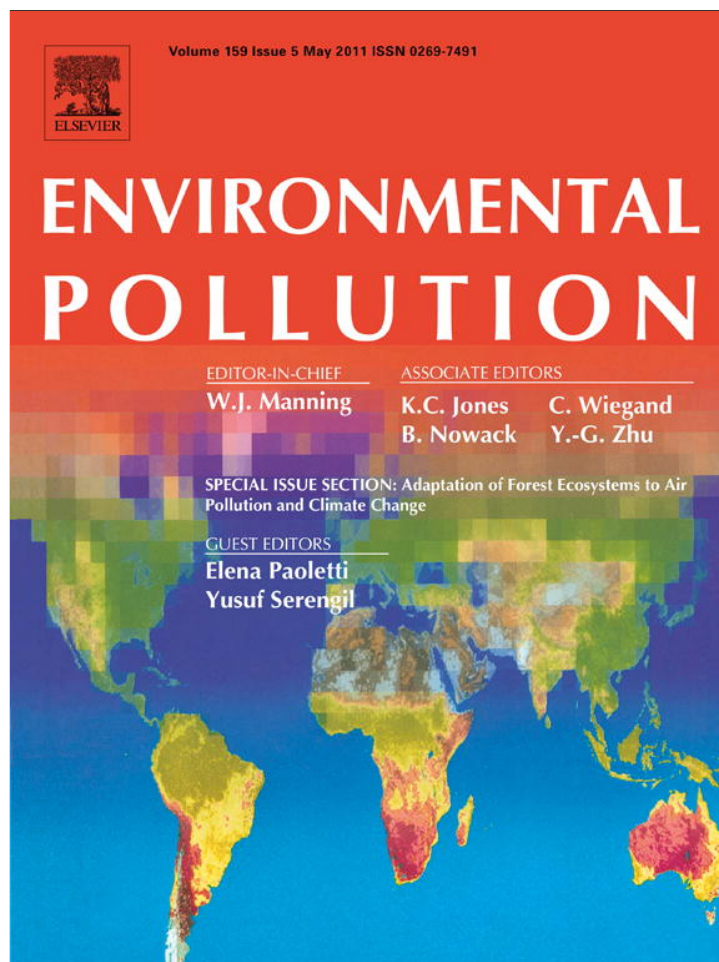


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Polychlorinated biphenyls in freshwater salmonids from the Kerguelen Islands in the Southern Ocean

A. Jaffal^a, N. Givaudan^{b,c}, S. Betoulle^a, A. Terreau^e, S. Paris-Palacios^a,
S. Biagianni-Risbourg^a, E. Beall^d, H. Roche^{b,c,*}

^a Laboratoire d'Eco-Toxicologie, EA 2069 Vignes et Vins de Champagne, Université de Reims Champagne-Ardenne, F51687 Reims Cedex 2, France

^b UMR8079, CNRS, Orsay F-91405, France

^c Univ Paris-Sud, Ecologie Systématique et Evolution, Orsay F-91405, France

^d ECOBIOP, UMR 1224 INRA-Université de Pau-Pays de l'Adour F63310 St-Pée-sur-Nivelle, France

^e IPEV Institut Polaire Français, F29280 Plouzané, France

Salmonids in hydrosystems of the Kerguelen Islands (Southern Ocean) show a high PCB bioaccumulation.

ARTICLE INFO

Article history:

Received 15 March 2010

Received in revised form

17 December 2010

Accepted 6 January 2011

Keywords:

PCB accumulation

Sub-Antarctic area

Salmonids

Kerguelen Islands

ABSTRACT

The Subantarctic Kerguelen Islands (49°S, 70°E) contain freshwater ecosystems among the most isolated in the world. Concentrations of polychlorinated biphenyls (PCBs) were assessed in the muscle of 48 brook trout and 38 brown trout caught during summer and spring 2006 in the rivers, lakes and ponds of Kerguelen. The sum of 29 PCBs averaged 404 and 358 ng g⁻¹ lipid, and dioxin-like PCB was 19 and 69 ng g⁻¹ lipid, in brook and brown trout, respectively. The values showed a high variability and some fish accumulated PCBs at levels similar to those of fish from impacted areas. While inter-sex differences were limited, the season and the morphotype appeared to have the most influence. Fish captured in summer had muscle PCB concentrations about three times higher than those caught in spring and the 'river' morphotype of brook trout showed the highest PCB levels.

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1. Introduction

Persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCBs) are ubiquitous in the aquatic environment. Their presence in remote sites far from their area of production and/or use is mainly due to atmospheric transport (Atlas and Giam, 1981). Climate processes lead to an atmospheric transport of PCBs, DDT and other organochlorine pesticides in an advection as gases or aerosols, to the polar or sub-polar regions (Wania and Mackay, 1993; Weber and Goerke, 2003). Condensation by cold, adsorption onto snow and accumulation into the soil or runoff waters lead to contamination of entire ecosystems, particularly aquatic food webs, impacting both pelagic and benthic organisms (Weber and Goerke, 1996, 2003; Van den Brink, 1997; Goerke et al., 2004; Bogillo and Bazylevska, 2008).

In the late sixties, PCBs and other organochlorines were already detected in polar and sub-polar regions (Risebrough et al., 1968). In sub-polar areas, snowfalls are abundant and snow acts as a dynamic reservoir (Wania et al., 1998). Its effectiveness in

trapping organic molecules depends on the pollutant characteristics (octanol/air ratio or Log K_{ow}) and the physical properties of the snow and temperature (Taillandier et al., 2006). Although the Northern hemisphere is more affected by these contaminants relating to human activities, they are also detected in the Southern hemisphere, even in Antarctic regions despite their geographical isolation, in concentrations considered the lowest in the world (Corsolini, 2009). Predictive models, taking into account climatology, quality of substrates and properties of organic pollutants, are currently being developed to evaluate the dynamic transfer of POPs (Ockenden et al., 2003). However, the case of the hydro-continental sub-Antarctic zone has not been studied.

The Kerguelen Islands, located 3300 kilometers away from the nearest inhabited country, constitute an archipelago in the Southern Ocean subjected to a cold sub-Antarctic climate. They receive precipitations (rain or snow) more than 300 days a year. The Kerguelen human population is limited to 50–100 scientific and technical staff inhabiting the French station of Port-aux-Français. This archipelago, originally devoid of any freshwater fish species, possesses a complete hydrographic network (rivers, lakes, ponds, many watersheds...) in which salmonid populations were introduced from France, Northern Europe and North America from 1955 to 1992, and scientifically monitored for about four decades

* Corresponding author.

E-mail address: helene.roche@u-psud.fr (H. Roche).

(Beall and Davaine, 1982; Davaine and Beall, 1997; Duhamel et al., 2005). Nowadays, the ichthyofauna of Kerguelen Islands is mostly constituted of two species, the brown trout *Salmo trutta* and the brook trout, *Salvelinus fontinalis*. Well acclimated, they have colonized a large extent of freshwaters. Now, these salmonids are probably one of the most isolated freshwater fish populations, unsubmitted to direct industrial or agricultural activities (Davaine and Beall, 1997). In addition to salmonids, the freshwater trophic web in the Kerguelen Islands is quite simple and consists of a few species: planktonic and benthic Entomostraca, small oligochaetes, nematodes and common chironomids. Indeed, the water of rivers is oligotrophic and little mineralized (Gay, 1981).

The liposolubility of PCBs, characterized by an octanol-water partition coefficient (log Kow) exceeding 5, renders such compounds subject to trophic transfer and to biomagnification (Hoekstra et al., 2003; Roche et al., 2009). Concomitantly, aquatic organisms can retain and bioconcentrate chemical compounds from their environment by direct transfer through the teguments and/or food uptake (Roche et al., 2009).

PCBs are hydrophobic organic chemicals, highly persistent in sediments and hazardous to aquatic life (Van der Oost et al., 2003). Able to accumulate in aquatic organisms, they are suspected to be responsible for long-term toxicological effects in fish populations (Sumpter and Jobling, 1995; Khan and Thomas, 2006). In addition, lipid-rich organisms tend to accumulate PCBs. Such are the cases of marine mammals in polar regions (Ross et al., 2000; Kumar et al., 2002) and of salmonids (Hites et al., 2004; Hansson et al., 2009). These fishes are commonly used to monitor loads of organic compounds and heavy metals and are present in high-latitude and high-altitude freshwater environments (Linde et al., 1998; Olsvik et al., 2000; Demers et al., 2007; Lamas et al., 2007). So far, the only study about the evaluation of POPs in the Kerguelen archipelago concerned the marine environment and revealed a contamination of biota by organochlorines (Monod et al., 1992). The snow scavenging of PCBs in Kerguelen freshwater systems receiving high precipitations and their isolation make Kerguelen fish species particularly interesting to study the ecotoxicological impacts of PCBs away from direct anthropogenic influence, under the Southern hemisphere situation.

Therefore, the present paper relates the first investigation of PCB contamination in the Kerguelen salmonids. Pollutant levels are considered in relation with the morphometry and the morphotype of the fish, defined as a function of the species and its habitat.

2. Material and methods

2.1. Study area and sampling sites

The Kerguelen Islands (49°S, 70°E, French Austral and Antarctic Territories), form an archipelago of about 7000 km² area and are located in the South Indian Ocean (Southern Ocean). Composed of over 400 islands and islets plus a mainland (Grande Terre), these sub-Antarctic islands are more than 3300 km away from the nearest inhabited country (South Africa), and 2000 km from Antarctica (Fig. 1a,b). The average temperature is about +4.5 °C at the French scientific station which receives 1117 mm of rainfall per year. The hydrological systems are various: streams and lakes in glacial valleys, rivers in the piedmont alluvial plains, shallow coastal ponds and bogs.

2.2. Fish sampling

Two species of salmonids, brown trout (*Salmo trutta*) and brook trout (*Salvelinus fontinalis*), were sampled at 4 stations located in the Courbet Peninsula: ponds and small streams close to the scientific station of Port-aux-Français (PAF); 2 fairly large streams a few kilometers away from the station, Sud and Château Rivers; and a lake system, Studer Lakes, 17 to 25 km away (Fig. 1c).

Thus, the brown and brook trout sampled belong to three morphotypes ('river', 'lake' and 'station' morphotypes) whose existence has recently been confirmed using otolithometry (Morat et al., 2008). Brown trout from Château River, Studer Lakes and Port-aux-Français (PAF), and brook trout from Sud River, Studer Lakes and

Port-aux-Français were classified as 'river', 'lake' and 'station' morphotypes, respectively, according to Morat et al. (2008).

Thirty eight brown trout and 48 brook trout were caught by angling, from January to March 2006 under higher temperature conditions – summer – ($\approx +11$ °C) and from October to November 2006 when the temperature and food availability start to increase – spring ($\approx +4.5$ °C). Fish were rapidly killed by section of the neural axis, sex was determined in the field by morphological observation, and biometric parameters of each fish were collected to calculate the condition index. The condition index (CI) was estimated by the ratio W/Ws, where W was the observed body weight and Ws the standard weight. The Ws was evaluated on the basis of the length-weight relation of the entire population through the standard equation $W = a^*L$, linearized by taking logarithms $\ln(W) = \ln(a) + b^* \ln(L)$ (Anderson and Neumann, 1996). The equations were $\ln(W) = 1.64 + 0.32^* \ln(L)$ ($r^2 = 0.99$) and $\ln(W) = 1.56 + 0.33^* \ln(L)$ ($r^2 = 0.98$) for brook and brown trout, respectively. Such equations were calculated on the basis of populations of 153 brook trout and 180 brown trout caught during the year 2006 in the Kerguelen hydrosystems. Muscle samples were dissected out and immediately frozen at -20 °C. Fish sampling procedures were conducted according to the research protocol approved by the Regional Ethic Committee of Midi-Pyrénées (France).

2.3. Analytical procedure

2.3.1. Chemical analyses

The extraction of lipids and hydrophobic compounds was performed using an accelerated solvent extraction (ASE200) System (Dionex, Voisins-le-Bretonneux, France). Muscles were homogenized using a ball mill and mixed with clean Fontainebleau sand (1:1 w/w) and 1 g hydromatrix. The mixture was introduced into a 33 ml ASE cell, then 20 ng of PCB30 and PCB204 were deposited as first internal standards. The extraction was carried out using dichloromethane:methanol (2:1 v/v) as solvent. The final volume was evaporated using a rotary evaporator (Buchi). Lipid amounts were gravimetrically determined, then 2 ml hexane was added to the crude extract and 50 ng of dicofol was introduced as a second internal standard, before purification. The extract was subsequently purified by solid phase extraction (SPE) on florisil (MgO₃Si), following the EPA method 3620 (Bond Elut Florisil, 1 g, 200 μ M particle size) (Varian, Les Ulis, France) with hexane, to eluate PCB. The eluent was carefully evaporated to dryness under a nitrogen stream and finally brought up to 200 μ l with hexane for analysis.

Organochlorine compounds were analyzed by gas chromatography with a Clarus 500 (Perkin-Elmer, Courtaboeuf, France), using ECD (electron capture detection) with a ⁶³Ni Source and nitrogen as make-up gas according to an adapted procedure of the EPA Method 8081a, previously described (Oliveira Ribeiro et al., 2008). The identification of compounds was achieved using a 30 m column, internal diameter 0.25 mm, PE5 fused silica column (PerkinElmer) and ultra-high purity helium as carrier gas. The injector and detector temperatures were 280 °C and 350 °C, respectively. Among the theoretical 209 PCB congeners, 7 compounds considered as indicator PCBs (PCB-ind) (IUPAC n° 28, 52, 101, 118, 138, 153, 180), 12 dioxin-like PCBs (PCB-dl) (IUPAC n° 77, 81, 105, 114, 118, 123, 126, 156/157, 167, 169, 170) and 11 others (IUPAC n° 8, 18, 31, 44, 70, 151, 128, 137, 189, 195, 194) were investigated. All reference materials were produced by the ISO9001 certified laboratories of Dr. Ehrenstorfer as part of the Reference Standards Program provided by the CIL Cluzeau Society (Sainte Foy la Grande, France). Under the specified conditions, the detection limit was about 0.01 ng and the limit of quantification ranged from 0.05 to 0.20 ng g⁻¹ in fish tissues (dry matter normalized data). The analyses were performed in the Department of Ecology, Systematic and Evolution in Paris 11 University (France).

2.3.2. Toxic equivalent evaluation (TEQ)

The TEQ of PCB-dl was calculated according to van den Berg et al. (1998) using the WHO-TEF (World Health Organization – Toxic Equivalent Factors) for fish as previously described (Oliveira Ribeiro et al., 2008). The TEF (Toxic Equivalent Factor) calculation is based on several criteria, amongst them a structural relationship with dioxins or furans, a binding to the Ah receptor (AhR) and the persistence and accumulation in the food chain. Due to different mechanisms of toxicity and unlike sensitivity to individual congeners, TEF values are computed differently for mammal, bird, and fish wildlife. For fish, this valuation gives an upper limit value for some PCBs (<0.00005); in such case TEQs were calculated in excess (TEF = 0.00005).

2.4. Statistical procedures

Statistical analyses of PCB data were performed with Statistica software (version 8).

Biological parameters (length, weight, condition index and lipid amounts) are expressed as mean \pm standard deviation (SD), if the homogeneity of variance was demonstrated, using the ANOVA test, then the Student *t*-test was used to compare the means and the Pearson test to assess correlations. For contaminant concentrations, data distribution was not gaussian, then the geometric mean and extreme values [min–max] were given and the non-parametric Mann–Whitney *U*-test was used. All tests were regarded as statistically significant when $p < 0.05$.

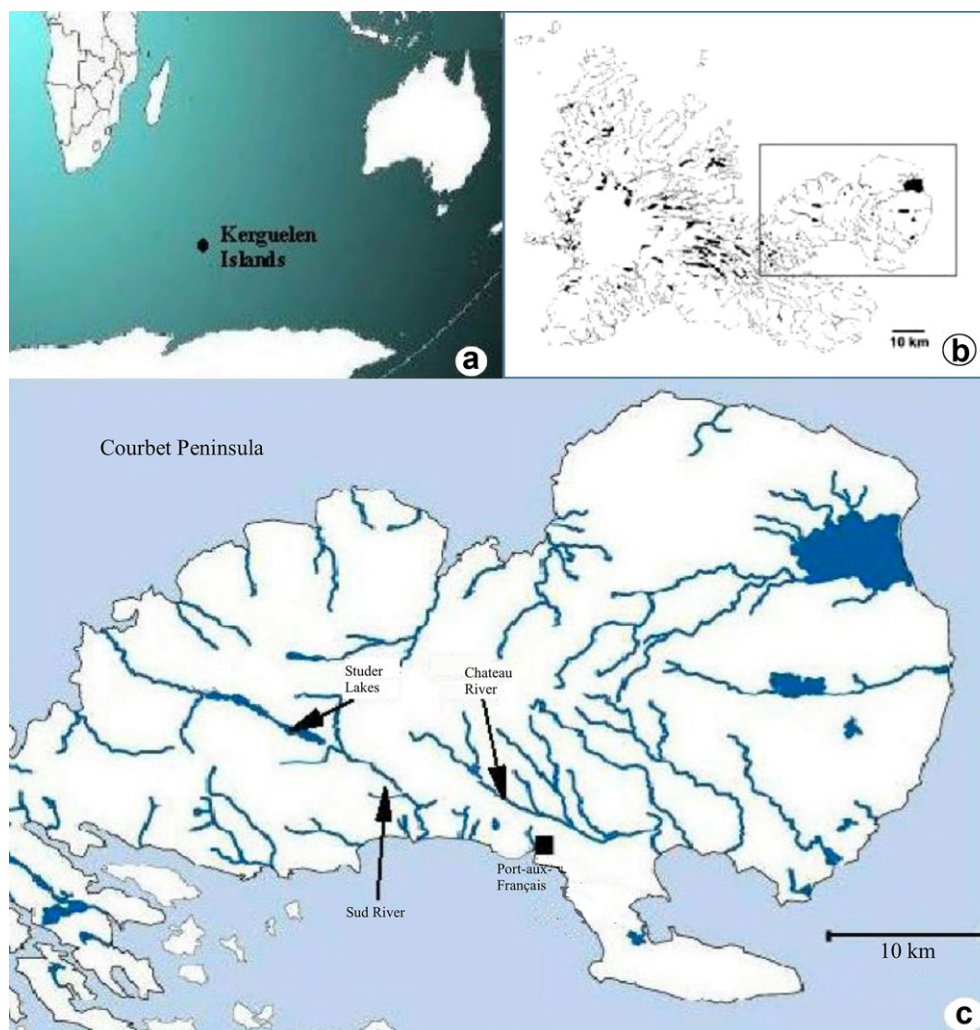


Fig. 1. Kerguelen Islands; a) Geographic situation b) localization of the study site c) experimental stations (©Patrick Davaine, 2003).

3. Results

3.1. Fish biometry and lipid content

The morphometric parameters of the fish sampled were examined according to four criteria: species, sex, season and morphotype (Table 1). The sex ratio was balanced as well as the seasonal sampling in summer and spring. In contrast, sampling in summer suffered from a lack of brown trout from 'river' and 'lake' morphotypes. Brown trout were bigger (length and weight) than brook trout.

The 38 brown trout (19 males and 19 females, 36.4 ± 4.7 cm; 491 ± 166 g) did not show seasonal variation. The brook trout (24 males and 24 females, 28.3 cm and 323, on average) caught during the austral summer were larger than those fished in early spring ($p < 0.05$). The length-weight relationship was close to 1 in both species, indicating a good condition of males and females caught for two seasons.

In muscle, the average lipid content was higher in brown trout ($239 \text{ mg g}^{-1} \text{ dw}$) than in brook trout ($164 \text{ mg g}^{-1} \text{ dw}$). In both brown and brook trout, the muscle lipid burden was higher during the austral summer than in early spring. It was up to nearly 3 times higher in brown trout in summer than early spring.

Despite the heterogeneity of morphometric parameters, the samples taken as a whole showed no statistically significant

differences. However, the brook trout from 'river' morphotype were mainly lower in size and weight than those from 'lake' morphotype, in which body mass may be close to 1 kg. The 'station' morphotype showed an intermediate body mass between the two other morphotypes. Such a variation of biometric parameters was not observed in brown trout sampled here. It can be noted that fish caught in all sampling sites had ages of three years at least and six years at most. In Kerguelen, salmonid size was related more to morphotype than to fish age. Indeed, at the same age, trout could present different sizes.

3.2. PCB impregnation of salmonids

The 29 PCB congener distribution in muscle of Kerguelen salmonids, including the 7 PCB-ind and 12 PCB-dl, is summarized in Table 2. The geometric mean of total PCB amount in muscle (29 congeners) was 404 ng g^{-1} and 358 ng g^{-1} lipid, in brook and brown trout, respectively. The 7 PCB-ind stood for 38–39% of the total PCBs measured here and the PCB-dl were 3% and 14% of the total PCBs in brook and brown trout, respectively.

As in all wild fish populations, the Kerguelen salmonids showed a high variability of their contamination profile. In this first exploratory study, the whole sampling was considered. One of the main findings of this assessment points out the high contamination level of certain individuals, in whom the sum of all PCBs was almost

Table 1
Species, sex, season and morphotype variations of biometric parameters and lipid concentration in muscle of salmonids sampled during austral summer and early spring 2006. Values are expressed as mean ± SD. Significant difference ($p < 0.05$): * for species; # for season; a: river vs. lake b: river vs. station c: lake vs. station for morphotype.

		Length, cm	Weight, g	Condition index	Lipids, mg g ⁻¹ dw
Total sampling					
Brook trout (48)		28.3 ± 9.4*	323 ± 312*	1.02 ± 0.11	164 ± 75*
Brown trout (38)		36.4 ± 4.7	491 ± 166	1.02 ± 0.16	239 ± 171
Male–female					
Brook trout	Males (24)	27.5 ± 8.9	295 ± 290	1.00 ± 0.10	138 ± 44
	Females (24)	29.1 ± 10.1	351 ± 337	1.04 ± 0.12	190 ± 90
Brown trout	Males (19)	36.1 ± 4.2	477 ± 151	0.99 ± 0.14	191 ± 141
	Females (19)	36.7 ± 5.3	505 ± 184	1.06 ± 0.17	287 ± 187
Season					
Brook trout	Summer (28)	25.2 ± 8.8#	242 ± 298#	1.04 ± 0.10	180 ± 67
	Early spring (20)	32.6 ± 8.8	437 ± 303	0.99 ± 0.11	142 ± 81#
Brown trout	Summer (18)	35.8 ± 4.2	467 ± 188	1.00 ± 0.15	360 ± 165
	Early spring (20)	37.0 ± 5.2	513 ± 146	1.04 ± 0.16	130 ± 78#
Morphotype					
Brook trout	River (24)	20.7 ± 2.1 ^a	85.4 ± 24.3 ^a	0.99 ± 0.11 ^{ab}	151 ± 49
	Lake (16)	39.3 ± 5.6 ^c	696 ± 230	1.06 ± 0.09	184 ± 98
	Station (8)	29.1 ± 6.3	289 ± 162	1.06 ± 0.09	163 ± 87
Brown trout	River (3)	38.2 ± 6.0	598 ± 208	1.08 ± 0.11	85 ± 49
	Lake (3)	37.7 ± 2.0	585 ± 66	1.12 ± 0.09	141 ± 134
	Station (32)	36.1 ± 4.8	472 ± 167	1.01 ± 0.16	263 ± 173

6 and 4 µg g⁻¹ lipid, in brook and brown trout, respectively, with, however, a low concentration of PCB-dl. The dominant PCBs in terms of concentrations (>0.02 ng g⁻¹ dw or >1 ng g⁻¹ lipid) were, in a descending order, PCB 101; 52; 138; 153; 70; 151; 118, in brook

trout, and PCB 153; 101; 138; 28; 123; 151; 180; 118; 18, in brown trout. In the whole sample, 21% of fish (brook or brown trout) exhibited a concentration of PCB-ind higher than 1 ng g⁻¹ lipid. Twenty seven percent and 31.6% of respectively brook and brown

Table 2
PCB impregnation in muscle of brown and brook trout collected in summer and spring 2006 in the Kerguelen Islands; concentrations of individual congener, sum of PCBs (29 congeners), PCB-ind (bold), PCB-dl (italic) and TEQ. Lipid and dry weight (dw) normalized data are expressed as geometric mean and extreme values [min–max]. (n): number of individuals; nd = not detected.

	Brook trout (48)		Brown trout (38)	
	ng g ⁻¹ lipid	ng g ⁻¹ dw	ng g ⁻¹ lipid	ng g ⁻¹ dw
CB 8	0.68 [nd–402]	5 × 10 ⁻³ [nd–73.5]	0.24 [nd–71.3]	1 × 10 ⁻³ [nd–17.5]
CB 18	0.25 [nd–550.3]	1 × 10 ⁻³ [nd–103]	2.41 [nd–400]	0.06 [nd–78.8]
CB 28	0.67 [nd–815]	7 × 10⁻³ [nd–153]	9.30 [nd–426]	0.82 [nd–264]
CB 31	0.52 [nd–278]	3 × 10 ⁻³ [nd–24]	0.20 [nd–876]	1 × 10 ⁻³ [nd–37.5]
CB 52	18.7 [nd–946]	1.55 [nd–110]	9.99 [0.01–994]	0.57 [nd–71.3]
CB 44	0.43 [nd–118]	2 × 10 ⁻³ [nd–11.6]	0.99 [nd–222]	8 × 10 ⁻³ [nd–34.8]
CB 70	2.79 [nd–1088]	0.08 [nd–129]	25.3 [nd–261]	0.02 [nd–84.4]
CB 101	50.4 [nd–2116]	6.74 [nd–245]	19.1 [nd–504]	2.33 [nd–293]
CB 81	0.11 [nd–25]	0.02 [nd–5.7]	0.83 [nd–144]	0.01 [nd–58.6]
CB 77	0.10 [nd–384]	2 × 10 ⁻⁴ [nd–35]	0.08 [nd–17.1]	1 × 10 ⁻⁴ [nd–1.2]
CB 151	3.50 [nd–2814]	0.08 [nd–447]	4.30 [nd–144]	0.38 [nd–47.4]
CB 118	1.40 [nd–1373]	0.02 [nd–258]	2.51 [nd–242.1]	0.07 [nd–79.9]
CB 123	0.32 [nd–96.9]	2 × 10 ⁻³ [nd–19.7]	6.48 [nd–227.9]	0.74 [nd–52.2]
CB 114	0.10 [nd–74]	2 × 10 ⁻⁴ [nd–6.4]	0.68 [nd–21.9]	0.02 [nd–4.6]
CB 153	4.10 [nd–570]	0.17 [nd–70.8]	19.3 [nd–1325]	2.71 [nd–437]
CB 105	0.27 [nd–202]	1 × 10 ⁻³ [nd–30.8]	0.39 [nd–76.2]	3 × 10 ⁻³ [nd–31.8]
CB 138	10.4 [nd–365]	0.76 [nd–47.4]	13.7 [nd–470]	1.36 [nd–211]
CB 137	0.11 [nd–185]	2 × 10 ⁻⁴ [nd–29.3]	0.08 [nd–71.2]	1 × 10 ⁻⁴ [nd–5.1]
CB 128	0.18 [nd–68.7]	6 × 10 ⁻⁴ [nd–13.7]	0.18 [nd–17.7]	1 × 10 ⁻³ [nd–3.5]
CB 126	0.15 [nd–47.3]	4 × 10 ⁻⁴ [nd–8.1]	0.31 [nd–45.5]	2 × 10 ⁻³ [nd–19.8]
CB 156	0.12 [nd–105]	3 × 10 ⁻⁴ [nd–18.2]	0.13 [nd–23.3]	4 × 10 ⁻⁴ [nd–2.3]
CB 157	0.12 [nd–81.2]	4 × 10 ⁻⁴ [nd–7]	0.55 [nd–25.9]	9 × 10 ⁻³ [nd–5.1]
CB 167	0.10 [nd–75.1]	2 × 10 ⁻⁴ [nd–6.5]	0.30 [nd–31.8]	2 × 10 ⁻³ [nd–3.2]
CB 180	0.28 [nd–61.8]	2 × 10⁻³ [nd–9.8]	3.76 [nd–693]	0.19 [nd–229]
CB 170	0.19 [nd–54]	1 × 10 ⁻³ [nd–4.6]	0.28 [nd–154]	1 × 10 ⁻³ [nd–50.8]
CB 169	0.09 [nd–54.9]	1 × 10 ⁻⁴ [nd–12.5]	0.83 [nd–150]	0.01 [nd–67.4]
CB 189	0.06 [nd–51.6]	1 × 10 ⁻⁴ [nd–4.4]	0.15 [0.05–19.5]	1 × 10 ⁻³ [nd–1.8]
CB 195	0.06 [nd–1.3]	1 × 10 ⁻⁴ [nd–0.4]	0.54 [nd–161]	5 × 10 ⁻³ [nd–64.7]
CB 194	0.18 [nd–128]	4 × 10 ⁻⁴ [nd–20.1]	0.78 [nd–317]	0.01 [nd–31.4]
Σ PCB	404 [nd–6040]	53.2 [nd–832]	358 [1.73–4298]	63.3 [0.18–1419]
Σ PCB-ind	174 [nd–3427]	23.3 [nd–634]	192 [nd–3307]	40.6 [nd–1091]
Σ PCB-dl	19 [nd–1406]	1.62 [nd–264]	69 [nd–1385]	10.9 [nd–457]
TEQ	3 × 10 ⁻⁴ [nd–4.73]	2 × 10 ⁻⁴ [nd–0.82]	0.47 [nd–6.7]	8 × 10 ⁻³ [nd–0.24]

trout showed PCB-ind concentrations $<0.1 \text{ ng g}^{-1}$ lipid. Moreover, five muscle samples of brook trout had a TEQ concentration $>1 \text{ ng g}^{-1}$ lipid [2.9–4.7], and only one brown trout (6.7 ng g^{-1} lipid).

Although most PCBs were generally the most concentrated PCB-ind, the abundance of non-indicator congeners PCB70 and 151 in 5 brook trout contributes to the burden of these individuals. These small individuals (mean length: 20 cm; mean weight: 85 g) captured at the end of summer in Sud River showed an unusual profile of contamination. In contrast, 11 brook trout out of 48 showed little detectable contamination ($<20 \text{ ng g}^{-1}$ dw); this group was mostly constituted of individuals caught after the austral winter in Lake Studer. In brown trout, 11 individuals of 38 were slightly contaminated ($<20 \text{ ng g}^{-1}$ dw). They were medium-sized fish compared to the entire sample, almost exclusively caught near Port-aux-Français, in early spring.

In muscle of brook trout, ΣPCB and $\Sigma\text{PCB-ind}$ concentrations were negatively correlated with the length and the body mass of fish ($p < 0.004$ and $p < 0.009$, respectively), i.e. the smallest individuals were the most contaminated. In contrast, PCB concentration and lipid content showed no statistical relationship.

In brown trout, no significant correlation was found between PCB concentrations and their body mass or size, whereas ΣPCB total, $\Sigma\text{PCB-ind}$ and $\Sigma\text{PCB-dl}$ were positively correlated with lipid amount ($p < 0.02$).

3.3. Intraspecific variations

3.3.1. Spatiotemporal variation

Depending on the success of sampling, seasonal changes were evaluated at both sites Port-aux-Français and Lake Studer (Fig. 2). Brown and brook trout from Kerguelen showed significant seasonal. Individuals fished in summer showed higher PCB muscle levels than those sampled in early spring, in brook trout from Port-aux-Français and Lake Studer, as well as in brown trout from Port-aux-Français. All classes of PCBs were concerned, so the concentrations of dioxin-like and non dioxin-like PCBs were found to be highest from January to March when the lipid contents in fish and water temperature were at a maximum (11°C). However, it should be noted that concentrations were very high in brown trout from Lake Studer collected in spring, unlike brook trout.

Concomitantly, the congener profiles showed a seasonal variation (Fig. 3). In summer, the PCB 151 was the dominant congener in brook trout (27%) and the PCBs 101, 52 and 70 came in second position ($\Sigma = 36\%$). In brown trout, PCB 153 (14%) was followed in a descending order by PCBs 101, 28 and 138 ($\Sigma = 31\%$) (Fig. 3a). In spring, the PCB profile was dominated by the indicator PCB 52,

which constituted 18% and 14% of ΣPCB in brook and brown trout, respectively. Second most abundant congeners were PCBs 31, 101 and 153 contributing 31% and 25% of the total PCBs in brook and brown trout, respectively (Fig. 3b).

3.3.2. Sex-specific variation

No sex difference was found in the total muscle concentration of PCBs in fish caught in one of the sites taken as example, the morphotype 'station' of brown trout from Port-aux-Français (Fig. 4). The class distribution of PCB-ind or PCB-dl also showed no significant variation depending on the fish gender. Tacking into account the seasonal variations, in male as in female brown trout, the level of ΣPCB measured, $\Sigma\text{PCB-ind}$ and PCB-dl were higher in summer than in spring. The low number of brook trout from the 'station' morphotype does not allow a similar analysis. Indeed the majority of trout from Port-aux-Français belong to the river.

3.3.3. Morphotype discrepancy

A very high impregnation of brook trout occurred in the morphotype 'river', in which the muscle concentration may reach over $0.8 \mu\text{g g}^{-1}$ dw (Table 3). Anyway, the maximum bioaccumulation was that of PCB-ind, whose concentration reached more than 600 ng g dry weight in some individuals caught in summer. The highest contamination of the 'river' morphotype was shown even among individuals captured in spring, when the bioaccumulation was lower overall. It affects all classes of PCBs, including PCB-dl, but without consequence on the TEQ. At the opposite, the lowest concentrations were found in the 'station' morphotype ($<150 \text{ ng g}^{-1}$ dw).

In contrast, the 'lake' morphotype was the most contaminated in brown trout (up to 150 ng g^{-1} dw). This observation can be made only in spring brown trout, because of the lack of fish from 'lake' and 'river' in summer, due to the difficulty of sampling. Moreover, brook trout belonging to the 'station' morphotype exhibited the lowest contamination rates.

4. Discussion

PCBs are semi-volatile chlorinated aromatic compounds, which have been extensively used for over 50 years (1929 to 1987) in the industrialized Northern hemisphere. Lei and Wania (2004) showed that semi-volatile organic chemicals were absorbed in the snow and sent back in the troposphere more easily than the rain does. As a consequence, the distribution of contaminants in aquatic ecosystems is more frequently related to climatic conditions than to direct discharges into the environment. Global re-distribution of PCBs results in their progressive evaporation from warm to cold

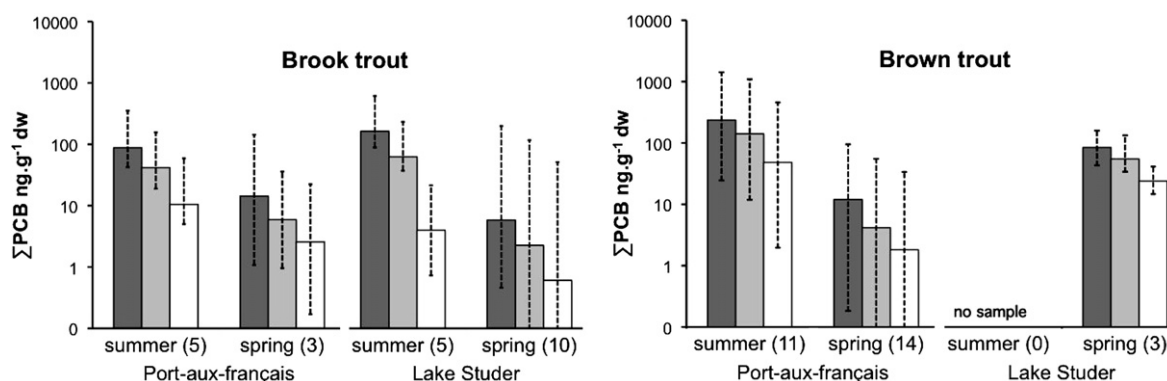


Fig. 2. PCB concentrations in muscle of brook and brown trout from two experimental sites, French scientific station: Port-aux-Français (morphotype 'station') and Lake Studer (morphotype 'lake'), in Kerguelen Islands in summer and spring 2006. ■ ΣPCB , ■ $\Sigma\text{PCB-ind}$, □ $\Sigma\text{PCB-dl}$. Geometric mean, ----- extreme values, (n) = number of individuals.

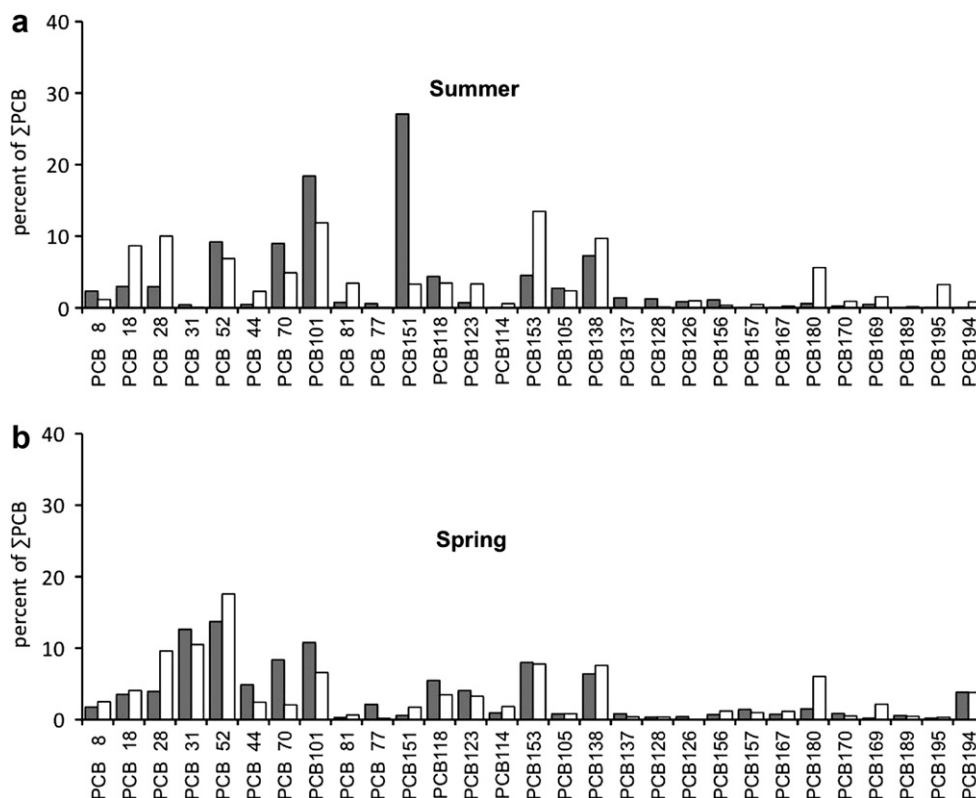


Fig. 3. Congener profile of PCB in ■ brook and □ brown trout a) in summer ($n = 28-18$); b) in early spring ($n = 20-20$). Values are expressed in percent of total concentration.

regions (Wania and Mackay, 1993). Therefore, PCB levels continue to rise in the southern hemisphere including Antarctica in relation to their slow degradation rate, their global redistribution and their continuous use in the southern hemisphere (Goerke et al., 2004; Bargagli, 2008). Located North of the Antarctic continent, the sub-Antarctic Kerguelen Islands contain freshwater ecosystems inhabited by populations of brown and brook trout. The results of our study indicate that in the Kerguelen Islands, salmonid populations accumulated PCBs. This contamination was sometimes similar to that measured in the same species living in other world regions, less isolated from pollution. In the present study, Σ PCB-ind (7 congeners) concentration was $40 \text{ ng g}^{-1} \text{ dw}$ on average, i.e. about $15 \text{ ng g}^{-1} \text{ ww}$ (wet weight) in brown trout muscle. Vives et al. (2005) found levels two times lower for similar PCBs in brown

trout from the lake Redo in Spain. In brown trout muscle from several high mountain lakes in Europe, Rognerud et al. (2002) reported mean concentrations between 1.4 and $23.4 \text{ ng g}^{-1} \text{ ww}$ for 5 PCB-ind. These data are similar in the Kerguelen salmonids (9 and $9.3 \text{ ng g}^{-1} \text{ ww}$ in muscle of brown and brook trout, respectively). None of the samples reached $10 \text{ ng TEQ g}^{-1} \text{ ww}$, which corresponds to the daily limit established by the WHO for human consumption. The highest TEQs were found in some brown trout and were due mainly to a very high level of PCB180 and, incidentally, of PCB169. These results need to be refined by additional measures on a broader scale.

Some studies have shown higher PCB fish contamination than that observed in Kerguelen salmonids. They mostly concerned eels, for example, which have higher lipid content, and thus are more prone to PCB accumulation. Indeed, in a Mediterranean lagoon we found $500-1000 \text{ ng g}^{-1} \text{ dw}$ of PCB-ind in the muscle (Oliveira Ribeiro et al., 2008). In contrast, in the present study, Kerguelen salmonids showed on average $23-31 \text{ ng g}^{-1} \text{ dw}$ (geometric mean in brook and brown trout, respectively) of PCB-ind. Corsolini (2009) in a critical review of industrial contaminants in Antarctica biota reported PCB levels in plankton, fishes, sea birds and marine mammals lower than in other world regions, although they are occasionally comparable to those found in industrial regions. It should be noted that, during the austral summer 2006, Kerguelen salmonids showed a PCB level notably higher than that reported for Antarctic fish (Corsolini, 2009) and closer to PCB concentration in fishes of regions subject to a direct and strong human impact.

Moreover, data showed important seasonal differences, in the local context of Kerguelen. Indeed, a significant increase of PCB contamination in trout was observed in summer. Summer fish showed a muscle concentration level about three times higher than those caught during early spring. No data exist on the

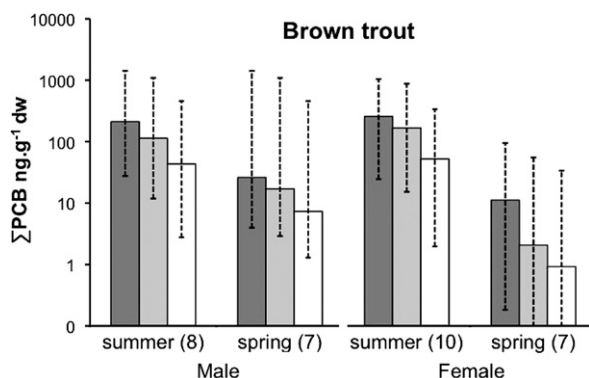


Fig. 4. Sex differences of PCB concentrations in muscle of brown trout from the French scientific station (Port-aux-Français) in Kerguelen Islands, in summer and in early spring 2006. ■ Σ PCB, ■ Σ PCB-ind, □ Σ PCB-dl. Geometric mean, ----- extreme values.

Table 3

Sum of muscle PCB concentration (29 congeners), Σ PCB-ind, Σ PCB-dl and TEQ in three morphotypes ('station', 'lake' and 'river') of brown and brook trout from Kerguelen hydrosystems in summer and spring. Data are expressed as geometric mean and extreme values [min–max]. Significant differences ($p < 0.05$): a: lake vs river, b: station vs river c: station vs lake.

	Brook trout		Brown trout	
<i>Summer</i>				
Lipids mg g ⁻¹ dw	Station (5)	183 [124–313]	Station (11)	314 [66–641]
	Lake (5)	226 [142–380] ^a	Lake	Not sampled
	River (18)	152 [81–261]	River	Not sampled
Σ PCB ng g ⁻¹ dw	Station (5)	74.6 [31–150] ^{bc}	Station (11)	311 [28–1861]
	Lake (5)	151 [84–269]	Lake	Not sampled
	River (18)	257 [31–832]	River	Not sampled
Σ PCB-ind ng g ⁻¹ dw	Station (5)	41.7 [19–73] ^b	Station (11)	141 [12–1092]
	Lake (5)	62.7 [37–107] ^a	Lake	Not sampled
	River (18)	110 [15–634]	River	Not sampled
Σ PCB-dl ng g ⁻¹ dw	Station (5)	10.5 [5.0–38]	Station (11)	48 [2–457]
	Lake (5)	4.00 [0.73–13]	Lake	Not sampled
	River (18)	1.19 [nd–264]	River	Not sampled
TEQ pg g ⁻¹ dw	Station (5)	2.71 [0.03–389]	Station (11)	0.09 [0.001–98]
	Lake (5)	0.14 [0.01–315]	Lake	Not sampled
	River (18)	0.04 [nd–816]	River	Not sampled
<i>Spring</i>				
Lipids mg g ⁻¹ dw	Station (3)	81 [25–181]	Station (14)	120 [36–262]
	Lake (11)	139 [73–351]	Lake (3)	106 [56–295]
	River (6)	120 [87–190]	River (3)	72 [29–118]
Σ PCB ng g ⁻¹ dw	Station (3)	11.6 [1.08–61] ^b	Station (14)	12.0 [0.18–95] ^c
	Lake (11)	2.29 [nd–189] ^a	Lake (3)	84.4 [43–159] ^a
	River (6)	102 [54–140]	River (3)	41.7 [11–87]
Σ PCB-ind ng g ⁻¹ dw	Station (3)	5.89 [0.96–24] ^b	Station (14)	4.17 [nd–55] ^c
	Lake (11)	0.85 [nd–113] ^a	Lake (3)	54.7 [34–133] ^a
	River (6)	51.1 [24–97]	River (3)	20.0 [4.2–55]
Σ PCB-dl pg g ⁻¹ dw	Station (3)	2.57 [0.17–17] ^b	Station (14)	1.81 [nd–34] ^c
	Lake (11)	0.26 [nd–50] ^a	Lake (3)	24.0 [14.7–41] ^a
	River (6)	9.19 [2.77–45]	River (3)	3.02 [0.48–13]
TEQ pg g ⁻¹ dw	Station (3)	0.17 [0.002–85]	Station (14)	0.08 [0.002–240]
	Lake (11)	0.001 [nd–240]	Lake (3)	0.23 [0.02–3.54]
	River (6)	0.07 [0.02–3.5]	River (3)	0.02 [0.02–0.03]

fluctuation of PCB contaminants at the seasonal temporal level in brook or brown trout. However, wild sea bream from the western Mediterranean Sea presented muscle PCB concentrations and lipid level strongly linked with seasonal variation and the biological cycle of the species (Blanes et al., 2009). It should be noted that the muscle PCB levels, expressed in tissue weight normalized data, were found to be highest when the lipid level was at a maximum (summer-autumn). But when expressed in lipid level PCBs, in winter the concentration became higher, in relation to dilution of PCBs in lipid as hypothesized by Blanes et al. (2009). However, in accordance with our results, PCB and lipid tissue levels were significantly lower in spring compared with summer and fall in white croaker filets of the sport fisheries species in San Francisco Bay (Greenfield et al., 2005). Such a difference is related with prey abundance and higher feeding rates in summer. River migrating Atlantic salmon had lower muscle lipid levels and higher PCB concentrations compared to salmon in their foraging phase in the sea (Hansson et al., 2009). Moreover, a transfer of muscle lipids and associated PCB contaminants towards the gonads after spawning in early spring can be involved in the sedentary freshwater salmonids sampled in our study. During winter, muscle lipid content may also decrease due to their energetic use in response to an increasing metabolic activity due to spawning, coupled with a lower food availability. Additionally, the congener profile of muscular PCBs was different according to the period of capture but not to the fish morphotype. This

suggests a modification of contaminant inputs, perhaps in relation to a seasonal modification of the climatic process and to ice melting in summer, a major cause of freshwater ecosystem contamination in polar regions (Corsolini, 2009).

The study presented here did not reveal significant inter-sex differences in brown trout. Yet, several studies showed higher PCB contamination in male fish than in females. The explanation of this fact was in relation to biological differences in reproduction. Indeed, PCB concentrations of females decline after spawning (Rypel et al., 2007; Bodiguel et al., 2009; Madenjian et al., 2010). Here, in summer, the high PCB amount in muscle of male brook trout rather suggests a potential sex specific difference in feeding behavior, causing consumption of more PCB contaminated preys or lower metabolized rates (Bodiguel et al., 2009). This assumption must be confirmed by the already planned analysis of the food chain and the stomach contents.

Recently, Morat et al. (2008) carried out a life history study of Kerguelen salmonids using otolithometric analyses. They demonstrated that brook and brown trout living in different aquatic ecosystems of the Kerguelen Islands belonged to three morphotypes: 'lake' morphotypes (from Lake Studer), 'river' morphotype (from the Sud River and Château River) and 'station' morphotype (from ponds and small streams in the vicinity of the scientific station of Port-aux-Français). They showed that fish from the 'station' morphotype were more stressed than fish from other morphotypes, according to the presence of aberrant vateritic otoliths. Moreover, 'river' and 'lake' morphotypes were linked to a behavioral variability and not a genetic difference between the forms (river, lake, pond, sea) (Guyomard et al., 1984).

The 'station' morphotype, described for the first time by Morat et al. (2008), would correspond to an adaptive population to this ecosystem composed of ponds and connecting small streams near the base buildings. Following this classification, we show here, that brook trout from the 'river' morphotype were significantly more contaminated by PCB than those from 'lake' and 'station' morphotypes. However, all sites were submitted to identical climatic conditions on the Courbet Peninsula of Kerguelen. In addition, the 'river' morphotype with the most contaminated fish, contained a majority of small individuals, suggesting that changes attributed to morphotype could be related to fish size or a change in growth rate depending on the habitat type. Indeed, as already demonstrated in other fish species, size has an influence on diet (Schafer et al., 2002). The stomach content analysis of Kerguelen salmonids has revealed a difference in diet composition between brown trout from 'river' and 'lake' or 'station' (Bryere and Charrier, unpublished data). Their diet is composed of small invertebrates. Such preys are more suitable to juveniles than to adults, which are preferentially ichthyophagous, but Kerguelen hydrosystems are devoid of native freshwater ichthyofauna (Davaine and Beall, 1997). The feeding behavior of the 'river' morphotype might explain the different levels of contamination. Samples of the 'river' morphotype consisted of smaller fish. This biometric feature may be related to population density (Jenkins et al., 1999). During the breeding season, a large run of sea trout uses the Château River for reproduction, but migratory fish cannot access the Sud River because of impassable falls. A sea trout female spawns between 5000 and 25 000 eggs. Young trout migrate after an age of two or three years, consequently their density is considerably increased in rivers during this period, leading to a prey deficiency, which could also affect the growth rate of fish.

5. Conclusion

The hydrosystems of the Kerguelen Islands are geographically isolated from direct anthropic impacts. However their

ichtyofauna, consisting of introduced salmonids, showed, in summer and spring 2006, average rates of PCB bioaccumulation similar to those areas most at risk. The nature of this contamination is particularly heterogeneous. Indeed, many fish were slightly affected, while some others were highly contaminated. As factors potentially influencing, it appears that the fish morphology, food availability and biometric parameters may partly explain the variability. The results of this first investigation require identifying the impact of abiotic events and biotic factors in the salmonid contamination. The isolated sub-Antarctic ecosystems offer an exceptional field of study to monitor climate and biogeochemical interactions that determine the transfer between ecosystem compartments and the accumulation of these chemicals and the possible eco-toxicological impacts on salmonid populations. This has led to the development of a scientific program currently underway.

Acknowledgements

The present study was financially supported by the French Polar Institute Paul-Emile Victor (IMMUNOTOXKER program 409) and by the French National Research Agency (ANR-RISKER Program). We thank the French Polar Institute for its logistic support in Kerguelen Islands as well as the French Austral and Antarctic Territories Administration and the staff of the 56th mission in Kerguelen for their help in the fieldwork.

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