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Mercury exposure in a large subantarctic avian community

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Abstract: Mercury (Hg) contamination poses potential threats to ecosystems worldwide. In order to study Hg bioavailability in the poorly documented southern Indian Ocean, Hg exposure was investigated in the large avian community of Kerguelen Islands. Adults of 27 species (480 individuals) showed a wide range of feather Hg concentrations, from 0.4 ± 0.1 to $16.6 \pm 3.8 \mu\text{g g}^{-1}$ dry weight in Wilson's storm petrels and wandering albatrosses, respectively. Hg concentrations increased roughly in the order crustacean- < fish- \leq squid- \leq carrion-consumers, confirming that diet, rather than taxonomy, is an important driver of avian Hg exposure. Adults presented higher Hg concentrations than chicks, due to a longer duration of exposure, with the only exception being the subantarctic skua, likely because of feeding habits' differences of the two age-classes in this species. High Hg concentrations were reported for three species of the poorly known gadfly petrels, which merit further investigation.

Key words: Feeding ecology; Kerguelen; Procellariiformes; seabirds; Southern Ocean.

Capsule: Mercury concentrations in feathers of sympatric subantarctic birds (27 species) are driven mainly by feeding habits and exposure duration.

Highlights

- Feather Hg concentrations were measured in 27 sympatric subantarctic bird species.
- Inter-specific variation in Hg exposure depends on feeding habits, not taxonomy.
- Hg concentrations were higher in adults than chicks due to longer exposure duration.
- Hg is highly bioavailable in the Southern Ocean, which merits further investigation.

1. Introduction

Mercury (Hg) is a pervasive non-essential metal affecting ecosystem health. Despite its natural origin, Hg has been mobilized by human activities such as mining and fossil-fuel combustion (UNEP 2013), thus resulting in a significant increase in Hg available for cycling among land, air and the ocean since pre-industrial times (Selin 2009). Hg emissions are transported through the atmosphere on a hemispheric-to-global scale, allowing for transport to remote locations such as sub-polar and polar regions (Fitzgerald et al. 1998). After atmospheric deposition and through biotic and abiotic mechanisms, Hg is readily transformed in methyl-Hg, the highly toxic form that bioaccumulates in the tissues of living organisms and biomagnifies up food webs, especially in aquatic environments (Fitzgerald et al. 2007). Top predators are thus exposed to significant quantities of Hg *via* their diet, providing information on Hg bioavailability within their food webs (Morel et al. 1998). Among consumers, birds have varied levels of ecological, spatial and temporal integration of contaminants depending on species, and they have been identified as effective indicators of Hg bioavailability in both terrestrial and marine environments (Burger and Gochfeld 2004, Solonen and Lodenius 1990).

The Kerguelen Islands are a remote subantarctic archipelago in the southern Indian Ocean, where the level of Hg bioavailability is poorly documented (Bocher et al. 2003, Bustamante et al. 2003, Cipro et al. 2014, Cossa et al. 2011). This archipelago hosts a large and highly diverse avian assemblage (35 different breeding species). The community includes a few terrestrial species and many seabirds, with Sphenisciformes (penguins) and Procellariiformes (albatrosses and petrels) dominating by mass and numbers, respectively (Guinet et al. 1996, Weimerskirch et al. 1989). Overall Kerguelen

seabirds feed on a few key species of marine organisms, including some crustaceans (euphausiids, hyperiids), fish (myctophids, notothenioids) and cephalopods (oceanic squids) (Bocher et al. 2001, Cherel et al. 2010, Cherel and Hobson 2005, Guinet et al. 1996), with some seabirds relying extensively on carrion. This biological richness can be related to the large and productive shelf surrounding the archipelago (Blain et al. 2001). Kerguelen seabirds show a wide range of contrasted feeding strategies, with species foraging in the benthic and pelagic environments and ranging from neritic to oceanic waters. Noticeably, the oceanic species forage over a large latitudinal gradient, from subtropical to Antarctic waters (Supplementary Table S1). Kerguelen seabirds therefore offer a unique opportunity to study Hg bioavailability over diverse water masses of the Southern Ocean.

The present study aims to assess Hg bioavailability in the southern Indian Ocean by using birds from the Kerguelen Islands as bioindicators. Hg exposure was evaluated by using body feathers, because feathers are the main route of Hg excretion in birds (Braune and Gaskin 1987). Importantly, this work complements a recent investigation on Hg in chicks (Blévin et al. 2013) by focusing on breeding adults and by including more species. While Hg concentrations in chick feathers are representative of a well-defined, relatively short period of exposure (the chick-rearing period), adult feathers provide a wider perspective on Hg exposure of the species over their whole life cycles (Evers et al. 2005). Thus adult feather Hg concentrations were determined in 27 representative species, including the only two terrestrial birds of the assemblage, in order to: (i) describe Hg exposure in a large number of sympatric bird species from the poorly documented southern Indian Ocean; (ii) compare the exposure pattern to that of avian communities from other subantarctic and oceanic remote locations worldwide; (iii) test the effect of age-class on feather Hg concentrations by using the recently published

Hg data on chicks (Blévin et al. 2013), and (iv) investigate the influence of various factors (taxonomy, diet, feeding habitats, moulting patterns) on Hg exposure. Taxonomy, which was not tested in Blévin et al. (2013), was expected to play a minor role in explaining feather Hg concentrations when compared to feeding strategies, since diet is considered to be the main factor driving Hg variation in birds (Becker et al. 2002, Blévin et al. 2013, Bocher et al. 2003, Monteiro et al. 1998, Stewart et al. 1999). In addition, adult birds were expected to show higher feather Hg concentrations than chicks, as they are exposed over a longer period to Hg *via* their diet and moulting patterns (Catry et al. 2008, Stewart et al. 1997).

2. Materials and methods

Fieldwork was carried out from 2003 to 2011 on the Kerguelen Islands (49°21'S, 70°18'E, Fig. 1), which are located in the southern part of the Polar Frontal Zone, in the immediate vicinity of the Polar Front (Orsi et al. 1995, Park and Gambéroni, 1997). Breeding adults from 27 bird species belonging to 5 orders and 10 families were sampled (n = 5 to 33 individuals per species, Supplementary Table S2). Sampling was conducted at different locations of the archipelago, depending on the species breeding sites. Resident neritic seabird species (Kerguelen shag and gentoo penguin) were sampled at colonies close to the open sea, while terrestrial species (lesser sheathbill and Kerguelen pintail) were sampled on islands of the large Morbihan Bay (closed sea). Birds were non-destructively captured by mist net or by hand, depending on species, and released immediately after sampling. A few whole body feathers (6-10) were pulled out from the lower back of the birds and then stored dry in sealed plastic bags until analysis at the University of La Rochelle, France.

Depending on bird and hence feather size, 1 to 5 whole feathers per individual were cleaned, oven-dried to a constant mass and homogenised as described in [Blévin et al. \(2013\)](#). An Advanced Mercury Analyzer spectrophotometer (Altec AMA 254) was used to measure total Hg, which approximates the amount of methyl-Hg in feathers ([Bond and Diamond 2009](#), [Thompson and Furness 1989a](#)). For each individual, analyses were run in duplicate-triplicate by taking sub-samples of the homogenised feathers (relative standard deviation < 10% for each individual). Accuracy was checked using certified reference material (Tort-2 Lobster Hepatopancreas, NRC, Canada; certified Hg concentration: $0.27 \pm 0.06 \mu\text{g g}^{-1}$ dry weight). Our measured values were $0.24 \pm 0.01 \mu\text{g g}^{-1}$ dry weight, $n = 22$. Blanks were analysed at the beginning of each set of samples and the detection limit of the method was $0.005 \mu\text{g g}^{-1}$ dry weight. Hg concentrations are presented $\mu\text{g g}^{-1}$ dry weight (dw).

Statistical analyses were performed using R 2.15.1 ([R Core Team 2012](#)). Data exploration was performed mainly following [Zuur et al. \(2010\)](#). The influence of taxa (species, genus, family and order) on adult feather Hg concentrations was tested by using generalized linear models (GLM) with a gamma distribution and an inverse link function. Model selection was based on Akaike's Information Criteria adjusted for small sample sizes (AICc) ([Burnham & Anderson 2002](#)). The sampling year was not included in the models because most species were sampled in only one year ([Supplementary Table S2](#)) and thus the year effect would be confounded by the species effect. Nonetheless, no inter-annual differences in feather Hg concentrations were found on the six species that were sampled in two different years (light-mantled sooty albatross, soft-plumaged and Kerguelen petrels, black-bellied storm petrel, South Georgia diving petrel and lesser sheathbill, data not shown). As biometric measurements were not performed on individual birds during the sampling procedure, the effect of size and mass on feather

Hg concentrations could not be incorporated in the models. However, mean values of size and mass were obtained for each species from the literature ([Supplementary Table S1](#)) and their correlations with mean feather Hg concentrations were tested. Finally, the effect of age-class on feather Hg concentrations was investigated on 21 out of the 27 species by comparing adult data from the present study with chick data from the same Kerguelen locations ([Blévin et al. 2013](#)). A significance level of $\alpha < 0.05$ was used for all statistical tests. Results are means \pm SD.

General information on the feeding ecology of Kerguelen birds was based on published and unpublished data obtained using various methods (stomach content and stable isotope analyses and tracking devices), and is summarized in [Supplementary Table S1](#). Importantly, dietary information was restricted to the chick food, because parent birds carry significant amounts of food in their stomach at that time only. By contrast, adult diet is poorly known both during and outside the breeding period. The relationship between Hg contamination and trophic ecology was not studied here using stable isotopes, because of the uncoupled temporal integration of Hg and stable isotopes in feathers of adult birds ([Bond 2010](#), [Thompson et al. 1998](#)).

3. Results

Feather Hg concentrations were measured in a total of 480 adult birds from the Kerguelen Islands (details in [Supplementary Table S2](#)). Feather Hg concentrations varied widely within the avian community, with means ranging from 0.42 ± 0.13 to $16.6 \pm 3.8 \mu\text{g g}^{-1}$ dw in Wilson's storm petrels and wandering albatrosses, respectively ([Fig. 2](#)). The lowest feather Hg concentration occurred in a South-Georgian diving petrel and the highest in a northern giant petrel (0.10 and $32.1 \mu\text{g g}^{-1}$, respectively). Model

selection showed that species was the most important factor explaining feather Hg concentrations when compared to other taxonomic levels (Table 1). Coefficients of variations (CV) also varied considerably between species, ranging from 13 to 109% (Supplementary Table S2). Mean feather Hg concentration was significantly related to species size (Pearson correlation, $r = 0.50$, $p = 0.008$, $n = 27$), but not to species mass ($r = 0.23$, $p = 0.256$, $n = 27$).

By combining feather Hg data of adults from this study with those of chicks from Blévin et al. (2013), a total of 654 individuals from 21 seabird species were analysed. The model including species, age-class and their interaction as explaining factors of feather Hg concentrations showed the best fit to the data (Table 1). Feather Hg concentrations were significantly higher in adults than in chicks in all but two species: the blue petrel (no statistical difference) and subantarctic skua (higher chick level) (Fig. 3). The ratio of adult to chick feather Hg concentrations varied between species, ranging from 0.5 to 20.7 in the subantarctic skua and South-Georgian diving petrel, respectively (Supplementary Table S2).

4. Discussion

To the best of our knowledge, this study is the first to report feather Hg concentrations for such a large number of adult sympatric birds, including representative species of all the four families of the order Procellariiformes, namely albatrosses, petrels, storm petrels and diving petrels. Hg exposure varied widely within the community, showing a remarkable 40-fold difference between the species with the lowest and highest Hg concentrations. The community exposure pattern agrees with results on chicks (Blévin et al. 2013): small petrels, penguins and terrestrial species generally showed low levels

of exposure ($< 2.5 \mu\text{g g}^{-1} \text{ dw}$), coastal seabirds, *Procellaria* petrels and small albatrosses had intermediate concentrations ($< 10 \mu\text{g g}^{-1} \text{ dw}$), while *Pterodroma* petrels, northern giant petrels and wandering albatrosses were the species having the highest concentrations ($> 10 \mu\text{g g}^{-1} \text{ dw}$).

4.1 Comparisons with other avian communities

The pattern of Hg concentrations among members of the Kerguelen avian community fits well with that of other subantarctic sites, such as South Georgia, southern Atlantic Ocean (Fig. 4). Feather Hg concentrations were comparable in seabirds from the two localities, with the exception of the northern giant petrel and wandering albatross (Anderson et al. 2009, Becker et al. 2002). This could be related to inter-site dietary differences of these two top predators. Moreover, similar feather Hg concentrations were reported for some species of albatrosses and petrels from the southern Pacific Ocean (Thompson et al. 1990, 1993). Hg bioavailability thus seems to be similar within the three sectors of the Southern Ocean, which agrees well with its circumpolar annular oceanographic structure (Sokolov and Rintoul 2007). At lower latitudes of the Southern Hemisphere, only the tropical seabird communities from the western Indian Ocean have been investigated, revealing much lower feather Hg concentrations ($\sim 0.05\text{--}1.5 \mu\text{g g}^{-1}$; Catry et al. 2008, Kojadinovic et al. 2007) than in Kerguelen birds. This trend could result from differences in the physical and biological factors driving methyl-Hg production and food web transfer in the two regions (i.e., the atmospheric deposition of inorganic Hg, the rate of primary productivity, the abundance of sinking organic matter and the structure of the microbial community, Mason et al. 2012). The wide range of Hg exposure of Kerguelen birds compares well with avian communities of remote archipelagos of the Northern Hemisphere, namely the tropical Midway Atoll, North

Pacific Ocean and the subtropical Azores Islands, North Atlantic Ocean (both $\sim 1\text{--}20 \mu\text{g g}^{-1}$; [Burger and Gochfeld 2000a](#), [Gochfeld et al. 1999](#), [Monteiro et al. 1998](#)). These wide ranges of contamination are related to the presence of highly contaminated species of albatrosses and gadfly petrels within the communities (see below). Indeed, the avian assemblage of the temperate Machias Seal Island, North Atlantic Ocean, which includes neither albatrosses nor gadfly petrels, had lower feather Hg concentrations ($0.7\text{--}7 \mu\text{g g}^{-1}$; [Bond and Diamond 2009](#)). Therefore, the specific composition of the avian communities rather than the proximity to highly industrialized countries seems to be a key factor driving the level of Hg exposure within avian assemblages from open sea regions. In this context, the range of Hg exposure within the Kerguelen avian community is remarkable, as it encompasses the concentrations reported worldwide in remote oceanic locations ([Blévin et al. 2013](#)).

4.2 Influence of taxonomy

The best taxonomic explanatory variable of feather Hg concentrations in the Kerguelen community was species, as it integrates a large range of ecological, behavioural, physiological and life-history traits that are susceptible to drive variation in feather Hg concentrations ([Anderson et al. 2009](#), [Bond and Diamond 2009](#)). Although inter-specific differences in avian Hg exposure have often been investigated, taxonomic-related variations were rarely tested in a large number of species ([Anderson et al. 2009](#), [Ochoa-Acuña et al. 2002](#)). Here, statistical models including genus, family or order as explanatory variables had a poor fit to feather Hg data. Indeed, closely-related species at Kerguelen often showed very different levels of exposure. For example, black-bellied storm petrels displayed higher Hg concentrations than the other two Hydrobatidae species, despite similar size and life-history traits. The same pattern was highlighted for

Sphenisciformes, with the gentoo penguins having higher feather Hg concentrations than the other three penguin species (Carravieri et al. 2013). Therefore, the effect of taxonomy seems to play a minor role in avian Hg exposure when compared to other ecological factors (Becker et al. 2002, Lock et al. 1992, Stewart et al. 1999). Nevertheless, the present study provides new and interesting results regarding a particular taxonomic group: the gadfly petrels (genus *Pterodroma*, Warham 1990), which were amongst the species with the highest Hg concentrations (Fig. 2). Our data together with a review of the scientific literature (Table 2) point out the high level of Hg contamination of almost all the *Pterodroma* petrels so far investigated, including species living in different marine ecosystems. Nevertheless, the Barau's Petrel *P. barau* from La Réunion Island, western Indian Ocean, showed surprisingly low feather Hg concentrations ($1.0 \mu\text{g g}^{-1}$), suggesting again a regional trend of low Hg bioavailability at tropical latitudes of the Indian Ocean (see subsection 4.1).

4.3 Influence of diet and feeding habitat

Inter-specific variability in Hg contamination is typically attributed to diet (Arcos et al. 2002, Monteiro et al. 1998, Stewart et al. 1999). Since Hg is efficiently biomagnified up food webs (Atwell et al. 1998, Campbell et al. 2005, Jarman et al. 1996), high trophic level prey, such as fish and cephalopods show higher Hg concentrations than crustaceans and other planktonic organisms (Bustamante et al. 2006, Kojadinovic et al. 2006, Stewart et al. 1997). This is consistent with feather Hg concentrations of Kerguelen birds increasing roughly in the order crustacean- < fish- ≤ squid- ≤ carrion-consumers (Fig. 2b), as previously shown in chicks (Blévin et al. 2013). This confirms that Hg is efficiently biomagnified and that diet plays a key role in explaining Hg exposure. Accordingly, the positive correlation highlighted between bird size and feather Hg concentrations is likely explained by a trophic effect, as larger avian species

tend to occupy higher trophic positions and/or to consume larger prey items ([Burger and Gochfeld 2000a](#)).

Differences in dietary exposure over diverse habitats within and outside the breeding period can also account for important variability in feather Hg concentrations ([Anderson et al. 2009](#), [Blévin et al. 2013](#)). Here, inshore non-migratory species (Kerguelen shag, kelp gull, gentoo penguin), which feed on benthic organisms, showed intermediate to high Hg concentrations. This agrees with high Hg bioavailability in benthic environments due to methyl-Hg production in coastal marine sediments ([Bustamante et al. 2006](#), [Fitzgerald et al. 2007](#)). In the oceanic domain, methyl-Hg concentration reaches a maximum in mesopelagic waters ([Driscoll et al. 2013](#), [Fitzgerald et al. 2007](#)), resulting in enhanced contamination of mesopelagic prey ([Chouvelon et al. 2013](#), [Choy et al. 2009](#)). This could explain the high feather Hg concentrations of oceanic species relying extensively on mesopelagic fish and cephalopods (e.g. gadfly petrels, [Ochoa-Acuña et al. 2002](#), [Ridoux 1994](#)). On the other hand, migratory seabirds can travel thousands of kilometres away from their breeding sites after reproduction (e.g., [Warham 1990](#)), being potentially exposed to different quantities of Hg. Here, species visiting northern subtropical and neritic waters during the non-breeding period (e.g. the wandering albatross) tended to have higher feather Hg concentrations than those that forage predominantly within the limits of the Southern Ocean year-round (e.g. the light-mantled sooty albatross) ([Cherel et al. 2013](#)). However, further investigations on i) the poorly known feeding strategies outside the breeding season and ii) Hg distribution and speciation in the Southern Ocean could elucidate the rationale of this latitudinal trend (see [Blévin et al. 2013](#)).

4.4 Influence of moulting patterns

Feather Hg concentrations reflect blood Hg levels at the time of moult (Bearhop et al 2000, Evers et al 2008). This means dietary Hg but also Hg accumulated over the inter-moult period and remobilized during feather synthesis (Furness et al. 1986, Thompson et al. 1998). Another important intrinsic driver of Hg concentrations in feathers is therefore the timing, duration and frequency of moult. For instance, the irregular and infrequent moulting patterns of large albatrosses are believed to contribute significantly to high Hg concentrations in their feathers (Anderson et al. 2009, Becker et al. 2002). However, enhanced feather Hg concentrations were also reported in Kerguelen species with annual moult cycles, like great-winged and white-chinned petrels. This indicates that moulting patterns alone cannot explain all the inter-specific variation in Hg contamination. In Procellariiformes, demethylation of Hg in the liver appears to be a significant detoxification strategy (Thompson and Furness 1989b, Thompson et al. 1993). The efficiency of demethylation mechanisms is species-dependent and could contribute to explain the inter-specific differences in feather Hg concentrations among members of the Kerguelen avian community.

4.5 Adults and chicks

As previously shown by several other studies (e.g., Burger and Gochfeld 2000b, Catry et al. 2008), feather Hg concentrations were higher in adults than in chicks in almost all Kerguelen species (Fig. 3). Indeed, adults have more time to bioaccumulate Hg in their tissues during the long inter-moult period (\geq one year) before excreting it in feathers (Monteiro et al. 1995, Thompson et al. 1991). By contrast, chick feather Hg concentrations represent the dietary exposure over the chick-rearing period (Ackerman et al. 2011, Becker et al. 1993), which ranges from several weeks to several months in Kerguelen species (Supplementary Table S2). Assuming a similar rate of Hg intake of

adults and chicks, species with short and long chick-rearing periods should show high and low adult-to-chick ratios in feather Hg concentrations, respectively. The hypothesis was verified in the two diving petrels (high ratios, ≥ 9) and in the wandering albatross and northern giant petrel (low ratios, $\sim 2-4$), respectively. Exceptions to this pattern are likely indicative of differential relative Hg exposures in the two age-classes, as observed in blue petrels and subantarctic skuas (ratios: 1.3 and 0.5, respectively). Adult blue petrels from the Kerguelen Islands feed at the same low trophic level in cold Antarctic waters both during the breeding and moulting periods (Cherel et al. 2002a, Cherel et al. 2006). By contrast, chick food includes a significant proportion of mesopelagic fish (Cherel et al. 2002a, Connan et al. 2008), which is consistent with their enhanced Hg exposure over adults. At Kerguelen, subantarctic skua chicks are mainly fed with blue petrels (Mougeot et al. 1998), thus explaining their high feather Hg concentrations. The chick data are in accordance with previous results on chicks of the closely-related great skua that feeds on bird meat (Stewart et al. 1997). The low Hg contamination of adult subantarctic skuas is puzzling and it strongly suggests that moulting adults do not rely on small petrels for feeding. Indeed, previous findings on subantarctic skuas from South Georgia suggest that they have a mixed diet of zooplankton and low trophic-level prey over the wintering grounds (Phillips et al. 2007). Therefore, both the duration of Hg exposure and feeding habits are key factors explaining differences in feather Hg concentrations between seabird chicks and adults.

5. Conclusions

Results from this study reinforce previous findings showing that taxonomy plays a minor role in determining avian Hg exposure when compared to feeding strategies (Stewart et al. 1999). Our results confirm that Hg concentrations are very high in some

subantarctic birds, with many species showing levels of potential concern. The most common used toxic threshold of feather Hg concentration in birds is $5 \mu\text{g g}^{-1}$ (e.g., [Evers et al. 2008](#)). Here, this level was exceeded by some individuals of 11 seabird species and by all individuals of wandering albatross, northern giant petrel, and white-headed and great-winged petrels. Although subantarctic species may have evolved to cope with high Hg exposure in their environment ([Blévin et al. 2013](#), [Thompson et al. 1993](#)), there is an urgent need to investigate the inter- and intra-specific physiological differences of Hg metabolism, excretion and toxicity, in order to establish whether some species, or some particular individuals, could be at risk. Evidence of Hg consequences on breeding, hatchling and fledging success has been reported in polar birds ([Goutte et al. in press](#), [Tartu et al. 2013](#)). Such investigations on risk related to Hg exposure are even more relevant in the context of global warming that would favour the methylation rate of Hg in the Ocean ([Cossa 2013](#)). Finally, the present study enables selecting the white-headed petrel as a good bioindicator species of Hg bioavailability in the Southern Ocean, considering its high level of exposure and low intra-specific variation. The white-headed petrel adds to the list of Kerguelen bioindicator species recently identified according to their foraging ecology and exposure patterns, i.e. the gentoo and king penguins, the black-browed, light-mantled sooty and wandering albatrosses ([Blévin et al. 2013](#), [Carravieri et al. 2013](#)). The periodic examination of feather Hg concentrations in species from these remote regions over the long-term will make it possible to monitor temporal trends of Hg bioavailability to predators in the open ocean in relation to global trends of Hg emissions.

Conflict of interest

The authors declare that there are no conflicts of interest.

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Table 1

AIC_c model ranking for adult feather Hg concentrations within the Kerguelen avian community. Models are GLM with a gamma distribution and an inverse link function. Abbreviations: AIC_c, Akaike's Information Criteria adjusted for small sample-sizes values; w_i , AIC_c weights.

Models	N° parameters	AIC _c	Δ AIC _c ^a	w_i ^b
Adults (N = 480)				
Species	28	1698	0	1
Genus	22	1719	20	0
Family	11	2226	528	0
Order	6	2422	723	0
Null	2	2459	760	0
Adults and chicks (N = 654)				
Species * Age-class	43	1684	0	1
Species + Age-class	23	2276	592	0
Species	22	2471	787	0
Age-class	3	2915	1231	0
Null	2	3037	1353	0

^a Scaled Δ AIC_c; Δ AIC_c = 0.00 is interpreted as the best fit to the data among the models

^b Weight of evidence interpreted as a proportion. Weights across all models sum to 1.00

Table 2

An overall synthesis of Hg concentrations in body feathers of adult gadfly petrels. Values are means \pm SD with ranges in parentheses.

Species	Site	Ocean	Breeding region	n	Hg ($\mu\text{g g}^{-1}$ dw)	Reference
Atlantic petrel (<i>Pterodroma incerta</i>)	Gough Island	South Atlantic	Subantarctic	23	13.9 ± 3.6^a	Thompson et al. (1990)
	Gough Island	South Atlantic	Subantarctic	15	13.5 ± 4.1 (3.9 - 20.1) ^a	Thompson et al. (1993)
Barau's petrel (<i>Pterodroma barau</i>)	La Réunion	Indian	Tropical	20	1.0 ± 0.3	Kojadinovic et al. (2007)
Bonin petrel (<i>Pterodroma hypoleuca</i>)	Midway Atoll	North Pacific	Subtropical	27	19.7 ± 1.1^b	Gochfeld et al. (1999), Burger and Gochfeld 2000a
Great-winged petrel (<i>Pterodroma macroptera</i>)	Kerguelen Archipelago	South Indian	Subantarctic	14	15.8 ± 4.4 (9.8 - 27.1)	This study
Juan Fernandez petrel (<i>Pterodroma externa</i>)	Juan Fernandez Archipelago	South Pacific	Subtropical	5 (M)	4.2 ± 0.3	Ochoa-Acuña et al. (2002)
				11 (F)	3.9 ± 0.2	
Soft-plumaged petrel (<i>Pterodroma mollis</i>)	Gough Island	South Atlantic	Subantarctic	21	10.3 ± 2.3^a	Thompson et al. (1990)
	Gough Island	South Atlantic	Subantarctic	17	9.8 ± 2.3 (5.4 - 13.4) ^a	Thompson et al. (1993)
	Kerguelen Archipelago	South Indian	Subantarctic	19	12.2 ± 4.2 (4.7 - 25.5)	This study
White-headed petrel (<i>Pterodroma lessonii</i>)	Kerguelen Archipelago	South Indian	Subantarctic	10	12.4 ± 2.0 (9.2 - 17.1)	This study

Studies with too low numbers of sampled individuals ($n < 4$) were excluded.

^a Values are in $\mu\text{g g}^{-1}$ wet weight.

^b Values are means \pm SE.

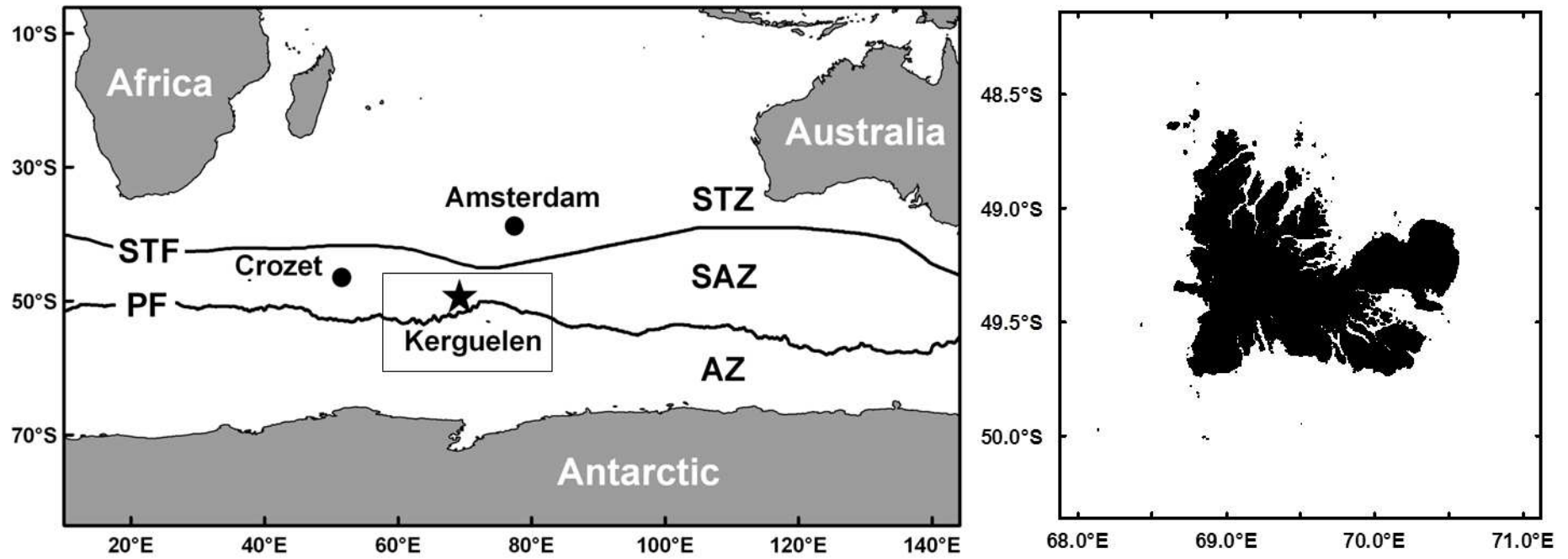


Fig. 1. Map and location of the Kerguelen Islands and of the main oceanic fronts and zones within the southern Indian Ocean. Abbreviations: STF, Subtropical Front; PF, Polar Front; STZ, Subtropical Zone; SAZ, Subantarctic Zone; AZ, Antarctic Zone.

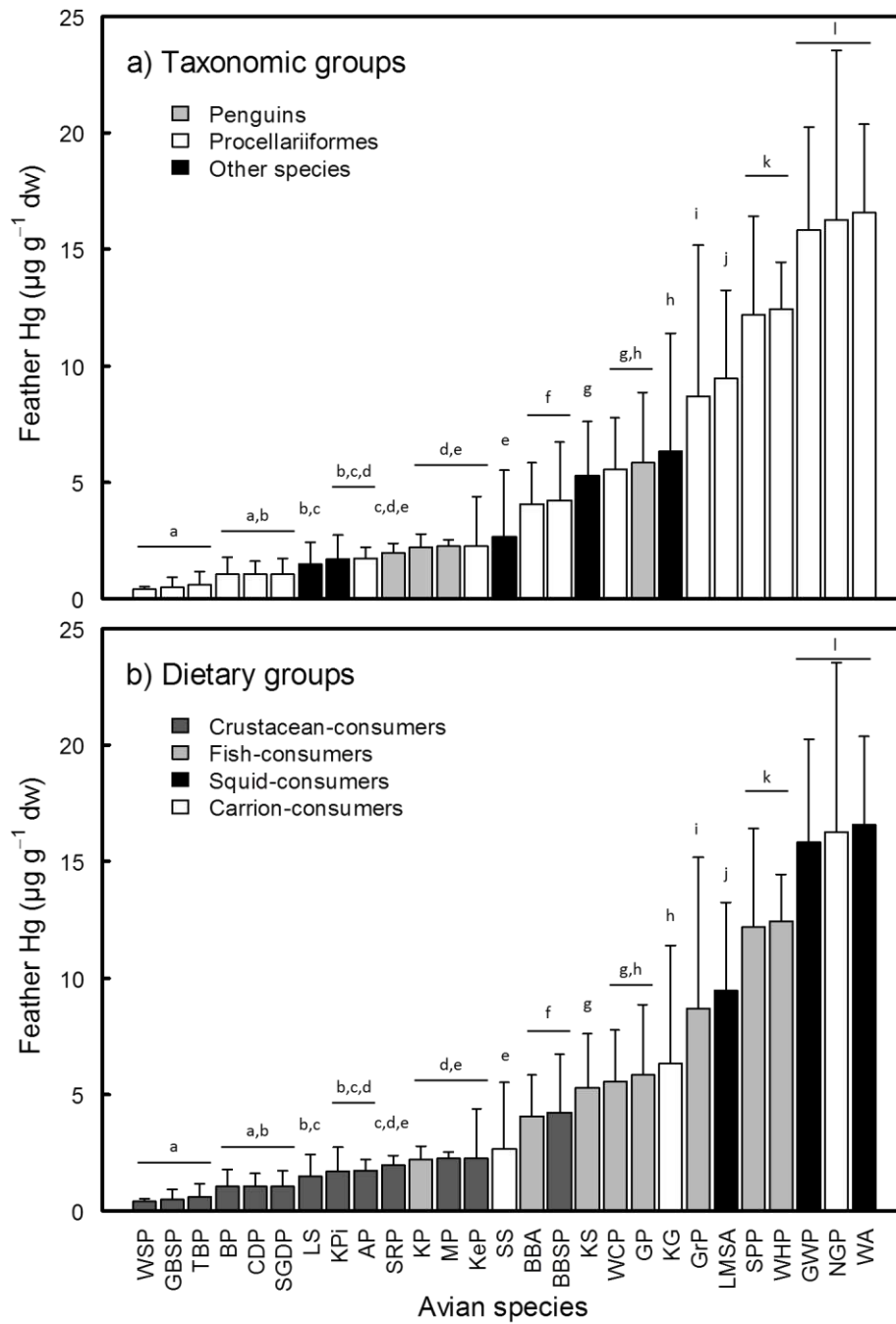


Fig. 2. Inter-specific differences in adult feather Hg concentrations within the Kerguelen avian community. Species are presented according to a) taxonomic groups: penguins (grey), procellariiform seabirds (white) and other species (black); and b) dietary groups: terrestrial species and crustacean- (dark grey), fish- (grey), squid- (black) and carrion- (white) consumers. Species sharing the same letter are not statistically different (Tukey HSD, $p < 0.05$). Values are means \pm SD. Species abbreviations: WSP, Wilson's storm petrel; GBSP, grey-backed storm petrel; TBP, thin-billed prion; BP, blue petrel; CDP, common diving petrel; SGDP, South Georgian diving petrel; LS, lesser sheathbill; KP_i, Kerguelen pintail; AP, Antarctic prion; SRP, southern rockhopper penguin; KP, king penguin; MP, macaroni penguin; KeP, Kerguelen petrel; SS, subantarctic skua; BBA, black-browed albatross; BBSP, black-bellied storm petrel; KS, Kerguelen shag; WCP, white-chinned petrel; GP, gentoo penguin; KG, kelp gull; GrP, grey petrel; LMSA, light-mantled sooty albatross; SPP, soft-plumaged petrel; WHP, white-headed petrel; GWP, great-winged-petrel; NGP, northern giant petrel; WA, wandering albatross.

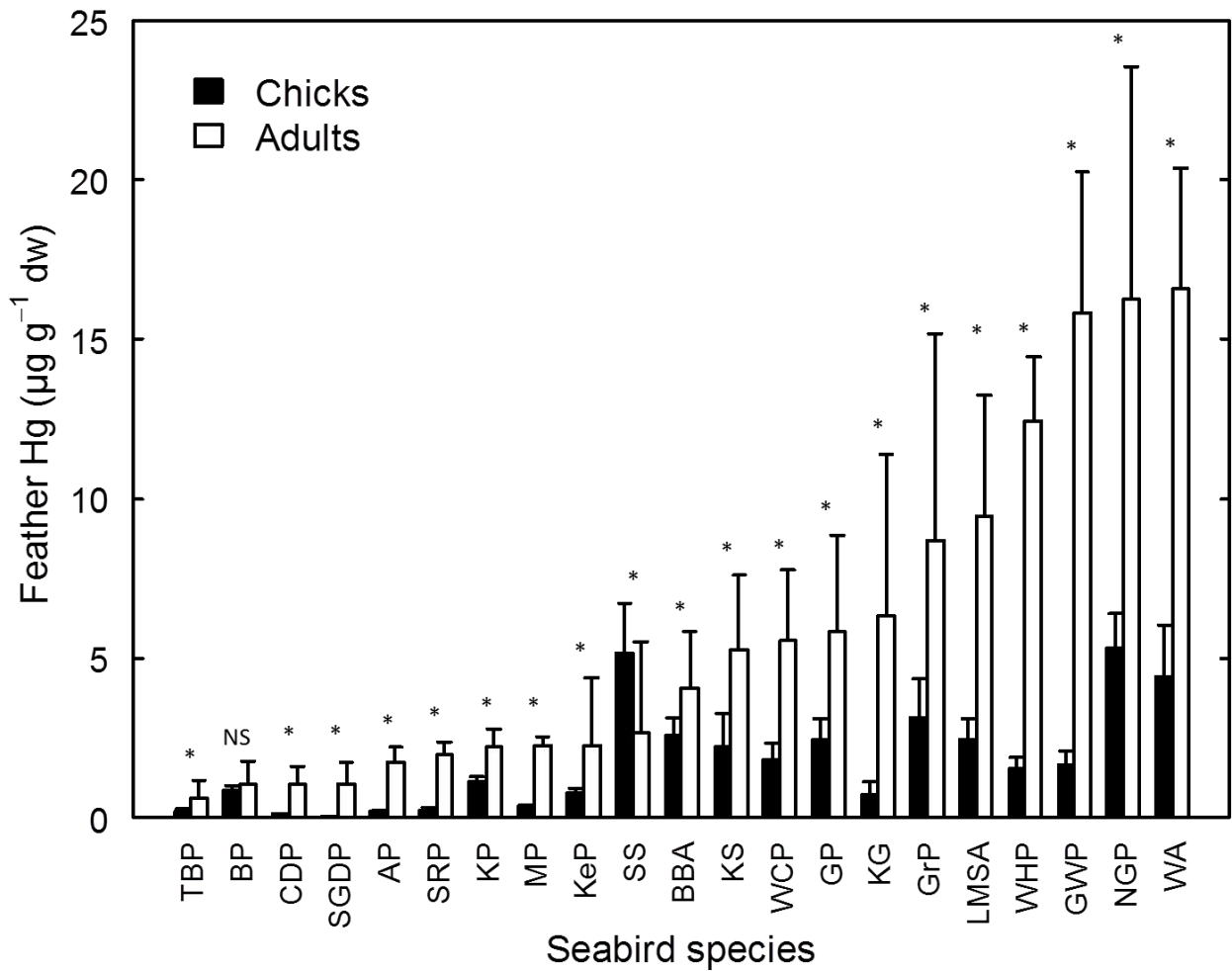


Fig. 3. Age-class differences in feather Hg concentrations within the Kerguelen seabird community. * Statistically different (Wilcoxon, $p < 0.05$); NS: not significant. Values are means \pm SD. Species abbreviations: TBP, thin-billed prion; BP, blue petrel; CDP, common diving petrel; SGDP, South Georgian diving petrel; AP, Antarctic prion; SRP, southern rockhopper penguin; KP, king penguin; MP, macaroni penguin; KeP, Kerguelen petrel; SS, subantarctic skua; BBA, black-browed albatross; KS, Kerguelen shag; WCP, white-chinned petrel; GP, gentoo penguin; KG, kelp gull; GrP, grey petrel; LMSA, light-mantled sooty albatross; WHP, white-headed petrel; GWP, great-winged-petrel; NGP, northern giant petrel; WA, wandering albatross.

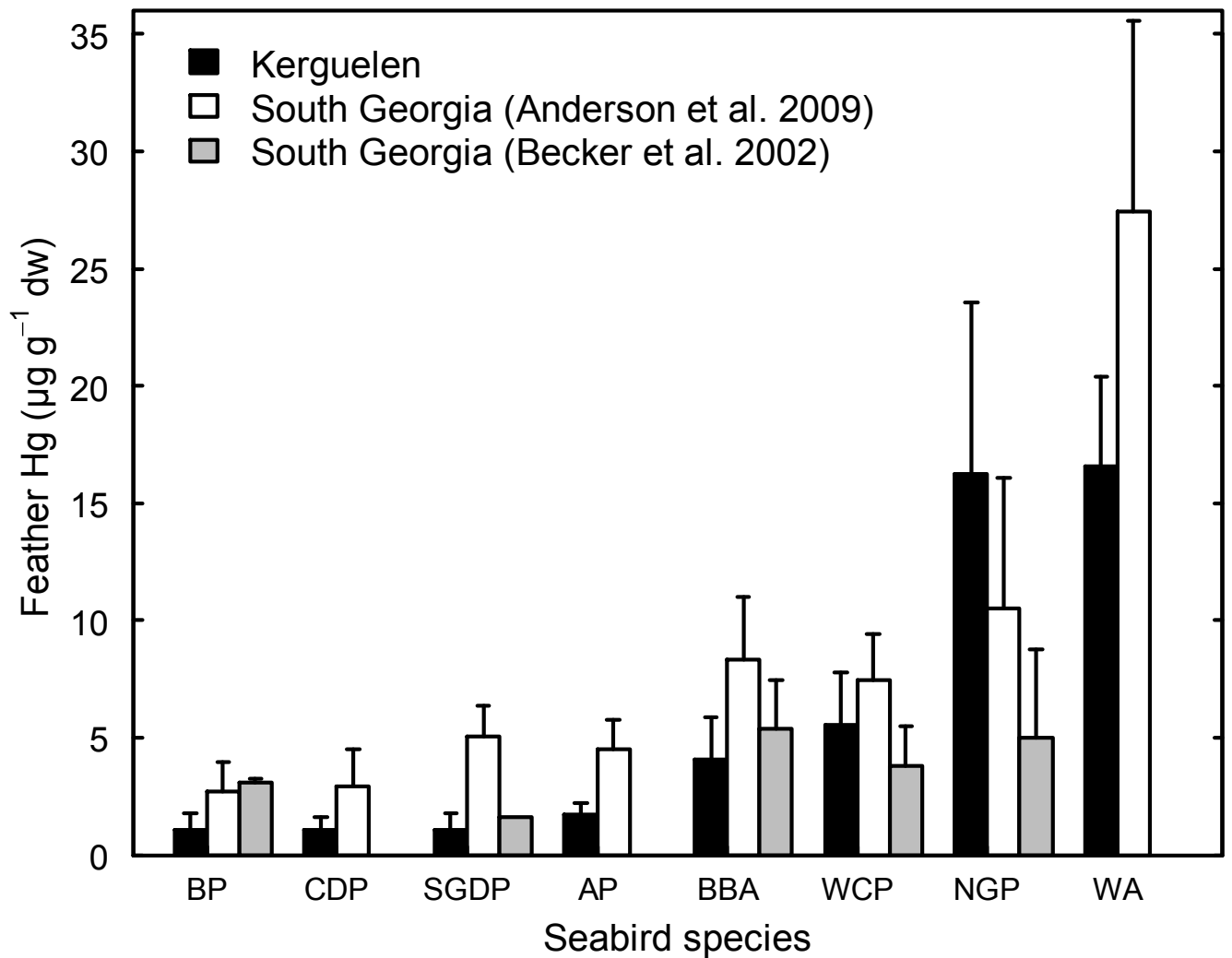


Fig. 4. Comparison of feather Hg concentrations between the same seabird species breeding in the southern Indian Ocean (Kerguelen Islands, present study) and in the southern Atlantic Ocean (South Georgia, Anderson et al. 2009, Becker et al. 2002). Species abbreviations: BP, blue petrel; CDP, common diving petrel; SGDP, South Georgian diving petrel; AP, Antarctic prion; BBA, black-browed albatross; WCP, white-chinned petrel; NGP, northern giant petrel; WA, wandering albatross.

Appendix A – Supplementary material

Supplementary Table S1. Species, biometric data, foraging habitats and dietary habits of marine and terrestrial birds breeding at the Kerguelen Islands.

Species	Abb.	Size (cm) ^a	Mass (kg) ^a	Foraging habitat			Chick food	References
				Breeding (horizontal, vertical)	Moulting (non-breeding)	Isotopes (adult feathers)		
Spheniscidae								
King penguin (<i>Aptenodytes patagonicus</i>)	KP	90	13.3	oceanic; epi-mesopelagic	unknown (likely oceanic)	Polar Front	mesopelagic fish	Bost et al. (2002), Cherel et al. (2010)
Gentoo penguin (<i>Pygoscelis papua</i>)	GP	83	6.5	neritic (open sea); benthic, pelagic	resident all year	Neritic waters	benthic fish (pelagic crustaceans)	Lescroël et Bost (2005)
Macaroni penguin (<i>Eudyptes chrysolophus</i>)	MP	71	4.9	neritic, oceanic; epipelagic	Polar Frontal Zone, oceanic	Subantarctic	pelagic crustaceans (fish)	Cherel et al. (2010), Thiebot et al. (2011a,b)
Southern rockhopper penguin (<i>Eudyptes chrysocome filholi</i>)	SRP	50	2.9	neritic (closed sea); epipelagic	Subantarctic and Polar Frontal Zone, oceanic	Subantarctic	pelagic crustaceans (fish)	Tremblay and Cherel (2000, 2003); Cherel et al. (2010); Thiebot et al. (2012)
Diomedidae								
Wandering albatross (<i>Diomedea exulans</i>)	WA	123	8.8	oceanic, sea surface	subtropical waters, oceanic	Subtropics	fish and cephalopods	Cherel et al. (2013)
Black-browed albatross (<i>Thalassarche melanophrys</i>)	BBA	88	3.8	neritic (open sea); sea surface	subtropical waters (southern Australia), neritic	Subtropics	benthopelagic fish (cephalopods)	Cherel et al. (2000a,b); Cherel et al. (2013)
Light-mantled sooty albatross (<i>Phoebastria palpebrata</i>)	LMSA	84	3.1	oceanic; sea surface	subantarctic waters; oceanic	Subantarctic, Antarctic	cephalopods (crustaceans, carrion)	Ridoux (1994) ^a ; Cherel et al. (2013)
Procellariidae								
Northern giant petrel (<i>Macronectes halli</i>)	NGP	88	4.4	on land and at sea surface	subantarctic to subtropical waters, oceanic	Subantarctic	carrion/seabirds	Ridoux (1994) ^a ; Thiers et al. (2014)
Grey petrel (<i>Procellaria cinerea</i>)	GrP	50	1.1	oceanic; sea surface	unknown	Subtropical Front	fish (cephalopods)	Ridoux (1994) ^a
White-chinned petrel (<i>Procellaria aequinoctialis</i>)	WCP	55	1.3	oceanic; sea surface	northern waters (Benguela current), neritic	Subtropics (Benguela)	fish (cephalopods, crustaceans)	Delord et al. (2010); Péron et al. (2010)
Great-winged petrel (<i>Pterodroma macroptera</i>)	GWP	39	0.56	oceanic; sea surface	unknown	Subtropics	cephalopods (crustaceans)	Ridoux (1994) ^a
White-headed petrel (<i>Pterodroma lessonii</i>)	WHP	43	0.70	oceanic; sea surface	unknown	Subantarctic	fish (cephalopods)	Zotier (1990)

Soft-plumaged petrel (<i>Pterodroma mollis</i>)	SPP	35	0.30	oceanic; sea surface	unknown	Subtropics	fish (cephalopods, crustaceans)	Unpublished data
Kerguelen petrel (<i>Aphrodroma brevirostris</i>)	KeP	35	0.36	oceanic; sea surface	Unknown	High Antarctic	crustaceans	Ridoux (1994) ^a
Blue petrel (<i>Halobaena caerulea</i>)	BP	29	0.20	oceanic; sea surface	Antarctic waters, oceanic	High Antarctic	crustaceans (mesopelagic fish)	Cherel et al. (2002a); Cherel et al. (2006)
Antarctic prion (<i>Pachyptila desolata</i>)	AP	26	0.16	oceanic; sea surface	subtropical waters, oceanic	Subtropics	crustaceans	Cherel et al. (2002b); Cherel et al. (2006)
Thin-billed prion (<i>Pachyptila belcheri</i>)	TBP	26	0.15	oceanic; sea surface	Antarctic waters, oceanic	High Antarctic	crustaceans	Cherel et al. (2002b); Cherel et al. (2006)
Hydrobatidae								
Wilson's storm petrel (<i>Oceanites oceanicus</i>)	WSP	17	0.039	neritic; sea surface	unknown	Subtropics	crustaceans	Ridoux (1994) ^a
Black-bellied storm petrel (<i>Fregetta tropica</i>)	BBSP	20	0.053	neritic, oceanic; sea surface	unknown	Subtropics	crustaceans and carrion (squid, fish)	Ridoux (1994) ^a
Grey-backed storm petrel (<i>Garrodia nereis</i>)	GBSP	18	0.033	neritic; sea surface	unknown	Subtropics	crustaceans	Ridoux (1994) ^a
Pelecanoididae								
Common diving petrel (<i>Pelecanoides urinatrix</i>)	CDP	23	0.14	neritic (closed sea); epipelagic	unknown	Subantarctic, low Antarctic	crustaceans	Bocher et al. (2000)
South Georgian diving petrel (<i>Pelecanoides georgicus</i>)	SGDP	20	0.12	oceanic; epipelagic	unknown	Subantarctic, low Antarctic	crustaceans	Bocher et al. (2000)
Phalacrocoracidae								
Kerguelen shag (<i>Phalacrocorax verrucosus</i>)	KS	65	1.9	neritic (open sea); benthic	resident all year	Neritic waters	benthic fish	Watanabe et al. (2011)
Stercoraridae								
Subantarctic skua (<i>Catharacta antarctica lönmbergi</i>)	SS	58	1.9	on land and at sea surface	unknown	Subtropics	small petrels	Mougeot et al. (1998)
Laridae								
Kelp gull (<i>Larus dominicanus</i>)	KG	60	1.1	on land and at sea surface	resident all year	Coastal	carrion/seabirds (limpets)	Stahl and Mougín (1986) ^a
Chionididae								
Lesser sheathbill (<i>Chionis minor</i>)	LS	40	0.83	on land	resident all year	Terrestrial/coastal	carrion, eggs, invertebrates, algae	Jouventin et al. (1996)
Anatidae								
Kerguelen Pintail (<i>Anas eatoni eatoni</i>)	KPi	40	0.48	on land	resident all year	Terrestrial	vegetation	unpublished data

^a Species average for size (length from the tip of the bill to the end of the tail) and mass (body weight) from Shirihai et al (2002).

^b Stahl and Mougín (1986) and Ridoux (1994) refer to the related Crozet Islands.

Supplementary Table S2. Adult feather Hg concentrations within the Kerguelen avian community. Abbreviations: Abb., species name abbreviation; Ad:Ch ratio, Adult to chick feather Hg ratio using Hg data from the present work and from [Blévin et al. \(2013\)](#).

Species	Abb.	Year	n	Feather Hg ($\mu\text{g g}^{-1}$ dw)				Ad:Ch ratio
				Mean \pm SD	Median	Min–Max	CV (%)	
Spheniscidae								
King penguin (<i>Aptenodytes patagonicus</i>)	KP	2007	12	2.22 \pm 0.59	2.04	1.45–3.21	26.58	2.0
Gentoo penguin (<i>Pygoscelis papua</i>)	GP	2007	12	5.85 \pm 3.00	6.15	1.28–9.43	51.33	2.4
Macaroni penguin (<i>Eudyptes chrysolophus</i>)	MP	2007	12	2.24 \pm 0.29	2.26	1.87–2.75	12.78	6.3
Southern rockhopper penguin (<i>Eudyptes chrysocome filholi</i>)	SRP	2007	12	1.96 \pm 0.41	1.96	1.22–2.62	20.91	7.3
Diomedeidae								
Wandering albatross (<i>Diomedea exulans</i>)	WA	2006	12	16.59 \pm 3.78	16.99	9.84–24.13	22.81	3.7
Black-browed albatross (<i>Thalassarche melanophrys</i>)	BBA	2005	33	4.07 \pm 1.78	3.20	1.71–7.75	43.76	1.6
Light-mantled sooty albatross (<i>Phoebastria palpebrata</i>)	LMSA	2005, 2007	16	9.47 \pm 3.78	10.12	2.31–14.22	39.92	3.6
Procellariidae								
Northern giant petrel (<i>Macronectes halli</i>)	NGP	2008	18	16.26 \pm 7.27	14.61	7.99–32.11	44.72	3.1
Grey petrel (<i>Procellaria cinerea</i>)	GrP	2005	16	8.71 \pm 6.47	6.48	2.22–25.56	74.29	2.8
White-chinned petrel (<i>Procellaria aequinoctialis</i>)	WCP	2005	14	5.54 \pm 2.24	4.92	2.82–9.38	40.36	3.0
Great-winged petrel (<i>Pterodroma macroptera</i>)	GWP	2005	14	15.82 \pm 4.44	15.00	9.76–27.13	28.09	9.6
White-headed petrel (<i>Pterodroma lessonii</i>)	WHP	2002	10	12.43 \pm 2.01	12.56	9.22–17.06	16.21	8.1
Soft-plumaged petrel (<i>Pterodroma mollis</i>)	SPP	2010, 2011	19	12.21 \pm 4.23	12.44	4.67–25.48	34.63	-
Kerguelen petrel (<i>Aphrodroma brevirostris</i>)	KeP	2007, 2008	24	2.27 \pm 2.11	1.67	0.62–10.89	93.13	2.9
Blue petrel (<i>Halobaena caerulea</i>)	BP	2003	25	1.05 \pm 0.72	0.86	0.43–3.32	68.01	1.3
Antarctic prion (<i>Pachyptila desolata</i>)	AP	2008	10	1.73 \pm 0.50	1.53	1.28–2.61	28.94	8.3
Thin-billed prion (<i>Pachyptila belcheri</i>)	TBP	2003	20	0.63 \pm 0.55	0.41	0.24–2.49	87.05	2.9
Hydrobatidae								
Wilson's storm petrel (<i>Oceanites oceanicus</i>)	WSP	2005	12	0.42 \pm 0.13	0.40	0.27–0.68	31.42	-
Black-bellied storm petrel (<i>Fregetta tropica</i>)	BBSP	2005, 2010	10	4.22 \pm 2.53	3.78	1.46–9.53	59.91	-
Grey-backed storm petrel (<i>Garrodia nereis</i>)	GBSP	2006	23	0.51 \pm 0.44	0.37	0.22–2.39	87.16	-
Pelecanoididae								

Common diving petrel (<i>Pelecanoides urinatrix</i>)	CDP	2003	29	1.06 ± 0.54	0.95	0.35–2.43	51.10	9.4
South-Georgian diving petrel (<i>Pelecanoides georgicus</i>)	SGDP	2009, 2010	24	1.07 ± 0.69	0.99	0.10–3.05	64.18	20.7
Phalacrocoracidae								
Kerguelen shag (<i>Phalacrocorax verrucosus</i>)	KS	2005	30	5.30 ± 2.33	4.83	1.80–9.71	44.00	2.4
Stercorariidae								
Subantarctic skua (<i>Catharacta antarctica lönnerbergi</i>)	SS	2009	26	2.65 ± 2.87	1.84	0.39–13.38	108.62	0.5
Laridae								
Kelp gull (<i>Larus dominicanus</i>)	KG	2010	5	6.33 ± 5.07	7.63	0.68–12.32	80.00	6.7
Chionididae								
Lesser sheathbill (<i>Chionis minor</i>)	LS	2009, 2010	26	1.49 ± 0.92	1.29	0.32–3.56	61.35	-
Anatidae								
Kerguelen pintail (<i>Anas eatoni eatoni</i>)	KPi	2010	16	1.69 ± 1.04	1.52	0.36–4.13	61.32	-

^a References: [Marchant and Higgins \(1990\)](#), [Shirihai et al. \(2002\)](#).