Jules M. Blais, David W. Schindler, Derek C.G. Muir, Martin Sharp, David Donald, Melissa Lafrenière, Eric Braekevelt and William M.J. Strachan

Melting Glaciers: A Major Source of Persistent Organochlorines to Subalpine Bow Lake in Banff National Park, Canada

Organochlorine pesticides and polychlorinated biphenyls (PCBs) are ubiquitous and persistent in the environment. They are known to concentrate in cold environments as a result of progressive evaporation from warm regions, and condensation in colder regions. In this study we show that melting glaciers supply 50 to 97% of the organochlorine inputs to a subalpine lake in Alberta, Canada, while contributing 73% of input water. Tritium analyses indicated that during the mid- to late summer warm period, at least 10% of the glacial melt originated from ice that was deposited in 1950–1970, when it was more contaminated with organochlorines. This finding suggests that climate warming may cause melting glaciers to become increasing sources of contaminants to freshwaters. Organochlorines from glacial streams were largely in dissolved form because the organic-poor glacial clays had a limited sorption capacity for the more hydrophobic chemicals.

INTRODUCTION

Persistent organic pollutants (POPs), have been shown to reach the most remote regions of the Earth (1). Among the pollutants of greatest concern are organochlorine pesticides (such as the hexachlorocyclohexanes (α and γ isomers), endosulfan, aldrin, dieldrin, chlordane), polychlorinated biphenyls (PCBs), polychlorinated dibenzodioxins and furans (PCDD/F) and DDT (see description of selected POPs in Table 1). The UN Economic Commission for Europe considers reducing future production and use of these chemicals as a top priority (2).

These chemicals are characterized as toxic, hydrophobic, and persistent in the environment. Their hydrophobicity causes them to assimilate rapidly in biological tissues, and as a result, they may be biomagnified in food chains. They reach concentrations in organisms from remote northern climates that are higher than those found in more industrialized parts of the world (3). This is of special concern because aboriginal people rely on these contaminated organisms for food (4). The concentrations of polychlorinated biphenyls (PCBs) in human breast milk from northern Inuit communities were 5 times higher than in southern areas where PCBs were heavily used (3). Hexachlorobenzene concentrations in human breast milk from Inuit communities were over 10 times higher than in southern areas (1). These results prompted a research program to study the transport and fate of POPs in the north (1). In Lake Lebarge, Yukon, the concentrations of toxaphene, a chlorinated pesticide transported through air from distant sources, were high enough in fish for Health Canada to issue a restriction on consumption of the fish on which local aboriginals relied (5).

The transport of POPs to northern latitudes results from volatilization from warm source areas and redeposition to cold Arctic areas. This contributes to high concentrations of POPs in Arctic food chains (1, 6). In earlier studies, we showed that similar condensation of airborne POPs in cold alpine environments results in surprisingly high concentrations of these chemicals in snow and surface waters (7, 8). In the mountains of western Canada, both the deposition of semivolatile organochlorines and the concentrations of certain organochlorines in fish increase dramatically with elevation (8), occasionally causing concentrations of POPs in fish to approach levels that would trigger health advisories (9). Organochlorine concentrations in fish also tend to be higher in glacier-fed lakes than in lakes at similar elevations that are fed only by annual precipitation and runoff, suggesting that glaciers may act as a source of these chemicals to surface waters (9). High concentrations of POPs are found in the foodweb of glacier-fed, subalpine Bow Lake near the continental divide between Alberta and British Columbia (8, 10). Donald (9) observed that concentrations of several organochlorines were higher in Bow Lake than other lakes surveyed in the area. Compounds identified included lindane, endosulfan, toxaphene, PCBs and DDT. This is not attributable to biomagnification along complex foodchains (10), as was observed in other lakes (5, 11). A possible alternative explanation is that elevated concentrations of POPs in the foodwebs of glacier-fed lakes reflect enhanced delivery of these contaminants to the lakes from glacial runoff sources.

Glaciers are known to accumulate atmospherically-derived contaminants, and have provided records of the deposition of POPs over time (12–14). For instance, at Snow Dome, 20 km north of Bow Lake, in Banff National Park, Alberta, Donald et al. (12) found elevated concentrations of several POPs in layers of ice deposited in the 1950s to as late as the early 1990s. For example, αHCH showed a steady decline over time in glacial strata, with 1 ng L^{-1} in strata deposited in the 1950s, but only 0.05 ng L^{-1} in horizons deposited in the early 1990s (12). Likewise, DDT peaked in glacial strata corresponding to the early 1980s at 2 ng L^{-1} compared to 0.01 ng L^{-1} in recent strata (12). Endosulfan peaked at 0.2 ng L^{-1} in horizons deposited in the late 1980s, compared to 0.03 ng L^{-1} in contemporary strata (12). Not all organochlorines followed this decreasing pattern, however. Hexachlorobenzene increased in the glacier, from 0.001 ng L^{-1} in horizons deposited in the 1960s, to a surface peak of 0.02 ng L^{-1}. Thus, older, contaminated ice at the surface of a glacier in its ablation zone is likely to result in release of POPs to the environment when surface melting occurs.

Another possibility is that dissolved phase concentrations of POPs in glacial runoff are unusually high because of low volatilization losses from low temperature meltwaters and limited catchment retention. The potential for adsorption of POPs onto glacial sediments may be limited by their low organic matter content (15). It may also be limited because, under summer conditions, much glacial runoff becomes channelized on the glacier surface, and is then routed rapidly through englacial and subglacial conduits, having little contact with catchment soils and sediments. By contrast, in nonglaciated alpine catchments, snowmelt is likely to percolate through the residual snowpack and infiltrate into underlying organic and mineral soils before it reaches a stream channel. This significantly increases the chances for POPs to be lost by adsorption onto soils and sediments. We tested these hypotheses by determining the potential for dissolved phase and particle-bound fluxes of organochlorines to Bow Lake in glacial streams and streams fed only by annual snowmelt and

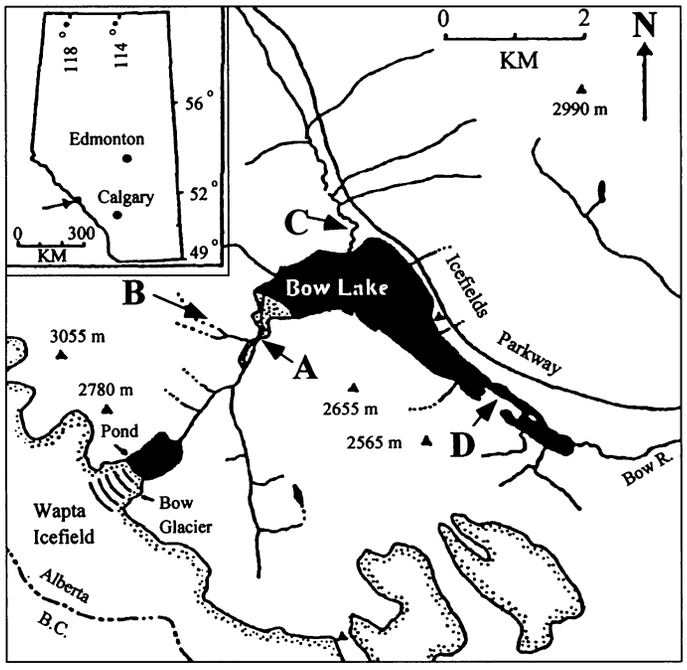


Figure 1. Study sites in the area around Bow Lake. The 4 streams sampled are shown with arrows. A is the glacial stream; B is the alpine stream; C is the valley stream; and D is the lake's outflow.

rainfall. This study is the first to investigate the impact of glaciers on the delivery of organochlorines to surface waters.

STUDY SITE

Subalpine Bow Lake, in Banff National Park, Alberta, Canada, is located near the Continental Divide between Alberta and British Columbia (Fig. 1). The principal inflow to the lake (with a surface area of 2.8 km^2) is a stream fed by meltwater from the Wapta Icefield. The catchment area of this stream is approximately 27 km^2, approximately 11 km^2 (41%) of which is glacial ice.

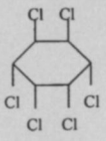
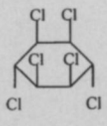
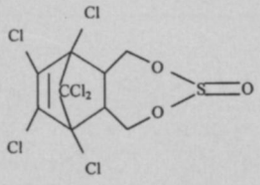
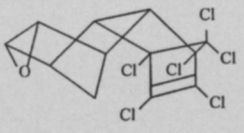
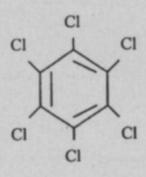
METHODS

Three streams draining into Bow Lake (Fig. 1) were sampled. The "glacial" stream (A; Fig. 1) is fed primarily from glacial melt waters. In contrast, the "alpine" stream (B) is located in an alpine catchment with steep slopes and little vegetation, but no permanent ice or snow. The "valley" stream drains a low gradient subalpine catchment (C) with a thick vegetation cover of low lying shrubs (*Salix* spp.) and a mixed forest of spruce and fir. The outflow stream from Bow Lake (D) was also sampled.

Water samples were collected from each stream twice a month between early June and late August 1997. This period spans the snow-free season at this location, which is generally from June to September or early October. At each sample site, hourly measurements of stream stage, electrical conductivity and water temperature were recorded using a data logger (Campbell Scientific). Stream waters were collected using methods in Donald et al. (8), and snow samples were collected using methods in Blais et al. (7). Rain samples were collected in a precipitation collector that passed rainwater immediately through a solid phase extraction column (XAD resin). This resin was leached into hexane by Soxhlet extraction in the laboratory to remove the analytes for analysis by gas chromatography.

Water was also collected in airtight vials for tritium analysis using scintillation counting. Tritium concentrations in precipitation were much higher during the period of atmospheric bomb testing (16), thus we hypothesized that increased levels of tritium in runoff would indicate that ice or groundwater > 10 yrs in age were contributing to runoff. Fluxes were calculated by multiplying streamwater concentrations of organochlorines with daily mean water discharge rates. Concentrations are expressed as C_w (concentration in water as pg L^{-1}) and C_{pv} (concentration on particles on a water volume basis, in pg L^{-1}). The distribution coefficients in this paper (K_d) account for suspended particle concentrations in the water and are calculated as the ratio of C_{pm} (in units of pg contaminant g^{-1} dry sediment) to C_w (pg contaminant L^{-1}).

Table 1. Details for selected organochlorines discussed in this paper (2).

Organochlorine	Structure	Use	Status
αHexachloro-cyclohexane (HCH)		By-product of insecticide manufacture	Major restrictions in N. America, W. Europe
γHexachloro-cyclohexane (HCH)		General insecticide (Mainly used as a seed dressing on corn, beans, peas, canola)	Minor restrictions in N. America, W. Europe
αEndosulfan		Insecticide (Fruit, vegetables, tobacco)	Minor restrictions in N. America, W. Europe
Dieldrin		Insecticide, termiticide	Prohibited in N. America, W. Europe
Hexachlorobenzene		General pesticide (insecticide, fungicide)	Prohibited use as pesticide in N. America, W. Europe. Still produced as a by-product of incinerators, chlorine-based metal extraction, etc.

Sample Extraction and Analysis by Gas Chromatography

Water samples were filtered through precombusted Gelman GF/A filters (pore size 0.6 mm). At least 65 L per sample were extracted into dichloromethane, using a high volume Goulden extractor (17). Internal standards were also extracted to determine extraction efficiencies. The solvent extracts were concentrated by roto-evaporation, and separated into 3 fractions with 1.2% deactivated Florisil as in other studies (7, 18, 19),

using the following solvent mixtures: fraction 1:37 ml hexane; fraction 2:38 mls of 80:20 hexane: dichloromethane; fraction 3:52 mls of 50:50 dichloromethane:hexane. This procedure allowed a separation of the more polar organochlorine pesticides (fractions 2 and 3), from the more nonpolar PCBs and chlorobenzenes (fraction 1). Extracts were injected into a gas chromatograph equipped with a ^{63}Ni electron capture detector using a 30 m DB-5 column with He carrier gas. Chromatographic interpretation of peaks was performed using HP Chemstation software.

All samples were filtered in the field through 0.45 micron cellulose nitrate membranes immediately after collection. Alkalinity and pH were measured on site following filtration, and filtered aliquots of sample were collected for ion analysis.

Alkalinity was measured by titration with sulfuric acid, the end point was determined colorometrically using brom-cresol green-methyl red indicator. The total error of the titration is less than ± 2% (for $HCO_3^- > 400$ μeq L^{-1}). pH was determined using a portable Orion 290A digital pH meter (error ± 0.1 pH unit).

Ion samples were stored in polyethylene vials and kept refrigerated until time of analysis. Cation samples were acidified to pH 2 with methanesulfonic acid upon return from the field. Major anion (Cl^-, NO_3^-, and SO_4^{2-}) and cation (Na^+, K^+, Mg^{2+}, and Ca^{2+}) concentrations were determined by ion chromatography on a Dionex 500 ion chromatograph.

Total dissolved solids (TDS) in mg L^{-1} were calculated as the sum of all ions and alkalinity as HCO_3^-. Dissolved organic carbon (DOC) was measured using an Ionics Corporation 1555 DOC analyzer with 100% Pt catalyst.

RESULTS AND DISCUSSION

The glacial stream supplied 73% of total water inputs to Bow Lake (Fig. 2). The valley and alpine streams had snowmelt-fed runoff pulses in spring, followed by gradual declines in water discharge over the summer (contributing 23% and 1% of water inputs to Bow Lake, respectively, with the remainder (3%) from rain). By contrast, discharge in the glacial stream remained high through the summer because ice-melt replaced snowmelt as a water source after annual snow cover melted. Maximal discharge from the glacial stream was observed in early June during snowmelt, and again in late July and early August during the ice melting period (Fig. 2). Rainfall was sporadic through the season (Fig. 2). Tritium activity was below detection limits (< 6 tritium units (TU)) in the alpine and valley streams, and also in rainfall throughout the sampling period. However, tritium was detectable in the glacial stream after late June, suggesting a contribution to runoff from ice deposited during the period when tritium levels in precipitation were elevated as a result of atmospheric bomb testing (1955–1970s). Tritium levels in glacier ice were not measured in this study. However, concentrations of tritium in precipitation at Ottawa, Ontario (latitude 45°25' N, longitude 75°40' W), peaked at 1000 TU in 1963. Tritium has a half-life of 12 years, so ice dating from this period that contained similar concentrations of tritium at the time of deposition would still have contained ~ 125 TU in 1997. Tritium concentrations in glacial runoff were below detection limits earlier in the summer because the glacier was still snow-covered and tritium-rich ice was not exposed to ablation. However, once it was exposed and tritium was detected in the glacial stream, it continued to be detected throughout the rest of the summer. It was also detected in the Bow Lake outflow stream in early August (Fig. 2). A profile from nearby Snow Dome shows that maximal enrichment of organochlorine pesticides in glacier ice coincides with the period of atmospheric nuclear weapons testing, when precipitation contained the highest levels of tritium (12). Organochlorines in glacial runoff during the period when tritium was detectable may therefore have been derived in part from sources in old glacier ice.

Figure 2. Stream discharge for the 4 streams, rainfall, and tritium activity are shown against Julian day for the summer of 1997.

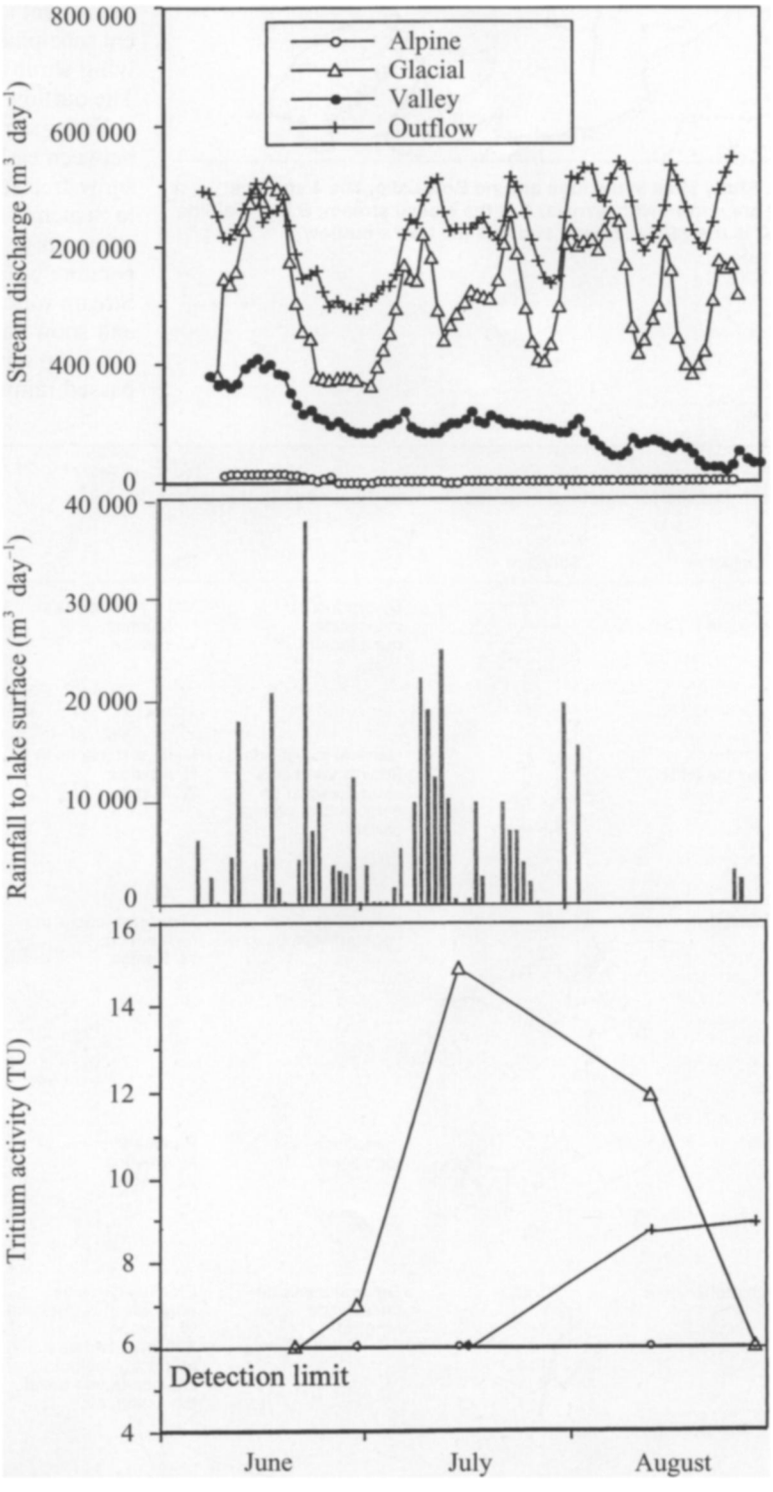


Table 2. Average concentrations (standard errors in brackets) of selected organochlorines in several environmental compartments (A). Dissolved (C_w) and particle-bound (C_{pv}) concentrations are shown separately. Fluxes for organochlorines in water (Φ_w) and suspended particles (Φ_p) from streams (B) were calculated in mg over the period spanning June–August, 1997. ND is nondetectable. Fluxes of organochlorines in precipitation were calculated as direct deposition in mg reaching the lake's surface (surface area = 2.8 km^2). Snowfall was based on snow concentrations of organochlorines in March, 1997, where snow pack was 180 mm water equivalent. Rainfall was measured over the June–August, 1997 period. Both snow and rain samples were unfiltered and include both wet and dry precipitation. A total of 120 mm of rain fell during that period. Mean organochlorine concentrations in rain during the summer season of 1994 were measured at Boulder, B.C., 50 km west of Bow Lake, and used in the flux calculations. HCH is hexachlorocyclohexane, and HCB is hexachlorobenzene.

A:
Concentrations (pg L^{-1})

	αHCH		γHCH		αEndosulfan		Dieldrin		HCB		Particle
	C_w	C_{pv}	C_w	C_{pv}	C_w	C_{pv}	C_w	C_{pv}	C_w	C_{pv}	Conc (mg L^{-1})
Streams:											
Glacial	220 (38)	1.9	110 (30)	0.9	19 (6)	4.8	22 (4)	3.2	5.7 (1)	0.2	5.4 (0.9)
Alpine	33 (7)	ND	25 (8)	ND	11 (5)	ND	11 (2)	ND	6.2 (1)	ND	0.3 (0.2)
Valley	24 (3)	1.2	20 (8)	1.0	6 (1)	3.8	7 (1)	2.8	5.0 (1)	0.0	2.0 (0.9)
Precipitation:											
Snow	270 (89)		220 (66)		360 (180)		62 (10)		15 (3)		
Rain	4300 (1700)		1200 (700)		790 (1000)		110 (150)		46 (30)		
log K_{ow}	3.8		3.7		4.7		3.7		5.0		

B:
Fluxes (mg season^{-1})*

	αHCH		γHCH		αEndosulfan		Dieldrin		HCB		Water flux m^3
	Φ_w	Φ_p	Φ_w	Φ_p	Φ_w	Φ_p	Φ_w	Φ_p	Φ_w	Φ_p	
Streams:											
Glacial	5200	44	2600	21	420	106	530	77	140	6	2.5×10^7
Alpine	13	0	10	0	4	0	4	0	2	0	3.6×10^5
Valley	184	9	157	8	46	28	57	23	40	0	8.0×10^6
Precipitation:*											
Snow	140		110		190		32		8		5.0×10^5
Rain	1400		400		260		36		15		3.4×10^5
$\frac{\Phi_{Streams}}{\Phi_{Atmosphere}}$	3.5		5.5		1.3		10.2		9.0		

* 'Season' is defined as the period between June and August 1997 for tributary and rain fluxes. 'Snow' refers to the snowpack that was sampled in March 1997 and represents that accumulation year.

In all, 9 chlorobenzenes, 15 organochlorine pesticides, and 80 PCB congeners were detected regularly in the streams, snow-fall and rainfall. A detailed budget of inputs from the 3 tributaries as well as rainfall and snowfall for 5 of the most abundant compounds is in Table 2. Fluxes of other constituents, including 8 of the chlorobenzenes, 8 other organochlorine pesticides, 7 of the PCB congeners and the sum of all detected 80 PCB congeners are shown in Table 3. Inputs of many compounds to Bow Lake, most notably the di- and trichlorobenzenes αHCH, γHCH, and dieldrin were supplied to Bow Lake predominantly from the glacial stream (Tables 2 and 3). This stream provided 50–97% of the stream inputs of these compounds (Tables 2B and 3), compared with only 73% of the input of water runoff.

Contributions by rain and snow to the lake surface were second only to glacial inputs as a source of POPs to Bow Lake, as expected from high fluxes of these compounds from the atmosphere (7). The contribution of rain was particularly important for

Table 3. Summary data for the transport of other organochlorine compounds to Bow Lake. All values are in mg season^{-1} as in Table 2. Fluxes for organochlorines in water (Φ_w) and suspended particles (Φ_p) from tributaries were calculated in mg over the period spanning June–August, 1997, as in Table 2. Fluxes of chemical on particles in the alpine stream (Φ_p) were too low to report. DCB is dichlorobenzene, TCB is trichlorobenzene, TTCB is tetrachlorobenzene, PECB is pentachlorobenzene. Log K_{ow} are from refs 22, 23.

Compound	Glacial stream		Valley stream		Alpine stream	Rain	Snow	$\frac{\Phi_{Streams}}{\Phi_{Atmosphere}}$	Log K_{ow}
	Φ_w	Φ_p	Φ_w	Φ_p	Φ_w	Φ_{total}	Φ_{total}	Ratio	
1,3-DCB	2300	3800	420	100	18	120	27	45.2	3.4
1,4-DCB	1100	4400	390	190	14	1700	1200	2.1	3.4
1,2-DCB	820	5000	220	94	7	89	110	30.9	3.4
1,3,5-TCB	130	16	76	0.9	3	46	2	4.7	4.1
1,2,4-TCB	280	140	83	2	3	19	25	11.5	4.1
1,2,3-TCB	92	30	24	0.4	1	17	6	6.4	4.1
1,2,3,4-TTCB	31	8	5	0.1	0.6	5	1	7.5	4.5
PECB	70	14	28	1	2	0	1	115.0	5.0
Heptachlor epoxide	190	38	10	5	0.9	43	5	5.1	5.0
γ–chlordane	33	1100	2	90	0.2	18	1	64.5	~6
α–chlordane	52	64	3	3	0.02	14	3	7.2	6.0
p,p'-DDE	20	28	7	1	0.2	16	2	3.1	5.7
Endrin	96	63	7	3	0.5	0	2	84.8	5.2
β-endosulfan	590	29	120	4	5	640	26	1.1	3.8
p,p'-DDD	81	90	4	5	0.2	0	2	90.1	5.5
p,p'-DDT	26	40	7	4	0.3	10	11	3.7	6.2
PCB 8/5	510	210	160	7	8	29	17	19.5	5.1
PCB 18	260	470	81	17	4	11	18	28.7	5.6
PCB 26	60	140	19	5	1	7	3	22.5	~5.8
PCB 31-28	640	3500	210	150	12	58	86	31.3	~5.8
PCB 52	330	2700	95	130	6	7	46	61.5	6.1
PCB 138-163	420	1400	100	32	6	12	5	115.2	~7
PCB 180	70	200	26	9	2	22	2	12.8	~7
Σ PCB	190 000	21 000	72 000	1400	3000	1300	560	154.5	4.3–8.2

HCH isomers, endosulfan (Table 2), and 1,4 DCB (Table 3). Lindane (γHCH) and endosulfan are still in use in Canada (2), thereby explaining in part their high contribution by rainfall.

Total concentrations (C_w+ C_{pv}) of most organochlorines in all streams were lower than in snowfall and rainfall (Table 2A). This indicates that losses occurred during melt and runoff, either by volatilization or catchment retention. Concentrations of most POPs were higher in the glacial stream than in the other streams (Fig. 3). Concentrations were between 2 and 50 times higher in the glacial stream than in the valley stream for most organochlorine pesticides. This suggests that losses of these compounds to retention and/or volatilization in the glacial catchment were less than in the valley catchment. However, concentrations of the more hydrophobic polychlorinated biphenyls (PCBs) tended to be similar in both streams, suggesting that for these hydrophobic compounds, losses to retention and volatilization were similar in the 2 catchments.

Total concentrations of POPs were, on average, 29 times higher in the glacial stream than the valley stream. Even though the mean particle concentration in the glacial stream was 2.8 times higher than in the valley stream, the dissolved fraction of POPs measured (C_w/(C_w+C_{pv})) was similar in the glacial (75 ± 35%) and valley (79 ± 34%) streams. This implies that the higher dissolved concentrations in the glacial stream can be explained at least in part by relatively low adsorption on the sediments transported by the glacial stream.

Retention of organochlorines in vegetated catchments is generally considered to be high as a result of sorption to soils and vegetation (20). The glacial stream is fed by cold meltwaters, which become channelized on the glacier surface and pass through major englacial and subglacial drainage conduits in which they have limited contact with catchment soils. This may diminish the potential for losses of organochlorines due to sorption. Although some fraction of the runoff probably does follow more distributed subglacial drainage paths that allow greater water-sediment contact, this fraction is normally small during the summer melt season, except under recession flow conditions. Under summer conditions it is probably never a major component of runoff from Bow Glacier because the glacier currently terminates in a small proglacial lake (Fig. 1) with an estimated water residence time of ca. 40 days. Water storage in this lake effectively mixes and homogenizes runoff from the glacier. If most glacial runoff has limited contact with soils and sediments, the potential for losses of organochlorines due to sorption is probably reduced relative to the potential for loss from snowmelt waters in the valley catchment. These likely infiltrate both organic and inorganic soils underlying the snowpack prior to draining to the valley stream. Comparison of the total dissolved solids, alkalinity, and dissolved organic carbon content of the waters from the glacial and valley streams (Table 4) indicates that waters from the valley stream have had greater contact with both mineral and organic soils than those from the glacial stream. Low retention of organochlorines in the glacial catchment may therefore also be attributable to the relatively low organic carbon content of sediments from the glacial stream (organic carbon fraction, f_{OC} = 0.05 ± 0.001) compared to that of sediments from the valley stream (f_{OC} = 0.15 ± 0.003). Particle-bound transport was more important for more hydrophobic compounds in all tributaries, including the glacial stream, because these compounds have a greater

Figure 3. Concentrations of αHCH, γHCH, dieldrin, α endosulfan and HCB are shown for the 3 inflowing streams into Bow Lake during the summer of 1997.

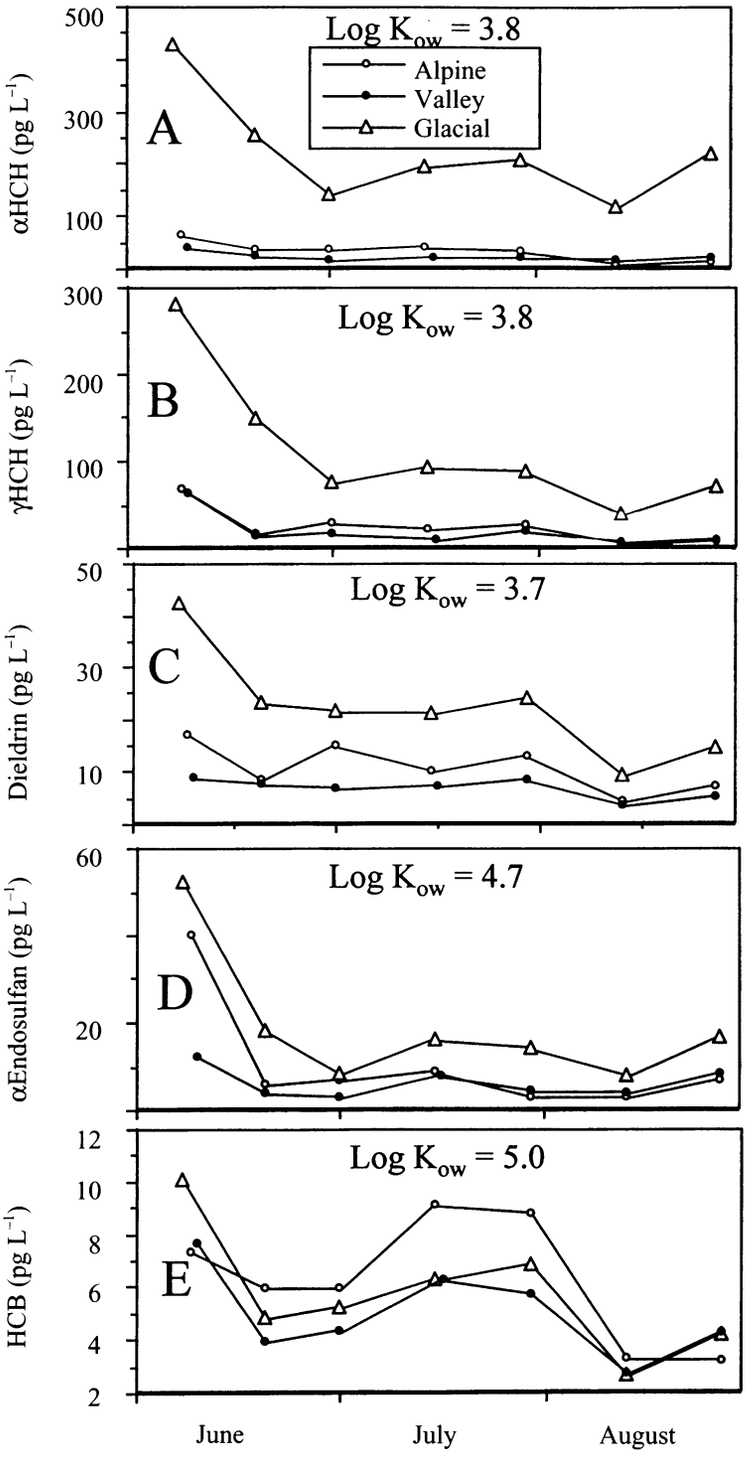


Table 4. Concentrations (mean ± standard error) of dissolved organic carbon (DOC), chlorophyll *a*, total dissolved solids (TDS), and alkalinity (Alk.) in the 3 streams.

Stream	DOC (mg L^{-1})	Chl. *a* (μg L^{-1})	TDS (mg L^{-1})	Alk. (μeq L^{-1})
Glacial	0.33 ± 0.02	0.04 ± 0.005	90 ± 2	916 ± 10
Valley	0.65 ± 0.2	0.06 ± 0.01	148 ± 3	1650 ± 20
Alpine	0.23 ± 0.01	0.005 ± 0.002	124 ± 3	1390 ± 20

affinity for mineral surfaces than less hydrophobic contaminants.

Further evidence of the higher sorptive capacity of subalpine soils for these organic compounds is provided by the distribution coefficients (K_d) for each compound in the different streams. Distribution coefficients are defined as the particle/dissolved concentration ratios (C_{pm}/C_w). For each stream, values of K_d are related to the hydrophobicity of each compound as measured by the octanol-water partition coefficients (K_{ow}, (21, 22) as follows:

Glacial stream:

$$\text{Log } K_d = -0.82 + 0.49 \log K_{ow},\ r^2 = 0.47,\ p << 0.05 \qquad \text{Eq. 1}$$

Valley stream:

$$\text{Log } K_d = 0.52 + 0.36 \log K_{ow},\ r^2 = 0.43,\ p << 0.05 \qquad \text{Eq. 2}$$

Thus, for most compounds, K_d is lower in the glacial stream than in the valley stream. This reflects the lower sorptive capacity of the glacial soils and sediments, which allows a higher proportion of these substances to remain in solution.

CONCLUSIONS

This study shows that glaciers are important contributors of persistent organic pollutants to surface waters. The melting of layers contaminated in the past by higher concentrations of some compounds (12) contributes to the high values, suggesting that as climate warming increases glacial melting, contaminant flow from glaciers may increase. Glacial streams contain unusually high proportions of POPs in solution, because of the low potential for these compounds to adsorb to suspended sediments in the glacial stream that are characterized by low organic matter content. This is partly a function of the low organic content of the sediments, and partly a function of hydrological flow routing in glacial systems which minimizes contact between runoff and catchment soils. The prevalence of inputs of organochlorine compounds in the dissolved phase, coupled with the low dissolved organic carbon concentrations in the lake water (0.46 ± 0.12 mg L^{-1}) indicates a high bioavailability of these compounds to aquatic biota (23). These results likely explain why concentrations of these compounds in fish and other aquatic biota are elevated in glacier-fed lakes (9).

References

1. Barrie, L.A., Macdonald, R., Bidleman, T. and 22 others. 1997. *Canadian Arctic Contaminant Assessment Report*. Ch. 2. Department of Indian and Northern Affairs, Ottawa, Canada.
2. IRPTC/UNEP 1999. *International Register of Potentially Toxic Chemicals*. IRPTC Databases. Health and Welfare Canada, Minister of Supply and Services Canada, Ottawa, Ontario. http://IRPTC.UNEP.CH/POPS/
3. Dewailly, E.A., Nantel, J.P., Weber, J.P. and Meyer, F. 1989. High levels of PCBs in breast milk of Inuit women from Arctic Quebec. *Bull. Environ. Contam. Toxicol. 43*, 641–646.
4. Schindler, D.W., Kidd, K.A., Muir, D.C.G. and Lockhart, W.L. 1995. The effects of ecosystem characteristics on contaminant distribution in northern freshwater lakes. *Sci. Tot. Environ. 160/161*, 1–17.
5. Kidd, K.A., Schindler, D.W., Muir, D.C.G., Lockhart, W.L. and Hesslein, R.H. 1995. High concentrations of toxaphene in fishes from a subarctic lake. *Science 269*, 240–242.
6. Wania, F. and Mackay, D. 1993. Global fractionation and cold condensation of low volatility organochlorine compounds in polar regions. *Ambio 22*, 10–18.
7. Blais, J.M., Schindler, D.W., Muir, D.C.G., Kimpe, L.E., Donald, D.B. and Rosenberg, B. 1998. Accumulation of persistent organochlorine compounds in mountains of western Canada. *Nature 395*, 685–688.
8. Donald, D., Stern, G.A., Muir, D.C.G., Fowler, B.R., Miskimmin, B.M. and Bailey, R. 1998. Chlorobronanes in water, sediment, and fish from toxaphene treated and untreated lakes in western Canada. *Environ. Sci. Technol. 32*, 1391–1397.
9. Donald, D. 1993. *Polychlorinated Biphenyls and Organochlorine Pesticides in the Aquatic Environment Along the Continental Divide Region of Alberta and British Columbia*. Inland Waters Directorate, Regina, Sask., Canada.
10. Campbell, L. 1997. *The Use of Stable Isotope Ratios to Discern Organochlorine Bioaccumulation Patterns in a Sub-Alpine Rocky Mountain Lake Foodweb*. MSc Thesis, University of Alberta, Edmonton, Alberta, Canada.
11. Rasmussen, J.B., Rowan, D.J., Lean, D.R.S. and Carey, J.H. 1989. Food chain structure in Ontario lakes determines PCB levels in lake trout (*Salvelinus namaycush*) and other pelagic fish. *Can. J. Fish. Aquat. Sci. 47*, 2030–2038.
12. Donald, D., Syrgiannis, J., Crosley, R., Holdsworth, G., Muir, D.C.G., Rosenberg, B., Sole, A. and Schindler, D.W. 1999. Delayed deposition of organochlorine pesticides at a temperate glacier. *Environ. Sci. Technol. 33*, 1794–1798.
13. Gregor, D.J., Peters, A.J., Teixeira, C., Jones, N. and Spencer, C. 1995. The historical residue trend of PCBs in the Agassiz Ice Cap, Ellesmere Island, Canada. *Sci. Tot. Environ., 160/161*, 117.
14. AMAP 1998. *Arctic Monitoring and Assessment Program: Arctic Pollution Issues*. AMAP Secretariat, PO Box 8100 Dep, N-0032 Oslo, Norway.
15. Braekevelt, E. 2000. *Effects of Suspended Glacial Particles on the Bioavailability of Hydrophobic Organic Contaminants in Two Subalpine Lakes in the Canadian Rocky Mountains*. MSc Thesis, University of Alberta, Edmonton, Alberta, Canada.
16. Clark, I. and Fritz, P. 1997. *Environmental Isotopes in Hydrogeology*. Lewis, Boca Raton. 328 p.
17. Goulden, P. and Anthony, D.J.H. 1985. *Design of a Large Sample Extractor for the Determination of Organics in Water*. NWRI Contribution 5–121; National Water Research Institute; Burlington, Ont., Canada.
18. Muir, D.C.G., Segstro, M.D., Welbourn, P.M., Toom, D., Eisenreich, S.J., Macdonald, C.R. and Welpdale, D.M. 1993. Patterns of accumulation of airborne organochlorine contaminants in lichens from the Upper Great Lakes region of Ontario. *Environ. Sci. Technol. 27*, 1201–1210.
19. Muir, D.C.G., Grift, N.P., Lockhart, W.L., Wilkinson, P., Billeck, B.N. and Brunskill, G.J. 1995. Spatial trends and historical profiles of organochlorine pesticides in Arctic lake sediments. *Sci. Tot. Environ. 160/161*, 447–457.
20. Bremle, G. and Larsson, P. 1997. Long-term variations of PCB in the water of a river in relation to precipitation and internal sources. *Environ. Sci. Technol. 31*, 3232–3237.
21. Mackay, D., Shiu, W.Y. and Ma, K.C. 1992. *Illustrated Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals. Volume 1: Monoaromatic Hydrocarbons, Chlorobenzenes, and PCBs*. Lewis Publishers, Boca Raton. 697 p.
22. Mackay, D., Shiu, W.Y. and Ma, K.C. 1997. *Illustrated Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals. Volume 5: Pesticide Chemicals*. Lewis Publishers, Boca Raton. 812 p.
23. Larsson, P, Collvin, L., Okla, L. and Meyer, G. 1992. Lake productivity and water chemistry as governors of the uptake of persistent pollutants in fish. *Environ. Sci. Technol. 26*, 346–352.

24. We are especially indebted to Toby Herman, Anthony Arendt, Mark Skidmore, and Luke Copeland who provided many hours of field work and advice. The manuscript was improved by the reviews of John Smol and Ian Clark. This research was funded by an NSERC Strategic Research Grant to DWS and MS, and an NSERC PG Scholarship to ML.
25. First submitted 5 Oct. 1999. Accepted for publication after revision 18 Dec. 2000.

Jules Blais is assistant professor of environmental science at the University of Ottawa, studying transport mechanisms and fate of persistent organic pollutants. His address: University of Ottawa, 30 Marie Curie Rd. Ottawa, Ontario, Canada, KIN 6N5.
E-mail: jblais@science.uottawa.ca

David Schindler is Killam Professor of Ecology at the University of Alberta in Edmonton, Alberta. His address: Department of Biological Sciences, University of Alberta, Edmonton, Alberta, Canada, T6G 2E9.
E-mail: d.schindler@ualberta.ca

Derek Muir is a senior research scientist with Environment Canada in Burlington, Ontario. His address: Environment Canada, 867 Lakeshore Road, Burlington, Ontario, Canada, L7R 4A6.
E-mail: derek.muir@odin.cciw.ca

Martin Sharp is professor of glaciology at the University of Alberta in Edmonton, Alberta. His address: Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada, T6G 2E9.
E-mail: martin.sharp@ualberta.ca

David Donald is a senior research scientist with Environment Canada in Regina, Saskatchewan. His address: Environment Canada, Room 300 Park Plaza 2365 Albert Street, Regina, Sask. Canada S4P 4K1.
E-mail: david.donald@ec.gc.ca

Melissa Lafrenière is a PhD candidate studying glacial hydrology at the University of Alberta in Edmonton, Alberta. Her address: Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada, T6G 2E9.
E-mail: melissa.lafreniere@ualberta.ca

Eric Braekevelt did his MSc, studying the fate of persistent organic pollutants in alpine lakes at the University of Alberta and is now a chemical analyst at the Freshwater Institute in Winnipeg, Manitoba. His address: Freshwater Institute 501 University Cres. Winnipeg, Manitoba, Canada, R3T 2N6.
E-mail: braekevelte@dfo-mpo.gc.ca

William Strachan is a senior research scientist with Environment Canada in Burlington, Ontario. His address: Environment Canada, 867 Lakeshore Road, Burlington, Ontario, Canada, L7R 4A6.
E-mail: william.strachan@ec.gc.ca