the production of brominated byproducts including polybrominated dibenzo-p-dioxins and furans.

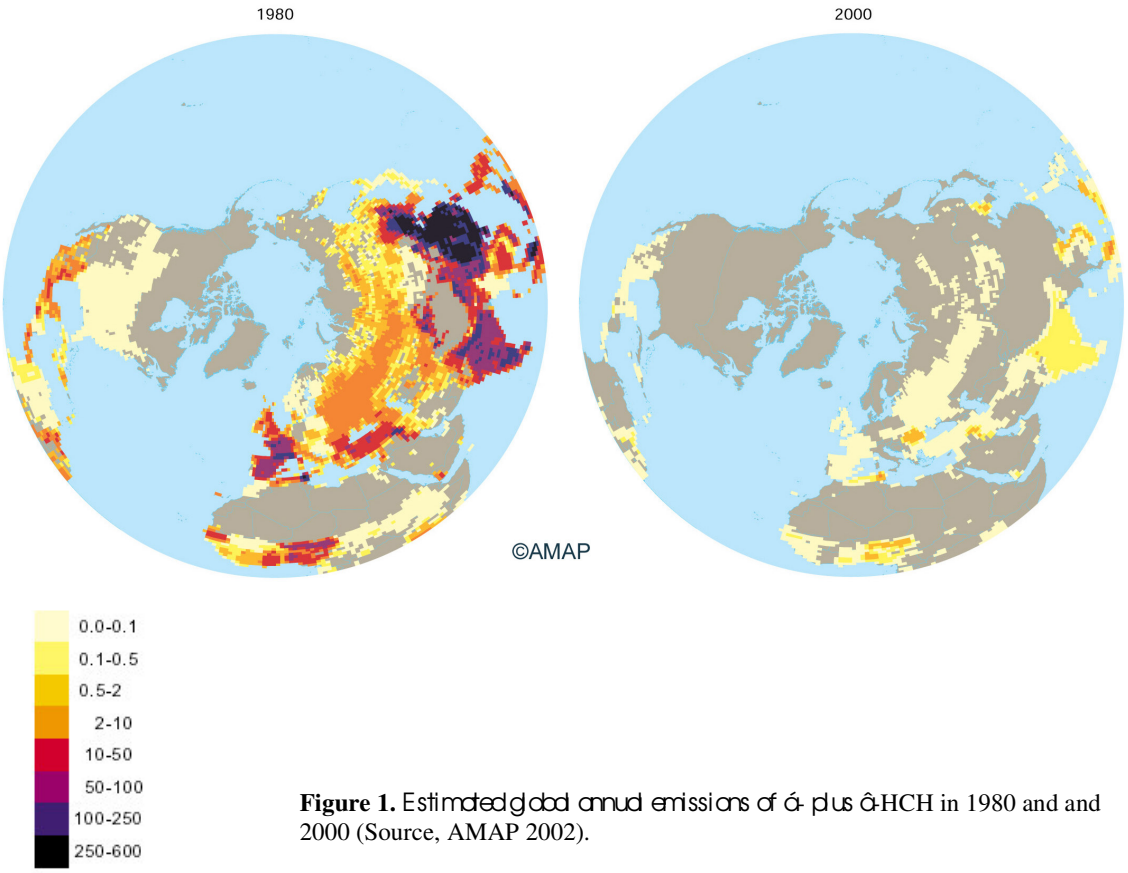

Figure 1. Estimated global annual emissions of á- plus â-HCH in 1980 and and 2000 (Source, AMAP 2002).

Polychorinated naphthalenes (PCNs) were produced as bi-products of PCBs and have recently emerged as a contaminant of concern. Some PCNs have been found to exhibit dioxin like toxicity. Similarly short chain chlorinated paraffins (SCCPs), a current use chemical used as a cutting oil in machining, have been measured in the Arctic.

Sources of contaminants within the Arctic consist primarily of abandoned and existing industrial complexes, mine and exploration sites, disposal facilities, military installations and commercial harbours. Many of these sites represent sources of PCBs that were used in electrical equipment and often disposed of directly onto the ground. Harbours and abandoned military installations provide examples of Arctic sources of PCBs. Documented cases exist for harbours in Russia and Norway as well as military installations in Greenland, Canada and Alaska.

Radionuclides

Radionuclides from fallout following atmospheric weapons testing conducted between 1945 and 1980 has been a major source of radioactive material to the Arctic. Nuclear accidents such as Chernobyl have also represented sources of radionuclides to parts of the Arctic.

Nuclear weapons testing has historically been the greatest source of global environmental radionuclide contamination, particularly cesium-137. With a half-life of only 30 years, and a global ban on nuclear weapons testing, however, levels of cesium-137 are now decreasing noticeably. Nuclear weapons test sites in the Arctic continue to represent local sources of radionuclide contamination. Two such sites are located at Novaya Zemlya in the Kola Sea and at Amchitka Island, Alaska.

Nuclear fuel reprocessing plants at Sellafield and Cap de la Hague have been discharging radionuclide contaminated wastewater since the early 1950s. Historically the most abundant radionuclide in reprocessing plant effluent has been cesium-137 and the greatest source has been Sellafield. The bulk of radionuclide discharge from Sellafield occurred throughout the 1970s and tailed off in the early 1980s. In 1994, British Nuclear Fuels started to treat a backlog of waste at Sellafield employing an Enhanced Actinoid Removal Plant. This process has proven effective at removing a number of radionuclides but is unable to capture technetium-99, a long lived fission product with a half live of 213 000 years. Consequently, in the 1990s technetium-99 discharge rates returned to levels similar to those that occurred in the 1970s. Similarly a new processing plant installed at Cap de la Hague in 1990 has resulted in the increased discharge of iodine-129, also a long lived fission product ($t_{1/2}$ = 16 000 000 years). Both radionuclides are water soluble and capable of long range transport via ocean currents. Monitoring of seawater has already shown increased concentrations of technetium-99 in seawater off the Norwegian coast and in the southern Barents Sea and a corresponding increase in Fucus seaweed. At current levels in seawater, radionuclides from these sources do not appear to present a radiological concern to marine biota.

In the past, these plants, Sellafield in particular, have also been sources of cesium-137 and isotopes of plutonium which resulted in contamination of sediments in the Irish and North Seas. Contaminated sediment in these Seas, as well as in the Baltic and Barents Seas, now appear to be acting as sources of cesium-137 and plutonium through sediment remobilization. These secondary sources of radionuclides will persist despite efforts to reduce primary releases.

There are other civilian and military facilities around the Arctic that may contain radioactive materials and therefore could become sources of radionuclides in the future. Unfortunately there is continuing uncertainty about the amount of such material present at a number of identified sources, as there is with the number of yet unidentified potential sources. This uncertainty is perpetuated by difficulties in accessing information about civilian and military sources. Russia is currently in the process of decommissioning its fleet of aging nuclear submarines and producing stockpiles of waste in the process. Many of the existing storage facilities are in poor condition and are contributing to localized radionuclide contamination that could be spreading into the adjacent marine environment.

Documented cases of submarine accidents and past dumping activities raise concerns for potential leaks into the marine environment. To date these sites appear to have only resulted in localized contamination of relatively insoluble and particle reactive isotopes like plutonium that settle close to the point of release. More soluble isotopes like cesium-137 would dissolve and be carried off by ocean currents. Another example of local contamination following an accident involving nuclear material is that which resulted from the 1968 crash of a US bomber near Thule Greenland, where contaminated marine sediments are estimated to contain 2.5-3 kg of plutonium.

Contaminant Pathways

Contaminants may enter the Arctic marine environment through any of the five physical modes of entry described by Macdonald and Bewers (1996): (1) inflowing ocean currents, (2) deposition from the atmosphere, (3) northward flowing rivers, (4) direct runoff from the land, and (5) direct disposal into the ocean. Some of these pathways are illustrated in Figure 2. The AMAP assessments have also identified biological contaminant transport (e.g. contaminants carried by migratory species) as an additional route of contaminant entry into the Arctic.

The Atlantic and Pacific oceans are huge receiving environments for pollutants deposited into them both diffusely, through long range atmospheric transport, and directly from rivers and large population centres that dominate coastal areas. The world's two largest oceans are also the only two that exchange seawater, and thus contaminants, with the Arctic Ocean. Table 1, provides a water budget for the top 200m of the Arctic Ocean that is useful for assessing incoming and outgoing transport of waterborne contaminants. North flowing rivers also have the capacity to carry contaminants from inland sources to the Arctic Ocean. Rivers basins that encompass large amounts of agricultural and industrial activity, particularly in Eurasia, have been shown to carry a significant amount of contamination.

Table 1. Simplified water budget for the top 200m of the Arctic Ocean. Total water import/export is estimated at 4.86 ± 1.3 Sverdrups ($1Sv = 10^6 m^3 s^{-1}$) and the corresponding mean residence time is estimated at 12.5 ± 3.3 years.

Import	Export
80% - North Atlantic seawater through Fram Strait and the Barents Sea	61% - to the North Atlantic through Fram Strait and the Barents Sea
16.5% - North Pacific seawater through Bering Strait	36% - to the North Atlantic through the Canadian Archipelago
2.3% - rivers	3% - ice export into the Atlantic
1.2% - precipitation, and ice import through Bering Strait	

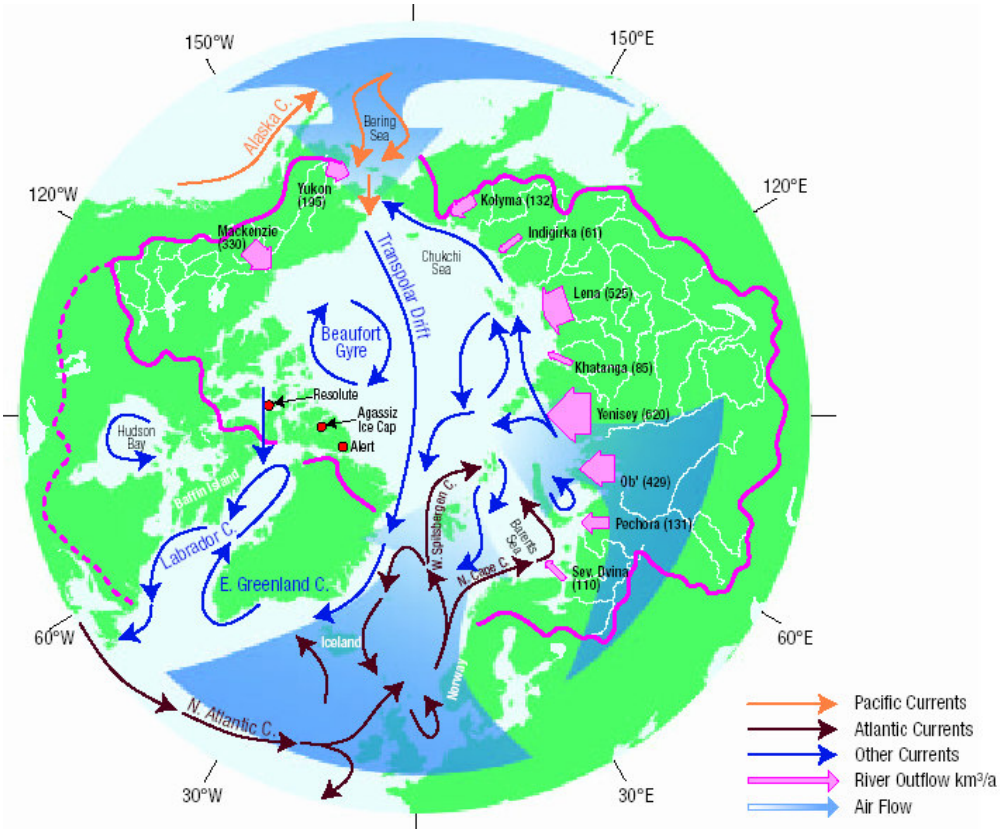

Figure 2. The major physical pathways (wind, ocean currents and rivers) that transport contaminants to the Arctic (Source, Bidleman *et al*., 2003).

Air currents that transport large masses of air from southern latitudes into the Arctic vary from season to season. In winter, the Arctic atmosphere is influenced primarily from Eurasian air masses whereas in the summer air delivery is primarily from the North Pacific and North Atlantic. Air currents are capable of transporting contaminants from industrial centres in North America, Europe, and Asia, to the Arctic in a matter of days, whereas ocean currents may take years.

Contaminant properties and transport pathways

The overriding criterion for any substance to be suitable for long range transport is that it be recalcitrant enough to make the journey and then persist in the Arctic receiving environment. The persistence of a chemical reflects its susceptibility to degradation through chemical or biological reactions. The very presence in the Arctic, far from potential sources, is one of the strongest pieces of evidence a chemical is indeed 'persistent'.

If this criterion is satisfied, a contaminant may be delivered to the Arctic marine environment by a combination of the following steps: first a substance must make it into the transport media at the source - air, river water, or seawater; then it must undergo long range transport to the Arctic via one or a combination of these media; over the Arctic substances transported through the atmosphere can be deposited directly to the ocean, to sea ice, or to terrestrial surfaces from which they may subsequently get washed into the ocean.

Once a contaminant is emitted to the receiving environment, its physicochemical properties will play a major role in determining its environmental fate. The physicochemical properties that are most important in describing a contaminant's behaviour in the environment are volatility, solubility and partitioning between particle bound, dissolved and gaseous phases.

Throughout the journey to the Arctic contaminants pass between phases according to their partitioning characteristics. In the atmosphere a certain proportion of a contaminant will be in each of the gaseous, particle bound and dissolved phases. Within the atmosphere and under relatively dry conditions a contaminant like HCH remains primarily in the gaseous phase, whereas PCBs will generally partition to particles. When water droplets are present HCHs will then partition strongly to the dissolved phase which is the reason why precipitation (as rain, snow or fog) has the ability to 'scavenge' HCHs from the air. Water droplets are also relatively efficient at scavenging particles and therefore particle-bound contaminants, like PCBs, can also be removed from the atmosphere by rain. These two types of partitioning are also responsible for direct air/water interaction at the ocean surface, and air/solid interactions on the surfaces of soil and vegetation. As with raindrops and particulate material, HCHs are more susceptible than PCBs to direct exchange with surface seawater, whereas PCBs partition strongly onto soil and vegetation. These mechanisms can remove contaminants from the atmosphere and deposit them on the land or in the ocean along the way to the Arctic. If a contaminant is deposited to the ocean, either particulate bound or dissolved, it may then continue its journey to the Arctic via northward flowing ocean currents. A volatile or semi-volatile contaminant deposited on land, however, may either be re-emitted to the atmosphere so that it may take another 'hop' towards the Arctic or become washed into a river that drains into the Arctic Ocean. The Arctic may become a 'cold trap' for such volatile or semi -volatile compounds.

Contaminants that partition too strongly to sediments or soil surfaces, may be effectively immobilized and unavailable for transport to the Arctic via the atmosphere. Some of these, however, may still ultimately complete the journey via the ocean. Contaminants that do not partition at all to the dissolved or particulate bound phase, but, for example remain in a gaseous state, may be transported to the Arctic only to be transported out of the region again without ever being deposited.

Contaminants that enter the ocean, either directly or from the atmosphere, are also subject to partitioning between dissolved, particle bound and gaseous phases. In surface water, contaminants like HCHs, are exchanged back and forth between air and water with the net transport direction depending on conditions. When technical HCH was still in widespread use (1940s-1980s), the atmosphere was continuously being supplied with fresh HCHs and the atmosphere subsequently supplied the ocean. Since technical HCHs have been banned, however, the atmospheric concentration of alpha-HCH dropped precipitously with the result that the net movement of HCH is now out of the water and back into the air. This example demonstrates how the oceans can become the long-term reservoir for contaminants that favor partitioning to water. Alternatively, solid media such as sediment and soil are the ultimate reservoirs for contaminants that partition preferentially to the particle bound phase. Particulate bound contaminants, such as PCBs, can be exchanged in small amounts with air and water thereby providing a long-term source to the other environmental media. Contaminated sediments are subject to chemical reactions, resuspension and uptake by benthic organisms and can become long term sources of contaminants directly to the marine environment.

Under current conditions, examples of substances that can make the journey to the Arctic by both atmospheric and oceanic pathways but for which the atmosphere is favoured include mercury, the lighter PCDD/Fs, intermediate PCBs, DDE, and HCBs. Those substances that are more likely to arrive in the Arctic dissolved in seawater include HCHs (especially β-HCH), and many other pesticides, certain radionuclides, including technecium-99 iodine-129, and cesium-137 and metals such as Cd. Finally, contaminants that tend to be tightly bound to particulates, including lead, perhalogenated aromatic hydrocarbons such as octachlorodibenzo-p-dioxin, decabromodiphenyl ether and decachlorobiphenyl also reach the Arctic via both the air and the ocean. Transport pathways can, however, change over time. Lead from vehicle emissions was initially widely distributed across the Arctic by atmospheric transport, but this pathway is less important since the introduction of lead free gasoline. Lead that entered the marine environment, however, continues to reach the Arctic Ocean through a slower aquatic pathway, coming up from the North Atlantic.

Contaminants are removed from the Arctic marine environment by outflowing seawater and ice, volatilization, sedimentation, and microbial degradation. The first of these mechanisms simply refers

to the physical transport of a contaminant from one water body to another and while this may remove the contaminant from the Arctic marine environment, the contaminant subsequently becomes the problem of the Atlantic. Sedimentation may remove contaminants from the marine environment, however, contaminants may still be taken up by benthic organisms and thereby enter the food web. Sedimentation tends to be a more important removal pathway for highly persistent lipophylic contaminants such as PCBs. Microbial degradation and chemical hydrolysis can be efficient means of removing some contaminants like the HCHs from the Arctic marine environment. Volatilization may also play a role in exporting contaminants from surface seawater. This mechanism is particularly important during the summer when significant portions of the Arctic seas are free of ice. At these times surface water has an opportunity to 'exhale' certain contaminants that may have built up during the long ice-covered season. Under permanent ice cover of the central Arctic Ocean this export pathway is essentially blocked. It should also be noted, however, that other contaminant levels, like PCBs, build up during the open water season and slowly decline under ice-cover due to particulate scavenging.

Hexachlorocyclohexanes – an illustrative case study

Hexachlorocyclohexanes (HCHs) are a good example of contaminants that are transported to the Arctic by both ocean and atmospheric currents. A large proportion of global emission of technical HCH, which contains three prominent isomers, á-, â-, and ã-HCH, has come from use in Asia. Once emitted to the atmosphere in Asia, HCHs begin to drift across the Pacific with the prevailing winds. During this journey over the Pacific, some of the HCH is washed out of the air by rain over the North Pacific Ocean. Ocean currents then take over and slowly deliver a portion of this HCH to the Arctic through the Bering Strait while the remainder of the airborne contaminant completes the journey in the atmosphere. Each HCH isomer possesses different physicochemical properties that have a strong influence on transport. In 1980, when technical HCH was still being used in SE Asia, monitoring data demonstrated that approximately equal amounts of á-HCH were delivered to the Arctic via the atmosphere and through the Bering Strait. In the same year, however, 80% of ß-HCH, which partitions 20 times more from air into water than á-HCH, was delivered through the Bering Strait, demonstrating how ocean currents can at times be the most important delivery mechanism for some of the more soluble POPs. Unfortunately, for the most persistent of these chemicals, the Pacific and Atlantic Oceans may represent a lasting source long after atmospheric emissions have been eliminated. Similar HCH monitoring data were collected again in 1995, following a dramatic decrease in global use of technical HCH. These data showed that relative to the Bering Strait, the atmosphere accounted for less than 10% and 2% of á- and ß-HCH delivery. This result reflected drastic reductions that have recently been made in Asian atmospheric emissions of technical HCH as well as a longer- lasting reservoir that remains in the Pacific Ocean.

A mass balance for the upper 200 m of the Arctic Ocean (Table 2), for conditions typical of the 1990s, illustrates the relative importance for various import and export pathways for á- and ã-HCH. The large net export of á-HCH (-369t) likely reflects the drastic decline in global use of technical HCH whereas the small net input of ã-HCH (+2t) may reflect continued use of lindane. The mass balance also illustrates the relative importance of ocean currents and rivers as sources of the largely banned and still-used substances as well as the importance of microbial degradation as a removal pathway.

Table 2. Mass balance for á- and ã-HCH in the upper 200m of the Arctic Ocean

á-HCH		ã-HCH	
Import - 186t	Export - 555t	Import - 81t	Export – 79t
58% - ocean currents 29% - atmospheric deposition 13% - rivers	49% - ocean currents 43% - microbial degradation 7% - volatilization 1% - ice export	39% - ocean currents 12% - atmospheric deposition 49% - rivers	58% - ocean currents 34% - microbial degradation 7% - volatilization 1% - ice export

Trends in air, freshwater sediments and glacial ice as indicators of atmospheric sources to the marine environment

Air

One of the best indicators of current sources of contaminants to the Arctic marine environment is the atmosphere. Collection of atmospheric contaminant data over the past 10 years has provided excellent data for the interpretation of recent temporal trends of contaminants in Arctic air. The Arctic air monitoring network covers most the Arctic including stations at Pt. Barrow (Alaska), Tagish, Alert and Kinngait in the Canadian Arctic; Ny-Ålesund (Svalbard), Stórhöfdi (Iceland) and Pallas (Finland) in the European Arctic; and, Amderma and Dunai in the Russian Arctic. Data have thus been collected at numerous locations, though not over the entire ten years at all sites.

Over the past ten years, trends in atmospheric concentrations of most legacy POPs, including those that are largely no longer used, appear to be relatively stable. Temporal trend data collected at Alert, for which the largest data set exists, indicate that levels of some contaminants, such as PAHs, HCHs, lower chlorinated PCBs, and chlordanes, are slowly declining whereas current use substances such as endosulfan are actually increasing in Arctic air. Examination of isomeric ratios of chlordane and DDT/DDE indicate periodic episodes when a relatively non-degraded source is influencing Arctic air implying fresh application in Russia and southeast Asia. Similarly peak measurements of HCHs in air over the North American Arctic have been associated with air masses originating over southeast Asia. In general, contaminant concentrations in air are much higher at stations closer to industrial centres than at the more remote Arctic locations. It is also likely that the major reductions in air concentrations of several POPs occurred soon after the introduction of bans and controls in the 1970s, before air monitoring for these contaminants in the Arctic was established. These Arctic stations, however, have the potential to play a significant role in tracking future trends in both 'legacy' and 'current use' POPs.

Several new contaminants recently identified in Arctic air samples include current use pesticides (endosulfan, methoxychlor, trifluralin, and pentachloroanisole), industrial by-products (trichloroveratrole, tetrachloroveratrole, and octachlorostyrene), chlroinated naphthalenes, polybrominated dephenyl ethers (PBDEs), and short-chain chlorinated paraffins (SCCPs).

Heavy metal concentrations in air have also been monitored over the past 10 years. Results of these measurements suggest relatively stable concentrations of cadmium in Arctic air but indicate declining levels of atmospheric lead. From data collected during the past 5 years, atmospheric mercury appears to be relatively stable from year to year with no discernable trend. Continuous atmospheric monitoring of mercury at Alert, however, did lead to the discovery of a phenomenon known as spring-time mercury depletion events. These events occur with polar sunrise. In a combination of chemical reactions involving solar radiation, ozone and seawater-derived halogens (most likely bromine), gaseous elemental mercury (Hg^0) is converted to a reactive gaseous species (Hg^{2+}) which is readily deposited onto Arctic surfaces. During these events atmospheric levels of elemental mercury may decrease by over an order of magnitude within a day. The conversion to reactive gaseous mercury and the subsequent deposition have been shown, at times, to result in 2-20 fold increases in mercury concentrations in freshly fallen snow. It appears that much of the deposited mercury is re-emitted to the air in the hours following a depletion event, however, a gradual build-up of mercury in snow over the spring period has also been demonstrated (Figure 3). This pathway is of great significance due to the potential for mercury to be carried by snow melt into marine and aquatic environments where it is biologically transformed into methyl mercury which is the toxic and bioaccumulative form that is found at elevated concentrations in marine mammals. There is still much to learn about this relatively new discovery and the potential implications for uptake and accumulation of mercury in the Arctic marine ecosystem.

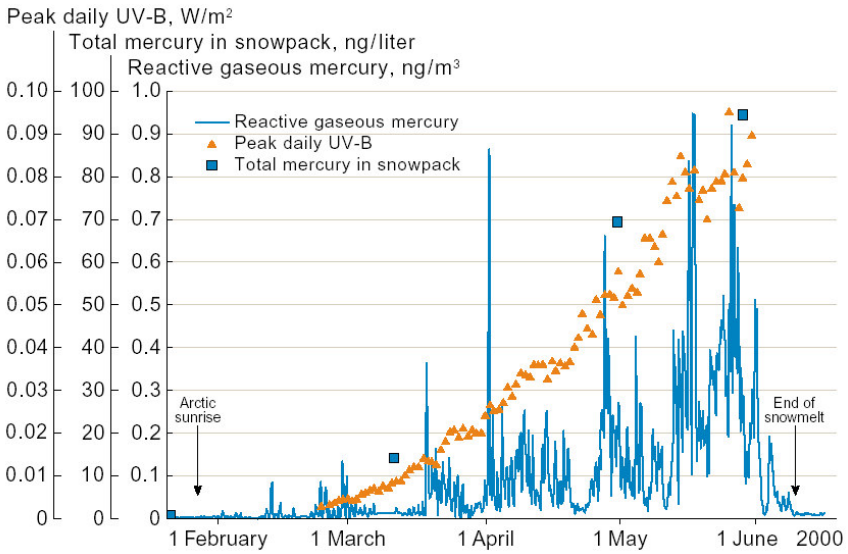

Figure 3. Production of reactive gaseous mercury at Barrow, Alaska, starts as UV-radiation increases following polar sunrise, and ends at snowmelt. Total mercury in the surface snow pack also increases over this period (Source, AMAP 2002).

Lake sediments, ice cores and peat bogs

Abiotic media that have been used to assess long term trends in contaminant deposition in the Arctic include dated cores collected from glacial ice, lake sediments and peat bogs. Data gathered from ice and sediment cores demonstrate that the levels of POPs generally reflect historical information on their production and use. For most POPs, the highest levels in the cores were found below the surface in layers that corresponded with past years of peak use. For example DDT levels in an ice core collected from the Lomonosovfonna Ice Cap on Svalbard suggested DDT deposition likely peaked before the 1970s and since then has been declining. Similar trends were observed in sediment cores collected in lakes from the Canadian Arctic. The historical record for lead measured in lake sediment and glacial ice cores (Figure 4) clearly reflects the rise in lead deposition associated with the use of leaded gasoline followed by a dramatic decrease in deposition between the 1980s and 2000. Lead concentrations measured in surface layers of ice and sediment now appear to be similar to pre-industrial levels. There is a relatively consistent set of sediment core data suggesting mercury deposition in the Arctic has increased by two to three fold since pre-industrial times, in some regions. Some remote lakes in the North American Arctic that are relatively far from industrial centres do not show this trend, though it is quite consistent in other circumpolar regions.

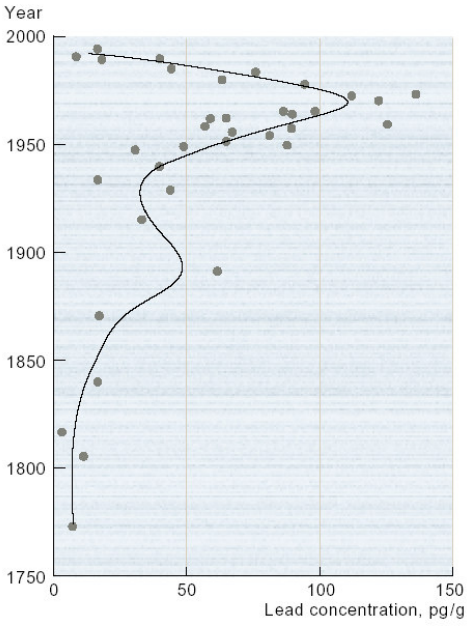

Figure 4. Lead concentrations in a Greenland ice core show increases during the industrial period, but decreases since the early 1970s when unleaded gasoline was introduced in North America (Source, AMAP 2002).

POPs in seawater

The most commonly measured contaminants in Arctic seawater, and the most abundant, are the HCHs. Alpha-HCH is by far the most abundant HCH isomer followed by γ-HCH and β-HCH. Unlike most contaminants α-HCH concentrations in the Arctic marine environment have at times been higher than in temperate oceans near their points of release. In general ΣHCH concentrations in surface seawater are lowest in the Greenland and Norwegian seas, higher in the central Arctic Ocean and highest in the Beaufort Sea and Canadian Archipelago. This geographic trend reflects the major inputs of HCHs from Asian sources carried by trans-Pacific air currents and Pacific seawater inflow through the Bering Strait and the outflow of Arctic seawater through the Canadian Archipelago. Data collected from the 1970s to the mid 1990s in the Bering and Chukchi seas indicates declining concentrations for α- and γ-HCH for the period however, concentrations of β-HCH have remained relatively stable.

Polychlorinated biphenyls were the second most commonly measured and abundant contaminant group in Arctic seawater. Measuring PCBs in seawater has, however, proven to be rather problematic owing to their relatively low concentrations and to difficulties with sample contamination from shipboard sources. Consequently it appears that sampling methods have had a profound influence on many of the results gathered during various shipboard sampling expeditions. For example, measurements that made use of ultra-clean techniques produced results for PCB concentrations in seawater that were ten times lower than measurements made using less rigorous techniques. The reason for the difference appears to be sample contamination from shipboard sources of PCBs. Due to these difficulties some past measures of PCBs in seawater may be overestimated.

Measurements of POPs in seawater demonstrate the importance of the oceans as long-term reservoirs and transport media for some of these contaminants. In certain instances, an examination of contaminant signatures (congener patterns or rations of certain isomers) can help identify fresh or weathered sources. By doing this researchers have found evidence of land-based sources of PCB in seawater originating from the North Pacific and flowing through the Bering Strait. Similarly fresh sources of toxaphene were found in seawater from the White Sea, potentially reflective of recent use in Russia.

Behaviour of POPs in Arctic marine food chains

Once in the Arctic marine environment, contaminants get taken up by the food web through processes of bioconcentration, bioaccumulation, and biomagnification. Bioconcentration describes the process whereby contaminants enter an organism directly from the water through cell membranes (diffusion) and concentrate to levels that can far exceed the concentration in the water. This process is particularly important for the phytoplankton and zooplankton that make up the base of the food web. At higher trophic levels the most important route of uptake is ingestion of contaminated prey. Once the contaminant has been ingested the only way an individual can get rid of it is through excretion or metabolism. If the rate of contaminant ingestion exceeds the rate of excretion and metabolism then the contaminant accumulates over time. This process is called bioaccumulation and explains how longer lived species can achieve high concentrations of POPs over a lifetime of exposure. Biomagnification describes how the burden of contaminants is passed from prey to predator resulting in increasing tissue concentrations with each step in the foodchain. Biomagnification up a food chain can lead to concentration increases of up to 10^7 -10^9 from water to apex feeders.

At the base of the food chain plankton absorb contaminants directly from the water column. The efficiency with which plankton adsorb contaminants depends on partitioning between the aqueous phase (seawater) and the organic phase (biological tissue). Partitioning between seawater and plankton can be extremely efficient for POPs resulting in concentrations in plankton that are three to seven orders of magnitude higher than concentrations in water. Bioconcentration over several orders of magnitude between seawater and the zooplankton Calanus (copepod) is shown for several POPs (HCHs, PCBs, chlordane and DDTs) in Figure 5. While bioconcentration likely explains the majority

of the contaminant uptake by the copepods, some bioaccumulation may also be responsible for the observed contaminant concentrations.

Invertebrates

Levels of POPs (quantified as contaminant group totals, eg. ÓHCHs, ÓPCBs, ÓDDTs and Óchlordanes) in Arctic marine invertebrates are generally quite low. In herbivorous copepods, levels are in the low single digit ng/g ww range. For higher trophic level invertebrates, those that prey on other zooplankton or scavenge on the carcasses of other animals, levels of various POPs groups can be significantly higher with concentrations in the range of 5 - 50 ng/g ww. In general POPs concentrations in invertebrates are higher in the North American Arctic seas than they are in the European and Russian Arctic seas.

Blue mussels are a benthic species widely used for monitoring POPs around the world. In the Arctic POPs concentrations are uniformly low and similar if not slightly higher than levels found in herbivorous zooplankton. The detection of elevated concentrations of PCBs in blue mussel has been an effective tool for identifying potential local sources of PCBs from military sites in the Aleutian Islands. Local sources have also been found to influence invertebrate POPs concentrations near Svalbard and in the vicinity of some communities in the Canadian Arctic.

Marine Fish

In general POPs concentrations in most Arctic marine fish are also considered quite low. Arctic cod provide an important monitoring species because it represents the link from benthic invertebrates to marine mammals and Arctic seabirds. In Arctic cod PCBs are the most abundant POPs followed by DDTs and HCHs with concentrations in the 1-25 ng/g ww range. Arctic cod from the North American Arctic generally have higher POPs concentrations than those from other Arctic locations which is consistent with geographic trends in zooplankton. Sea-run Arctic char muscle (including skin) from the Canadian Arctic, an important subsistence species for Inuit, displayed concentrations similar to Arctic cod for most POPs but generally had higher concentrations of PCBs, in the 10 - 50 ng/g ww range, potentially due to higher lipid content or trophic position.

Large, long-lived, predatory fish can accumulate much higher concentrations of POPs than other fish species. Greenland shark have concentrations of some POPs that are comparable to levels seen in apex feeders such as polar bears and scavenging seabirds. Concentrations of DDT measured in Greenland shark livers from Davis Strait and Cumberland Sound were in the thousands of ng/g range and are among the highest ever measured in Canadian Arctic biota.

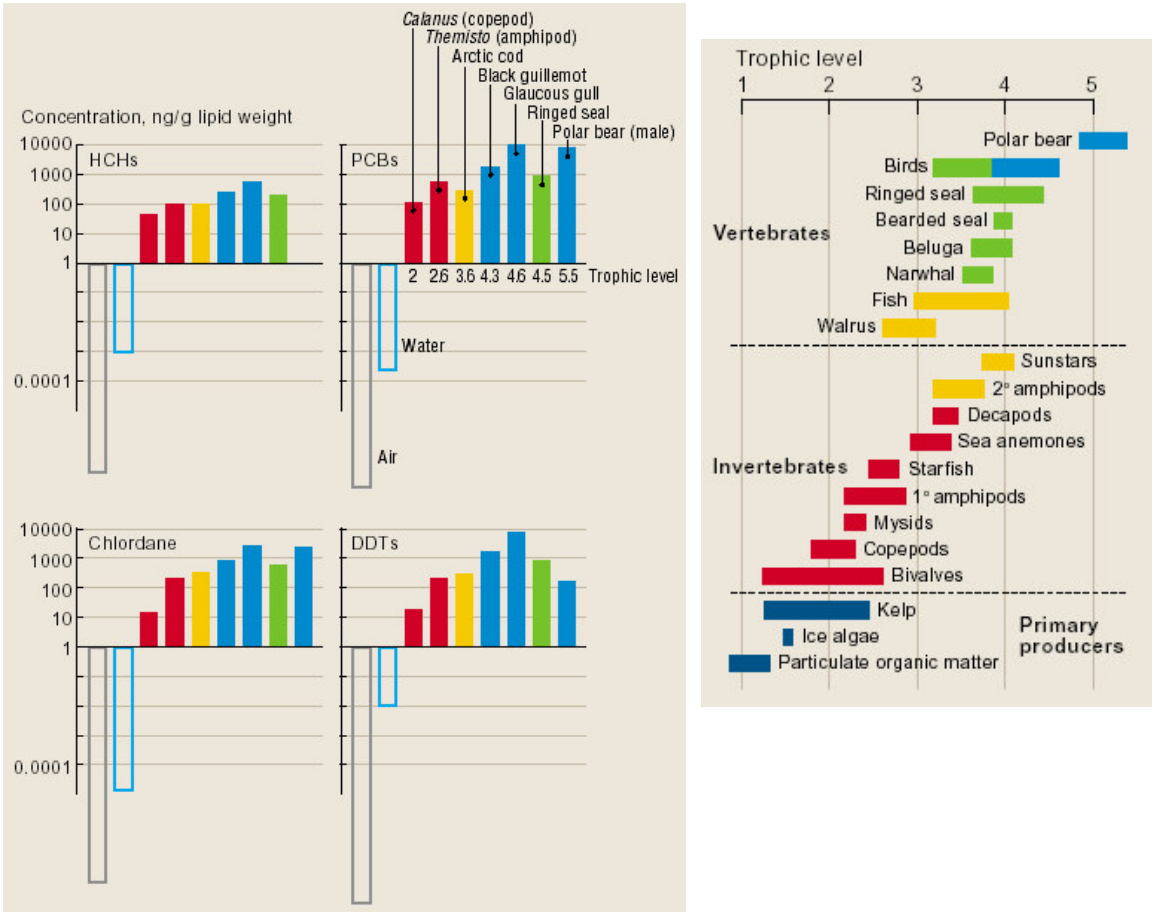

Figure 5. The marine food web structure observed during the North-water project. Shown in the panels (left) are average concentrations of selected contaminants in air, water and biota at various trophic levels (Source, AMAP 2002).

Seabirds

Arctic seabirds have been very useful for monitoring POPs in the Arctic marine environment. The level of contamination in Arctic seabirds varies greatly from one species to another depending primarily on dietary and migratory habits. Lower concentrations are generally found in diving alcids such as guillemots, murres and dovekies, where levels of POPs measured in the liver are in the 10 - 500 ng/g ww range for PCBs, DDT and chlordane, and in the 1-10 ng/g range for HCH, and HCB. Species with the highest concentrations of POPs are glaucous gulls, great skua and great black-backed gulls all of which scavenge and prey on other seabirds and occasionally the carcasses of marine mammals. Chlordanes, DDT and PCBs are measured in the 50 - 5000 ng/g ww range in livers of scavenging seabirds, levels for HCHs and HCB are in the 1 - 50 ng/g ww range. In general concentrations of most POPs were highest in seabirds from the Barents Sea and lowest in the North American Arctic, with groups differing by over two orders of magnitude for PCBs and DDTs. The exception to this trend was HCHs for which higher concentrations were found in the North American Arctic as a result of relatively recent use and long-range transport from Asian sources.

Temporal trends of POPs in archived egg and liver samples from birds collected between 1975 and 1998 on Prince Leopold Island in the Canadian Arctic demonstrate decreasing trends for PCBs and DDTs in black legged kittiwakes, northern fulmar and thick billed murres (Figure 6). An increasing trend was observed for â-HCH which, despite a dramatic decrease in emissions of technical HCH, is still being delivered to the Arctic in seawater.

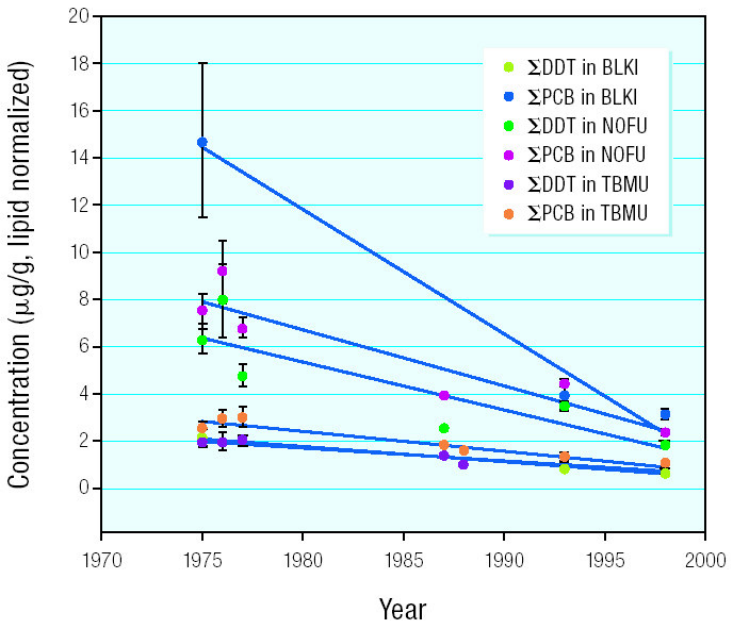

Figure 6. Concentrations of • PCBs and • DDTs in seabird eggs from Prince Leopold Island, Canada. BLKI = black legged kittiwake, NOFU = northern fulmar and TBMU = thick billed murre (Source, Fisk *et al*., 2003).

The most commonly measured new contaminant in seabirds was the brominated flame retardants PBDEs which were generally measured at higher levels in birds from the European Arctic than in Canadian birds, which had 1-10 ng/g ww levels in eggs and livers. PBDEs concentrations rose in Canadian seabirds between 1975 and 1993.

Pinnipeds

Ringed seal are the most abundant and widely distributed seal species in the Arctic and have been commonly used to monitor levels of POPs in marine mammals. They are also a very important source of traditional food to indigenous Arctic peoples. In general ΣPCB and ΣDDT concentrations ranged from about 500 - 5000 ng/g ww in ringed seal blubber. Concentrations of Σchlordanes ranged from 100 - 1500 ng/g ww and ΣHCHs from 50 - 500 ng/g ww. Total toxaphene concentrations range from 50 - 500 ng/g ww in ringed seal blubber. With the exception of HCHs, POPs concentrations were highest in seals from the Eurasian Arctic seas and lowest in the Chukchi and Beaufort seas. Potential sources of POPs in Russian rivers and other industrial sources may be responsible for the elevated levels seen in Eurasian seals. HCH concentrations were highest near the inflow from the Bering Strait.

Stellar's sealions from the Eastern Aleutian Islands in Alaska had elevated levels of ΣPCBs and ΣDDTs in their scat indicating potential local sources to the region, possibly from remote military stations as was suggested for elevated concentrations in blue mussels from the same region. Walrus are typically benthic feeders and as such an important indicator species for benthic based food webs, however, it has been shown that certain groups of walrus occasionally prey on ringed seals as well. This difference in feeding habits can result in levels of POPs being an order of magnitude higher, or more, in seal-eating walrus than in those that do not eat seal.

Based on ringed seal data corresponding to the early 1970s, early 1980s, mid 1990s and late 1990s, levels of ΣPCBs and ΣDDTs appear to have significantly decreased and current chemical signatures reflect weathered, not fresh sources. Total chlordane levels did not appear to change although the signature appears to be more weathered. The ratio of â-HCH: ΣHCH rose by 400% between the 1970s and the late 1990s reflecting the sharp decline in technical HCH use and the slower oceanic delivery and greater persistence of â-HCH.

Polybrominated diphenyl ethers have displayed an exponential rise in the blubber of ringed seals from the Holman region of Canada. Concentrations of ΣPBDEs have increased from levels that were less than 1 ng/g lw in 1981 to levels exceeding 4 ng/g lw in 2000 (Figure 7). Based on these trends, concentrations appear to be increasing at a doubling rate (t_2) of 4-5 years.

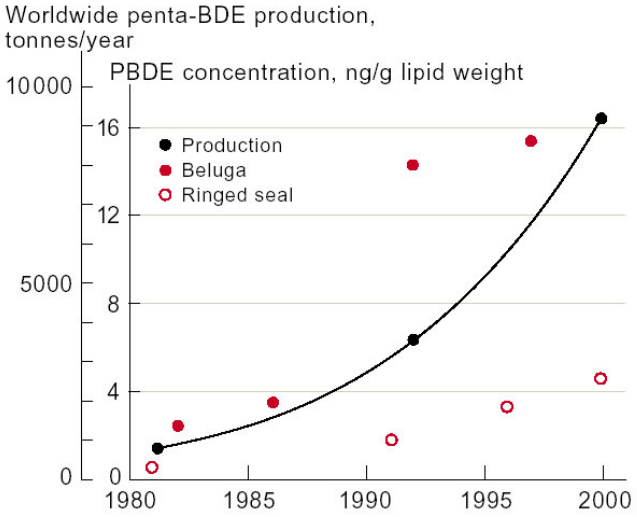

Figure 7. Comparison of temporal trends of PBDEs in ringed seal and beluga in the Canadian Arctic with estimated global production of penta-BDE over the same period (Source, AMAP 2002).

Perfluorooctane sulphonate (PFOS), a stain resistant additive used in the production of synthetic materials, has been measured in the liver and/or blood of ringed seal from Cumberland Sound, Canada, and Svalbard, Norway, as well as northern fur seal from the Bering Sea. Other new contaminants that have been measured in Arctic seals or other marine mammals include, short-chain chlorinated paraffins (SCCPs), polychlorinated naphthalenes (PCNs), and tris(4-chlorophenyl) methanol (TCPM-OH).

Whales

Several species of baleen and toothed whales have been assessed for POPs contamination in the Arctic marine environment. As predicted by a lower trophic position, baleen whales, which feed primarily on invertebrates and small fish, have lower concentrations of POPs than toothed whales. Minke whales, a common baleen whale in the North Atlantic and European Arctic, generally have blubber levels of ΣDDTs in the 500 - 2000 ng/g ww range and ΣPCBs in the 1000- 4000 ng/g ww range. In general, there is a slight increasing trend in concentrations of ΣPCBs and ΣDDTs from Greenland in the west to the Barents Sea in the east. Concentrations of POPs in blubber of grey whales from the Bering Sea and bowhead whales from the Beaufort Sea appear to be relatively low compared to minke whales from the North Atlantic.

Concentrations of POPs in blubber of beluga and narwhal, common toothed whales and important traditional food species for Inuit, range from 1000 - 5000 ng/g ww for both ΣDDTs and ΣPCBs. Concentrations of Σchlordanes in beluga and narwhal blubber range from 500 - 4000 ng/g ww. Concentrations of Σtoxaphene are in the same range as ΣDDTs and ΣPCBs but can actually be even higher with levels in excess of 10 000 ng/g ww. Concentrations of ΣHCHs and Σchlorobenzenes are relatively low in beluga and narwhal blubber, with concentrations ranging from 100-500 ng/g ww. In general the lowest concentrations of POPs in beluga blubber are found in southern Alaska and off the west coast of Greenland whereas higher concentrations are found in whales from Svalbard and in the North American Arctic.

Long finned pilot whales from the Faroe Islands had higher concentrations of ΣPCBs than most other toothed whales in the Arctic. Possible contamination from local sources in Norway may be contributing the levels in the Norwegian porpoises. Butyltin compounds used as antifouling agents have been measured in several species of marine mammal including harbour porpoises. Concentrations of butyltins appear to be highest in the vicinity of active harbours, such as the west coast of Norway. Since several European countries restricted the use of tributyltin as an antifouling agent in the late 1980s, concentrations in marine mammals near Norway appear to have declined significantly.

Concentrations of POPs in beluga blubber that was collected from Cumberland Sound, Canada, between 1982 and 1997 demonstrated a significant decreasing trend for á-HCH, but no discernable trends for â- or ã-HCH. While total DDT concentrations showed no discernable trend, the ratio of DDE:DDT indicated an increasingly weathered source. Total chlordane concentrations increased slightly in beluga blubber whereas no clear trend was evident for Σtoxaphene. Temporal trends in PCB concentrations examined on a congener basis indicated that dioxin like congeners had decreased by margins of 1.7-2.6 fold, however, total concentrations for the hexa- and heptachlorobiphenyl groups did not show significant change. Concentrations of endosulfan sulphate, a metabolite of the current use pesticide endosulfan doubled over the 15 year period as did tetracholorobenzene. Hexachlorobenzene levels appeared to decrease for the first ten years but then rose thereafter and dieldrin concentrations decreased significantly. Narwhal from the Canadian Arctic exhibited similar trends for ΣPCBs, ΣDDTs, Σchlordanes and Σtoxaphenes, whereas ΣHCH levels showed not discernible trend.

Polybrominated diphenyl ethers have been measured in beluga, long-finned pilot whales and minke whales. Concentrations of ΣPBDEs are in the 10 - 20 ng/g ww range in blubber of Canadian Arctic beluga, whereas concentrations closer to 100 ng/g ww were detected in beluga blubber from the Svalbard area. The highest concentrations of ΣPBDEs were measured in blubber of long-finned pilot whale from the Faroe Islands, where concentrations ranged from 144 - 1620 ng/g ww. So far there is insufficient data to explore possible explanations for the interspecies and geographic differences that have been observed. Over the fifteen year study of temporal trends in Canadian beluga blubber, PBDEs showed a dramatic rise with increases of 6.5-fold for the most prominent PBDE congenger, BDE47 (2,2',4,4'tetrabromodiphenylether). This trend is similar to those observed in ringed seal (Figure 7) and seabirds from the Canadian Arctic. Levels of penta-BDEs appear to have peaked in the Baltic Sea and recent trends are now showing declining levels, possibly in response to penta-BDE products having been withdrawn from European markets. Penta-BDEs are still widely used in North America.

Polar bear

Polar bears represent the top predator in the Arctic marine ecosystem and feed primarily on ringed seals, but may also feed on other seal species such as harp and bearded seals. Polar bears are also known to preferentially consume the fat of the seal, which also contains the highest concentrations of POPs. The most prominent POPs in polar bear fat are PCBs followed by chlordanes, DDTs and HCHs. Total PCBs can range in concentration from low thousands to high tens of thousand of ng/g ww in polar bear fat. Total chlordanes and ΣDDTs range from mid hundreds to low thousands of ng/g fat whereas ΣHCHs are generally in the low hundreds of ng/g fat. The highest concentrations of HCHs were found in the fat of polar bears from the Bering and Chukchi Seas, reflecting the dominant Asian source of HCHs being transported to the Arctic through the Bering Strait. In general levels of PCBs, chlordanes and DDTs in polar bears are highest in the Russian Arctic, near Franz Josef Land and the Kara Sea, lower around Svalbard and East Greenland and lowest in the Bering and Chukchi Seas and the Canadian Arctic.

One of the most prominent new contaminants measured in polar bear is PFOS. In liver samples from Alaskan polar bears PFOS levels were high enough to make it one of the most prominent POPs. Polybrominated diphenyl ethers have also been measured in polar bear fat.

Temporal trends of POPs in polar bears from Hudson Bay show recent (1991-1999) declines in concentrations of HCB, á-HCH, and ÓPCBs, but no significant change in levels of Óchlordanes, ÓDDTs, dieldrin, á-HCH or total HCHs. Despite a lack of change in recent times, ÓDDT levels declined dramatically in Hudson Bay polar bears between 1968 and 1999, likely owing to a cessation of use in local communities and at a military base. Concentrations of ÓPCBs were just as high in the 1990s as they were in the 1960s. Concentrations of ÓPCBs in polar bears from Svalbard actually declined in the early 1990s, although levels have recently levelled off and appear to be stable. One hypothesis for the relatively stable concentrations of ÓPCBs is that they are more or less at a steady state with respect to global distribution and that future declines, particularly in the Arctic will be slow. In contrast to the Hudson Bay polar bears, â-HCH concentrations decreased in Svalbard bears.

Biological Effects of POPs

The risk of biological effects due to the presence of a contaminant can be assessed as a combination of exposure and the toxic potential of the contaminant. The previous section considers the level of exposures Arctic marine species are experiencing for a variety of POPs. In this section the toxic potential of various POPs and the potential risks they pose to highly exposed biota are discussed. Biological effects can also be measured through toxicological assessments. A number of Arctic marine organisms have been the subject of toxicological study and some of the finding from these studies will also be presented.

Persistent organic pollutants can affect biological function in a number of ways to produce toxic effects. Some of the main biological systems that can be affected by POPs include the immune, reproductive, nervous, and endocrine (hormone) systems. Each of these systems is thought to be most sensitive to contaminant related interference during developmental stages of life. It is also during these developmental stages that high levels of POPs are passed from mother to offspring. Seabirds pass on high doses of POPs to their lipid-rich eggs where they are incorporated into the developing embryo. Mammals also pass on high doses of POPs to their developing fetus as well as young through lipid-rich breast milk. This passage of POPs from mother to young actually results in a net decrease in contaminant burden for the mother, but can result in dangerously high levels of exposure to the developing offspring. It is during these early life stages that an organism is thought to be most at risk.

Biological effects can occur, and be measured, at various levels of biological organization. Biomarker studies can measure contaminant related changes in the levels of key biochemicals (eg. thyroid hormone) that may have implications for a variety of biological functions. Alternatively studies may examine more overt signs of toxicity such as the incidence of gross deformities, hatching success or offspring survival. Studies that examine toxic effects across a broad range of exposures may develop thresholds for toxicity that are specific to a certain combination of contaminant, effect and species. Toxicity thresholds that are useful for assessing risk include no observable effects levels (NOELs) and low observable effects levels (LOELs). These thresholds are statistically determined levels of exposure at which a certain contaminant has no adverse effects (NOEL) on a given organism, or has some adverse effects (LOEL) on the organism. In general exposure levels below the NOEL are considered relatively safe, whereas exposure at levels exceeding the LOEL are considered risky. Unfortunately there have been relatively few studies carried out on Arctic marine species. It is therefore necessary to make very uncertain extrapolations of risk from toxicity thresholds developed for similar species.

Invertebrates and fish

Since the levels of exposure for marine fish and invertebrates are relatively low, the probability of adverse effects in these lower trophic level organisms seems to be low with a couple of exceptions. Comparison with existing thresholds for fish toxicity support this assertion. While the majority of Arctic marine fish and invertebrates themselves do not appear to be at risk of adverse effects, most do exceed guidelines designed to protect the health of fish eating wildlife.

One possible exception may be the Greenland shark that, through a diet including marine mammals, has been exposed to contaminant levels similar to other top marine predators. Despite the elevated level of exposures measured in Greenland shark, the risk of adverse effects is still not considered to be major.

Dog whelks, a common marine invertebrate appear to be very sensitive to low levels of tributyltin (TBT). Dog whelks exposed to TBT develop imposex, a condition that renders the whelk sterile. Imposex has been observed among exposed dog whelk populations in harbours in West Greenland, Iceland, northern Norway, the Faroe Islands and Svalbard. A significant reduction in the incidence of imposex has been observed in Norwegian and Icelandic harbours since restrictions on TBT were introduced in 1996.

Seabirds

There have been numerous studies of contaminant related toxic effects on wild seabirds that are relatively well suited to comparisons with Arctic species. Many of these studies have taken place on the North American Great lakes where seabirds have been exposed to many of the same POPs that are present in the Arctic marine environment. Figure 8 provides a simple comparison of PCB exposure in Arctic birds and a number of toxicity benchmarks that have been determined for similar species. The rising levels of new contaminants like PBDEs, that appear to have similar toxic characteristics to legacy POPs, are cause for concern. Since these POPs are relatively new, toxicity thresholds have yet to be determined for many avian species. It is important to note that each of the thresholds presented in Figure 8 relates to lethal endpoints. There are a variety of sub-lethal endpoints, such as immune suppression, that could also seriously compromise long term survival and which could be induced at lower levels of exposure. Caution must also be exercised when applying single contaminant thresholds to organisms that are exposed to multiple contaminants. The cumulative effects of multiple contaminants are not very well understood, however, it seems likely to result in increased risk. Other environmental factors that may put stress on wildlife are also likely to increase overall health risks when combined with contaminant related effects.

Clearly there are a number of Arctic birds being exposed to levels of PCBs that exceed existing thresholds of effects for other species. Among the most highly exposed, and consequently those that are most at risk, are the scavenging seabirds and birds of prey. In general, sea ducks (eg. eiders) and alcids (eg. guillemots, dovekies, murres) that feed lower in the food chain do not have levels of exposure that exceed applicable thresholds.

This assessment of risk seems to be reflected in field studies that have been carried out on Arctic seabirds. Such studies have demonstrated a variety of effects associated with POPs exposure including: egg shell thinning and reduced hatching success in peregrine falcons; reduced reproductive success in Alaskan bald eagles; behavioral alterations, poor body conditions of chicks, suppressed immune systems, decreased hatching success and decreased probability of adult survival in glaucous gulls; and decreased hatchling weight and vitamin-A levels in Shag.

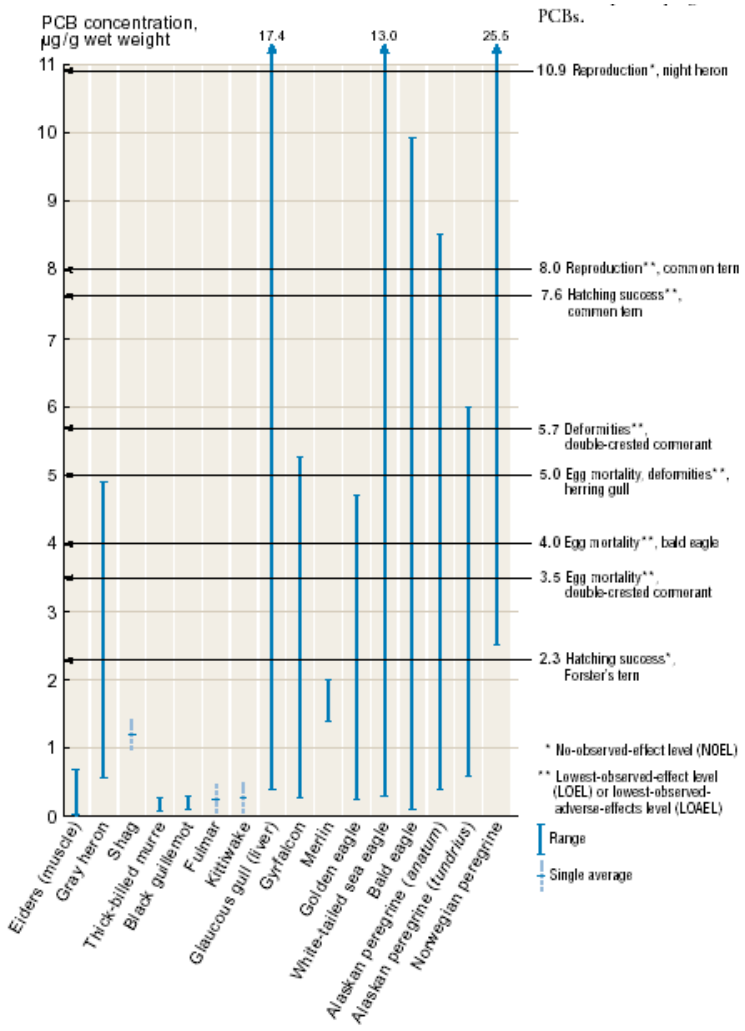

Figure 8. Comparison of measured tissue PCB concentrations in Arctic birds and toxicity benchmarks measured in other avian species (Source, AMAP 2002).

Pinnepeds

Very few toxicological studies have been carried out on marine mammals, let alone Arctic marine mammals, although there are a few. Figure 9 provides a comparison for PCB exposure in various Arctic marine mammals to available toxicity thresholds for mammals. Contaminant levels in several species of seal, including ringed seal, harbour seal and grey seal, generally have levels of exposure at which subtle neurobehavioural effects may be a possibility. In regions with higher levels of exposure there may also be concern from effects on vitamin A levels, immune function and possibly reproduction. PCB exposures among seal-eating walrus may be high enough, when compared to

threshold toxicity levels, to cause subtle neurological effects and for the most highly exposed individuals, potentially immune suppression. These comparisons must be used cautiously, however, since extrapolation of toxic effects between species is problematic.

Whales

For most species of Arctic toothed whale, minke whales and some grey whales, levels of PCB exposure are high enough to indicate risks of subtle neurobehavioural effects, as well as effects on reproduction and vitamin A metabolism. For more highly exposed populations, such as harbour porpoises from northern Norway, some resident killer whales, and all transient killer whales from Alaska, and some long-finned pilot whales from the Faroe Islands, there may also be a risk of adverse affects on immune function and reproduction. With the exception of those mentioned above, baleen whales generally have levels of POPs exposure that are below thresholds for effects.

Polar Bears

Concerns of adverse biological effects in polar bears have long been a concern owing to their extremely high levels of exposure to POPs. There is also concern for Arctic fox that have similar levels of POPs due to a diet that includes remnants of polar bear kills. Previous assessment of health risks to polar bears were all based on toxicity thresholds determined for other species and single contaminant toxicity and did not provide an accurate enough assessment of potential risks.

Norwegian and Canadian scientists have teamed up to investigate POPs related effects in polar bears at Svalbard, Norway and Hudson Bay, Canada. Observations of cub survival between the more highly exposed Svalbard bears and those from Hudson Bay suggested that an unusual number of Svalbard bears were not surviving and that the female reproductive cycle at Svalbard was shorter than normal. These results, however, could have been attributed to other factors unrelated to contaminants. In a study of Canadian bears, it was demonstrated that contaminant concentrations in polar bear milk from mothers whose cubs eventually died were consistently higher than in mothers whose cubs survived. High levels of PCB exposure were associated with lower levels of testosterone, thyroid hormone and vitamin A, although the biological significance of the altered levels was unknown. In another study high levels of PCBs were correlated with suppressed immune function, an effect that could put the health of the bears at risk. The results of these studies in combination with comparisons to established toxicity thresholds provide further evidence that polar bears throughout the Arctic are likely at risk of subtle neurobehavioral effects and alteration of vitamin A stasis. At several sites in Alaska, Canada, East Greenland, Svalbard, and Russia, exposures may be high enough to have reproductive effects. In the most highly exposed populations, near Svalbard, Frans Josef Land, and the Kara Sea there may also be risks of immune suppression.

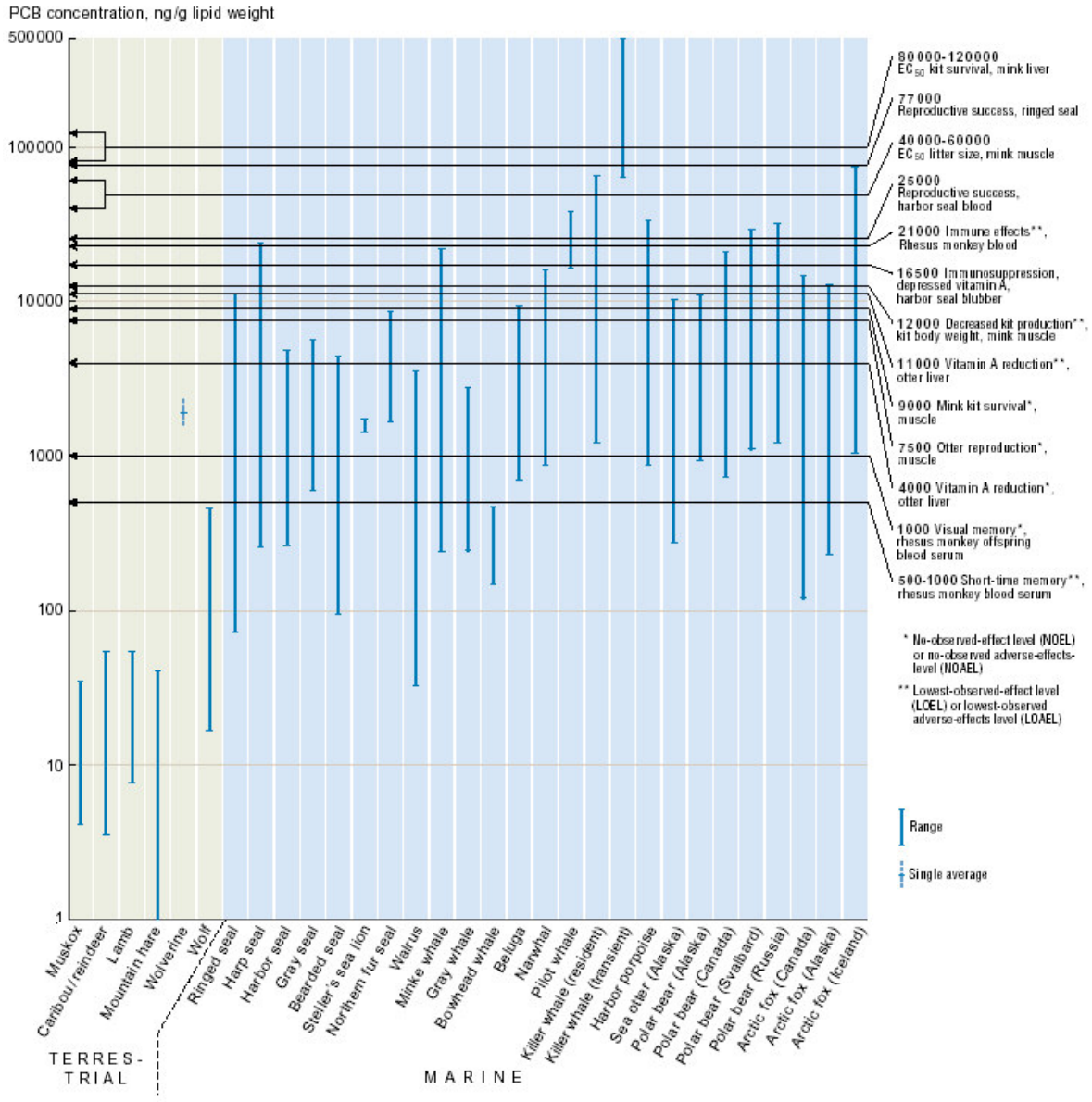

Figure 9. Comparison of measured tissue PCB concentrations in Arctic mammals and toxicity benchmarks measured in other mammalian species (Source, AMAP 2002).

Lead, Cadmium and Mercury in seawater

AMAP 1997 reported levels of lead in surface seawater that were estimated to be elevated by over an order of magnitude from pre-industrial times. This modern increase in ocean lead concentrations is almost entirely attributed to the atmospheric deposition of lead from the combustion of leaded gasoline. Since leaded gas is largely no longer used, atmospheric deposition of lead appears to have declined dramatically to near pre-industrial levels, as demonstrated in dated glacial ice core studies (Figure 4). Residence times for lead in the water column are thought to be short (<5 years) since lead is a relatively insoluble metal and likely to bind rapidly to particulate and settle to the bottom. Despite the short residence time however, lead may still be delivered to and within the Arctic on

ocean currents. Upon sedimentation, lead is not normally subject to recycling through the water column, however, sediment entrainment in ice can effectively transport particulate bound lead. Elevated levels of lead have been measured in near shore sea water close to mine sites. Seawater near mines in Greenland and Baffin Island can have levels of lead that are one to two orders of magnitude higher than background levels.

Unlike lead, cadmium is relatively water soluble and may cycle between particulate bound and dissolved phases. Cadmium follows a natural cycle of dissolution, biological assimilation and sedimentation. The geographic distribution of cadmium in the water column is therefore heavily influenced by natural processes such as primary production, mixing of water masses and coastal up welling. Since cadmium is a naturally occurring element with a variable geographic distribution, it is difficult to assess the relative input of anthropogenic and natural sources in the marine environment. The main source of cadmium to the Arctic seas is from the Pacific Ocean, which has natural levels of cadmium that are five times higher than in the Atlantic. Like lead, however, elevated levels of cadmium have been observed in seawater close to mines in both Greenland and Baffin Island. Past mining activity at the lead zinc mine at Nanisivik on Strathcona Sound, northern Baffin Island and at the Black Angel mine in northwest Greenland as well as a cryolite mine in Ivittuut South Greenland were documented in AMAP 1997 as the sources of localized marine lead and cadmium contamination.

Mercury is supplied to the ocean by direct air-seawater exchange with the atmosphere, including mercury depletion events, by precipitation scavenging, runoff and rivers. Once in seawater, elemental mercury may be removed by re-emission to the air under ice-free conditions or through particulate binding and sedimentation. Natural sources of mercury also contribute to that which reaches the Arctic marine environment through various pathways. Mercury also has the potential to be transformed into organic methyl mercury which is toxic and can be efficiently biomagnified in marine food chains. In general, methyl mercury accounts for less than 10% of mercury measured in seawater (AMAP 1997).

Behaviour of Pb, Cd, and Hg in Arctic marine food chains

The uptake, accumulation and toxicity of heavy metals in Arctic marine food chains depends largely on the chemical form of the metal. The chemical form, in large part, dictates bioavailability, which is the term used to describe the efficiency with which an organism can assimilate a substance. Metals in a bioavailable form are easily passed across biotic membranes and may be subject to bioconcentration. Similarly bioavailable metals that are ingested may also be adsorbed by the organism. If a metal is not in a bioavailable form it will not bioconcentrate and when ingested will simply be excreted.

Lead

Lead dissolved as Pb (II) is considered to be the most bioavailable form of lead and the form most likely to be absorbed by biota. In the marine environment, however, lead is typically found sorbed to particulate matter in a form that is not very bioavailable. As a result lead does not appear to accumulate in marine biota to any significant degree. Lead is also not subject to biomagnification, and is generally not considered a risk to ecosystem health. Exceptions may exist in areas close to local sources of lead contamination. Direct exposure by the consumption of lead shot is also a risk, particularly for some populations of seabirds.

The highest levels of biotic lead exposure are among avian species exposed to lead shot. Elevated concentrations of lead have been found in the blood of Stellar's eiders that breed in Alaska. Blood lead levels display an increasing trend over the summer suggesting exposure to lead shot which accumulates in shallow water bodies inhabited by the waterfowl.

Cadmium

Cadmium in the free ionic form (Cd (II)) is also the most bioavailable form of cadmium. Compared to lead, cadmium is relatively bioavailable in the marine environment and is subject to bioaccumulation and biomagnification in marine biota. Figure 10 illustrates cadmium pathways and biomagnification in an Arctic marine food chain. It can be seen from Figure 10 that cadmium does not biomagnify (biomagnification factor <1) between certain trophic levels, and certain species. Cadmium accumulates in internal organs rather than in muscle and fat. Over time the kidneys accumulate the highest concentrations of cadmium followed by the liver. Cadmium does bioaccumulate over time and therefore concentrations increase with age.

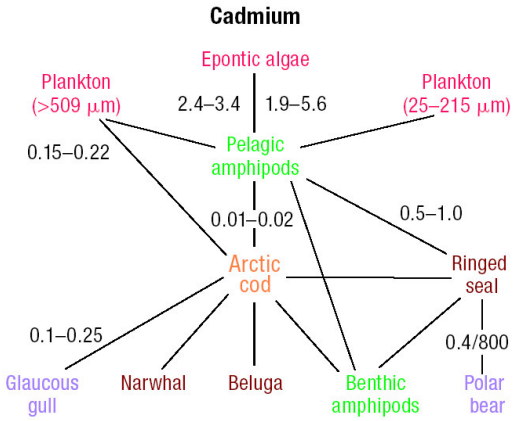

Figure 10. Biomagnification factors (BMFs) and pathways for cadmium in the Arctic marine food web (Source, Bidleman *et al*., 2003).

Little is known about what factors influence the distribution of cadmium in the Arctic seas, however, it appears that natural geochemical distribution and processes play a more important role than anthropogenic sources. Monitoring of Arctic marine biota has not revealed any discernable temporal trends in biotic cadmium levels. Walrus, sediment and mollusks from the Canadian Arctic suggest that levels of cadmium have not changed over the past few centuries, supporting the notion that natural sources are responsible for observed levels in marine biota. More recent trends also do not indicate any significant changes in levels in beluga and narwhal from the Canadian Arctic, mussels from Alaska, Greenland, Iceland and Norway, or sculpin from Greenland.

High exposure to cadmium has the potential to cause kidney and liver dysfunction. Laboratory studies have established toxicity thresholds for such effects, although these studies may not relate directly to Arctic species. In general, the levels of cadmium that have been measured in Arctic marine species do not appear to be above toxicity thresholds. Some seabird species may exceed thresholds for terrestrial birds, however, seabirds are known to be adapted to higher levels of cadmium found naturally in the marine environment and are therefore not considered to be as sensitive as terrestrial birds. Ringed seals from Greenland that display relatively high concentrations of cadmium in their kidneys did not display any signs of adverse effects.

Mercury

Methylmercury is thought to be the most bioavailable form of mercury, whereas most inorganic forms are not considered to as bioavailable. Methylmercury is created by the microbial methylation of inorganic mercury and is efficiently biomagnified in Arctic marine foodchains. Mercury concentrations measured in apex feeders, which is almost entirely in the methylated form, can be 1000-3000 times higher than concentrations in suspended particulate organic matter. Figure 11 illustrates mercury pathways and biomagnification in an Arctic marine food chain. Mercury is bioaccumulative and concentrates in liver and muscle tissue.

Mercury concentrations in Arctic marine fish are relatively low (tens of ng/g ww). In blue mussels and shorthorn sculpin, two species where sample collections are relatively well distributed, there was no discernable geographic trend.

Arctic seabirds generally have mercury concentrations in muscle that are over an order of magnitude higher than in fish (hundreds of ng/g ww). Concentrations of mercury in seabird livers can be in the high hundreds and low thousands of ng/g ww. As with POPs, mercury concentrations increase with trophic level and therefore scavenging seabirds like glaucous gulls tend to have higher levels than smaller species like dovekie. Examination of geographic trends indicates that levels are generally lower in seabirds from the Barents Sea than they are in birds from Greenland, the Canadian Arctic and northeastern Siberia. Faroese fulmars and black guillemots have levels comparable to the more contaminated Canadian fulmars and guillemots.

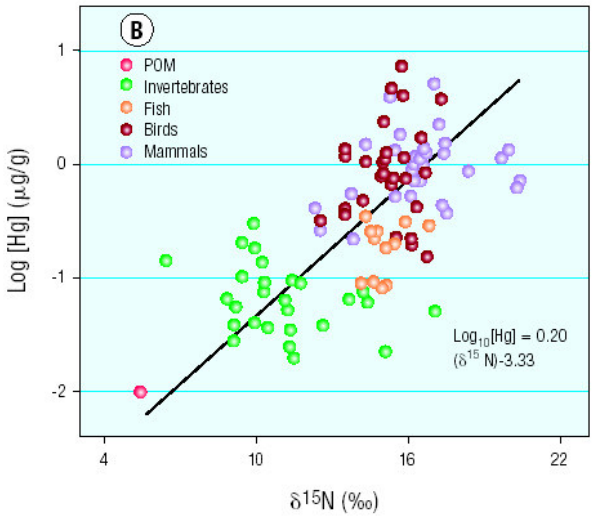

Figure 11. Biomagnification of mercury in an Arctic marine food chain (Source, Bidleman *et al.*, 2003).

Temporal trends data from archived seabird eggs collected from Prince Leopold Island in the Canadian Arctic exhibits general increasing mercury trends for northern fulmar and thick billed murre (Figure 12).

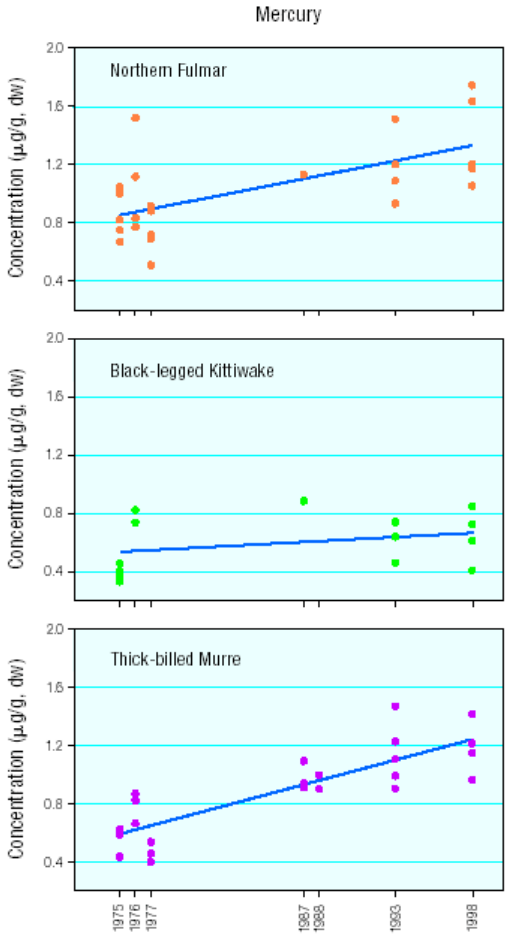

Figure 12. Concentrations of mercury in seabird eggs collected between 1975 and 1980 from Prince Leopold Island, Canada (Fisk *et al.*, 2003).

Levels in murres have nearly doubled since the mid 1970s, and have increased by 50% in Northern Fulmars. Mercury concentrations have been stable in black-legged kittiwakes over the same period of time. A possible explanation for the species related difference in trends may lie in differences in overwintering habitats. Black-legged kittiwakes winter in lower latitudes where mercury concentrations have generally been in decline in response to local source reduction efforts, whereas fulmars and murres winter in higher latitudes where mercury deposition appears to be rising. In migratory birds from the Eurasian Arctic the opposite trend has been observed where birds that winter in eastern Asia display higher concentrations of mercury than birds wintering elsewhere. There are numerous factors, however, that could play a role in determining mercury concentrations in seabirds. Some of these factors include food availability and feeding preferences and regional differences in geologic sources of mercury.

Some evidence suggests that mercury concentrations in ringed seals and beluga increase from east to west in the Canadian Arctic. Ringed seal data from four locations in the Canadian Arctic display differing temporal trends since the 1970s. Conclusions drawn from this data suggests that there is no discernable overall trend in ringed seal mercury levels but that other factors such as shifting dietary habits are likely

responsible for the temporal variation. Archaeological samples of teeth from Beaufort Sea beluga dated to the 15-17th century AD were compared to teeth from beluga that were harvested in the early 1990s. Results demonstrated an age dependent increase in mercury concentrations between the pre-industrial and modern samples. In 10-year old beluga the increase was about four-fold, whereas in 30-year old animals the increase was 17-fold. The magnified increase in older animals, and increases that are much larger than those observed in abiotic media, is due to the influence of biomagnification and bioaccumulation in older animals. Recent temporal trends in liver mercury concentrations of Canadian beluga have been observed over the past ten to 20 years. Observations suggest regional differences and indicate that whales residing near the outflow of major rivers have experienced recent increases, whereas whale residing in other locations have not. These data suggest that riverine input of mercury may have increased in recent years and may be an indication of climate related increases in the release of natural mercury. Increased biological activity and permafrost degradation have been identified as potential causes for increased mercury mobilization under the influence of global change.

Additional geographic trends data indicate that minke whales from around Jan Mayen and the North Sea have higher mercury concentration than whales from around Svalbard or West Greenland. Gray seals from the Faroe Islands display similar mercury concentrations as those from Sable Island, off the east coast of Nova Scotia, Canada, but higher than levels in seal from Jarfjord, Norway.

Polar Bear data indicates that concentrations in the northwestern Canadian Arctic are higher than in bears from southern, northeastern and eastern Greenland. There is insufficient data to establish temporal trends in polar bear mercury levels.

The toxicity of mercury is relatively well understood owing to a large number of published laboratory and field toxicity studies. In mammals, where there is the highest risk of effects in the Arctic, mercury is known to cause nerve and brain damage, particularly in the early life stages of development and may interfere with sperm production. Arctic seabirds may also be vulnerable to mercury related effects which can cause erratic behaviour, appetite suppression and weight loss. Lower levels of exposure may reduce the production and viability of eggs and decrease the probability of chick survival. Non-Arctic seabirds with accumulated exposure to mercury have shown signs of kidney damage. Toxicity thresholds have been established for a number of fish and animals, however, no such thresholds exist for Arctic marine species. Figure 13 compares exposure levels in the Arctic to some toxicity thresholds. Some polar bear, toothed whales, seals and walrus appear to exceed the threshold for liver damage in marine mammals, however, to date there have been no adverse effects, such as lesions or poor body condition, observed in these animals. The lack of toxicity thresholds specific to the most exposed Arctic species requires that the assessment of risk based on thresholds for other species be used with caution. The levels of mercury observed in the organs of some marine mammals and seabirds in the Arctic are still a cause for concern.

An examination of mercury distribution in beluga whales found that mercury accumulated in several body organs including brain and spinal cord. Only a small proportion of the mercury, however, was found to be toxic methylmercury. The results of mercury speciation suggested that the whales had the ability to demethylate, and thereby detoxify, mercury by transforming it into mercury selenide (an inert mineral form that combines mercury and selenium). The levels of total mercury that had been observed in some beluga from the Canadian Arctic are high enough to raise concerns over potential neurological effects. It is possible, however, that the whale's apparent ability to transform the toxic methylmercury to non-toxic mercury selenide may provide some natural level of protection. It is not known weather other animals, or even humans, possess similar abilities. It is suspected, however, that selenium may provide a potential mitigating influence over mercury toxicity in other species.

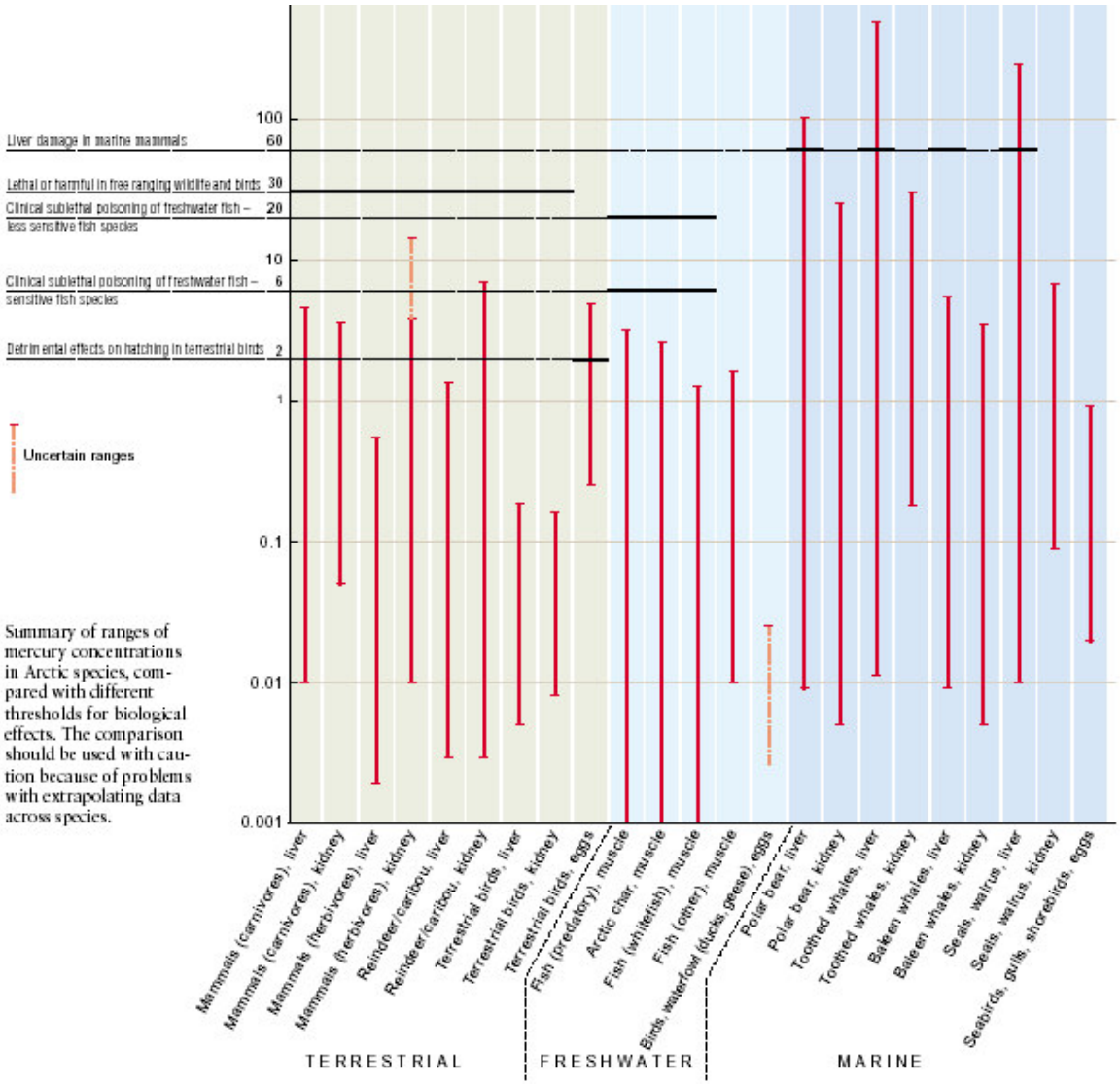

Figure 13. Comparison of measured tissue mercury concentrations in Arctic biota and toxicity benchmarks measured in other species (Source, AMAP 2002).

Human Health

Assessing human health effects related to Arctic pollution incorporates the same general components that were used for the assessment of biological effects. These include an assessment of contaminant exposure, a review of relevant guidelines and comparison to known levels of exposures and a review of epidemiological studies.

Dietary exposure

Since the most important source of contaminants to people in the Arctic is from the food they eat, contaminant exposures can be modeled by combining the results of dietary surveys and contaminant measurements in food items. To date surveys of traditional food consumption have been conducted among Inuit of Canada and Greenland, and Dene and Metis from Canada. Inuit from Canada and Greenland include a substantial amount of marine mammal tissues in their diet, whereas the traditional diet of Dene people contains primarily terrestrial and freshwater species. The difference in

contaminant exposure between populations that consume marine mammals and those that do not is will illustrated in the comparison of modeled contaminant exposure between Inuit and Dene from Canada. The five most popular food items for Baffin region Inuit, as determined by dietary questionnaires, include caribou, seal, char, narwhal and beluga, whereas the most popular food items among Dene are moose and caribou, and freshwater fish such as whitefish and lake trout. When data on contaminant levels in these food items, and others, are combined with estimates of average daily intakes for each population group, researchers are able to estimate daily contaminant exposures. Such calculations estimate Inuit exposures to POPs like chlordane and toxaphene are more than an order of magnitude higher than Dene exposure. Similarly, mercury exposures among Inuit are six times higher than among Dene. The difference in exposure is entirely due to Inuit consumption of marine mammals.

Dietary surveys have estimated that meat and blubber from seal, walrus, whale and polar bear can represent 20-28% of the energy intake of Inuit in the Baffin Region of Canada. The consumption of marine mammals also makes up a substantial portion of the diet among Greenland Inuit and in the Faroe Islands the meat and blubber from pilot whales are popular foods. While these foods provide tremendous nutritional benefits they also contribute the largest proportion of contaminant exposure. Based on the results of dietary surveys and biological monitoring of contaminant levels in country foods from southwest Greenland, it is estimated that over 95% of PCB exposure comes from the consumption of seal meat, blubber, kidney and liver as well as whale meat and blubber (figure 14). Seal blubber alone accounts for over 50% of PCB exposure among

Inuit of southwest Greenland. Similar estimates of dietary exposure to heavy metals also demonstrate how the consumption of marine mammal meat and organs contributes to elevated exposure to mercury and cadmium. It is interesting to note that a diet rich in marine mammals also leads to high exposure to selenium, an element thought to provide some protection against mercury toxicity. Mercury, cadmium and selenium exposure among Greenland and Canadian Inuit are an order of magnitude higher than for other populations that do not consume large amounts of marine mammal tissues.

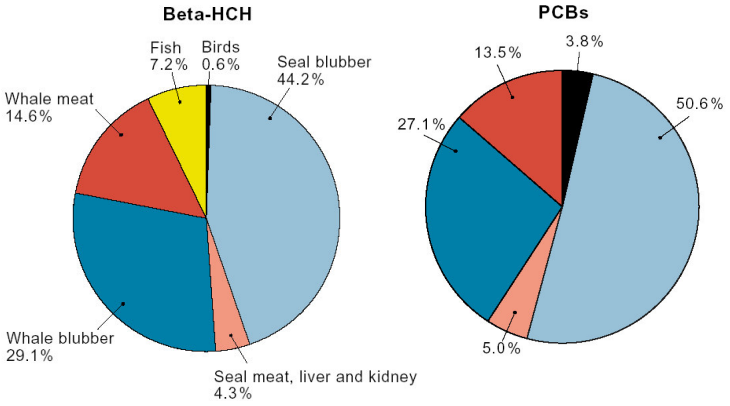

Figure 14. The contribution of different traditional foods to the dietary exposure of beta-HCH and PCBs among Inuit of Southwest Greenland (Source, AMAP 2003a)

Blood levels

Contaminant exposure has been evaluated based on measured concentrations in maternal blood for each of the circumpolar countries. In Canada these surveys have included indigenous groups (Inuit, Dene, and Metis) and non-indigenous groups (Caucasians and others). Results of these surveys indicate that Inuit, particularly those from the eastern Arctic who are known to consume large amounts of marine mammals, consistently had the highest concentrations of POPs (PCBs, chlordanes, toxaphene and mirex) and mercury in their blood. In general concentrations of â-HCH were low in every group with the exception of the "others" a non-indigenous group dominated by people of African or Asian decent. The most likely source of â-HCH among this population group is from prior exposure in their country of origin, or from imported foods. Non-indigenous Caucasians from

Northern Canada had the lowest levels of POPs and mercury among all circumpolar countries consistent with low levels of marine food consumption.

Concentrations of POPs and mercury in maternal blood of Greenland Inuit were generally higher than the levels measured in Canadian Inuit. Concentrations of PCBs in blood of Greenland Inuit ranged from 6.4 - 36 ug/L whereas levels in Canadian Inuit ranged from 2.4 - 8.0 ug/L. Relative concentration of DDT demonstrated a similar pattern. The difference in contaminant levels is likely due to greater consumption of marine mammals among Greenland Inuit. Among Greenland Inuit, the highest concentrations were measured in the regions of Ittoqqortoormiit and Tassiilaq, regions also known to have the highest consumption of marine mammals. These regions, on the East coast of Greenland, have also have relatively elevated concentrations of POPs in marine mammals. Elevated concentrations of POPs in blood of Greenland Inuit were highly correlated to ratios of n-3/n-6 fatty acids, which is a biomarker of marine food consumption.

In Alaska, POPs were measured in blood of indigenous men and women from Aleut villages, as well as mothers from Yupik and Inupiat villages. In each case POPs exposure was thought to come primarily from the consumption of marine fish and seal, and in the case of Inupiat women, from bowhead whale as well. While comparative results for most POPs were not available, it appears that Alaskan indigenous populations that were examined are not as highly exposed as Inuit from Greenland and Canada. Concentrations of DDE and DDT and the ratio of DDE:DDT from the Aleutian and Pribilof groups were significantly higher than for the Yupik and Inupiat mothers. The main source of the DDT and DDE among the Aleutian and Pribilof groups is likely from seal that feed in the north Pacific and Bering seas and was thought to reflect past use of the pesticide in Asia.

In the Faroe islands the mains source of POPs and Hg exposure is from the consumption of pilot whale meat and blubber. In the 1980s it was estimated that the average intake of pilot whale blubber was approximately seven grams per day. Since 1998, when a pubic health notice was issued advising against the consumption of pilot whale for women who intended to have children, the estimated intake of whale meat and blubber is estimated to have decreased by a factor of ten. This appears to have resulted in a dramatic decrease in maternal blood mercury concentrations, from 12.1 ug/L to 1.3 ug/L, over the same time period. In contrast to this result, PCB concentrations have not decreased, probably because they are more persistent in human tissues than mercury is. Consequently, PCB concentrations in Faroese maternal blood are about two to three times higher than corresponding levels in other Scandinavian countries.

The primary source of POPs and mercury in Iceland comes from the consumption of marine fish. Consequently, levels of contaminants in maternal blood are relatively low compared to populations that consume marine mammals. Levels in Iceland are similar to other Scandinavian populations. In Finland, Sweden and Norway, the primary source of POPs and mercury exposure is also from consumption of marine fish. Concentrations are similar in all three countries with Norway and Sweden displaying slightly higher concentrations of PCBs than Finland.

With the exception of some coastal communities in Chukotka, indigenous and non-indigenous Russians do not consume large amounts of marine food and do not appear to exhibit high concentrations of contaminants related to Arctic marine pollution. It is interesting to note however, that non-indigenous Russians from Archangelsk and Nikel had the highest circumpolar concentrations of â-HCH as well as high levels of DDT and DDE. It is thought that local use of these pesticides and/or their presence in domestic foods, perhaps as a result of agricultural use, are potential sources of exposure. Indigenous people that consumed more traditional foods from the terrestrial and freshwater ecosystems displayed lower contaminant levels, though â-HCH was still higher than in other countries.

There are too few temporal data points with which to evaluate recent temporal trends of contaminants in human tissues. Continued blood monitoring programs in circumpolar countries will be required to monitor these trends. Analysis of hair samples from archaeological samples of human and animal

hair samples from Greenland have been used to compare pre- and post-industrial mercury exposure (Figure 15).

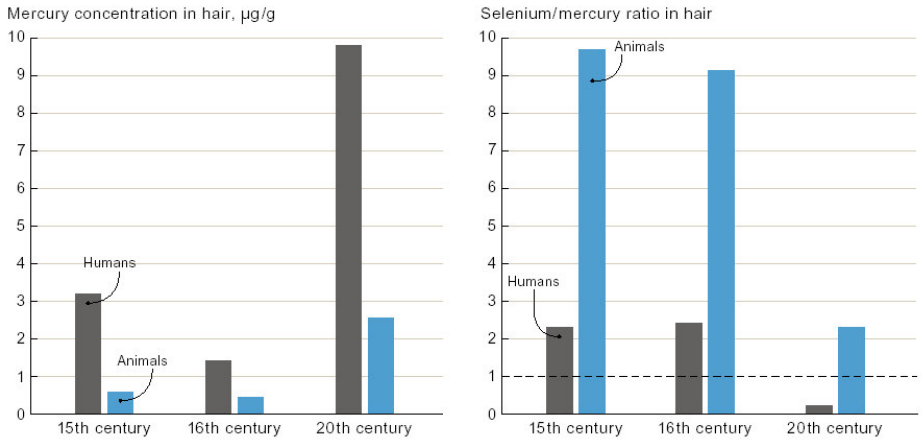

Figure 15. Comparison of current mercury levels and selenium/mercury ratios in human and animal hair to those collected from an archaeological site in Greenland (Source, AMAP 2002).

These results show a three- to seven-fold increase in mercury concentrations between the 15th and 16th century and the present. The same samples do not show a corresponding increase in selenium concentrations. This result may indicate a reduced capacity to detoxify mercury under the present exposure scenario relative to that of 15th and 16th century.

The levels of exposure to POPs and mercury that are being experienced as a result of marine mammal consumption are high enough to cause concern among public health authorities. There is little consensus among international health authorities over a safe guideline for mercury exposure. The most conservative guideline is 1.2 ug/g in maternal hair (or 5.8 ug/L in cord blood) which is applied by the United States Environmental Protection Agency. The World Health Organizations recommends an increasing risk range of 10 - 20 ug/g in maternal hair. Health Canada employs a range of 20 - 100 ug/L as being indicative of increasing risk, whereby concentrations exceeding 100 ug/L constitute a health risk. When these guidelines are applied to measured concentrations in Arctic populations (Figure 16), it can be seen that over 50% of Inuit from the Baffin and Nunavik Regions of Canada and the Ilullissat and Ittoqqortoormiit regions of Greenland exceed the lower US guideline. In these same groups, 10 - 45%, exceed the Canadian guideline. Nearly 50% of Yup'ik (Alaska) exceeded the US guideline.

A similar comparison was made between PCB concentrations in blood of women of reproductive age and Health Canada guidelines. The Health Canada maternal blood guideline for PCBs stipulates a level of concern at 5 ug/L and an action level at 100 ug/L. In comparison to these the guidelines (Figure 17), over 50% of Inuit from Baffin, Kivalliq and Nunavik Canada and Greenland as well as non-indigenous populations of the Faroe Islands, Vestvagoy, Norway, and Kiruna area, Sweden all exceed the Canadian level of concern. In the Ittoqqortoormiit region of Greenland, 100% of both pregnant and non-pregnant women exceeded the level of concern and 12% and 52% exceeded the action level, respectively.

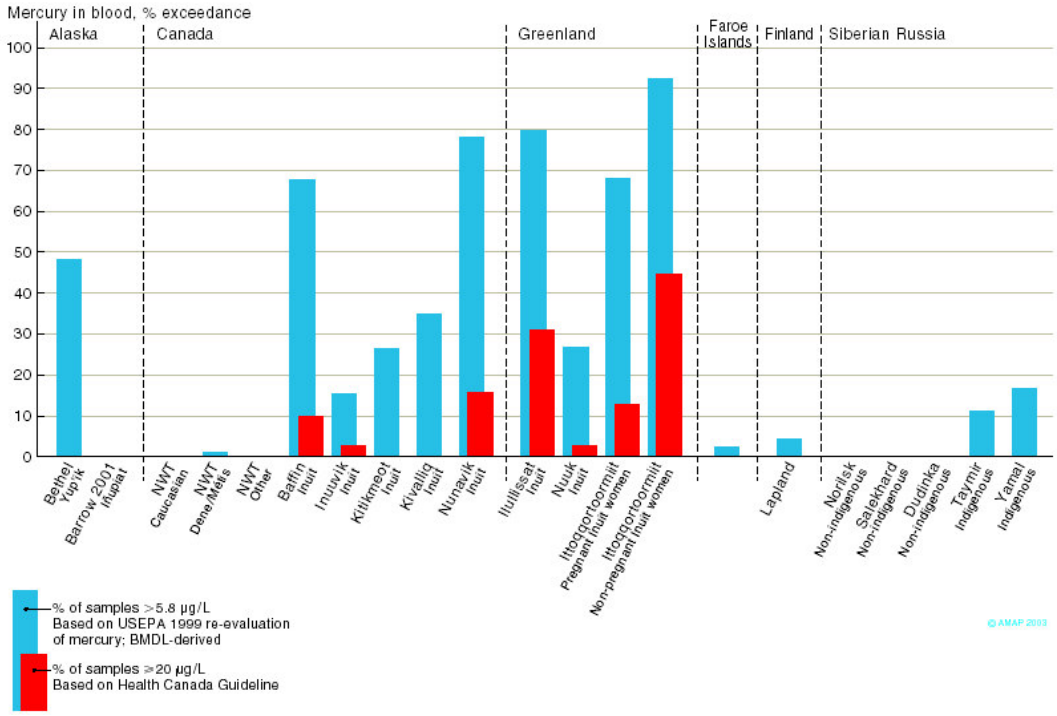

Figure 16. Mercury levels in blood of women of reproductive age as they relate to US EPA and Canadian guidelines for inreasing risk (Source, AMAP 2002).

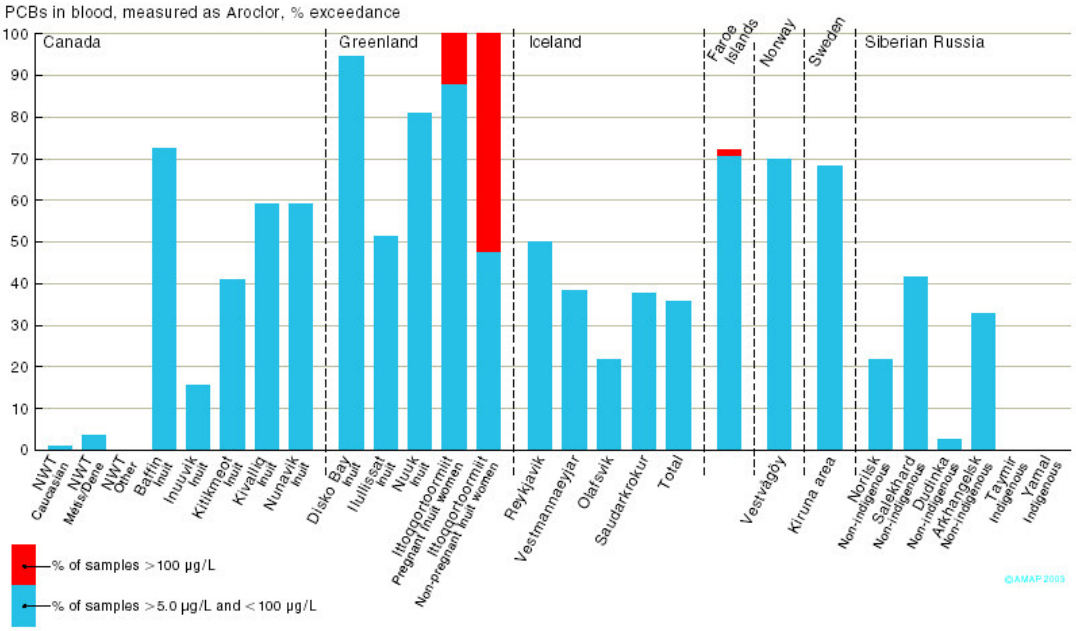

Figure 17. PCB levels in blood of women of reproductive age; percentage of samples exceeding public health guidelines for levels of concern and action (Source, AMAP 2002).

Epidemiological studies

The greatest health risks arising from exposure to Arctic marine pollution are thought to be associated with Hg and POPs, specifically PCBs. Over the past few decades, since the risks of these pollutants were first realized, a number of epidemiological studies have examined potential effects related to pre-natal exposure and children's health. Most of these studies have focussed on the neurological system but recently studies have also started looking at hormonal effects, immune deficiency and cardiovascular effects. For various reasons, including the relatively recent discovery of high contaminant levels, the remoteness of communities and small population sizes, very few of these studies have taken place in the Arctic. Two such studies have examined the effects of prenatal exposure to mercury and PCBs in Nunavik, Canada, and the Faroe Islands.

Mercury

The effects of high level pre-natal exposure to methylmercury are fairly well known from publicized cased in Japan and Iraq where children born to exposed women displayed a range of symptoms including mental retardation, severe sensory impairment, seizures and general paralysis. More recently there have been three well-designed studies that have examined the effects of low-level prenatal exposure to mercury; in the Faroe Islands, New Zealand and the Seychelles. In each of these studies the source of mercury was the consumption of marine foods, however, marine mammals were only consumed in the Faroe Islands. Unlike the severe cases that were documented in Japan and Iraq, none of the children demonstrated any obvious signs of neurological impairment. In both the Faroe Islands and New Zealand studies, however, pre-natal mercury exposure was correlated with subtle neurobehavioral effects. The Seychelles study did not find any exposure related effects. In each of these studies maternal hair concentrations ranged from 4.3 to 8.8 ug/g. In the Faroe Islands study mercury exposure was correlated with pregnancy period, and performance on neurobehavioral tests of fine motor function, concentration, language, visual-spatial abilities and verbal memory. It was calculated that a doubling in prenatal mercury exposure corresponded to a one to two month delay in child development over the first seven years of life. The long-term significance of these effects (ie. as the child grows up), however, are unknown. Based on these results it appears that pre-natal exposure to mercury at levels below some current guidelines can have subtle effects on brain development. A second major cohort study examining prenatal exposure to POPs and mercury has been undertaken in Nunavik, Canada. Since the publication of the AMAP assessment (2003) some preliminary results have been reported in Nunavik indicating subtle neurobehavioral effects associated with mercury. The interpretation of these results is ongoing and should be published in the very near future.

A Finnish found the risk of coronary heart disease in men who consumed freshwater fish was significantly associated with mercury concentrations in hair. Mercury has been found to promote lipid peroxidation resulting in the formation of low-density lipoproteins which have been implicated as initiators of arteriosclerosis. Previous observations in the same population also associated increased risk of death from coronary heart disease to low serum concentrations of selenium, an antioxidant that can block the mercury induced lipid peroxidation process. Like the Finnish men, Inuit consume high concentrations of mercury in fish and marine mammals yet mortality from coronary heart disease is extremely low. It is possible that Inuit are protected by the high levels of selenium and polyunsaturated fatty acids that are also contained in the marine foods. The Faroe Islands cohort study examined potential associations between pre-natal mercury exposure and cardiovascular development. The study showed that pre-natal mercury exposure was associated with increased blood pressure and reduced heart rate variability in seven year old children.

PCBs

The effects of prenatal exposure to PCBs have also been studied in a number of epidemiological studies. Studies in Michigan and Oswego, New York, examined pre-natal effects in children of women exposed to PCBs from the consumption of fish from the Great Lakes. In a similar study conducted in the Netherlands exposure was from contaminated dairy products and in a fourth study from North Carolina background exposures were examined and not attributed to any particular source.

Results of these studies and others have associated PCB exposure with lower birth weight, slower growth, poorer visual recognition memory, deficiencies in psychomotor development, and poorer intellectual functioning. The Faroese study that examined pre-natal effects of mercury exposure also measured exposure to PCBs. In this case, however, it was difficult to determine which contaminant was responsible for the observed effects. It is possible that the presence of both PCBs and mercury resulted in worse effects than would have been caused by the individual contaminants alone. Very recent results from the Nunavik cohort study also suggest that pre-natal exposure to PCBs is associated with subtle neurological effects.

In Taiwan, children born to mothers that were accidentally exposed to PCBs and PCDFs were found to have more cases of bronchitis and/or Pneumonia during their first six months of life. Later in life, at ages eight to fourteen, the same group of children were found to more prone to middle-ear diseases than non-exposed children. In Nunavik, an epidemiological study investigated potential associations between incidences of infectious disease and exposure to organochlorine contaminants. The study examined biomarkers of immune function in infants at three, seven and twelve months of age and found no associations with contaminant exposure. The study did find, however, that pre-natal exposure to organochlorines, including DDTs and PCBs, were associated with increased risk of otitis media and respiratory infections.

It is becoming more and more apparent that Arctic marine pollution is leading to increased risk of adverse health effects in populations that consume large amounts of marine foods, particularly marine mammals. To date the weight of evidence for mercury and PCBs strongly suggests their implication in pre-natal effects on the developing nervous, immune and cardiovascular systems. Recently a suite of new chemicals, including polychlorinated naphthalenes, chlorinated paraffins, perfluoroalkanes, and brominated flame retardants have also been measured in Arctic marine food species. While the concentrations of most of these substances are currently low, some of the more toxic congeners among them are approaching levels similar to those of dioxin like PCBs. Rapidly increasing trends in levels of brominated flame retardants in the marine environment are of particular concern. As of yet there is not enough information to assess the environmental impact and human health implications for these new substances.

Reducing exposure

International efforts to reduce the use and emissions of POPs and heavy metals will eventually lead to reduced contaminant levels in marine biota, however, the benefits will be slow to develop. In the mean time dietary advice is being used in some regions to help reduce levels of exposure. Particular attention has been paid to reducing pre- and post-natal exposure to infants, the best way of which is to reduce the lifetime accumulation of contaminants in mothers. Lower contaminant burdens in mothers reduce in-utero infant exposure and also reduces levels of contaminants in breast milk, a major source of contaminants to newborns. Despite breast milk related contaminant exposure, breast feeding is still recommended because of the overwhelming benefits it provides.

To reduce contaminant levels in Faroese, health authorities are advising adults not too consume the meat or blubber from pilot whales more than once or twice a month. To reduce PCB exposure to infants, girls and women are recommended not to eat pilot whale blubber at all until after they have given birth to their children. It is also recommended that women do not eat pilot whale meat within three months of getting pregnant and during pregnancy to reduce levels of mercury. Monitoring has shown that levels of mercury in Faroese women have declined by approximately 80% since the advice was issued, although similar declines in PCB levels have not been seen. Food advisories have also been used to successfully reduce exposures among target populations in Canada, Norway and Sweden.

Dietary advise should be generated by local health authorities working in cooperation with community representatives to ensure that consideration is given to potential negative social, cultural and/or nutritional impacts. To date, Canadian health authorities and Inuit representatives have concluded that the benefits of a traditional Inuit diet outweigh the risks posed by contaminants. As

such, extensive education and communications programs have been implemented in an attempt to provide Inuit with the information they need to make independent dietary choices. In Nunavik, health authorities and community members have successfully implemented a pilot program to promote the consumption of Arctic char among pregnant women. In this case the promotion of a healthy traditional food with relatively low contaminant levels was seen as preferable to the restriction of other traditional foods. The char promotion program in Nunavik is a good example of a strategy that has incorporated community values through effective communication and consultations.

The influence of global change on contaminant pathways

The complex systems of atmosphere and ocean responsible for contaminant transport are subject to change due to natural climate variability and global climate change. Climate can influence numerous factors that all interact to produce specific contaminant related conditions. Physical factors such as temperature, precipitation, winds, ocean currents, and snow and ice cover are all subject to temporal changes. Biological factors such as invertebrate community structure, increased productivity, invasion of foreign species, could alter marine ecosystems and patterns of biomagnification. Contaminant behaviour in the Arctic marine environment is determined by a combination of physical and biological processes and therefore both need to be considered at the same time.

One measure of natural system variability that has recently been monitored is the Arctic Oscillation, which describes variations in sea-level pressure and resultant winds in the polar region. A shift in Arctic Oscillation that occurred during the early 1990s resulted in widespread climatic and oceanographic changes that are important to the delivery and internal transport of contaminants. For example, under these conditions there was a shift in the transpolar drift that ended up carrying seawater from the Russian Arctic into the Canada Basin. Consequently water, ice, and contaminants, that would normally have passed into the North Atlantic through Fram Strait, ended up in the North American Arctic seas. Such a shift in oceanic transport could result in increased contaminant concentrations in the Canadian Arctic.

Under scenarios of global warming the amount of permanent ice in the Arctic is expected to be drastically reduced. A longer ice-free season and larger ice-free area would increase the air-water exchange of contaminants during summer months. This would essentially allow the Arctic seas to exhale the more volatile contaminants, such as HCHs, that would otherwise be trapped under ice. Alternatively, contaminants that are primarily deposited by the atmosphere, and are generally depleted under ice-capped conditions, would see enhanced transfer to ice-free waters. Longer ice free conditions and higher water temperatures could result in increased biological productivity. Increased biological productivity would produce a greater amount of biomass to which contaminants become sorbed and with which they eventually settle to the bottom. This process could actually increase the rate of removal for more insoluble contaminants, like PCBs.

Biological monitoring has demonstrated how important dietary habits are in determining contaminant concentrations in biota. For example, a crash in capelin populations in the North Atlantic resulted in minke whales shifting from a diet of capelin to one that was primarily zooplankton. The shift in diet essentially amounted to a lowering of trophic position and a corresponding dramatic decrease in contaminant exposures. It is also possible, however, that a trophic level could be added to an ecosystem through the introduction of new species thereby increasing contaminant exposures to apex feeders.

It is unclear how much recent changes due to climate variability or global climate changes may have already influenced observed contaminant trends. A potential example of climate induced temporal trends is that of increasing mercury in beluga whales of Mackenzie Bay. A possible explanation for these trends is that warming within the Mackenzie valley has enhanced the mobilization of mercury resulting in increased levels in Mackenzie River and Mackenzie Bay.

Examination of the potential influences of climate variability and global change on contaminant pathways illustrates how cautiously trends in monitoring results should be interpreted.

Some items/issues for considerations in the context of development of an Arctic Marine strategy

- The pathways that carry contaminants to, from and within the Arctic marine environment, and the processes by which contaminants move through Arctic physical environments and ecosystems are complex interactive systems that are susceptible to influences of climate variability and global

climate change. These influences may affect observed geographic and temporal trends in contaminant levels.

- There is evidence that the levels of some legacy POPs are gradually declining in the Arctic marine environment, however, environmental reservoirs will continue to release these POPs for many years to come. New substances, including current use pesticides and industrial chemicals such as flame retardants, on the other hand, are now appearing in the Arctic and levels of some of these are increasing.
- Despite the fact that there have been relatively few studies aimed at detecting biological effects in Arctic biota, there is growing evidence that high exposure to POPs is resulting in adverse health effects among certain Arctic species, including: polar bear, northern fur seal, glaucous gulls, peregrine falcons and dog whelks. In this regard it is important also to consider pollution effects in combination with other relevant factors. Understanding of biological effects associated with Arctic pollution, and in particular potential effects at the population level, is necessary to ensure that proposed and existing controls are adequate to afford the necessary level of protection.
- Recent studies have shown that deposition of atmospheric mercury to Arctic surfaces is enhanced during the period of polar sunrise. Recent and future environmental changes may have influenced this process. Some of this deposited mercury may enter aquatic and marine ecosystems in forms that are bioavailable, and at times of peak biological productivity. This process may therefore introduce, and result in elevated mercury concentrations in Arctic marine food webs. It is vital for the continuing viability of Arctic fisheries that its resources, currently recognized as some of the least contaminated that are to be found anywhere on the planet, continue to be so.
- There is evidence that levels of mercury may be increasing in marine biota in some parts of the Arctic (e.g. the Canadian Arctic and West Greenland), however, the effects of these levels are not well understood. Further assessments of mercury related trends and effects in the marine environment will be needed to determine whether current controls on mercury emissions are being protective, and whether new global agreements concerning mercury emissions may be required.
- Cadmium has been measured at high level in the liver and kidneys of Arctic marine birds and mammals. As yet there is no evidence of adverse effects, however knowledge concerning possible biological effects and human exposure is still limited.
- The introduction of unleaded gasoline has been effective in reducing lead contamination throughout the northern hemisphere. However, concentration of several metals that are used in catalytic converters (the technology which produced the demand for unleaded gasoline), including platinum, palladium and rhodium, appear to have been increasing rapidly in Greenland snow and ice since the 1970s. Little is known about the potential impact that these contaminants may have on the Arctic marine environment.
- Sediments previously contaminated with cesium-137 and plutonium, from sources including European reprocessing plants and nuclear accidents, appear to be capable of mobilization and redistribution so that they may now be acting as a source to the Arctic marine environment.
- There is continuing uncertainty about the number and location of radionuclide containing waste sites and the amount of waste at known sites throughout the circumpolar Arctic. Consequently, there is a need for greater access to information that is currently restricted. This information will also be required to develop a sound long-term management plan for this waste.
- Both civilian and military facilities in the Arctic are known to be sources and/or potential sources of (at least) localized contamination by POPs and radionuclides. At present, information concerning the number, location and pollution characteristics of both of these categories of source in the Arctic is inadequate.

- The first AMAP assessment presented information concerning threats to the Arctic environment and its ecosystems from pollution associated with the development of Arctic oil and gas reserves, and related issues such as transportation, etc. A new assessment of these issues is currently underway, however, given the expansion in development that is currently taking place or planned in the Arctic, this area will undoubtedly be a focus of future Arctic initiatives.
- It has been well established that contaminant exposure among Inuit of Greenland and Canada are the highest in the Arctic and that the elevated levels of exposure are due to the consumption of marine mammals. Comprehensive information about dietary habits of different communities, together with information on levels of contaminants in food items is necessary to support risk assessment of human exposure to mercury and POPs, to establish temporal trends and elaborate on geographic trends.
- There is evidence that contaminant exposure from the consumption of Arctic marine foods is leading to subtle health effects in some parts of the Arctic. Evidence suggests that the greatest concern is for fetal and neonatal development. Further human health effects studies will be needed to provide a better base for human risk assessment, especially concerning pre- and neonatal exposures.

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