THE POTENTIAL IMPACT OF CLIMATE ON HUMAN EXPOSURE TO CONTAMINANTS IN THE ARCTIC

Lisa D. Kraemer 1, James E. Berner 2, Christopher M. Furgal 3

1 Institut national de la recherche scientifique – Eau, Terre, Environnement (INRS-ETE), Université du Québec, Québec, Canada
2 Division of Community Health Services, Alaska Native Tribal Health Consortium
3 Nasivvik Centre, Unité de recherche en santé publique, CHUQ-CHUL, Department of Political Science, Université Laval. Ste-Foy, Québec, Canada

ABSTRACT

Many northern indigenous populations are exposed to elevated concentrations of contaminants through traditional food and many of these contaminants come from regions exterior to the Arctic. Global contaminant pathways include the atmosphere, ocean currents, and river outflow, all of which are affected by climate. In addition to these pathways, precipitation, animal availability, UV radiation, cryosphere degradation and human industrial activities in the North are also affected by climate change. The processes governing contaminant behaviour in both the physical and biological environment are complex and therefore, in order to understand how climate change will affect the exposure of northern people to contaminants, we must have a better understanding of the processes that influence how contaminants behave in the Arctic environment. Furthermore, to predict changes in contaminant levels, we need to first have a good understanding of current contaminant levels in the Arctic environment, biota and human populations. For this reason, it is critical that both spatial and temporal trends in contaminant levels are monitored in the environment, biota and human populations from all the Arctic regions.

(Int J Circumpolar Health 2005;64(5):498-508.)

Keywords: traditional food, climate change, Inuit, indigenous people, models
INTRODUCTION

Once thought to be a pristine ecosystem, it is now known that the circumpolar Arctic is impacted by various contaminants such as heavy metals (eg. mercury) and persistent organic pollutants (POPS; eg. dioxin, PCBs) (1). These contaminants are mostly produced and used at lower latitudes and transported north via various pathways where they can enter marine and terrestrial food chains. As Indigenous people are located at the top of the Arctic food chain, this has direct implications for human exposure as many of these contaminants not only bioaccumulate but they also biomagnify, resulting in elevated concentrations in many animals that are important components of a traditional diet.

Although there are other routes of exposure for Indigenous northern people (2), traditional foods coming from hunting, fishing and collection activities are the major vector through which people are exposed to these contaminants (3). Furthermore, traditional food not only constitutes a source of nutrition for Indigenous northern people, but it also represents a central component of their economic viability as well as social, cultural and spiritual well-being. Although the diet of many northern people consists of a mix of traditional and store-bought foods, dietary survey results show that traditional foods are still widely consumed in many northern communities today (3). These dietary patterns result in exposure to contaminants such as heavy metals through the consumption of fish and organ meats, and persistent organic pollutants (POPs) through the consumption of fat mainly from marine mammals (4).

This exposure has resulted in significantly higher concentrations of certain contaminants in northern people compared to concentrations observed in more southern populations (5). Deleterious health affects such as immunodeficiency and neurodevelopmental impacts have been noted in some northern communities (6, 7), despite the fact that variables such as alcohol consumption and smoking often confound interpretation of these data making direct links between exposure to contaminants and health endpoints difficult. Traditional foods provide several nutritional benefits as these foods are low in saturated fats, rich in omega 3 fatty acids and consumption has been linked to a low incidence of heart disease, diabetes and some cancers as well as protection against high blood pressure (3, 8, 9). From these studies, it is apparent that an assessment of the health benefits of consuming traditional foods requires a thorough understanding of both the nutritional benefits for indigenous people, as well as the risks associated with elevated exposure to certain contaminants.

An accurate evaluation of the level of contaminant exposure was recently reported by Van Oostdam et al., (3) as an important knowledge gap in assessing the health implications for Indigenous people consuming a diet composed largely of traditional foods. To address this knowledge gap projects funded under programs such as the Canadian Northern Contaminants Program (10) have monitored concentrations of contaminants in traditional food species. Factors such as age, socioeconomic status and sex are currently considered important determinants of traditional food consumption, and therefore who is exposed to contaminants via this route of exposure (3, 11).
Climate change is an emerging factor that may also influence the exposure of Indigenous northerners to contaminants. With a warming climate the range and distribution of some animals is predicted to shift which in turn may alter their accessibility to Arctic residents. Climate change is predicted to affect the timing and rate of snow and ice melt as well as increase precipitation which in turn could alter the geochemical cycling of some contaminants. The objective of this paper is to briefly outline how climate change events predicted, or currently being observed in some cases in the Arctic, may affect contaminant levels in traditional foods, thereby influencing human exposure in Arctic communities.

General predicted climate change trends in the north

Air and sea surface temperature changes

There is substantial scientific evidence indicating that the global climate is warming at an accelerated rate (12). While emissions of greenhouse gases originate largely in southern latitudes, climate change trends and models project that northern circumpolar regions will be first impacted by warming. While specific warming trends in the various northern regions are predicted to be non-uniform (13), a general warming of air and sea surface temperatures is anticipated. Sea ice is a sensitive indicator of warming air and sea surface temperatures in the North and trend analysis of historical data from the last century shows that ice coverage is receding at an accelerated rate (14). Not only is the total area of sea ice cover affected by this warming, but also the ice coverage is thinner now than in the past. Many climate change models predict that these decreases in sea ice coverage and thickness will continue into the next century (15, 16), which may ultimately lead to an ice-free Arctic Ocean year-round.

Possible implications of these predicted air and sea surface temperature changes

Many developing countries still use some pesticides that are environmentally persistent chemicals. Due to the warm, humid climates in many of these regions, as well as the volatile nature of some chemicals used, these contaminants enter the atmosphere, and as a result of prevailing winds, are transported north where condensation occurs in relation to colder ambient temperatures. This long range transport and global distillation describes how many volatile contaminants, such as persistent organic pollutants (17) are now detected in northern ecosystems where few local sources of these substances exist.

Bans and restrictions on many of these volatile persistent contaminants in southern regions have resulted in declines in their concentrations in the North. For example, since the ban on DDT in Canada and the United States in the 70s, concentrations of this chemical have declined in many arctic species over the last few decades (18, 19). As many of these species are important components of traditional diets, DDT concentrations in northern people have mirrored this decreasing trend seen in these animals (20). This example shows the link between contamination in traditional foods, exposure to humans and pesticide use at lower latitudes. Climate warming in southern regions may cause the emergence or re-emergence of pests or disease vectors, which in turn may require the lifting of pesticide bans and restrictions, or the introduction of new persistent chemicals to protect human popula-
tions in these regions. For example, to combat the threat of mosquito-borne diseases such as West Nile virus and malaria, southern regions may need to adopt the use of persistent pesticides to control insect populations, which may have implications for northern communities if these compounds are then transported to the North.

Warming events predicted in some southern regions may also increase the importance of the atmosphere as a global transport vector for some contaminants, independent of their use. Of particular importance are pesticides such as lindane and toxaphene, whose behaviour in the environment is known to be strongly influenced by temperature. Increased volatilization of lindane (γ-hexachlorocyclohexane; γ-HCH) from soils has been shown to be positively correlated with increasing temperature (21). Annual temperature trends over the last 20 years show an increase an average of 0.5-1°C in many regions where this pesticide is still used (e.g. North America; 22, 12). These increases in temperature will cause an increase in volatilization of HCH, and may ultimately lead to an increase in HCH concentrations in many northern regions. A recent study by Polder et al., (22) has shown that β-HCH is currently one of the main contaminants in human breast milk among people living in the Russian Arctic. As Western Europe contributes 48% of the γ-HCH currently found in the Russian Arctic (23), increases in temperature over the European landmass may be of special concern to northern Russian residents as they may experience an increase in this exposure.

The hypothesis of increased temperature and increased HCH transport and human exposure is complicated by the fact that climate change is expected to occur in many northern regions which in turn will decrease the thermodynamics that currently force contaminants such as HCH from southern to northern regions (24). In addition, the Arctic Ocean currently represents a substantial sink for HCH, and warming events in the North may alter the behaviour of this pesticide in the arctic environment as the warming of surface waters by a few degrees could result in a significant evasion of HCH from the ocean into the atmosphere (24).

Table I. Comparison of mean concentrations (ng l⁻¹) of POPs in snow from the permafrost region of Canada (60), the Ob–Yenisey watershed (38).

| Contaminant | Canada 1991/1992 | Ob–Yenisey watershed 1992/1993 |
|------------|-----------------|-------------------------------|
| ∑ HCH      | 0.76            | 1.2-2.4                       |
| ∑ CHLOR    | 0.04            | -                             |
| ∑ DDT      | 0.09            | 0.5-0.7                       |
| HCB        | 0.16            | Trace levels                  |
| ∑ PCB      | 4.1 (69 congeners) | 0.4-0.6 (9 congeners)         |

The cryosphere also represents an important sink for many contaminants in the circumpolar north. Results to date show elevated concentrations of some contaminants in snow from some arctic regions (Table I). Due to overall warming trends that are predicted to occur in these regions, contaminants stored in the cryosphere will be remobilized into the environment as a result of ice, snow and permafrost melt. The implications of snow and ice melt on contaminant remobilization depend on the characteristics of the contaminant. One possible outcome is that contaminants stored within snow and ice will be released to aquatic environments via runoff. This may have implications for people of the Russian Arctic as concentrations of contaminants such as DDT and HCH are elevated in snow from that region (Table I). Due to its high solubility, HCH concentrations are expected to increase.
in melt water and due to runoff, this contaminant will be able to enter aquatic ecosystems and possibly the food chain (25). In contrast, hexachlorobenzene (HCB) is predicted to volatize into the atmosphere during melting of snow (25). Also, the presence of sea ice acts as a barrier preventing atmospherically transported contaminants such as PCBs and toxaphene from directly entering the ocean. With reduced ice coverage associated with climate warming, these contaminants will be loaded directly into the Arctic Ocean where they would enter the marine food chain.

**Biotic changes**

Since many of the species consumed by Indigenous people are components of aquatic food chains, it follows that changes in contaminant levels in freshwater aquatic systems either directly through inputs, or indirectly through changes in food web structure have the potential to influence human contaminant exposure. As a result of warming, more light penetration and a lengthened growing season, some Arctic lakes are already experiencing increases in primary productivity (26). Located at the base of aquatic food chains, primary producers such as algae and diatoms can influence contaminant transfer in the food chain. For example, significant and rapid increases in algae population size can decrease mercury accumulation in higher trophic levels (i.e. fish), as large numbers of algae actually dilute the concentration of Hg entering the base of the food chain as a result of bloom dilution (27).

In response to the warming of surface waters, microbial degradation of some contaminants is also likely to occur. Significant microbial degradation of hexachlorocyclohexane (HCH) has been observed in the Arctic Ocean, representing 29-37% of the total annual loss of HCH from this body of water (28). As microbial activity is positively influenced by temperature, small increases in surface water temperatures may increase the proportion further, resulting in greater loss of HCH from the Arctic Ocean with climate warming.

However, in some cases microbial activity may increase the risk of human contaminant exposure. For example, methyl mercury (MeHg), the most toxic mercury species, enters the base of the food chain and biomagnifies at higher trophic levels in organisms such as fish, creating an increased risk of exposure to humans (3). The methylation process is carried out by bacteria, which are present in many different ecosystems including the Arctic (29). Loseto et al., (30) studied the production of MeHg in laboratory experiments conducted on frozen soil collected from the high Arctic and found that increased methylation rates were associated with rising temperatures.

**Increased ultraviolet radiation**

Global reductions in the stratospheric ozone layer have been reported during the latter half of this century and despite regulations to phase out the production and use of ozone-depleting compounds, the damaged stratospheric ozone layer is not expected to repair significantly in the North for many decades, in part due to increasing concentrations of greenhouse gases and climate change trends (31). As a consequence, more solar ultraviolet (UV) radiation is reaching the Earth’s lower atmosphere and surface. In arctic regions, there has been an ozone loss of 3% / decade during the period 1979-2000, and with climate change, these trends are expected to continue (32).
Possible implications of increased ultraviolet radiation (UV)
Perhaps the most significant impact of UV radiation on changes in contaminant behaviour relevant to human health will occur via mercury (Hg). Foods such as certain fish and marine mammals are significant sources of mercury exposure for indigenous northern people (3). Chronic methylmercury (MeHg) exposure has been linked to sensory and motor dysfunction in humans (33). Increases in UV radiation will no doubt affect mercury cycling in the North, however the net result of these changes is difficult to predict. It is known that UV radiation plays an important role in mercury depletion events, where reactive Hg is removed from the atmosphere and deposited in terrestrial and aquatic environments (10). However, Lalonde et al., (34) showed that photo-oxidation of mercury is also occurring, resulting in a flux of Hg from water to the atmosphere. Furthermore methylmercury degradation and production in surface waters have both been linked to solar radiation (35, 36). Indirectly, UV radiation could increase the bioaccumulation potential of Hg in the aquatic food chain by breaking down large, recalcitrant organic matter to low molecular weight organic compounds which when associated with Hg are readily taken up by aquatic organisms (37). From these studies it is apparent that more information is needed to understand the relative importance of these changes in the Arctic environment in order to be able to accurately predict how increases in solar radiation will affect Hg exposure to humans.

Changes in Arctic oscillation
Although climate change in the North is commonly thought to be linked to anthropogenic activities, the Arctic’s climate also varies naturally. The Arctic Oscillation Index (AO) is used to describe different atmospheric regimes, and varies naturally between positive (AO+) and negative (AO-) (see Messener et al., this edition). These two climate regimes involve changes in sea-level pressure resulting in atmospheric circulation conditions that are either cyclonic (moving in a counterclockwise direction about the earth’s axis) during AO+ conditions or anticyclonic during AO- conditions. At the end of the 1980s, the circumpolar region entered a positive AO phase of unprecedented strength. It is currently not certain whether this strong shift to an AO+ phase is the result of natural climate cycling, or rather a sign that the Arctic is responding to anthropogenically-induced climate warming (24).

Positive Arctic Oscillation
Under AO+ conditions there is a significant shift in oceanic currents and instead of moving from the Laptev Sea in Russia across the Eurasian Basin and ending up in the Greenland Sea, predominant currents take a cyclonic diversion to the Canadian Basin. The Russian coastline is heavily industrialized and consequently concentrations of some contaminants such as polycyclic aromatic hydrocarbons (PAHs) and metals are elevated in this region (38, 39). Accordingly, concentrations of some contaminants are elevated in Russian biota (40, 41) and people (1, 23). A shift in oceanic currents due to changes in the arctic oscillation would change the transport pattern of contaminants originating in Russian regions, and in this example could possibly reduce exposure of contaminants to Indigenous people of eastern Greenland while
increasing exposure to Inuit of the Canadian Arctic Archipelago.

In addition to changes in oceanic currents, under a positive AO the amount of precipitation falling in some northern regions has increased (42) and the total annual precipitation is expected to increase in the Arctic, with most of this increase likely coming as rain (43). Under the normally dry conditions of the Arctic, scavenging of particulate and aerosol-associated contaminants is low; however increased precipitation will increase the removal of contaminants from the atmosphere (24). How increased precipitation will affect the removal efficiency of different contaminants from the atmosphere depends on the characteristics of the contaminant (ie. solubility), the atmospheric temperature, as well as whether the precipitation is falling as snow or rain (44). For example, HCH is generally more readily scavenged by rain, whereas PCBs tend to be more efficiently scavenged by snow (44). Increased removal of persistent contaminants from the atmosphere by precipitation will result in their increased deposition on land, ice and in the ocean and lakes where they can then enter marine and terrestrial food chains, ultimately increasing the potential of exposure to humans consuming traditional foods in these regions. This could be of particular concern to inhabitants of northern Scandinavia and eastern Greenland; regions where the most dramatic increases in precipitation are predicted to occur in winter months (24).

As a result of increased precipitation and snow and ice melt, runoff and river discharge into the Arctic Ocean has increased in many arctic regions (45). Models predict that discharge from Arctic rivers such as the Mackenzie and the Ob may increase up to 20% (of the pre-Industrial Period level) by the middle of the 21st century and by up to 40% or more in a few centuries (46). This will be of particular concern in industrialized regions of the North such as some areas of Russia where, due to industrial and agricultural practices, rivers are already a major source of metals (47), pesticides (48) and radionuclides (49). Increased runoff and river discharge will increase the loading of these contaminants into the eastern Arctic Basin, ultimately leading to higher contaminant concentrations in marine mammal species that are important components of a traditional diet. This could dramatically increase the contaminant exposure for indigenous people of Russia and eastern Greenland, as concentrations of DDT and PCBs are already elevated in ringed seals from these regions, and will likely increase further with increased contaminant loading from increases in river discharge into the eastern Arctic basin (40).

**Wildlife as pathways of contaminant exposure: changes in habitat range and availability**

Climate warming in the northern hemisphere will influence the distribution and habitat range of some animals. One example is the change in distribution of sockeye salmon (*Oncorhynchus nerka*) in the Pacific Ocean as a result of warming. This species of fish is anadromous, spending time in both freshwater and marine environments. During the marine phase of its life cycle, sockeye salmon accumulate lipophilic contaminants such as POPs. After spawning in freshwater, they die and their carcass becomes an additional source of contaminants in freshwater ecosystems.
In a study by Ewald et al., (50) input of contaminants from migrating salmon into freshwater lakes was shown to be significant, outweighing the importance of atmospheric transport for their Alaskan study lakes. Models predict that the importance of this route of exposure will increase in the North Pacific as the range of salmon in this ocean is further confined to more northern regions due to climate change and warming of ocean waters (51).

Changes in ice and snow cover also affect the distribution of certain species that are important traditional foods. Ice and snow are ecologically important for many marine mammals acting as substrates for rearing young, foraging, resting and moulting (52). As a result, the distribution of many marine mammals is linked to the recession and formation of landfast and pack ice. Seals are an important part of Inuit subsistence in many circumpolar regions (53, 54). Seal meat and liver are also high in certain contaminants such as mercury (53, 54). As ice and snow represent critical habitats for many pinnipeds, it is expected that a reduction in the cryosphere due to climate warming will reduce the abundance of these species. In support of this prediction, Moulton et al., (55) observed reduced ringed seal abundance in relation to the presence of melt water on the ice surface in the Alaskan Beaufort Sea. With climate warming in the North, accessibility to seals will likely be reduced, and therefore this source of contaminants will be diminished in the diet. However, seals also represent an important source of lipids, vitamins and minerals, and therefore loss of this species from a traditional diet would have negative consequences as well (3).

**Climate influenced changes in human industrial activities as a mechanism of contaminant exposure**

Due to reductions in ice coverage and thickness, it is predicted that there will be improved shipping accessibility and access to resources such as offshore oil in the circum-polar North. With increased sea traffic there is an increased risk of hazardous waste spills in Arctic waters. Oil and gas exploration is expected to increase in many Arctic regions making spills associated with this industry more likely as transportation south either via pipelines or marine shipping will be required. An oil spill resulting in significant increases in PAHs in the arctic environment is especially pertinent to human health as this group of contaminants have been implicated in breast, lung, and colon cancer in humans (56).

In addition to increases in shipping traffic and oil transportation in the North, other industries such as aquaculture of fish species (e.g. salmon and trout spp) could increase in these regions. Slightly warmer water predicted for some regions, in combination with declines in many wild fisheries could increase the popularity of aquaculture in the North. Due to the location of many aquaculture farms in coastal waters, as well as the artificial diet fed to penned fish, higher levels of certain contaminants such as PCBs, organochlorine pesticides, and polybrominated diphenyl ethers (PBDEs) have been reported in farmed salmon (57, 58). It is estimated that up to two million Atlantic salmon escape from aquaculture cages each year, thus representing a significant introduction of these organic contaminants into the surrounding aquatic food web (59). Furthermore, due to the high density of farmed fish, sediments directly below the cages become
enriched in organic carbon and trace metals (Cd, Cu, Fe and Zn) due to the sedimentation of unused food.

Conclusions and recommendations

Major pathways of contaminant transport to the North include wind and ocean currents, and river outflow, all of which are affected by climate variables. In addition to these pathways, precipitation, animal availability and accessibility, UV radiation, cryosphere degradation and human industrial activities in the North are also influenced by climate change and will in turn have an effect on levels of human exposure to environmental contaminants in Arctic regions. The interacting processes governing how contaminant levels in traditional foods will be affected by climate change are in many cases very complex, and currently not well understood, making predictions of trends in contaminant levels, on a regional basis difficult at this time. In the context of northern human populations, exposure to contaminants is the culmination of both physical (eg. changes in atmospheric transport), biological (eg. changes in the availability of key species) and behavioural (eg. changes in desirability of country foods, access to store foods) factors and therefore an understanding of these changes and processes is crucial in predicting how contaminant exposure will change in response to long term climate variability and change in the circumpolar North.

Research recommendations

To predict long-term changes in the North, models able to describe contaminant transport are ideal, however many of the processes governing contaminant behaviour in both the physical and biological environment are too complex and not understood well enough to be included in realistic, predictive models. Therefore, in order to understand how climate change will affect contaminant cycling in the North, we must have a better understanding of the processes that influence how contaminants behave in the Arctic environment. It is critical also that there are accurate models that can predict exactly how the Arctic climate is changing on a regional scale. Furthermore, since all contaminant pathways are linked in some direct or indirect manner to climate variables, models that directly link contaminant movement with climate changes would be extremely valuable.

Recommendations for action and monitoring

If we are to predict changes in contaminant levels, we need to first have a good understanding of current contaminant levels in the Arctic environment, biota and human populations. For this reason, it is critical that sufficient spatial and temporal trend data be collected for contaminant levels in abiotic and biotic components of the Arctic environment and in human populations from all the Arctic regions.

With increases in industrialization in the North, including increased maritime traffic, there is an increased likelihood of accidents and large scale oil spills that may prove to be the most damaging contamination event for local and regional ecosystems and residents, and therefore, international efforts should also focus on the monitoring and prevention of such events.
REFERENCES

1. Van Oostdam JC, Dewailly É, Gilman A, et al. Circumpolar maternal blood contaminant survey. 1994-1997 organochlorine compounds. Sci Tot Environ 2004; 330: 55-70.

2. Revich, BA. Public health and ambient air pollution in Arctic and Subarctic cities of Russia. Sci Tot Environ 1995; 160/161: 585-592.

3. Van Oostdam, J, Gilman A, Dewailly É, et al. Human health implications of environmental contaminants in Arctic Canada: a review. Sci Tot Environ 1999; 230: 1-82.

4. Johansen P, Muir D, Asmund G, Riget F. Human exposure to contaminants in the traditional Greenland diet. Sci Tot Environ 2004; 331: 189-206.

5. Dewailly É, Nantel A, Bruneau S, Laliberté C, Ferron L, Gingras S. Breast milk contamination by PCDDs, PCDFs and PCBs in Arctic Québec: a preliminary assessment. Chemosphere 1992; 25: 1245-1249.

6. Dallaire F, Dewailly É, Muckle G, et al. Acute infections and environmental exposure to organochlorines in Inuit infants from Nunavik. Environ Health Perspect 2004; 112: 1359-1364.

7. Despres C, Beuter A, Richer F, et al. Neuromotor functions in Inuit preschool children exposed to Pb, PCBs, and Hg. Neurotoxicol Teratol 2005; 27: 245-257.

8. Receveur O, Boulay M, Kuhnlein HV. Decreasing traditional food use affects diet quality for adult Dene/ Métis in 16 communities of the Canadian Northwest Territories. J Nutr 1997; 127: 2179-2186.

9. Dewailly É, Blanchet C, Lemieux S, et al. n-3 fatty acids and cardiovascular disease risk factors among Inuit of Nunavik. Am J Clin Nutr 2001; 74: 464-473.

10. CACAR. Northern Contaminants program: Canadian Arctic Contaminants Assessment Report. Dept. of Indian and Northern Affairs. 2003.

11. Duhaime G, Chabot M, Gaudreault M. Food consumption patterns and socioeconomic factors among the Inuit of Nunavik. Ecol Food Nutr 2002; 41: 91-118.

12. IPCC. Climate change 2001: The scientific basis. 2001.

13. Manabe S, Stouffer RJ, Spelman MJ, Bryan K. Transient responses of a coupled ocean atmosphere model to gradual changes of atmospheric CO2. I. Annual mean response. J Climate 1991; 4: 785-818.

14. Maslanik JA, Serreze MC, Barry RG. Recent decreases in Arctic summer ice cover and linkages to atmospheric circulation anomalies. Geophys Res Lett 1996; 23:1677-1680.

15. Manabe S, Spelman MJ, Stouffer RJ. Transient responses of a coupled ocean atmosphere model to gradual changes of atmospheric CO2. J. Climate 1992; 5:105-126.

16. Vinnikov KY, Robock A, Stouffer RJ, et al. Global warming and northern hemisphere sea ice extent. Science 1999; 286: 1934-1937.

17. Wania F. Assessing the potential of persistent organic chemicals for long-range transport and accumulation in polar regions. Environ Sci Technol 2003; 37: 1344-1351.

18. Muir D, Braune B, DeMarch B, et al. Spatial and temporal trends and effects of contaminants in the Canadian Arctic marine ecosystem: a review. Sci Tot Environ 1999; 230: 83-144.

19. Olafsdottir K, Petersen A, Magnusdottir EV, Bjornsson T, Johannesson T. Temporal trends of organochlorine contamination in Black Guillemots in Iceland from 1976 to 1996. Environ Pollut 2005; 133: 509-515.

20. Dallaire F, Dewailly É, Muckle G, Ayotte P. Time trends of persistent organic pollutants and heavy metals in umbilical cord blood of Inuit infants born in Nunavik (Quebec, Canada) between 1994 and 2001. Environ Health Perspect 2003; 111: 1660-1664.

21. Ma J, Daggupaty S, Harner T, Li Y. Impacts of lindane usage in the Canadian prairies on the Great Lakes ecosystem. J. Coupled atmospheric transport model and modeled concentrations in air and soil. Environ Sci Technol 2003; 37: 3774-3781.

22. Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for alpha-, beta-, gamma-, and deltahexachlorocyclohexane. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.1999.

23. AMAP. Persistent toxic substances, food security and Indigenous peoples of the Russian North. Final report. AMAP secretariat, Oslo, Norway.2004; ISBN: 82-7971-036-1: 192 pp.

24. Polder A, Oladion JO, Tkachev A, Foreid S, Savinova TN, Skareau JU. Geographic variation of chlorinated pesticides, toxaphenes and PCBs in human breast milk from sub-arctic and arctic locations in Russia. Sci Tot Environ 2003; 306: 179-195.

25. Macdonald RW, Harner T, Fyfe J. Recent climate change in the Arctic and its impact on contaminant pathways and interpretation of temporal trend data. Sci Tot Environ 2003; 342:5-86.

26. Wania F. Modelling the fate of non-polar organic chemicals in an ageing snow pack. Chemosphere 1997; 35: 2345-2363.

27. Korhola A, Sorvari S, Rautio M, et al. A multi-proxy analysis of climate impacts on the recent development of subarctic Lake Saanajärvi in Finnish Lapland. J of Paleolimnol 2002; 99: 4419-4423.

28. Pickhardt PC, Folt CL, Chen CY, Klaue B, Blum JD. Algal blooms reduce the uptake of toxic methylmercury in freshwater food webs. Proc Natl Acad Sci 2002; 99: 4419-4423.

29. Harner T, Jantunen LMM, Bidleman TF, et al. Microbial degradation is a key elimination pathway of hexachlorocyclohexanes from the Arctic Ocean. Geo- phys Res Lett 2000; 27: 115-1151.

30. Knoblauch C, Jorgensen BB, Harder J. Community size and metabolic rates of psychrophilic sulfate-reducing bacteria in arctic marine sediments. Appl Environ Microbiol 1999; 65: 4230–4233.

31. Loseto LL, Siciliano SD, Lean DRS. Methylmercury contamination of arctic marine food webs. Environ Health Perspect 2003; 111: 23-27.

32. Schindell DT, Rind D, Lonergan P. Increased polar stratospheric ozone losses and delayed eventual recovery owing to increasing greenhouse-gas concentrations. Nature 1998; 392: 589-592.
32. Weatherhead B, Tanskanen A, Stevermer A. Chapter 5, Ozone and ultraviolet radiation. ACIA report (www.acia.uaf.edu) 2005; 151-182.
33. Newland MC. Neurobehavioral toxicity of methylmercury and PCBs effects – profiles and sensitive populations. Environ Toxicol Pharm 2002; 12: 119-128.
34. Lalonde JD, Amyot M, Kraepiel AML, Morel FMM. Photooxidation of Hg(0) in artificial and natural waters. Environ Sci Technol 2001; 35: 1367-1372.
35. Seller P, Kelly CA, Rudd JWM, Machutchon AR. Photodegradation of methylmercury in lakes. Nature 1996; 360: 694-697.
36. Lean DR, Siciliano SD. Production of methylmercury by solar radiation. J. de Physique 2003; 107: 743-747.
37. Bonzongo JC, Donkor AK. Increasing UV-B radiation at the earth's surface and potential effects on aqueous mercury cycling and toxicity. Chemosphere 2003; 52: 1263-1273.
38. Melnikov S, Carroll J, Gorshkov A, Vlasov S, Dahle S. Snow and ice concentrations of selected persistent pollutants in the Ob–Yenisey River watershed. Sci Tot Environ 2003; 306: 27-37.
39. Savinov VM, Savinova TN, Matishov GG, Dahle S, Naes K. Polycyclic aromatic hydrocarbons (PAHs) and organochlorines (OCs) in bottom sediments of the Guba Pechenga, Barents Sea, Russia. Sci Tot Environ 2003; 306: 39-56.
40. Muir D, Riget F, Cleemann M, et al. Circumpolar trends of PCBs and organochlorine pesticides in the arctic marine environment inferred from levels in ringed seals. Environ Sci Technol 2000; 34: 2431-2438.
41. Muir DCG, Norstrom RJ. Geographical differences of PCBs and organochlorine (OC) compounds in Ah serum of Atlantic salmon, Salmo salar. Can J Fish Aquat Sci 1998; 51: 40-47.
42. L'Heureux M, Mann ME, Cook BI, Gleason BE, Vose JR. Atmospheric circulation influences on seasonal precipitation patterns in Alaska during the latter 20th century. J Geophys Res 2004; 109: D06106.
43. McBean G. Chapter 2: Arctic climate past and present. ACIA report (www.acia.uaf.edu). 2005; pp. 22-55.
44. Lei YD, Wania F. Is rain or snow a more efficient scavenger of atmospheric mercury and PCBs effects – profiles and sensitive populations? Environ Sci Technol 2002; 36: 2797-2805.
45. Hites RA, Foran JA, Carpenter DO, Hamilton MC, Knuth BA, Schwager SJ. Global assessment of organic contaminants in farmed salmon. Science 2004; 303: 226-229.
46. McClelland JW, Holmes RM, Peterson BJ, Steiglitz M. Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change. J Geophys Res 2004; 109: D18102.
47. Moran SB, Woods WL, Cd, Cr, Cu, Ni and Pb in the water column and sediments of the Ob-Irtysh Rivers, Russia. Mar Pollut Bull 1997; 35: 270-279.
48. Zhulidov AV, Headley, JV, Pavlov DF, et al. Riverine fluxes of the persistent organochlorine pesticides hexachlorocyclohexane and DDT in the Russian Federation. Chemosphere 2004; 41: 829-841.
49. Standring WJF, Oughton DH, Salbu B. Potential Remediation of 137Cs, 60Co, 99Tc, and 90Sr from contaminated Mayak sediments in river and estuary environments. Environ Sci Technol 2002; 36: 2330-2337.
50. Ewald G, Larsson P, Linge H, Okla L, Szarzi N. Biortransport of organic pollutants to an inland Alaska lake by migrating sockeye salmon (Oncorhynchus nerka). Arctic 1998; 51: 30-47.
51. Welch DW, Ishida Y, Nagasawa K. Thermal limits and ocean migrations of sockeye salmon (Oncorhynchus nerka): long-term consequences of global warming. Can J Fish Aquat Sci 1998; 55: 937-948.
52. Tynan CT, DeMaster DP. Observation and predictions of arctic climate change: potential effects on marine mammals. Arctic 1997; 50: 308-322.
53. Chan HM, Kim C, Khoday K, Receveur O, Kuhnlein HV. Assessment of dietary exposure to trace metals in Baffin Inuit food. Environ Health Perspect 1995; 103: 740-746.
54. Johansen P, Pars T, Bjergaard P. Lead, cadmium, mercury and selenium intake by Greenlanders from local marine food. Sci Tot Environ 2000; 245: 187-194.
55. Moulton VD, Richardson WJ, McDonald TL, Elliott RE, Williams MT. Factors influencing local abundance and hault behaviour of ringed seals (Phoca hispida) on landfast ice of the Alaskan Beaufort Sea. Can J Zool 2002; 80: 1900-1917.
56. Ramesh A, Walker SA, Hood DB, Guileen MD, Schneidder K, Weyand EH. Bioavailability and risk assessment of oral ingested polycyclic aromatic hydrocarbons. Int J Toxicol 2004; 23: 301-333.
57. Jacobs M, Covaci A, Schepens P. Investigation of selected persistent organic pollutants in farmed Atlantic Salmon (Salmo salar), salmon aquaculture feed, and fish oil components of the feed. Environ Sci Technol 2002; 36: 2797-2805.
58. Hites RA, Foran JA, Carpenter DO, Hamilton MC, Knuth BA, Schwager SJ. Global assessment of organic contaminants in farmed salmon. Science 2004; 303: 226-229.
59. McGinity P, Proehl P, Ferguson K, et al. Fitness reduction and potential extinction of wild populations of Atlantic salmon, Salmo salar, as a result of interactions with escaped farm salmon. Proc Roy Soc Lon Ser B-Biol Sci 2003; 270: 2443-2450.
60. Macdonald RW, Barrie LA, Bidleman TF, et al. Contaminants in the Canadian Arctic: 5 years of progress in understanding sources, occurrence and pathways. Sci Tot Environ 2000; 254: 93-234.

Lisa D. Kraemer
Institut national de la recherche scientifique – Eau Terre, Environnement (INRS-ETE)
Université du Québec
Québec, Canada
Email: lisa_kraemer@inrs-ete.uquebec.ca