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Influence of the diet on the bioaccumulation of heavy metals in zooplankton-eating petrels at Kerguelen archipelago, Southern Indian Ocean

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Abstract Concentrations of cadmium, mercury, copper and zinc were measured in muscle, kidney and liver tissues and in the main prey of five species of zooplankton-eating petrels: blue petrel (*Halobaena caerulea*), thin-billed (*Pachyptila belcheri*) and Antarctic (*P. desolata*) prions, and South Georgian (*Pelecanoides georgicus*) and common (*Pelecanoides urinatrix*) diving petrels. Since some of these species are closely related species with respect to body size, timing of moult and life span, their diet has been examined to evaluate its influence on heavy-metal bioaccumulation. Inter-specific differences were significant for Hg concentrations in the liver and for Zn concentrations in both liver and kidney tissues. Blue petrels exhibited the highest Hg concentrations in the liver (3.9 ± 2.02 $\mu g.g^{-1}$ wet weight). No significant differences were found in Cd concentrations between species. Exposure to heavy metals through the most important prey species in the diet during the breeding period was evaluated. The most evident result was the influence of fish prey on Hg levels. Although crustacean species exhibit different cadmium concentrations, the diet composition does not appear to be discriminant for Cd bioaccumulation within the small petrel community at Kerguelen.

Introduction

The use of seabirds as monitors of the marine environment has been much discussed (Furness et al. 1993; Furness and Camphuysen 1997). It has been shown that they are suitable bioindicators of food supply (Cairns 1987; Montevecchi 1993; Cherel and Weimerskirch 1995; Barrett and Krasnov 1996; Montevecchi and Myers 1997; Regehr and Montevecchi 1997), and of pollution, particularly oil pollution (Camphuysen and Van Franeker 1992; Burger 1993). Many seabirds are top marine predators and long-lived and, therefore, are also suitable as biomonitors of pollutants such as organochlorines or heavy metals. Given that they are entirely anthropogenic, the biological significance of organochlorines is better understood, compared to heavy metals, which occur naturally in marine systems and are therefore always present in the tissues of marine vertebrates (Thompson 1990). Among the heavy metals, cadmium (Cd) and mercury (Hg) have the ability to bioaccumulate in food webs, and most of the long-lived predatory species exhibit high concentrations of these toxic elements. This process is particularly exacerbated at high latitudes (Wagemann et al. 1990; Dietz et al. 1996; Elliot and Scheuhammer 1997; Dietz et al. 1998) where the baseline concentrations are probably higher than at more temperate latitudes. In addition, numerous other factors such as phylogeny, moult pattern, sex, life span and diet are likely to influence trace-element bioaccumulation in seabird tissues, with Cd and Hg levels showing the largest variation among seabird species (Walsh 1990; Furness 1993; Stewart et al. 1997, 1998, 1999). Among all these factors, it has been suggested that diet is one of the more important factors for explaining differences in Hg and Cd concentrations among species. For example, cephalopods have been shown to be an important vector for the transfer of Cd to top marine predators (Honda et al. 1983; Muirhead and Furness 1988; Caurant and Amiard-Triquet 1995; Bustamante et al. 1998). Moreover, seabird species with appreciable amounts of crustaceans in their diet had lower Cd and Hg concentrations than those whose diet was predominantly squid and fish (Stewart et al. 1999). Zinc and copper are essential elements and, as such,

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their concentrations in the body are regulated (Walsh 1990). However, concentrations in internal tissues will fluctuate, resulting from co-accumulation with cadmium, as all three bind onto the same, metallothionein low molecular-weight protein (Elliot et al. 1992; Elliot and Scheuhammer 1997; Stewart et al. 1998).

Trace-element concentrations found in crustaceans from the Antarctic Ocean also exhibit considerable interspecific heterogeneity (Petri and Zauke 1993; Sanchez-Hernandez 2000) and, therefore, a more detailed knowledge of the diet is required for the interpretation of metal concentrations in predators.

Most of the studies concerning the concentrations of selected trace elements in Antarctic and subantarctic seabird communities (Muirhead and Furness 1988; Szefer et al. 1993a, 1993b; Kim et al. 1998; Hindell et al. 1999; Stewart et al. 1999) cover a wide range of species of different body sizes from storm petrels to albatrosses. In addition, they differ by sex, in their timing of moult, life span and trophic composition of their diet (crustaceans, cephalopods or fish). The species chosen in this study were five small petrels very similar in their body size and mass (Table 1) relative to other petrel species in Kerguelen. They are also similar in their timing of moult (Marchant and Higgins 1990) and some are closely related. The life spans are also relatively similar among the five species compared with larger petrel species (Schreiber and Burger 2002), from 5.6 years for the common diving petrel (Bried and Jouventin 2002) to 8.8 years for the blue petrel (Chastel 1995), thus limiting differences in their exposure to heavy metals. It is therefore expected that the main difference in trace-element bioaccumulation among the five species should be due to their diet, which has been supposed to be a very discriminant factor for trace-element bioaccumulation (Stewart et al. 1997, 1999; Monteiro et al. 1998; Thompson et al. 1998). The main objectives of this study were: (1) to determine if trace-element concentrations were significantly different within a community of zooplankton-eating petrels, (2) to determine if these differences could be explained by differences in the trophic composition of the diet, and (3) to establish whether these elements could be used as tracers to determine diet of these seabird species.

The non-essential elements cadmium (Cd) and mercury (Hg), and the essential elements copper (Cu) and zinc (Zn), were analysed in individuals of five species of zooplankton-eating petrels breeding on the Kerguelen archipelago: blue petrel (*Halobaena caerulea*), thin-billed (*Pachyptila belcheri*) and Antarctic (*P. desolata*) prions, and South Georgian (*Pelecanoides georgicus*) and common (*Pelecanoides urinatrix*) diving petrels. Their diet during the breeding season is given in Bocher et al. (2000), and Cherel et al. (2002a, 2002b). To evaluate the extent to which the five species of petrel are exposed to the above-mentioned trace elements, we sampled their main prey species in the Kerguelen area and determined the concentration of each of the four trace elements.

Materials and methods

Sampling

Fieldwork was carried out in the eastern part of the Kerguelen archipelago, and more particularly in study colonies at two adjacent islands of "Morbihan Bay", a large gulf (about 700 km^2) in which large populations of petrels breed (Weimerskirch et al. 1989). Blue petrels, thin-billed prions and common diving petrels were collected on Mayes Island (49°28′S, 69°57′E), and Antarctic prions and South Georgian diving petrels were collected on Verte Island (49°31′S, 70°04′E). A few other individuals were also collected at other sites on the archipelago. To avoid killing birds, only fresh dead birds (as the result of predation by subantarctic skuas, *Catharacta skua lönnbergi*, or collisions at night with the lights of buildings or ships) that were largely intact were collected. Thus, the number of individuals collected varied greatly for each species. The sample of birds collected might have included both breeding adults and non-breeders since it is not possible to discriminate between them.

Macrozooplanktonic and micronektonic species were collected for analysis according to the known diet of the five petrel species. Samples were collected on board cruises of the research vessel (*R/V*) *La Curieuse* during several austral summers. The amphipod (*Themisto gaudichaudii*) and the copepod (*Paraeuchaeta antarctica*) were sampled using an ORI-net (2 m^2; 1 mm mesh) inside Morbihan Bay in March 1997 (Omori and Ikeda 1984). *T. gaudichaudii*, the euphausiids (*Euphausia vallentini* and *E. triacantha*) and myctophids were collected outside the bay in the eastern slope waters in February 1998, using a IYGPT trawl (International Young Gadoid Pelagic Trawl; opening: 12×7 m) with 10-mm mesh size at the codend. Pelagic species including fish and squid were collected during February 1999 on board cruises of the *RV La Curieuse*.

Petrels, macrozooplanktonic and micronektonic samples were weighed, immediately frozen and stored at −20°C in the field before being sent to the laboratory for analysis. All birds were thawed overnight, sexed, and samples of liver, kidney and pectoral muscles removed. For each crustacean species, 3 sets of 5–40 individuals were collected for analysis and the smallest and the largest individuals measured to establish the size range. The euphausiid, *Thysanoessa* sp., was absent in zooplankton samples and was provided from stomach samples of the South Georgian diving petrel. Myctophids and squids were individually analysed.

Table 1 Body mass and broad prey class composition by reconstituted mass of the diet during three consecutive chick-rearing periods for five species of petrel at the Kerguelen Islands. Values are means ± SD with ranges in *parentheses* (from Bocher et al. 2000, 2001 and Chérel et al. 2002a, 2002b)

Species	Body mass		Prey class (% by reconstituted mass)			
	(g)	(*n*)	Crustaceans	Fish	Cephalopods	Other
Blue petrel	198 ± 20 (154–268)	103	37.4	56.8	2.1	3.7
Thin-billed prion	154 ± 14 (129–194)	83	81.9	11.6	6.0	0.6
Antarctic prion	159 ± 12 (128–188)	103	82.2	12.9	2.9	2.0
Georgian diving petrel	141 ± 12 (116–168)	97	98.0	2.0	–	–
Common diving petrel	154 ± 11 (124–190)	109	100.0	< 0.1	–	–

Heavy-metal analysis

Prey and petrel tissue samples were analysed using the same method. For Cd, Cu and Zn determination, two aliquots of approximately 200–300 mg of each homogenised dried sample were digested in 5 ml of suprapure 14 N nitric acid at 60°C on a hot plate until the solution was clear. After evaporation, the residue was dissolved in 10 ml of 0.3 N suprapure nitric acid. Cd, Cu and Zn were determined by flame or furnace Atomic Absorption Spectrophotometry (AAS) with a Varian spectrophotometer Spectra 250 Plus with a deuterium background correction.

Mercury analysis was carried out with an Automatic Mercury Analyser spectrophotometer, ALTEC AMA 254, which does not require an acid-digestion of the samples. Aliquots ranging from 10 to 50 mg of dried sample were directly analysed after being inserted in the oven of the apparatus. After drying, the samples were heated under an oxygen atmosphere for 3 min, and the Hg liberated and subsequently amalgamated on an Au-net. The net was then heated to liberate the collected Hg, which was measured by Absorption Spectrophotometry.

Accuracy and reproducibility of the methods were tested using dogfish liver (DOLT-2) and muscle (DORM-2) (National Research Council, Canada) reference standards. Standard and blanks were analysed along with each set of samples. Measurements were also validated by the IAEA Intercalibration Exercise (Coquery et al. 2001).

Concentrations are expressed as $\mu g.g^{-1}$ wet weight (w.wt.), to interpret our results in the context of metal transfer between prey and predator. The percentage of humidity is also included in the tables to facilitate comparisons with other studies.

Diet of petrels

The diets of petrels were analysed by collecting stomach samples during the middle of the chick-rearing period, when adults return to the nest to feed their chick, during three consecutive breeding seasons (1995–1997). Full details of the methods and results are given in Bocher et al. (2000) and in Cherel et al. (2002a, 2002b).

The diet composition by percentage of reconstituted mass is summarised in Table 1. Crustaceans dominated the diet in all the species except for the blue petrel where fish was predominant, representing 57% of reconstituted mass (Table 1). In contrast, fish was insignificant in the diet of diving petrels. Among fish, the Myctophidae were the most important, representing 24%, 89% and 35% of the reconstituted mass of fish for the blue petrel, thin-billed prion and Antarctic prion, respectively. Cephalopods never exceeded 6% of the reconstituted mass and were absent in the diet of diving petrels. Among the crustaceans (Fig. 3), the amphipod *T. gaudichaudii* was the major prey item for all petrel species except for the South Georgian diving petrel, whose diet was dominated by the euphausiid *Thysanoessa* sp. (Bocher et al. 2001). *Thysanoessa* sp. was the second major prey item for the thin-billed prion and an important prey item for the blue petrel. Other euphausiids represented an important part of the diet for the surface feeding petrels, e.g. *E. vallentini* in the diet of the Antarctic prion, and *E. superba* in the diet of the blue petrel. These last two species of euphausiid were also present in both prions. The copepod *Paraeuchaeta antarctica* was the second most important prey captured by the common diving petrel. Other crustacean species were considered to be of minor importance with respect to their mass.

Results

Heavy metal in petrel tissues

Comparison between tissues

Cd, Cu, Zn and Hg concentrations in muscle, kidney and liver tissues of the five species are presented in Table 2.

Table 2 Concentrations of copper, zinc, cadmium and mercury in muscle, kidney and liver tissues for small petrels at the Kerguelen archipelago. Mean values in wet weight ($\mu g.g^{-1}$) ± SD with ranges in *parentheses* and coefficient of variation (*CV*) are presented

Species	*n*	Tissue	Moisture (%)	Copper		Zinc		Cadmium		Mercury	
				Concentration	CV%	Concentration	CV%	Concentration	CV%	Concentration	CV%
Blue petrel	10	Muscle	70.5	4.37 ± 1.04 (3.36–6.07)	23.8	20.1 ± 5.8 (12.1-28.4)	28.7	1.2 ± 0.6 (0.2–2.3)	47.6	0.52 ± 0.27 (0.01–0.85)	51.9
(5 mal.-5 fem.)	10	Kidney	74.8	4.04 ± 0.80 (2.70–5.08)	19.8	40.3 ± 10.3 (25.1–56.8)	25.6	40.5 ± 17.0 (9.4–62.8)	42.0	1.44 ± 0.90 (0.05–3.20)	62.5
	10	Liver	69.4	7.14 ± 4.31 (3.66–18.8)	60.4	61.2 ± 24.7 (39.7–119.0)	40.4	15.0 ± 6.9 (2.4–25.1)	45.8	3.90 ± 2.02 (0.10–6.55)	51.8
Thin-billed prion	5	Muscle	69.1	5.43 ± 0.77 (4.58–6.19)	14.2	16.4 ± 4.6 (12.0–22.6)	28.0	0.7 ± 0.4 (0.1–1.3)	64.2	0.08 ± 0.06 (0.01–0.18)	75.0
(2 mal.-3 fem.)	5	Kidney	74.4	4.41 ± 0.69 (3.20–4.88)	15.6	43.2 ± 7.5 (38.6–56.3)	17.4	29.8 ± 14.4 (8.5–48.5)	48.3	0.18 ± 0.12 (0.01–0.35)	66.7
	5	Liver	67.2	26.1[a] ± 42.5 (5.30–102.0)	162.8	56.9 ± 14.3 (43.2–81.1)	25.1	8.5 ± 2.7 (5.7–11.4)	31.6	0.68 ± 0.55 (0.03–1.43)	80.9
Antarctic prion	2	Muscle	71.3	5.44 (5.38–5.49)		13.5 (13.3–13.7)		2.0 (1.5–2.4)		0.08 (0.08–0.08)	
(1 fem.-1 und.)	2	Kidney	75.5	2.80 (2.62–2.98)		29.9 (28.5–31.3)		25.6 (24.0–27.2)		0.18 (0.16–0.19)	
	2	Liver	71.0	5.08 (4.96–5.20)		30.7 (30.0–31.3)		9.4 (8.3–10.6)		0.33 (0.31–0.35)	
Georgian diving petrel	5	Muscle	70.3	5.39 ± 0.46 (4.79–5.81)	8.5	12.5 ± 1.6 (9.7–13.6)	12.7	0.7 ± 0.5 (0.2–1.3)	71.6	0.05 ± 0.04 (0.02–0.12)	80.0
(3 mal.-2 fem.)	5	Kidney	74.3	3.99 ± 0.82 (2.85–5.09)	20.6	44.3 ± 9.5 (31.3–56.4)	21.4	30.9 ± 8.6 (22.4–44.8)	27.8	0.13 ± 0.08 (0.07–0.27)	61.5
	5	Liver	68.9	4.98 ± 1.29 (3.67–6.44)	25.9	38.0 ± 7.9 (27.2–44.5)	20.9	5.9 ± 3.3 (2.6–9.5)	56.1	0.21 ± 0.11 (0.08–0.39)	52.4
Common diving petrel	13	Muscle	69.9	5.78 ± 0.72 (4.90–7.65)	12.5	15.5 ± 3.2 (11.8-21.8)	20.7	1.3 ± 0.9 (0.4–3.8)	70.5	0.06 ± 0.04 (0.03–0.20)	66.7
(7 fem.-5 mal.-1 und.)	13	Kidney	73.4	3.73 ± 0.76 (2.78–5.19)	20.4	44.9 ± 7.5 (32.6–55.9)	16.6	47.2 ± 22.6 (18.3–108.7)	47.9	0.18 ± 0.09 (0.07–0.39)	50.0
	13	Liver	66.3	5.12 ± 1.55 (3.48–9.33)	30.3	42.2 ± 15.1 (26.2–83.7)	35.8	11.1 ± 4.5 (4.7–19.3)	40.7	0.34 ± 0.20 (0.14–0.85)	58.8

[a] 7.13 ± 1.81 when the higher value 102 is excluded.

The tissue exhibiting the highest Zn and Cu concentrations varied between species. Cu concentrations were always lower in kidney tissue, and Zn concentrations were always lower in muscle tissue. In all species, Cd concentrations were higher in kidney than in liver and muscle tissues, and Hg concentrations were higher in liver than in kidney and muscle tissues. The coefficients of variation reflected the individual variation typical of each element in each species: a low coefficient reflected limited individual variation as a consequence of homeostasis processes, which is usually the case for the essential elements such as Cu and Zn. Considering only blue petrels and common diving petrels, which had larger sample sizes, there were no large differences in the coefficients of variation between the essential and non essential elements in some tissues, and the pattern was not the same between the two species. Thus, blue petrels exhibited a relatively high coefficient of variation for Cu in the liver (as much as Cd) compared with common diving petrels, and common diving petrels exhibited particularly low coefficients of variation for Hg in the three tissues.

Comparison between species

Since the number of individuals per species was low, we used the Kruskal-Wallis non-parametric test to make statistical comparisons between species. For the essential elements, inter-specific comparisons showed a different pattern for Zn concentrations in the liver ($\chi^2=13.6$; $P=0.0087$; $n=35$) and for Zn concentrations in the muscle ($\chi^2=9.7$; $P=0.0458$; $n=35$). Multiple comparisons based on the Kruskall-Wallis rank sums to test for pairwise differences among species indicated that blue petrels had significantly higher Zn concentrations in the muscle (20.1 $\mu g.g^{-1}$ w.wt.) than South Georgian diving petrels (12.5 $\mu g.g^{-1}$ w.wt.). There was no difference among all other species (Table 2; Fig. 1a). For Zn concentrations in the liver, no pairwise differences were found (Fig. 1b) and there were no significant differences found among the five species for Cd ($\chi^2=7.36$, $P=0.118$, $n=35$; $\chi^2=5.46$, $P=0.243$, $n=35$; $\chi^2=8.15$, $P=0.086$, $n=35$ for kidney, liver and muscle, respectively).

There were significant differences in Hg concentrations in the three tissues among the five seabird species (Table 2) (kidney: $\chi^2=14.65$, $P=0.0055$, $n=35$; liver: $\chi^2=15.76$, $P=0.0034$, $n=35$; muscle: $\chi^2=15.72$, $P=0.0034$, $n=35$). Multiple pairwise comparisons showed that concentrations of Hg in the liver and kidney were significantly higher in blue petrels (3.9 and 1.44 $\mu g.g^{-1}$ w.wt., respectively) than in South Georgian diving petrels (0.21 and 0.05 $\mu g.g^{-1}$ w.wt., respectively) (Fig. 1d,e). Hg concentrations in the muscle were significantly higher in blue petrels (0.52 $\mu g.g^{-1}$ w.wt.) than in South Georgian diving petrels (0.05 $\mu g.g^{-1}$ w.wt.) and common diving petrels (0.06 $\mu g.g^{-1}$ w.wt.) (Fig. 1c).

Relationships between Cd concentrations in kidney tissue and Hg concentrations in liver tissue (i.e. the organs where there is long-term storage) showed the bioaccumulation of both of these non-essential elements, and there were differences between species and individuals (Fig. 2). The correlation between Hg concentrations in the liver and Cd concentrations in the kidney was only significant for blue petrels ($r=0.82$, $P<0.01$, $n=10$) and thin-billed prions ($r=0.91$, $P<0.05$, $n=5$).

Heavy metals in prey

The exposure of the different petrel species to trace elements has been estimated from the heavy-metal analysis of their known prey collected during cruises (Table 3). Although the number of prey analysed was low, there were strong differences in the concentration of Cd among species, with concentrations being highest in *T. gaudichaudii* and lowest in squids. In *T. gaudichaudii*, the difference in the concentration of Cd between samples from outside of Morbihan Bay (21.4 $\mu g.g^{-1}$w.wt.) and inside the bay (8.4 $\mu g.g^{-1}$ w.wt.) is probably due to differences in body size, with individuals outside the bay being larger. Squids also exhibited the highest Cu concentrations (14 $\mu g.g^{-1}$ w.wt.), whereas the lowest were in fish (1 $\mu g.g^{-1}$ w.wt.). In crustaceans, Cu concentrations varied between 2.3 $\mu g.g^{-1}$ w.wt. in *Paraeuchaeta antarctica* to 7.5 $\mu g.g^{-1}$ w.wt. in *Thysanoessa* sp. The copepod *Paraeuchaeta antarctica* exhibited the highest Zn concentrations (55 $\mu g.g^{-1}$ w.wt.), which were at least 2 times higher than in other species. Hg concentrations were higher in myctophids (0.039 $\mu g.g^{-1}$ w.wt.) and to a lesser extent in squids (0.022 $\mu g.g^{-1}$ w.wt.) compared to crustaceans. Among crustaceans, *T. gaudichaudii* exhibited the lowest Hg concentrations, compared to the other species.

Discussion

Copper and zinc

Zn and Cu are essential elements and low inter-specific variations are expected. Moreover, the seabird exposure to Cu is not discriminated by their diet since only the cephalopods exhibited higher concentrations, compared to the other preys (Table 3). According to the dietary study, blue petrel, thin-billed prion and Antarctic prion exhibited cephalopods in their diet, but they represented low proportions of the reconstituted mass (Table 1). This is consistent with the fact that Cu concentrations in the three tissues were not significantly different between seabird species.

Zn concentrations in liver and muscle tissue were significantly different between seabird species, with significantly lower concentrations in the muscle of South Georgian diving petrels than in blue petrels. The presence of *Paraeuchaeta antarctica* in the diet could influence the concentration of Zn in the tissues of predators

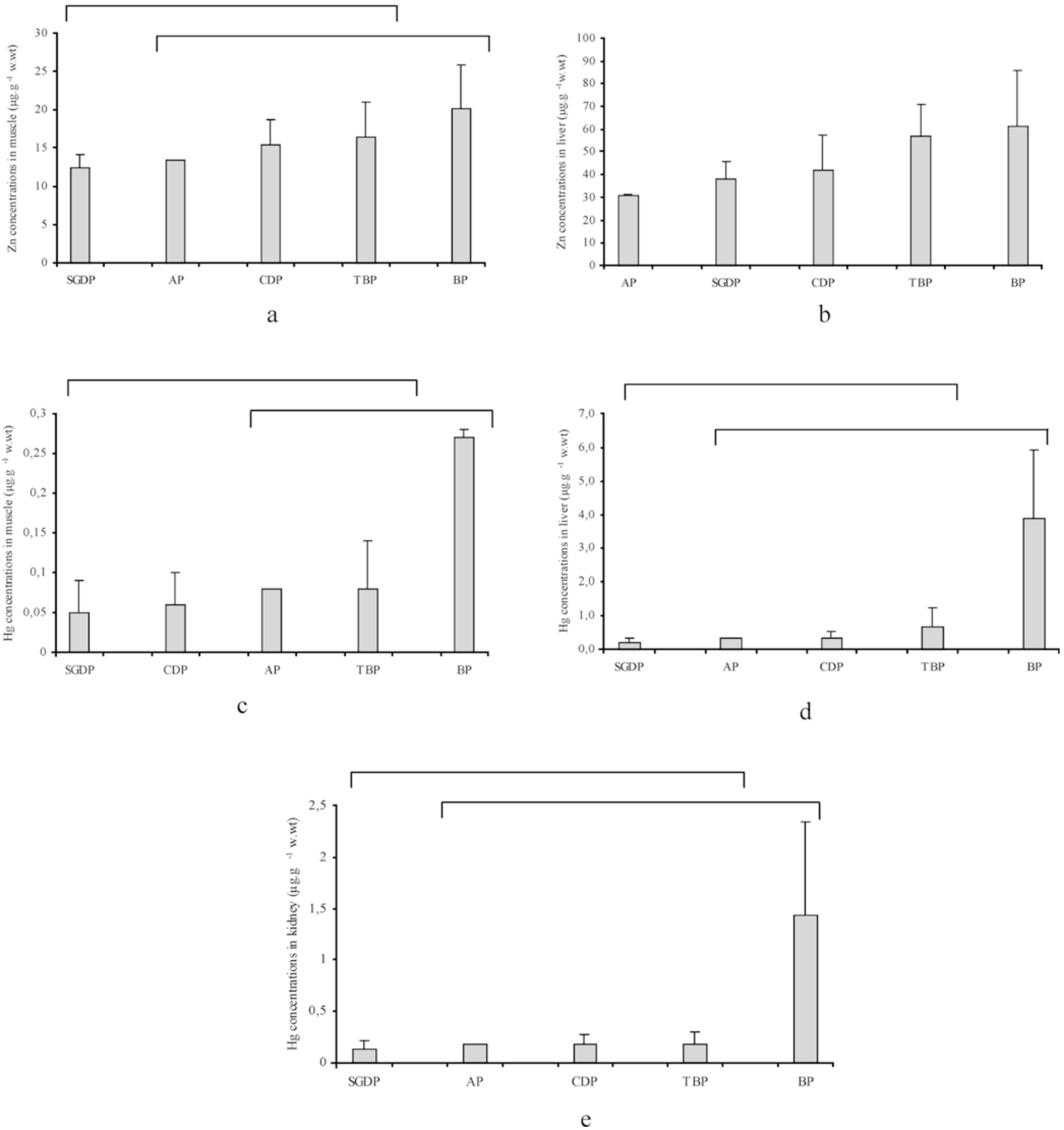

Fig. 1a–e Interspecific differences in the concentration of zinc (Zn) in the **a** muscle and **b** liver and the concentration of mercury (Hg) in the **c** muscle, **d** liver and **e** kidney for five species of zooplankton-eating petrel at the Kerguelen archipelago. Means ± SD are given. Homogeneous groups are given by an *overhead line* (*SGDP* South Georgian diving petrel, *AP* Antarctic prion, *CDP* common diving petrel, *TBP* thin-billed prion, *BP* blue petrel)

since this species exhibited higher concentrations (55 ± 32 µg.g^{-1}) compared with other species (Table 3). However *Paraeuchaeta antarctica* represented a greater proportion of the diet in the common diving petrel compared with other petrels (Fig. 3), but this petrel species did not exhibit the highest Zn concentrations (Table 2).

It is not surprising that Zn and Cu concentrations in seabird tissues do not reflect dietary intake since, as essential elements, a homeostatic control exists as a consequence of a regulation of their absorption in vertebrates, which in turn depends upon the nutritional requirements of the individual (Underwood 1977; Walsh 1990). However, in spite of these homeostasis processes, inter-specific variations have often been shown in Zn

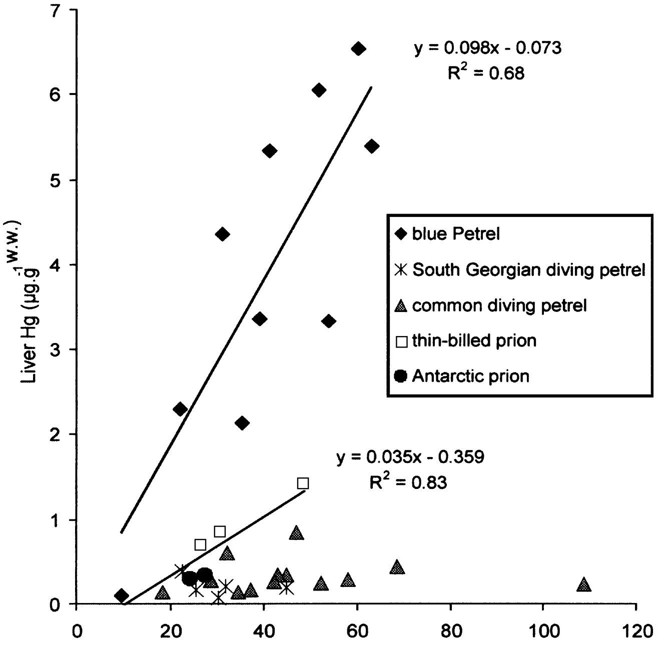

Fig. 2 Relationship between mercury concentrations in the liver and cadmium concentrations in the kidney (µg.g^{-1} wet weight) for five species of zooplankton-eating petrels at the Kerguelen archipelago

and Cu levels in seabirds (Muirhead and Furness 1988; Elliot et al. 1992; Szefer et al. 1993a; Kim et al. 1998; Stewart et al. 1999), which could be attributed to different dietary intake. Nevertheless, since metallothioneins have been found in seabirds (Elliot et al. 1992; Elliot and Scheuhammer 1997; Stewart et al. 1998), this high variability could also be related to molecular interactions between the essential elements Cu and Zn and the toxic metal Cd. This may be due to a consequence of their affinities for metallothioneins, as observed in mammals (Webb 1987). Besides this, it has been shown that the antagonism between Cd, Zn and Cu implies that their respective levels in the diet would modify the absorption, retention and distribution of the other two in the organism (Underwood 1977). This could be the case for the common diving petrel, which was highly exposed to Zn through a high proportion of *Paraeuchaeta antarctica* in its diet, and even more exposed to Cd through a high proportion of *T. gaudichaudii*. Thus the high Cd intake would modify and decrease Zn absorption in this species.

Mercury and cadmium

The most interesting tissues for inter-specific comparisons of Hg and Cd concentrations are liver and kidney tissues, respectively, which are the main sites for long-term storage in higher vertebrates. Only two studies have included identical or closely related species in their analysis. In New Zealand, two individuals of the fairy prion (*Pachyptila turtur*) were included in a study on procellariiforms (Stewart et al. 1999). Muirhead and Furness (1988) analysed Cd in liver and kidney tissues and Hg in liver tissue from 17 common diving petrels and 31 broad-billed prions (*Pachyptila vittata*) from Gough Island, South Atlantic Ocean. In both studies, Hg concentrations are similar to our own results. However, the distribution pattern of Hg in liver and kidney tissues is different between the fairy prions (Stewart et al. 1999) and the thin-billed and Antarctic prions from this study. In fairy prions, mean Hg concentrations were similar in the liver and kidney (2.6 ± 0.8 and 2.5 ± 0.8 µg.g^{-1} d.wt., respectively), whereas they were 2–4 times lower in the kidney compared to the liver in the thin-billed prion and Antarctic prion in this study (Table 2). This different pattern of Hg distribution between the two organs could reflect a difference in Hg detoxification between the species. The protective effect of selenium (Se) against Hg toxicity has been observed in a number of different organisms and different mechanisms have been proposed for it (Cuvin-Aralar and

Table 3 Mean concentrations of trace elements by wet weight (µg.g^{-1}) ± SD in crustaceans, fish and cephalopods collected during cruises of the *R/V La Curieuse* during the austral summer in the Kerguelen archipelago (*IG* inside Morbihan Gulf, *OG* outside gulf)

Species	*N* (set[a])	Range size (mm)	Moisture (%)	Cd	Cu	Zn	Hg
Crustaceans							
Euphausiacea							
Euphausia vallentini	3	16–24	61 ± 3	0.19 ± 0.09	7.0 ± 0.8	23 ± 4	0.016 ± 0.001
E. triacantha	3	27–36	70 ± 3	0.09 ± 0.01	4.4 ± 2.1	16 ± 1	0.010 ± 0.003
Thysanoessa sp.	6	10–23	76 ± 5	0.80 ± 0.40	7.5 ± 2.6	7 ± 2	0.015 ± 0.007
Amphipoda							
Themisto gaudichaudii (OG)	3	–	71 ± 1	21.4 ± 2.1	4.7 ± 2.1	24 ± 1	0.007 ± 0.001
T. gaudichaudii (IG)	3	17–27	71 ± 1	8.4 ± 2.0	3.5 ± 0.3	15 ± 1	0.008 ± 0.002
Copepoda							
Paraeuchaeta antarctica	3	5.4–9.6	67 ± 3	0.48 ± 0.24	2.3 ± 0.7	55 ± 32	0.017 ± 0.008
Fish							
Myctophidae	45	–	66 ± 3	0.011 ± 0.007	1.0 ± 0.3	9 ± 2	0.039 ± 0.028
Cephalopods							
Squids	20	–	78 ± 3	13.0 ± 9.3	14.0 ± 8.1	20 ± 7	0.022 ± 0.013

[a] Except for fish and cephalopods (individuals).

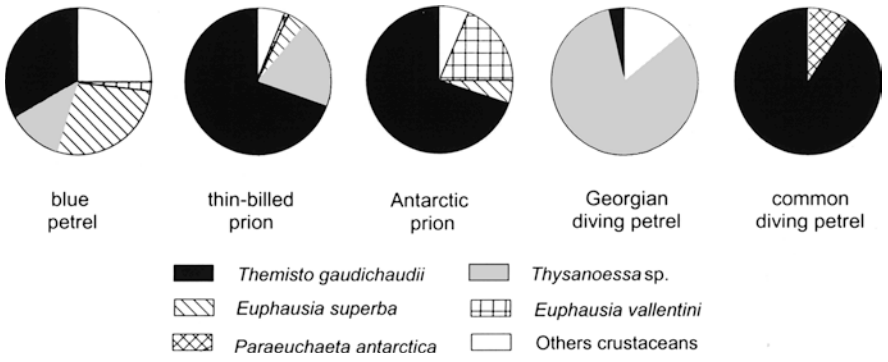

Fig. 3 Composition by reconstituted mass of the crustacean diet during three consecutive rearing periods in five species of zooplankton-eating petrels at the Kerguelen archipelago (from Bocher et al. 2000, 2001 and Chérel et al. 2002a, 2002b)

Furness 1991). In species exhibiting high levels of Hg (which includes marine mammals as well as seabirds), Hg would be demethylated from its more toxic methyl form to the less toxic inorganic form through binding to (Se). The formation of this Hg-Se complex in the liver could be one of these detoxification processes leading to the fossilisation of Hg (Koeman et al. 1975; Martoja and Berry 1980; Thompson and Furness 1989; Palmisano et al. 1995). In seabirds, the moult also acts as a means for eliminating methylmercury (Furness et al. 1986). Both of these processes are often associated with the displacement of Hg from the kidney to the liver, a less vulnerable organ (Cuvin-Aralar and Furness 1991). The levels and the physico-chemical form of Hg and selenium (Se) in prey may influence this detoxification (Caurant et al. 1996). Therefore, despite comparable low levels of Hg in the liver, different concentrations found in the kidney could reflect either a different diet or different Hg behaviour between prion species. However, in both studies, sample sizes were small, and since individual variation is high in the concentration of Hg, these mean values should be considered with caution.

Mean Cd concentrations reported by Muirhead and Furness (1988) in the kidney and liver of the common diving petrel were similar to our own results for this species. In the broad-billed prion from the same study, mean Cd concentrations were also comparable to those of the thin-billed and Antarctic prion analysed in this study (Table 2). Fairy prions, analysed by Stewart et al. (1999), exhibited mean Cd concentrations also very similar to our results for the two prion species.

Stewart et al. (1999) classified different seabird species according to their pattern of accumulation of Hg in the liver and Cd in the kidney. The third category discriminated by a low or very low Hg level (from 2.5 to 35 μg.g^{-1} d.wt.) but high Cd levels (from 74 to 151 μg.g^{-1} d.wt.) included the Buller's albatross, shy albatross, sooty shearwater, grey-faced petrel and the cape petrel and fairy prion. The five species of petrels analysed in this study, which included two prions, belong to this category. However, there were differences between our species (Fig. 2). Blue petrels exhibited significantly higher mean Hg concentrations in the three tissues compared with the other species (Fig. 1c,d,e). This could be explained by the higher percentage of fish in their diet (Table 1), which also exhibited the highest Hg concentrations among prey (Table 3). Blue petrels also feed on cephalopods, which in this study represented only 2% of the reconstituted mass of their diet, but exhibited higher Hg concentrations than crustaceans and might have contributed to Hg exposure (Table 3). Nevertheless, the higher Hg levels in this species were also expected, due to the long life span of this species (Chastel 1995) and thus the greater period of exposure to Hg. The few reported results on age-related variation of Hg levels in soft tissues are contradictory (Monteiro and Furness 1995), but it would not be surprising that in the individuals exposed to a great amount of Hg through the diet, the possible elimination of methylmercury through the plumage during the annual moult would be insufficient to balance the high dietary intake. Thus, the older individuals would exhibit higher Hg levels as a consequence of the demethylation process and storage in the inorganic form in the liver. In this study, differences in age among individuals may explain the relationship between the accumulation of Hg in the liver and the accumulation of Cd in the kidney (Fig. 2). Nevertheless, evidence for the accumulation of heavy metals throughout a bird's life span is lacking. For example, no significant relationship was found between age and cadmium concentrations in the kidney or liver of Cory's shearwaters or great skuas of known age (Stewart and Furness 1998).

Since the amphipod *T. gaudichaudii* was the main food item for common diving petrels, thin-billed prions and Antarctic prions (Fig. 3), and since it exhibited exceptionally high Cd concentrations (both inside and outside the gulf) compared to the other crustaceans analysed in this study (Table 3) or in other studies (Sanchez-Hernandez 2000), the theoretical Cd exposure is probably higher for this species. According to the estimated Cd exposure through this amphipod, significantly higher Cd concentrations in common diving petrels, intermediate Cd levels in prions, and significantly lower Cd levels in blue petrels and especially South Georgian diving petrels would have been expected in the liver and kidney. Despite a maximum concentration of 109 μg.g^{-1} w.wt. in one individual of the common diving petrel, there were no significant differences in Cd concentrations among species in all the three tissues. This implies that either Cd in the amphipods is not bioavailable or that elimination processes would balance the Cd dietary intake. The relatively low coefficients of variation of Cd concentrations in the kidney of seabirds in this study would support this hypothesis. However, it should also be noted that diet has only been studied during the breeding season and may not reflect the year-round exposure to Cd. This may be particularly true during the inter-breeding season when birds are absent from the archipelago. For example, the stable isotopic composition (δ^{13}C and δ^{15}N) of adult feathers sampled early in the breeding season when birds feed offshore has been shown to be identical in South Georgian and common diving petrels, indicating no trophic segregation between these two species during the moulting (inter-breeding) period (Bocher et al. 2000). However, during the breeding season, there is a trophic segregation (Fig. 3), confirmed by a different stable isotopic composition of chick food and chick feathers between the two species (Bocher et al. 2000). Indeed, *Thysanoessa* sp., which feeds on phytoplankton and small zooplankton (especially crustaceans; Hopkins 1985), is likely situated at a lower trophic level than *T. gaudichaudii*, which is regarded as an obligate carnivorous species (Hopkins 1985). Since the biological half-life of Cd in the kidney is several years in vertebrates (Friberg et al. 1974; Underwood 1977), the bioaccumulation of Cd in this organ reflects the long-term exposure of the individual. Thus, the segregation observed during the breeding season would be insufficient to differentiate the long-term exposure between the species.

Conclusions

This study highlights, for the first time, heavy-metal accumulation in a community of small petrels. The low number of individuals analysed for some species, due to the difficulties of obtaining freshly dead birds, leads us to be cautious about the results obtained for prions and South Georgian diving petrels. Nevertheless, there were clear interspecific variations in Hg concentrations, which reflected the different dietary intakes, especially for fish in the blue-petrel diet. In contrast, Cd concentrations did not significantly differ between the five petrel species, despite clear differences in Cd concentrations among prey species. Even if high levels of Cd are reached in Antarctic seabirds, the interactions of this element with Cu and Zn through competition for binding with metallothioneins in prey or competition for absorption in seabirds could lead to a lower bioavailability of this toxic element. Studies on the physico-chemical forms of Cd in crustaceans would allow one to evaluate the influence of these prey on Cd accumulation in seabirds. Another explanation might be a similar diet and thus a similar Cd exposure during the non-breeding period. Unfortunately, the diet of seabirds outside the breeding period is very difficult to establish since birds forage at sea without returning to the colony. In summary, within the five species of petrel studied, only the bioaccumulation of Hg is related to diet. Therefore, the use of trace elements as indicators of diet for these five species of petrel appears to be limited. However, it would appear interesting to study the whole community of seabirds in Kerguelen (and not only this community of five species of petrel) and determine the influence of main prey groups (crustaceans, fish and cephalopods) on bioaccumulation of heavy metals in different seabird guilds.

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