

WECC Report 3/98

The Significance of Long Range Transport of Persistent Organic Pollutants by Migratory Animals

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September 1998

This research has been carried out on commission of the Chemical Manufacturers
Association, Arlington, Virginia, U.S.A.

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Introduction

The transboundary nature of a pollution issue necessitates concerted action on an international level, because its solution is no longer within the jurisdiction of a single state. The classical long range transport (LRT) medium has been the atmosphere, and typical atmospheric transboundary pollution issues such as “acid precipitation” have been addressed within international conventions such as the protocol on the long range transport of air pollutants (LRTAP) within UN-ECE. Increasingly, it is realized that other modes of transport can also move pollutants over long distances and from one jurisdiction to another. Examples are (AMAP, 1997):

transport in ocean currents: The oceanic movement of radionuclides released from nuclear fuel reprocessing plants in Europe, namely Windscale/Sellafield, can be traced to the Arctic Ocean.

transport in rivers: The Siberian rivers are suspected to be conduits for a variety of pollutants from agriculturally and industrially developed areas in central Asia into the North.

Whether the transport of pollutants, particularly persistent organic pollutants (POPs) in migratory animals may also be a significant pathway, is a valid question, because:

1. some animals cover long distances, often crossing international boundaries and linking industrialized/agricultural and remote regions during their migration.
2. as a result of bioconcentration and biomagnification animals accumulate certain pollutants, namely persistent lipophilic substances, to concentrations which can be many orders of magnitude higher than in air and water.

Particularly selected marine mammals and birds fulfill both these conditions, i.e. cover long distances on their migration pathways and, being at the top of the food chain, accumulate significant amounts of lipophilic pollutants.

This report aims to assess the significance of this transport mode for POPs relative to other modes of transport, namely in the atmosphere and hydrosphere.

Clarifying the Question

The question of the significance of LRT of POPs by migrating organisms can be asked in several different ways.

1. How much chemical is transported to a particular system by migrating organisms?
2. How much chemical is delivered (or net-transported) to a particular system by migrating organisms?
3. How much chemical is delivered to a particular organism/population by migrating organisms?

It is likely that the importance of the migratory animal transport mode relative to other transport routes will be very different for each of these perspectives.

How Much Chemical is Transported to a Particular System by Migrating Organisms?

In this context a boundary around a system of interest is defined and the question is simply how much chemical is crossing that boundary by various transport modes during a particular time period (Figure 1). For example, the question could be how much chemical is transported annually across 60° Northern latitude into the Arctic by (1) atmospheric currents, (2) sea water currents, and (3) migrating animals?

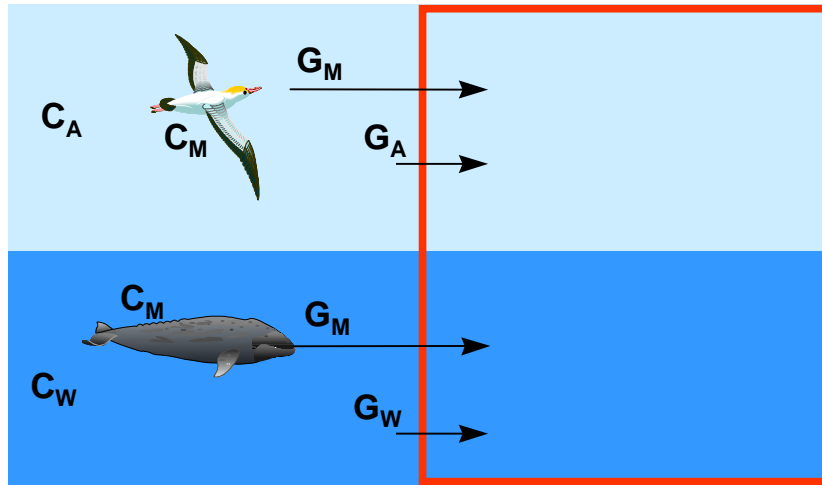


Figure 1

The chemical transfer rates N (e.g. in mol/m^3) are the product of the rates of movement of the transport media G (e.g. in m^3/h) and the chemical concentrations C in these media (e.g. in mol/m^3):

air	$N_A = G_A \cdot C_A$
water	$N_W = G_W \cdot C_W$
migrating organisms	$N_M = G_M \cdot C_M$

How Much Chemical is Delivered (or Net-Transported) to a Particular System by Migrating Organisms?

Of course, transport across such a boundary often occurs in both directions and the interest may be in the net transport of contaminant (Figure 2) rather than the gross flux. The net transport obviously depends on the net flux of the transport media across the boundary ($G_1 - G_2$) and the concentrations in these media on either side of the boundary.

$$N_1 - N_2 = G_1 \cdot C_{\text{out}} - G_2 \cdot C_{\text{in}}$$

Sometimes the movement of air and water across a system boundary balances out for long enough time periods, i.e. G_1 equals G_2 . Then the concentration difference ($C_{\text{in}} - C_{\text{out}}$) determines the net exchange of chemical in air and water. This is for example the case for air and water movement across latitudinal boundaries, but of course not if transport occurs in river water.

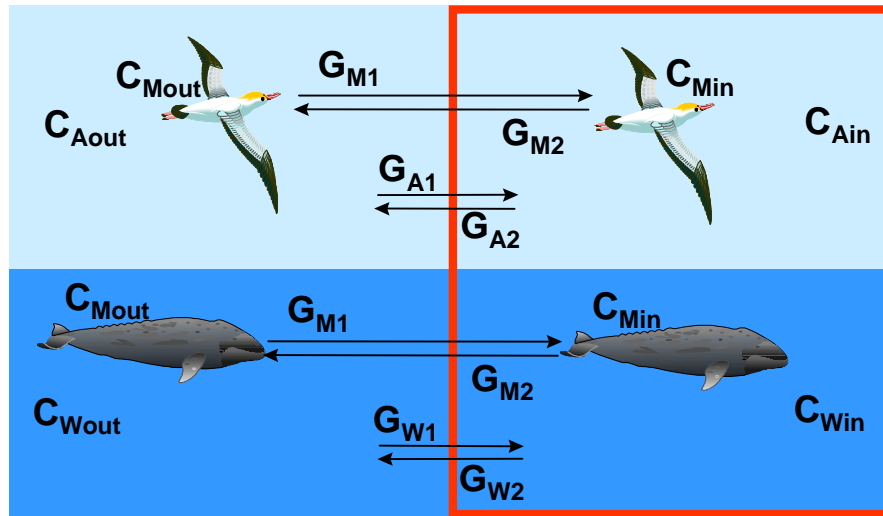


Figure 2

The concentration in the transport media within the system of interest C_{in} , and thus the net exchange across the system boundary, is determined by the processing of the chemical in this system, i.e. its intermedia transfer and permanent loss (e.g. degradation) (Figure 3).

advection intermedia exchange permanent loss

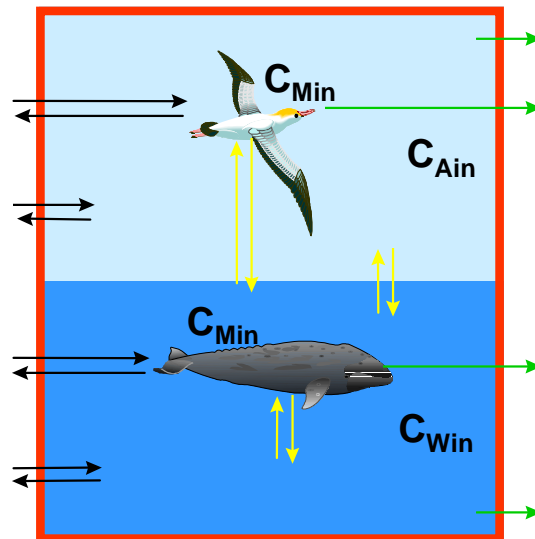


Figure 3

Long distance animal migrations tend to be back and forth on a seasonal time scale. However, the volume or mass of organisms moving either way does not need to balance out over an annual cycle, because organisms may get born, grow and die at different rates at either side of the boundary ($G_{M1} \neq G_{M2}$).

How Much Chemical is Delivered to a Particular Organism/Population by Migrating Organisms?

The third possibility to evaluate the significance of LRT by migrating organisms is to evaluate its contribution to the exposure of a particular target organism or population. For example, the question of interest could be (Figure 4): Of the total amount of a chemical present in polar bears, how much reached the Arctic in migrating animals? Or: What is the relative contribution of POPs which reached the Arctic in migrating animals to the exposure of the Greenland Inuit?

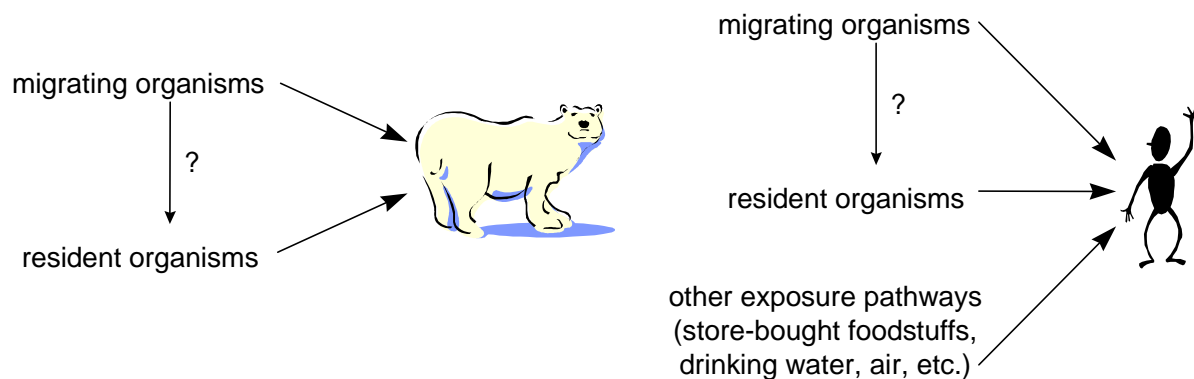


Figure 4

It is immediately obvious that these third type of questions can not be answered in a general valid fashion, because the significance of LRT by migrating animals will be entirely dependent on the dietary habits of a particular wildlife population or a human individual. It is conceivable that even among the residents of one Inuit community, food preferences may vary so widely, that the exposure of some individuals could be entirely due to migrating animals, whereas the exposure of others may be totally controlled by other exposure pathways. These questions are thus best addressed in a comprehensive risk assessment which takes into account all potential exposure pathways.

Estimating Gross Transport Rates of Selected POPs into the Arctic

In order to evaluate the significance of LRT by migrating organisms from the first perspective, an attempt was made to address the example question posed above:

How much chemical is transported annually across 60° Northern latitude into the Arctic by (1) atmospheric currents, (2) sea water currents, and (3) migrating organisms?

A very rough estimation of the gross transport rates of three selected POPs, namely hexachlorocyclohexanes (HCHs), DDT related substances (DDTs), and polychlorinated biphenyls (PCBs), is presented in the following paragraphs. It should be stressed that these are order-of-magnitude estimates for the illustration and evaluation of the relative significance of various transport pathways and should not be interpreted as anything more than that.

Transport of POPs with Atmospheric Currents

The flux of air in and out of the Arctic atmosphere G_A in m^3/h can be estimated using: $G_A = V_A / \tau_A$

V_A total volume of Arctic atmosphere North of 60°

τ_A average residence time of air in the Arctic atmosphere North of 60°

The volume V_A in m^3 can be calculated using:

$$V_A = 2 \cdot \pi \cdot r^2 \cdot (\sin 90^\circ - \sin 60^\circ) \cdot h_A$$

r global radius (6370289.6 m)

h_A average height of Arctic atmosphere

Assuming an average residence time τ_A of five days and an average atmospheric height h_A of six kilometers, the average transport rate for air G_A is $1.71 \cdot 10^{15} m^3/h$. When combining this estimate with typical atmospheric concentrations C_A of the three selected POPs in remote air (Barrie et al., 1997), atmospheric fluxes N_A of across $60^\circ N$ can be calculated (Table 1).

Table 1

	air concentration	transport rate	
	in g/m^3	in kg/h	in t/a
HCHs	$75 \cdot 10^{-12}$	128	1120
PCBs	$20 \cdot 10^{-12}$	34	300
DDTs	$1 \cdot 10^{-12}$	1.7	15

These data indicate that the gross fluxes of POPs into the Arctic atmosphere are on the order of tons to thousand of tons per year.

Transport of POPs with Ocean Currents

The amount of sea water flowing annually into the Arctic Ocean has been estimated (Barrie et al. 1997, Table 6.1):

$$G_W = 14.88 \cdot 10^4 km^3/a = 1.488 \cdot 10^{14} m^3/a = 1.7 \cdot 10^{10} m^3/h$$

The gross flux of air G_A is thus approximately five orders of magnitude higher than the flux of sea water G_W into the Arctic. Typical oceanic concentrations C_W for the three POPs in sub-polar waters (Iwata et al. 1993) allow the calculation of oceanic contaminant fluxes into the Arctic Ocean:

Table 2

	sea water concentration	transport rate	
	in g/m^3	in kg/h	in t/a
HCHs	$1.5 \cdot 10^{-6}$	25	220
PCBs	$15 \cdot 10^{-9}$	0.25	2.2
DDTs	$1 \cdot 10^{-9}$	0.017	0.15

Although concentrations of POPs in the atmosphere tend to be lower than in sea water, they tend to be less than five orders of magnitude apart. Thus, the atmosphere is usually the dominant transport medium by about two orders of magnitude, even though the reservoir of contaminants in the oceans tends to be larger than in the atmosphere. Only for POPs with a relatively high water solubility, such as the HCHs, this very rough estimation suggests that transport in the oceans can be of the same order of magnitude as the transport in the atmosphere. This is confirmed by much more sophisticated transport calculations (Wania and Mackay, 1998).

Transport of POPs with Migratory Animals

The potential transport of POPs with migratory animals into the Arctic is exemplified with two types of organisms, seabirds and whales.

Example 1: Seabirds

It is extremely difficult to accurately estimate bird population numbers. For some seabird species, a very approximate estimate of the number and mass of birds migrating annually from Arctic to Atlantic water was provided by T. Gaston (Canadian Wildlife Service, Ottawa, pers. comm.). Using these estimates and measured concentrations of PCBs, DDTs and HCHs in these birds, a very rough estimate of the amount of contaminants in the birds (and thus of the annual transport rate) was attempted (Table 3).

Table 3

Seabird Species	Number of birds ¹	Mass of one bird ¹	Concentration in µg/kg ²			Mass in g		
			HCHs	PCBs	DDTs	HCHs	PCBs	DDTs
Thick-billed Murre	3 million	1 kg	10	300	200	30	900	600
Black-legged Kittewake	300,000	0.275 kg	5	350	100	0.4	30	8
Northern Fulmar	1 million	0.8 kg	5	350	300	4	280	240
Common Eider	200,000	2 kg	1	8	6	0.4	3.2	2.4

¹ T. Gaston, Canadian Wildlife Service, pers. comm., 1998

² Concentrations are based on data in Braune (1994a and b, 1995). Preferably breast muscle concentration were employed. If these were not available liver, chick and egg concentrations were used instead.

The amount of POPs transferred in and out of the Arctic with these birds is thus in the range of grams to kilograms per year.

Example 2: Whales

Many of the marine mammals in Northern waters (e.g. narwhal, beluga whale, bowhead whale, ringed seal, polar bear) are year-round Arctic residents, even though they may undertake extensive regional migration. They thus do not contribute to contaminant transport in to and out of the Arctic. Many baleen whales and some toothed whales undertake regular annual large-scale latitudinal migrations.

However, these migrations rarely extent into truly Arctic waters, but rather occur between subtropical/tropical waters and temperate/sub-polar water (Baker, 1978, Lockyer and Brown, 1981). We sought to estimate the amounts of POPs contained in two whale species that do undertake annual return migration over a wide latitudinal range, namely the gray whale and the sperm whale. These species are representatives of the two main types of whales, the baleen whales (Mysticeti) and the toothed whales (Odontoceti). The latter typically have much higher contaminant concentrations because they feed at a higher trophic level than the baleen whales (O'Shea and Brownwell, 1994).

Gray whales (*Eschrichtius robustus*) spend the summer in the Bering and Chukchi Sea, and the winters off the Pacific coast of Mexico and California (Baker, 1978). Relatively reliable population estimates and recent contaminant concentrations in stranded individuals exist for this species, allowing for an estimate of the amount of some POPs contained in these whales. It is believed that there are approximately 21,000 gray whales in the eastern North Pacific (95 % confidence limit: 19,800-22,500) (IWC International Whaling Commission, 1998). Concentrations of PCBs and DDTs in two individuals stranded in Alaska were 150 to 1,200 µg/kg and 10 to 330 µg/kg wet weight blubber, respectively (Varanasi et al., 1993). Assuming that (1) a typical gray whale weighs 30,000 kg, (2) a fifth of this weight is blubber, (3) most of the contaminants are in the blubber and (4) the blubber concentrations reported above are representative, this means that a typical gray whale contains 1 to 10 g PCBs, and 0.05 to 2 g DDT. The total amount contained in and therefore transported annually with gray whales is thus in the range of 20 to 150 kg PCBs, and 1 to 40 kg DDT (Table 4). Other smaller baleen whales have similar contaminant concentrations as the gray whales (Aono et al., 1997, O'Shea and Brownwell, 1994), yet some have considerably higher population numbers (e.g. minke whales: 910,000, 95 % confidence: 630,000 to 1,320,000, IWC, 1998), so the total amount of PCBs and DDTs in the world's baleen whales is likely in the order of a few tons.

Sperm whales (*Physeter macrocephalus*) were chosen as an example for the toothed whales because at least the male individuals undertake long distance migrations (Baker, 1978, Lockyer and Brown, 1981) and because they are rather numerous. Though the population size is controversial, minimum estimates suggest 500,000 individuals, other estimates are as high as 2 million (IWC, 1998). Few measurements of POP concentrations in sperm whales exist in the literature. However, a recent study reported concentrations of approximately 100 µg/kg of poly-brominated diphenylethers, a flame retardent, in sperm whale blubber (de Boer et al. 1998). It is thus not unlikely that the levels of PCBs and DDT in sperm whales are similarly high as those found in other toothed whales. Based on a compilation of organochlorine residues in Odontoceti from around the world (Appendix 1), wet weight blubber concentrations of 10,000 µg/kg PCBs, 10,000 µg/kg DDTs, and 500 µg/kg HCHs are considered typical. Using these concentrations and assuming a weight of 30 tons, a blubber content of 20 % and a population of 0.5 million, the amount of PCBs contained in the world's sperm whales is estimated at as much as 30 tons PCBs, 30 tons of DDTs, and 1.5 tons of HCHs (Table 4). Again, the total amount in toothed whales is likely to be a multiple of this number because other

smaller odontoceti species have POP concentrations and population sizes similar to that of the sperm whale (e.g. 0.78 mio. pilot whales in the Central and Eastern North Atlantic, 95 % confidence: 0.44 to 1.37 mio., IWC, 1998). However, very few toothed whale species undertake long annual return migrations.

Table 4

Species	Gray Whales	Sperm Whales
number of animals	21,000	500,000
blubber weight per animal	6 t	6 t
blubber weight (total world population)	126,000 t	3 Mio. t
HCHs concentration in blubber	-	500 µg/kg wet wt.
amount in one whale	-	3 g
amount total world population	-	1.5 tons
PCBs concentration in blubber	150 to 1,200 µg/kg wet wt.	10,000 µg/kg wet wt.
amount in one whale	1 to 10 g	60 g
amount total world population	20 to 150 kg	30 tons
DDTs concentration in blubber	10 to 330 µg/kg wet wt.	10,000 µg/kg wet wt.
amount in one whale	0.05 to 2 g	60 g
amount total world population	1 to 50 kg	30 tons

Comparison of Gross Fluxes

The above assessment suggests that the amount of some POPs transported in migrating organisms, particular whales, may be on a similar order of magnitude as the gross transport rates estimated for the physical transport media atmosphere and ocean currents (Table 5).

Table 5

annual gross fluxes	HCHs	PCBs	DDTs
atmospheric currents	1120 t/a	300 t/a	15 t/a
sea water currents	220 t/a	2.2 t/a	0.15 t/a
migrating birds	0.00005 t/a	0.001 t/a	0.001 t/a
migrating whales	few t/a	tens t/a	tens t/a

As mentioned before, only selected whales (many baleen whales, male sperm whales) undertake large scale latitudinal migrations. Nevertheless the amount of PCBs and DDTs moved around in these whales is likely on the order of tens of tons per year. Especially for DDTs, the gross fluxes with whales may be comparable to those in air and ocean currents. On the other hand, for the more water soluble, more volatile and less bioaccumulative HCHs the amounts in organisms are negligible. Gross fluxes in migrating birds are much lower for all three POPs than the transport rates in the physical media. The importance of biological transport media obviously

increases with decreasing volatility and water solubility, and with increasing bioaccumulation potential of a chemical.

Gross vs. Net Transport

However, the above calculations address only the first of the three question posed in the introduction. Even though **gross** fluxes may be similar in magnitude, this does not necessarily imply that the **net**-transport, or delivery, of POPs to the Arctic is of the same significance for the various transport modes. However, it may be fair to state that if the gross fluxes of a contaminant in various transport modes are of the same order of magnitude, then also the net fluxes are likely to be in a similar range.

No answer to the second question, i.e. no numerical calculation of net chemical transport rates of POPs into or out of the Arctic, will be attempted, because the issue is too complex for this brief assessment (see Figure 3). To illustrate this complexity, it may suffice to state that the net rate of transport for POPs across 60 °N in atmosphere and ocean, even the direction of this transport, changes in time. For example, water concentrations of HCHs in the 1970s were likely higher in mid-latitude oceans than in the Arctic Ocean and there thus was net transfer of HCHs into the Arctic by ocean currents. In the 1990s the situation is reversed and inflowing ocean currents are diluting HCHs in the Arctic surface ocean (Wania and Mackay, 1998). Not only net transport in physical media is difficult to assess, so is net transport in migrating organisms.

Net Transport of POPs in Migrating Organisms

The estimation of the quantity of POPs that is net-transported with migratory animals from one location to another is a very complex issue and for a reasonably reliable assessment detailed information would be required on the biology of the organisms (migration pathways, population estimates, body mass, feeding habits, breeding habits, toxicokinetics, etc.) as well as their contaminant burdens. This is why we discuss this issue only in very general terms.

The net transport of POPs with migrating organisms across a boundary will depend on where the organisms take up and where they release their contaminants. Organisms at higher tropic levels take up POPs primarily with their food, whereas the release back to the environment occurs mainly with the feces (in fish and birds also with the eggs), and upon death of the animal. Net transport thus occurs if feeding, fecal excretion or death occur to a different extent in different regions, i.e. on either side of the boundary in question (figure 2). Several examples may serve as an illustration.

Distinct Feeding Areas

As mentioned before, baleen whales spend the winter in subtropical and tropical waters and the summers in high latitudes. However, they feed, and thus take up POPs, almost exclusively in high latitudes. In absence of other information, it may be assumed that the likelihood of a whale to die in a certain area is correlated to the

time the whale spends in that area. Interestingly, this implies a net transport of POPs from high latitude waters to warmer oceans in migrating baleen whales.

Distinct Areas of Fecal Excretion

In general, it may be reasonable to assume that the likelihood of an organism to excrete at a location is correlated to the time it spends at that location. On a small scale, bird cliffs are areas of intense accumulation of feces. It is thus likely that POPs accumulate in the vicinity of bird colonies, as there is a constant delivery of contaminants with the feces (Pecher, 1992). On a local scale that process can cause elevated contamination levels (Wania, 1998).

Distinct Areas of Death

Some migrating fish die in particular, clearly constrained areas. For example, salmon, after spending a large part of their life in the sea, migrate, spawn and die in the fresh water systems of their origin. Eel undertake a similar, though inverted journey returning to their sea water spawning grounds after living in fresh water for several years. In addition to the studies on salmonids and eel as vectors for the LRT of POPs in the Great Lakes-St. Lawrence River ecosystem which will be discussed in more detail below (Dutil et al., 1985, Merna, 1986, Lum et al. 1987, Castonguay et al. 1989, Scrudato and McDowell, 1989), Ewald et al. (1998) have described the entry of PCBs and DDT into the grayling population of the Copper river in Alaska by migrating sockeye salmon. The grayling in a salmon spawning lake had contaminant concentration more than double those found in grayling from a nearby, but salmon free lake.

Transport of Mirex in the Great Lakes Ecosystem

In the literature, we found one study trying to estimate and compare POP transport rates by abiotic media and migrating organisms. Comba et al. (1993) quantified the transport of the pesticide mirex from Lake Ontario to the St. Lawrence river system. For the time period 1950 to 1990, they estimated that 290 kg of that pesticide were transferred downstream with water and sediments, and another 60 kg by migrating eels, suggesting that biotransport was of a similar order of magnitude as the transport in abiotic media. In an earlier estimate, Lum et al. (1987) concluded that eels transfer more mirex out of Lake Ontario than suspended particulate matter. Interestingly, this case is an example of transboundary LRT by migrating organisms, as the mirex was of US American origin (Niagara Falls, NY and Oswego River), whereas the eels passed through Canadian waters and likely deposited, upon spawning and death, the accumulated contaminants in international waters in the Sargasso Sea. Migrating fish in major European rivers, such as the Rhine or Danube, are very likely to carry POPs across international boundaries.

In general, mirex proved a very suitable contaminant for the study of biotransport, because:

1. its sources to the environment are few, localized and well-defined,

2. its physical chemical properties are such (very low solubility and vapor pressure) that it is not subject to significant transport in the atmosphere or the aqueous phase, and
3. it is bioaccumulating.

In addition to the downstream transport of mirex in eels, there are other examples where this pesticide has been instrumental in the study of biological transport of POPs:

1. During investigations of Arctic waterfowl and game birds, it was observed that “birds collected from eastern locations generally contained higher levels of organic contaminants than comparable collections from western sites” (Muir et al. 1997). The hypothesis that this is because the eastern birds pick up POPs in their more contaminated eastern wintering grounds (i.e. the lower Great Lakes and St. Lawrence river system) could be illustrated by the fact that only the eastern birds had measurable residues of mirex, which does not occur in the physical environment of either the western wintering grounds or the Arctic breeding grounds (Muir et al. 1997). Interestingly, this also implies that exposure of Arctic residents to mirex, if it occurs, must be entirely due to LRT in migratory animals.
2. When studying the Salmon River draining into Lake Ontario, Scudato and McDowell (1989) showed that “greater concentrations of mirex were found in the resident brown trout of tributaries accessible to migrating salmonids than in nearby reference tributary inaccessible to migration”. Merna (1986) observed the same for PCBs in resident fish of Lake Michigan tributaries.

The Bioaccessability of POPs Transported by Various Modes

Ewald et al. (1998) pointed out that the pollutants in biological transport media are more readily available for bioaccumulation than those in abiotic media. In the case of the investigated Alaska fresh water system, they point out that the “migrating salmon, the salmon roe and the carcasses are fed directly upon by such predators such as bald eagles, bears, and grayling, allowing the pollutants to be transferred to biota in a direct and efficient way” (Ewald et al., 1998). Similarly, the studies on migrating salmonids in the Great Lakes (Merna 1986, Scudato and McDowell, 1989) concluded that resident fish in salmon-accessible tributaries derived their excess pollutant load by directly ingesting the contaminated salmon eggs. The fact that lower trophic levels and sediments in these tributaries were not enriched in mirex excludes the possibility that mirex was processed within the local food chain prior to uptake in brown trout (Scudato and McDowell, 1989). Although Lum et al. (1987) concede that it is not known whether St. Lawrence Beluga feed on the eel migrating downstream from Lake Ontario, they performed a small calculation indicating that feeding on eel could easily explain the observed mirex levels in these whales. In contrast to biologically transported pollutants, POPs that enter an ecosystem via LRT in abiotic media (air, water, particles) first have to enter the food chain, in order to be taken up by top predators.

Summary and Conclusions

1. Migrating organisms, such as birds, fish and marine mammals, do transport POPs over long distances and across international boundaries.
2. The gross transport rates of POPs with these migrating organisms are usually smaller than, but can under some circumstances be of a similar order of magnitude as, the fluxes in the abiotic media air and water. On a local scale biotic focusing of POPs can even become more significant than contaminant input via abiotic pathways.
3. The relative significance of the biotic transport of a chemical increases with decreasing volatility and solubility in water (i.e. abiotic transport is limited) and increasing bioaccumulation potential (i.e. concentrations in biota are high). A chemical has to be very involatile, very water insoluble as well as highly bioaccumulative for biotic transport to be significant relative to other transport modes. A prime example for such a chemical is mirex. Ewald et al. (1998) even suggested that biotransport may provide a transport mode for POPs, whose physical chemical properties prevent them from LRT in atmospheric and water currents (extremely low volatility or water solubility, high atmospheric degradability, but resistance to metabolic degradation).
4. Whether net transport of POPs by migrating organisms occurs, depends on whether the organisms feed, excrete, spawn or die in distinct areas. The direction of pollutant transport is from the feeding areas to the areas of excretion, spawning and death/decay/consumption.
5. The availability of biologically transported POPs to other organisms, including humans, tends to be higher than for POPs transported in abiotic media. As a means of contaminant delivery to remote organisms and human populations POP transport in migrating organisms may thus be very significant.

References

- AMAP, Arctic Monitoring and Assessment Programme (1997). *Arctic Pollution Issues: A State of the Arctic Environmental Report*. ISBN 82-7655-060-6. AMAP, Oslo, Norway, 188pp.
- Aono, S., Tanabe, S., Fujise, Y., Kato, H., and Tatsukawa, R. **1997**. Persistent organochlorines in Minke Whale (*Balaenoptera acutorostrata*) and their prey species from the Antarctic and the North Pacific. *Environ. Pollut.* **98**, 81-89.
- Baker, R.R. **1978**. Seasonal return migrations by cetaceans. Chapter 28, In: *The evolutionary ecology of animal migration*. London: Hodder & Stoughton, pp. 745-770.
- Barrie, L., MacDonald, R., Bidleman, T., Diamond, M., Gregor, D., Semkin, R., Strachan, W., Backus, S., Bewers, M., Halsall, C., Gobeil, C., Hoff, J., Li, A., Lockhart, L., Mackay, D., Pudykiewicz, J., Reimer, K., Smith, J., Stern, G., Schroeder, W., Wagemann, R., Wania, F. and Yunker, M. **1997**. Chapter 2. Sources, Occurrence and Pathways. In: Jensen, J., Adare, K., and Shearer, R. (Eds.), *Canadian Arctic Contaminants Assessment Report*, Indian and Northern Affairs Canada, Ottawa, 1997, pp. 25-182.
- Braune, B. **1994a**. Trends and effects of environmental contaminants in arctic seabirds, waterfowl, and other wildlife. I. Contaminants in water fowl: native harvest in NWT. In: J.L. Murray, R.G. Shearer (Eds.) *Synopsis of Research Conducted under the 1993/4 Northern Contaminants Program*. Department of Indian Affairs and Northern Development, Environmental Studies No. 72, Ottawa, Canada, pp. 305-311.
- Braune, B. **1994b**. Trends and effects of environmental contaminants in arctic seabirds, waterfowl, and other wildlife. II. Contaminants in Arctic seabirds. In: J.L. Murray, R.G. Shearer (Eds.) *Synopsis of Research Conducted under the 1993/4 Northern Contaminants Program*. Department of Indian Affairs and Northern Development, Environmental Studies No. 72, Ottawa, Canada, pp. 312-326.
- Braune, B. **1995**. Trends and effects of environmental contaminants in arctic seabirds, waterfowl, and other wildlife. II. I. Contaminants in water fowl: native harvest in the Yukon. In: J.L. Murray, R.G. Shearer, S.L. Han (Eds.) *Synopsis of Research Conducted under the 1994/5 Northern Contaminants Program*. Department of Indian Affairs and Northern Development, Environmental Studies No. 73, Ottawa, Canada, pp. 223-228.
- Castonguay, M., Dutil, J.D., and Desjardin, C. **1989**. Distinction between American eels (*Anguilla rostrata*) of different origins on the basis of their organochlorine contaminant levels. *Canadian Journal of Fisheries and Aquatic Sciences* **46**: 836-843.
- Comba, M.E., Norstrom, R.J., Macdonald, C.R., and Kaiser, K.L.E. **1993**. A Lake Ontario-Gulf of St. Lawrence dynamic mass budget for mirex. *Environmental Science and Technology* **27**, 2198-2206.
- De Boer, J., Wester, P.G., Klamer, H.J.C., Lewis, W.E., and Boon, J.P. **1998**. Do flame retardants threaten ocean life? *Nature* **394**, 28-29.
- Dutil, J.-D., Legare, B., and Desjardins, C. **1985**. Discrimination d'un stock de poisson, l'anguille (*Anguilla rostrata*), basee sur la presence d'un produit chimique de synthese, le mirex. *Canadian Journal of Fisheries and Aquatic Sciences* **42**: 455-458.

- Ewald, G., Larsson, P., Linge, H., Okla, L., and Szarzi, N. **1998**. Biotransport of organic pollutants to an inland Alaska lake by migrating sockeye salmon (*Oncorhynchus nerka*). *Arctic* **51**: 40-47.
- Iwata, H., Tanabe, S., Sakai, N., and Tatsukawa, R. **1993**. Distribution of persistent organochlorines in the oceanic air and surface seawater and the role of ocean on their global transport and fate. *Environmental Science and Technology* **27**: 1080-1098.
- IWC (International Whaling Commission), **1998**. Whale Population Estimates: (<http://ourworld.compuserve.com/homepages/iwcoffice/Estimate.htm>).
- Lockyer, C.H. and Brown, S.G. **1981**. The migration of whales. In: Aidley, D.J. (Ed.) *Animal Migration*, Cambridge University Press, Cambridge, 105-137.
- Lum, K.R., Kaiser, K.L.E., and Comba, M.E. **1987**. Export of mirex from Lake Ontario to the St. Lawrence estuary. *The Science of the Total Environment* **67**: 41-51.
- Merna, J.W. **1986**. Contamination of stream fishes with chlorinated hydrocarbons from eggs of great lakes salmon. *Transactions of the American Fisheries Society* **115**: 69-74.
- Muir, D., Braune, B., DeMarch, B., Norstrom, R., Wagemann, R., Gamberg, M., Poole, K., Addison, R., Bright, D., Dodd, M., Duschenko, W., Eamer, J., Evans, M., Elkin, B., Grundy, S., Hargrave, B., Hebert, C., Johnstone, R., Kidd, K., Koenig, B., Lockhart, L., Payne, J., Peddle, J., and Reimer, K. **1997**. Chapter 3. Ecosystem Uptake and Effects. In: Jensen, J., Adare, K., and Shearer, R. (Eds.), *Canadian Arctic Contaminants Assessment Report*, Indian and Northern Affairs Canada, Ottawa, 1997, pp. 183-294.
- O'Shea, T.J. and Brownwell Jr., R.L. **1994**. Organochlorine and metal contaminants in baleen whales: a review and evaluation of conservation implications. *Science of the Total Environment* **154**: 179-200.
- Pecher, K. **1992**. Schadstoffe auch in Polargebieten? Organochlorverbindungen als Indizien globaler Umweltverschmutzung. *Geographische Rundschau* **44**:231-236
- Scudato, R.J. and McDowell, W.H. **1989**. Upstream transport of mirex by migrating salmonids. *Canadian Journal of Fisheries and Aquatic Sciences* **46**: 1484-1488.
- Varanasi, U., Stein, J.E., Tilbury, K.L., Meador, J.P., Sloan, C.A., Brown, D.W., Chan, S.-L., and Calambokidis, J. **1993**. Chemical contaminants in gray whales (*Eschrichtius robustus*) stranded in Alaska, Washington, and California, U.S.A. NOAA Technical Memorandum NMFS-NWFSC-11.
- Wania, F., and Mackay, D. **1998**. Global chemical fate of α -hexachlorocyclohexane. 2. Use of a global distribution model for mass balancing, source apportionment, and trend predictions. Accepted for publication in *Environ. Toxicol. Chem.*
- Wania, F. **1998**. On the origin of elevated levels of persistent chemicals in the environment. Submitted to *ESPR - Environ. Sci. Pollut. Res.*

Appendix I:**Compilation of Typical Concentrations of PCBs, DDTs and HCHs in Odontoceti**

Mean or range of concentrations in
blubber mg/kg wet wt.

Species, location	n	DDTs	PCBs	HCHs	Ref.
11 odontoceti species, N- Pacific + Indian Ocean	50	33	32	1.1	Prudente et al. 1997
long-finned pilot whales, Faroe islands	130	5 to 27	10 to 35	-	Borrell et al. 1995
narwhal, Pond Inlet, NWT	M15 F 6	M 5.9 F 2.5	M 5.2 F 2.7	M 0.16 F 0.16	Muir et al. 1992
Baid's beaked whale, NW Pacific	37	M 13 F 10	M 3.3 F 2.5	-	Subramanian et al. 1988
beluga whale, St Lawrence Estuary	26	1.2 to 225	5.7 to 576	-	Martineau et al. 1987
bottlenose dolphins, Wales	2	37, 40	148, 156	n.d.	Law et al. 1995
wide-sided dolphin, Ireland + Scotland	17	0.1 to 55	0.7 to 64	-	McKenzie et al. 1997
harbour porpoise, NE-America	196	1 to 20	1.5 to 75	0.03 to 0.9	Westgate et al. 1997
harbour porpoise, North Sea	16	1.4 to 19		0.08 to 1	Vetter et al. 1996

Borrell, A., Bloch, D., and Desportes, G. **1995**. Age trends and reproductive transfer of organochlorine compounds in long-finned pilot whales from the Faroe islands. *Environ. Pollut.* **88**, 283-292.

Law, R.J., Allchin, C.R., and Morris, R.J. **1995**. Uptake of organochlorines (chlorobiphenyls, dieldrin; Total PCB & DDT) in bottlenose dolphins (*Tursiops truncatus*) from Cardigan Bay, West Wales. *Chemosphere* **30**, 547-560.

Martineau, D., Béland, P., Desjardins, C., and Lagacé, A. **1987**. Levels of organochlorine chemicals in tissues of beluga whales (*Delphinapterus leucas*) from the St Lawrence Estuary, Québec, Canada. *Arch. Environ. Contam. Toxicol.* **16**, 137-147

McKenzie, C., Rogan, E., Reid, R.J., and Wells, D.E. **1997**. Concentrations and patterns of organic contaminants in Atlantic white-sided dolphins (*Lagenorhynchus acutus*) from Irish and Scottish waters. *Environ. Pollut.* **98**, 15-27.

Muir, D.C.G., Ford, C.A., Grift, N.P., Stewart, R., and Bidleman, T.F. **1992**. Organochlorine contaminants in narwhal (*Monodon monoceros*) from the Canadian Arctic. *Environ. Pollut.* **75**: 307-316.

Prudente, M., Tanabe, S., Watanabe, M., Subramanian, A., Miyazaki, N., Suarez, P., and Tatsukawa, R. **1997**. Organochlorine contamination in some Odontoceti Species from the North Pacific and Indian Ocean. *Marine Environmental Research* **44**, 415-427.

Subramanian, A., Tanabe, S., and Tatsukawa, R. **1988**. Estimating some biological parameters of Baird's beaked whales using PCBs and DDE as tracers. *Marine Pollution Bulletin* **19**, 284-287.

Vetter, W., Luckas, B., Heidemann, G., and Skirnisson, K. **1996**. Organochlorine residues in marine mammals from the Northern hemisphere - A consideration of the composition of organochlorine residues in the blubber of marine mammals. *Sci. Total Environ.* **186**, 29-39.

Westgate A.J., Muir, D.C.G., Gaskin, D.E., and Kingsley, M.C.S. **1997**. Concentrations and accumulation patterns of organochlorine contaminants in the blubber of harbour porpoises, *Phocoena phocoena*, from the coast of Newfoundland, the Gulf of St. Lawrence and the bay of Fundy/Gulf of Maine. *Environ. Pollut.* **95**, 105-119.