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**Mercury in a community of subantarctic seabirds: Chick feather concentrations and influence of foraging habitat and diet**

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# Mercury in a community of subantarctic seabirds: Chick feather concentrations and influence of foraging habitat and diet

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## Abstract

Using top predators as sentinels of the marine environment, Hg contamination was investigated within the large subantarctic seabird community of the Kerguelen Islands, a remote and poorly known area located in the Southern Indian Ocean. Focusing on chicks (21 species), Hg analysis pointed out large inter-specific variations in body feather Hg concentrations, which ranged from  $0.08 \pm 0.01$  to  $5.31 \pm 1.12 \mu\text{g}\cdot\text{g}^{-1}$  dry mass. Seabirds from Kerguelen thus encompass the whole range of chick feather Hg values that were previously collected worldwide. Using stable isotopes, the effects of foraging habitat (reflected by  $\delta^{13}\text{C}$ ) and trophic positions (reflected by  $\delta^{15}\text{N}$ ) on Hg concentrations were then investigated. A multivariate analysis showed that the species-related Hg variations were highly and positively linked to feather  $\delta^{15}\text{N}$  values, thus highlighting biomagnification processes occurring throughout the subantarctic marine trophic webs. By contrast, Hg contamination overall correlated poorly with seabird foraging habitat. However, when focusing on oceanic species, seabird Hg concentration was related to feather  $\delta^{13}\text{C}$  values, with species feeding in colder waters south of Kerguelen Islands being less prone to be contaminated than species feeding in northern warmer waters. In conclusion, the study emphasizes the global effect of anthropogenic Hg emission that is detectable in remote subantarctic islands. Those isolated localities therefore appear as ideal study sites to monitor the temporal trends of global Hg contamination, with the help of some carefully selected seabird species.

*Key words:*

Biomagnification

Contamination

Kerguelen

Southern Ocean

Stable isotopes

Trophic level

## 1. Introduction

Mercury (Hg) is a highly toxic non-essential metal that negatively impacts wildlife (Scheuhammer et al., 2007; Wolfe et al., 1998). Although Hg derives from natural sources (Gustin et al., 2000), human activities have contributed to increase the global Hg pool (Wang et al., 2004). Indeed, anthropogenic Hg represents approximately two-thirds of the total Hg cycling around the world (Lindberg et al., 2007). Despite their remote location, isolated islands and polar and sub-polar regions are affected by Hg contamination *via* global transport and geological seepage (Fitzgerald et al., 1998). Owing to its high volatility and high atmospheric residence time, Hg can reach these isolated areas through atmospheric transport (Ebinghaus et al., 2002). Once deposited in aquatic ecosystems, inorganic Hg is subject to biotic reaction (methylation) carried out by marine bacteria (Fitzgerald et al., 2007). Thereafter, methylmercury, the persistent and highly toxic form of Hg, is assimilated by living organisms *via* food intake and tends to bioaccumulate in individuals over time and biomagnify within food webs from lower to higher trophic levels (Morel et al., 1998). Hence, top predators have been used to monitor Hg contamination in various ecosystems (Monteiro and Furness, 1995), with still limited existing information for significant parts of the World Ocean, including the southern Indian Ocean (Bocher et al., 2003).

Seabirds are considered as potential sentinels for monitoring Hg in the marine environment (Furness and Camphuysen, 1997), mainly because they are long-lived animals that prey at the top of the food webs (Burger and Gochfeld, 2004; Monteiro and Furness, 1995). Birds excrete > 90% of the total Hg body burden during moult, so feathers are considered as the main route for Hg elimination (Braume and Gaskin, 1987). Blood Hg and Hg previously stored within tissues such as liver and kidney are

transferred and sequestered in the growing feathers, where it binds to sulfhydryl groups of keratin (Burger, 1993) and cannot be re-incorporated into living tissues (Appelquist et al., 1984; Goede and De Bruin, 1984). Since body feather Hg concentrations relate positively and linearly with blood Hg (Jackson et al., 2011), body feathers provide a representative tissue for estimating whole-bird Hg load (Furness et al., 1986). Feather sampling has also the benefit to be non-invasive (Burger, 1993).

Here, we investigated feather Hg concentrations within the large community of seabirds that breed in the subantarctic Kerguelen Islands (21 species; Weimerskirch et al., 1989). In a first descriptive step, Hg was determined in order to quantify contamination in the southern Indian Ocean. In a second explanatory step, the effect of the foraging ecology of the different seabird species on their feather Hg concentrations was tested, because diet is the principal Hg intake pathway in seabirds (Burger and Gochfeld, 2004). The isotopic niche was used as a proxy of the ecological niche of the species, with the ratios of stable isotopes of carbon ( $\delta^{13}\text{C}$ ) and nitrogen ( $\delta^{15}\text{N}$ ) reflecting their foraging habitats and trophic positions, respectively (Newsome et al., 2007). The isotopic method was already validated in the area, with seabird  $\delta^{13}\text{C}$  values indicating their latitudinal foraging grounds and depicting offshore versus inshore consumers (Cherel and Hobson, 2007; Jaeger et al., 2010) and their  $\delta^{15}\text{N}$  values increasing with trophic level (Cherel et al., 2005).

In agreement with a preliminary investigation on Kerguelen seabirds (Bocher et al., 2003) and taking into account the species' foraging ecology, we make the following predictions. Firstly, when comparing to seabirds living in different marine environments, Kerguelen species should contain relatively low Hg concentrations due to the remoteness of the archipelago. Secondly, foraging habitat (reflected by  $\delta^{13}\text{C}$ ) should play an important role in seabird Hg contamination, because Hg is not homogeneously

distributed in marine ecosystems. Given the negative relationship between latitude and Hg distribution in surface air (Bergan et al., 1999), lower feather Hg concentrations were expected in seabirds known to forage in colder waters. Moreover, benthic foragers should have relatively higher Hg concentrations than pelagic species, because benthic habitats are reducing environments where Hg accumulates in sediment (Fitzgerald et al., 2007). Thirdly, Hg concentrations should increase with trophic level. Once mercury has entered the food web, it suffers biomagnification through food chains (Bryan, 1979; Eisler, 1987). Hence, birds with the highest trophic positions (reflected by the highest  $\delta^{15}\text{N}$  values) should show the highest Hg concentrations in their feathers. Finally, the longer the chick rearing period, the higher the feather Hg concentrations should be, because Hg is known to bioaccumulate over time in consumers' tissues (Bryan, 1979).

In this study, we focused on chick rather than on adult birds for three main reasons. Firstly, since chicks are exclusively fed by their parents, their Hg concentrations and stable isotope signatures reflect those of the adult foraging ecology during the chick-rearing period, a period during which dietary information were previously collected using complementary methods (dietary analysis, bio-logging; e.g. Cherel et al., 2000). Secondly, the integration period is almost identical for Hg and stable isotopes in body feathers of chicks, because (i) Hg that accumulates during the chick-rearing period is excreted during moult that takes place at its end, and (ii) feather isotope ratios reflect diet at the time of their synthesis (Hobson and Clark, 1992; Monteiro and Furness, 1995). In adult feathers, unlike stable isotopes, Hg concentration reflects Hg accumulated since the end of the last moult, i.e. during months and even years, depending on the moult pattern (Monteiro and Furness, 1995). Thirdly, chick body feathers are synthesized almost simultaneously, thus containing similar Hg concentrations (Lewis, 1991 in Monteiro and Furness, 1995), while sequential moult in

adults induces larger Hg concentrations in the first than in the late growing feathers (Furness et al., 1986).

## **2. Materials and methods**

### *2.1. Study area, species and sample collection*

Fieldwork was carried out from 2003 to 2012 on Kerguelen archipelago (49°21'S, 70°18'E; southern-Indian Ocean), which is located in the southern part of the Polar Frontal Zone, in the immediate vicinity of the Polar Front (Park and Gambéroni, 1997). We define the Southern Ocean as the ocean south the Subtropical Front and the Subantarctic and Antarctic Zones, as the zones between the Subtropical and Polar Fronts, and between the Polar Front and Antarctica, respectively. We sampled 21 species belonging to 4 orders and 7 families. The seabird assemblage includes coastal and/or benthic species as well as offshore and/or pelagic ones that forage along a latitudinal gradient from subtropics to Antarctic waters where they overall feed on a large diversity of prey (mainly crustaceans, cephalopods and fish; Table 1). Feather sampling was performed on large chicks at fledging, i.e. at the end of the breeding season. The sampling was conducted at different locations of the archipelago, depending on the species' breeding sites. Once collected, body feathers were stored dry in sealed plastic bags and analysed at La Rochelle, France. Prior to chemical analysis, feathers were cleaned to remove surface lipids and contaminants using a 2:1 chloroform:methanol followed by two successive methanol rinses.



## 2.2. Hg analysis

After being oven dried for 48 hours at 50°C, feather samples were analyzed directly in an advanced mercury analyzer spectrophotometer (Altec AMA 254). Hg determination involved evaporation of Hg by progressive heating until 800°C under oxygen atmosphere for 2'30 mn and subsequent amalgamation on an Au-net. Thereafter, the net was heated to liberate the collected Hg and then measured by UV atomic absorption spectrophotometry. Samples were analysed for total Hg, which approximates the amount of methylmercury, since > 90% of feather Hg is under organic form (Thompson and Furness, 1989). All analyses were repeated 2-3 times until having a relative standard deviation < 10%. Accuracy was checked using a certified reference material (Tort-2 Lobster Hepatopancreas, NRC, Canada; mean  $0.27 \pm 0.06 \mu\text{g}\cdot\text{g}^{-1}$  dry mass). Our measured values were  $0.24 \pm 0.01 \mu\text{g}\cdot\text{g}^{-1}$  dry mass,  $n = 56$ . Moreover, blanks were analysed at the beginning of each set of samples and the detection limit of the method was  $0.005 \mu\text{g}\cdot\text{g}^{-1}$  dry mass.

## 2.3. Stable isotopic analysis

After cleaning, body feathers were cut with scissors into small fragments. One sub-sample of homogenized feathers was then weighed (~0.3 mg) with a microbalance and packed into a tin container. Relative abundance of C and N isotopes were determined with a continuous flow mass spectrometer (Thermo Scientific Delta V Advantage) coupled to an elemental analyzer (Thermo Scientific Flash EA 1112). The ratio of stable isotopes is expressed in the usual  $\delta$  notation:  $\delta X = ((R_{\text{sample}}/ R_{\text{standard}}) - 1) \times 1000$  where X represents  $^{15}\text{N}$  or  $^{13}\text{C}$  and R is the corresponding ratio  $^{15}\text{N}/^{14}\text{N}$  or

$^{13}\text{C}/^{12}\text{C}$ . For C, the international standard is Peedee Belemnite (PDB) marine fossil limestone formation from South Carolina (Craig, 1957). The standard for N is atmospheric  $\text{N}_2$  (Ehleringer and Rundel, 1989). Replicate measurements of internal laboratory standards (acetanilide) indicated measurement errors of  $< 0.10\text{‰}$  for both  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values.

#### 2.4. *Statistical analysis*

Statistical tests were performed using R 2.7.1 (R Development Core Team, 2008). The influence of the species, foraging habitat, trophic level (inferred from feather  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values, respectively) and of the duration of the chick rearing period on feather Hg concentrations was investigated using General Linear Models (GLMs). Full GLMs were parameterized as follows: log transformed Hg concentration as the dependant variable, species as a factor, and  $\delta^{15}\text{N}$ ,  $\delta^{13}\text{C}$  values and the duration of the chick rearing period as covariates. Model fit was assessed by a chi-square goodness-of-fit test and residuals were tested for normality using Shapiro-Wilk test and Q-Q plot. The most parsimonious models were thus selected according to the lowest Akaike's Information Criterion (AIC) (Akaike, 1973; Burnham and Anderson, 2002). As a general guideline, if AIC values differ by more than 2, the model with the lowest AIC value is the most accurate, whereas models with AIC values differing by less than 2 are fairly similar in their ability to describe the data, regardless of the magnitude of the AIC value. The likelihood of a model, referred to as the Akaike weight ( $w_i$ ) was estimated following Johnson and Omland (2004). The  $w_i$  can be interpreted as approximate probabilities that the model  $i$  is the best one for the observed data, given the candidate set of models. All samples submitted to statistical tests were first checked for normality

and homogeneity of variances by means of Shapiro-Wilk and Fisher tests, respectively. Depending on the results, parametric or non-parametric tests were used. Correlations between Hg and explanatory variables were also tested using Pearson correlation. A significance level of  $\alpha < 0.05$  was used for all tests. Values are means  $\pm$  SD.

### 3. Results

Hg contamination varied widely within the seabird community (Table 2), with chick feather Hg concentrations differing significantly between species (Kruskal-Wallis,  $H = 245.42$ ,  $p < 0.001$ ,  $n = 21$ ). Mean Hg concentrations ranged from  $0.08 \pm 0.01$  to  $5.31 \pm 1.12 \mu\text{g}\cdot\text{g}^{-1}$  dry mass in South-Georgian diving-petrels and northern giant petrels, respectively (Fig. 1). The highest feather Hg concentration occurred in a wandering albatross and the lowest in a common diving-petrel ( $8.43$  and  $0.07 \mu\text{g}\cdot\text{g}^{-1}$  dry mass, respectively).

In univariate analyses, no overall significant correlation between feather Hg and  $\delta^{13}\text{C}$  values was found (Fig. 2; Pearson correlation  $r = -0.12$ ,  $t = -1.90$ ,  $p = 0.06$ ,  $n = 267$ ), while feather Hg concentration was highly significantly and positively correlated with  $\delta^{15}\text{N}$  values (Fig. 2; Pearson correlation  $r = 0.44$ ,  $t = 7.97$ ,  $p < 0.001$ ,  $n = 267$ ). Feather Hg concentration was also significantly related to the duration of the chick rearing period (Pearson correlation  $r = 0.24$ ,  $t = 4.00$ ,  $p < 0.001$ ,  $n = 267$ ).

In multivariate analysis, the most parsimonious GLM model selected by AIC was  $\text{Log Hg} = \text{species} + \delta^{15}\text{N}$  (Table 3). Mercury concentrations in body feathers differed significantly among species ( $F = 186.19$ ,  $p < 0.001$ ) and were significantly related to their  $\delta^{15}\text{N}$  values ( $F = 31.89$ ,  $p < 0.001$ ). Models including the duration of the

chick rearing period had a low likelihood (Table 3), indicating that the parameter explained poorly Hg concentrations when compared to both species and feather  $\delta^{15}\text{N}$  values.

When focusing on seabirds foraging in oceanic waters (12 species and 145 individuals; Table 1), a highly significant and positive correlation was found between feather Hg and both  $\delta^{13}\text{C}$  (Pearson correlation  $r = 0.63$ ,  $t = 9.63$ ,  $p < 0.001$ ) and  $\delta^{15}\text{N}$  values (Pearson correlation  $r = 0.78$ ,  $t = 14.94$ ,  $p < 0.001$ ). Furthermore, feather  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  values were positively correlated within that group (Pearson correlation  $r = 0.68$ ,  $t = 11.03$ ,  $p < 0.001$ ).

#### **4. Discussion**

To the best of our knowledge, this study is the first to investigate Hg contamination in such a large number of sympatric seabirds at a given location, and the first to focus on chicks rather than on adults. It completes the few studies previously conducted on seabirds in the southern Atlantic (Anderson et al., 2009; Muirhead and Furness, 1988) and the southern Pacific (Lock et al., 1992; Stewart et al., 1999) Oceans, thus partly filling the gap of knowledge from the southern Indian Ocean sector (Bocher et al., 2003). In a first descriptive step, we showed that large variations in feather Hg concentrations occurred at the species level within the Kerguelen seabird community. In a second explanatory step, the species-related Hg variations were linked to the species trophic levels ( $\delta^{15}\text{N}$ ), thus highlighting biomagnification processes occurring throughout the marine trophic webs of the Southern Ocean. By contrast, chick Hg contamination

overall correlated poorly with seabird foraging habitats ( $\delta^{13}\text{C}$ ), and it was little explained by the duration of the chick rearing period.

#### *4.1. Feather Hg concentrations: comparison with other species and areas*

Kerguelen seabirds present a wide range of Hg concentrations, with the highest contaminated species (the northern giant petrel) containing ~66 times more feather Hg than the less contaminated species (the South Georgian diving petrel). No other feather Hg values are available from Kerguelen seabirds, but a preliminary analysis conducted on internal tissues of adults of five species of zooplankton-eating petrels (Bocher et al., 2003) ranked the species in the same decreasing order than in the present study, with blue petrels containing more Hg than prions and diving petrels. In the same way, the hierarchical decreasing order is roughly the same in the only other comparable investigation that was conducted on 10 procellariiform seabirds breeding in the southern Atlantic Ocean (Anderson et al., 2009). Feather Hg was higher in albatrosses and giant petrels, intermediate in the white-chinned petrel and lower in the blue petrel, prions and diving petrels. Hg concentrations were however much higher in south Atlantic seabirds than in the present study, with the most likely explanation being that the previous investigation was conducted on adult breeding birds, not on chicks. Indeed, adult birds are known to have higher feather Hg concentrations than chicks, due to accumulation processes over their life time and to longer inter-moult periods (Monteiro and Furness, 1995).

A review of the existing literature on seabird chicks (Table 4) shows that feather Hg concentration ranges from 0.05 to 5.57  $\mu\text{g}\cdot\text{g}^{-1}$  (the sooty tern and black-footed albatross, respectively). This range is remarkably similar to that from the present

investigation, indicating that seabirds from only one location (Kerguelen) encompass the whole range of values that were collected worldwide. A direct consequence of that unexpected result is that comparison of Hg contamination between distant locations necessitates collecting feathers from many seabirds, and not only from a small subset of species that could not be fully representative of the whole seabird assemblage, and thus of the surrounding marine environment. Another possibility to use seabirds to monitor Hg contamination consists in making comparisons between single or closely related species. For example, wandering albatross chicks have almost identical feather Hg concentrations in Kerguelen than in South Georgia (Becker et al., 2002), as are the levels of Hg contamination of the subantarctic skua from Kerguelen and of the great skua from Scotland (Bearhop et al., 2000; Stewart et al., 1997). Such comparisons suggest roughly similar Hg contamination of various distant marine environments.

At the community level, chick Hg contamination was previously investigated in only three assemblages of sympatric seabirds that were located either in the tropical Pacific Ocean (Midway Atoll,  $n = 6$  species, Burger and Gochfeld, 2000) or in the tropical Indian Ocean (the Seychelles and La Réunion Islands,  $n = 7$  and 4 species, respectively) (Catry et al., 2008; Kojadinovic et al., 2007). Based on feather Hg concentrations, the Kerguelen seabird community compares well with Midway Atoll ( $0.34\text{-}5.57 \mu\text{g}\cdot\text{g}^{-1}$ ), thus again suggesting similar marine contamination levels in distant and isolated localities. By contrast, chick feather Hg concentrations were overall higher in Kerguelen species than in seabirds from the Seychelles ( $0.15\text{-}0.70 \mu\text{g}\cdot\text{g}^{-1}$ ) and La Réunion ( $0.07\text{-}0.42 \mu\text{g}\cdot\text{g}^{-1}$ ), thus suggesting higher contamination levels in the Southern Indian Ocean than further in tropical waters. Overall, data from the bibliography do not verify our first hypothesis stating that Kerguelen species should contain low Hg concentrations due to the remoteness of the archipelago. Further investigations

conducted in other oceanic locations (e.g. in the subtropics and in high-Antarctica) and in neritic areas close to land masses (South Africa, Australia) are needed to better depict the overall Hg contamination seascape of the Indian Ocean.

#### *4.2. Potential adverse effect*

Hg contamination can be an environmental concern with regard to its detrimental effects on humans and wildlife, including birds (Grandjean et al., 2010; Scheuhammer et al., 2007; Seewagen, 2010). Although studies investigating Hg effects are scarce, a large range of 2.4-40  $\mu\text{g}\cdot\text{g}^{-1}$  in feathers is considered to be associated with adverse effects on birds (Evers et al., 2008; Jackson et al., 2011), with the most commonly used toxicity threshold being 5  $\mu\text{g}\cdot\text{g}^{-1}$ . Indeed, for a wide range of species, concentrations  $\geq 5 \mu\text{g}\cdot\text{g}^{-1}$  (Burger and Gochfeld, 2000) have been linked to sub-lethal effects such as organ damage, alteration of locomotion, thermoregulation and behaviour, and a decrease in reproductive productivity (Bourgeois, 2011; Eisler, 1987). In Kerguelen seabirds, Hg analyses revealed contamination levels  $\geq 5 \mu\text{g}\cdot\text{g}^{-1}$  in individuals from four species (Fig. 3). Namely, 64%, 50%, 33% and 13% of chicks of northern giant-petrels, subantarctic skuas, wandering albatrosses and grey petrels, respectively, exceeded the threshold value and were thus potentially threatened by Hg. However, no obvious detrimental effects have been recorded during the fieldwork. Since most Hg is stored in the marine environment (Fitzgerald et al., 2007), seabirds have to deal with relatively high Hg concentrations and so, their harmful threshold values could be expected to be higher than 5  $\mu\text{g}\cdot\text{g}^{-1}$ . Moreover, most previous studies investigating Hg toxicity focused on adults, and thresholds values are likely to vary between adults and

growing chicks. Thus, more experimental and fieldwork investigations are needed to determine Hg toxicity levels in chicks of the main groups of seabirds.

#### *4.3. Feather Hg concentrations and foraging habitats*

Statistical analysis indicated no overall  $\delta^{13}\text{C}$  effects on feather Hg concentrations within the Kerguelen seabird community. This result seems to contradict our second hypothesis that foraging habitat should play an important role in shaping seabird Hg contamination. However, the large range of seabird  $\delta^{13}\text{C}$  values indicates that several isotopic gradients were pooled (e.g. the benthic-pelagic, inshore-offshore and oceanic latitudinal  $\delta^{13}\text{C}$  gradients), thus resulting in a confounding effect for the interpretation of feather Hg concentrations (Cherel and Hobson, 2007). For example, the five species with  $\delta^{13}\text{C}$  values  $\geq -18\text{‰}$  were all neritic species feeding either along the shoreline (the kelp gull) or on pelagic (the southern rockhopper penguin and common diving petrel) or benthic (the gentoo penguin and Kerguelen shag) prey. Within that context, it is noticeable that the two latter species showed relatively high feather Hg concentrations, which is in agreement with the hypothesis that benthic habitats are Hg-enriched when compared to the pelagic environment. In the same way, the positive relationship between feather Hg concentrations and  $\delta^{13}\text{C}$  values in oceanic seabirds together with the well known oceanic latitudinal  $\delta^{13}\text{C}$  gradient (Cherel and Hobson, 2007; Jaeger et al., 2010) indicates that species foraging in cold waters south of Kerguelen Islands are less prone to be contaminated than species feeding in northern warmer waters. This result is in agreement with the negative relationship between latitude and Hg distribution in surface air (Bergan et al., 1999), and it suggests low contamination of seabirds in Antarctic waters.



#### 4.4. Feather Hg concentrations and diet

As expected, the overall statistical analysis indicated a  $\delta^{15}\text{N}$  effect on feather Hg concentrations within the Kerguelen seabird community. The positive correlation verifies our third hypothesis stating that Hg concentration should increase with trophic level, because  $\delta^{15}\text{N}$  is a proxy of consumers' trophic position (Minagawa and Wada, 1984). Noticeably, the relationship was partially hindered by, again, the pooling of species foraging in very distinct habitats marked by different isotopic baselines. Within that context, the highly positive correlation between Hg and  $\delta^{15}\text{N}$  is particularly relevant, underlining the strength of the biomagnification processes of Hg through the marine environments of the Southern Ocean. Indeed, the relationship was even stronger when looking at the oceanic seabirds only (Fig. 2). The feather  $\delta^{15}\text{N}$  values of the 12 species ranged from 8.9 (the crustacean-eater South Georgian diving petrel) to 14.2‰ (the squid-eater wandering albatross), which, assuming a trophic enrichment factor of  $\sim 3\text{‰}$  (Minagawa and Wada, 1984), corresponds to  $< 3$  trophic levels. The corresponding Hg values indicated a 56-fold Hg enrichment along the oceanic trophic web. This result is consistent with the literature indicating that Hg is the only metal showing clearly a biomagnification pattern (Atwell et al., 1998). In addition, Hg magnification in seabirds is likely enhanced in species feeding on mesopelagic fish and squid because these prey originate from deep and poorly oxygenated waters where Hg concentrations are higher due to high bacterial methylation activity (Monteiro et al., 1996, 1998; Thompson et al., 1998).

The subantarctic skua was clearly an outlier species within the Kerguelen seabird assemblage, with chick Hg concentration being too high when compared to its

feather  $\delta^{15}\text{N}$ , and, to a lesser extent,  $\delta^{13}\text{C}$  values (Fig. 2). At the study site, adult skuas forage on land where they feed their chicks almost exclusively with small seabirds, including mainly blue petrels (Mougeot et al., 1998). Tissues of adult blue petrels do not disproportionately contain large amounts of Hg (Bocher et al., 2003; Anderson et al., 2009; authors' unpublished data), thus precluding a trophic explanation to the high Hg levels of skua chicks. Hence, Hg contamination level is more probably related to some intrinsic physiological and biochemical factors involved in detoxification processes that differ between skuas and other seabirds (phylogenetic effect).

In conclusion, the level of Hg contamination of Kerguelen seabirds is comparable to that occurring worldwide in many marine environments. It highlights the global effect of anthropogenic Hg emission that is detectable in remote oceanic islands and archipelagos. Since Hg global emissions are predicted to increase by 2050 (Streets et al., 2009), Hg contamination is likely to increase worldwide. Within that context, Kerguelen together with other isolated areas located far away anthropogenic sources can be considered as ideal study sites to monitor the temporal trends of global Hg contamination. Our study allows selecting some seabirds (sentinel species) to help detecting those trends according to their high Hg concentrations with relatively low variances and to their contrasted foraging ecology (Table 2). At a first glance, we propose to select three representative species, namely the gentoo penguin (a benthic neritic forager), black-browed albatross (pelagic neritic forager) and light-mantled sooty albatross (southern oceanic forager). Despite its larger variance in feather Hg concentrations, we shall also include the wandering albatross (northern oceanic forager), because this iconic seabird is known to be the most Hg contaminated vertebrate species (Hindell et al., 1999).

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## List of figures

**Fig. 1.** Inter-specific differences in chick feather Hg concentrations ( $\mu\text{g}\cdot\text{g}^{-1}$  dry mass) within the Kerguelen seabird community. Values are means  $\pm$  SD.

**Fig. 2.** Relationship between chick feather Hg concentrations ( $\mu\text{g}\cdot\text{g}^{-1}$  dry mass) and both foraging habitat ( $\delta^{13}\text{C}$ ) and trophic position ( $\delta^{15}\text{N}$ ) of Kerguelen seabirds. Filled diamonds refer to oceanic species. Values are means  $\pm$  SD.

**Fig. 3.** Feather Hg concentrations of individual chicks from the five most contaminated species from the Kerguelen seabird community (see text for toxicity threshold).

**Table 1**

Species, foraging habitats, dietary habits and duration of the chick rearing period (days) of seabirds breeding at the Kerguelen Islands.

Species	Abb. <sup>a</sup>	Foraging habitats		Diet (% mass)		Duration of the chick rearing period	References <sup>d</sup>
		Horizontal	Vertical	> 50%	> 30%		
Spheniscidae							
King penguin ( <i>Aptenodytes patagonicus</i> )	KP	slope, oceanic	epi-mesopelagic	pelagic fish		315	Bost and Cherel unpublished data
Gentoo penguin ( <i>Pygoscelis papua</i> )	GP	coastal, neritic	benthic	benthic fish		72	Lescroël et al., 2004
Macaroni penguin ( <i>Eudyptes chrysolophus</i> )	MP	neritic, slope, oceanic	epipelagic	pelagic fish		65	Bost unpublished data
Southern rockhopper penguin ( <i>Eudyptes chrysocome</i> )	SRP	coastal, neritic	epipelagic	crustacean		71	Cherel unpublished data
Diomededidae							
Wandering albatross ( <i>Diomedea exulans</i> )	WA	slope, oceanic	surface	cephalopod		275	Ridoux, 1994
Black-browed albatross ( <i>Thalassarche melanophrys</i> )	BBA	neritic, slope	surface	benthic fish <sup>b</sup>	cephalopod	125	Cherel et al., 2000
Light-mantled sooty albatross ( <i>Phoebastria palpebrata</i> )	LMSA	slope, oceanic	surface	cephalopod		154	Ridoux, 1994
Procellariidae							
Northern giant petrel ( <i>Macronectes halli</i> )	NGP	on land/ sea surface		carrion		113	Ridoux, 1994
White-chinned petrel ( <i>Procellaria aequinoctialis</i> )	WCP	neritic, slope, oceanic	surface	pelagic fish <sup>b</sup>	cephalopod <sup>c</sup>	96	Ridoux, 1994
Grey petrel ( <i>Procellaria cinerea</i> )	GrP	neritic, slope, oceanic	surface		cephalopod, fish <sup>c</sup>	128	Cherel unpublished data
White-headed petrel ( <i>Pterodroma lessonii</i> )	WHP	oceanic	surface	cephalopod <sup>b</sup>	pelagic fish	101	Zotier, 1990
Great-winged petrel ( <i>Pterodroma macroptera</i> )	GWP	oceanic	surface	cephalopod		126	Ridoux, 1994
Kerguelen petrel ( <i>Aphrodroma brevirostris</i> )	KeP	oceanic	surface	crustacean		60	Ridoux, 1994
Blue petrel ( <i>Halobaena caerulea</i> )	BP	slope, oceanic	surface	pelagic fish	crustacean	55	Cherel et al., 2002a
Antarctic prion ( <i>Pachyptila desolata</i> )	AP	neritic, slope, oceanic	surface	crustacean		50	Cherel et al., 2002b
Thin-billed prion ( <i>Pachyptila belcheri</i> )	TBP	neritic, slope, oceanic	surface	crustacean		50	Cherel et al., 2002b
Pelecanoididae							
Common diving-petrel ( <i>Pelecanoides urinatrix</i> )	CDP	coastal, neritic, slope	epipelagic	crustacean		54	Bocher et al., 2000
South-Georgian diving-petrel ( <i>Pelecanoides georgicus</i> )	SGDP	neritic, slope	epipelagic	crustacean		55	Bocher et al., 2000
Phalacrocoracidae							
Kerguelen shag ( <i>Phalacrocorax verrucosus</i> )	KS	coastal	benthic	benthic fish		56	Cherel unpublished data
Stercorariidae							
Subantarctic skua ( <i>Catharacta antarctica</i> )	SS	on land/ sea surface		petrel sp		45	Mougeot et al., 1998
Laridae							
Kelp gull ( <i>Larus dominicanus</i> )	KG			penguin sp		49	Stahl and Mougin, 1986

<sup>a</sup> Abbreviation<sup>b</sup> Diet (mass) > 40%<sup>c</sup> Diet (mass) > 20%<sup>d</sup> Ridoux 1994 and Stahl and Mougin 1986 deal with diet composition of seabirds from Crozet archipelago.

**Table 2**

Chick feather Hg,  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of Kerguelen seabirds. Values are means  $\pm$  SD (range).

Species	<i>n</i>	Hg ( $\mu\text{g}\cdot\text{g}^{-1}$ dry mass)	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)
King penguin	12	1.12 $\pm$ 0.16 (0.83-1.50)	-21.6 $\pm$ 0.3	10.6 $\pm$ 0.3
Gentoo penguin	12	2.45 $\pm$ 0.67 (1.14-3.66)	-16.5 $\pm$ 1.2	12.4 $\pm$ 0.8
Macaroni penguin	12	0.36 $\pm$ 0.07 (0.25-0.52)	-18.3 $\pm$ 0.5	10.0 $\pm$ 0.5
Southern rockhopper penguin	12	0.27 $\pm$ 0.06 (0.20-0.37)	-15.3 $\pm$ 0.4	11.5 $\pm$ 0.4
Wandering albatross	15	4.45 $\pm$ 1.60 (2.19-8.43)	-19.3 $\pm$ 0.4	14.2 $\pm$ 0.4
Black-browed albatross	18	2.58 $\pm$ 0.59 (1.54-3.70)	-18.5 $\pm$ 0.8	12.9 $\pm$ 0.5
Light-mantled sooty albatross	15	2.46 $\pm$ 0.67 (1.56-3.69)	-21.0 $\pm$ 0.4	12.6 $\pm$ 0.4
Northern giant petrel	12	5.31 $\pm$ 1.12 (4.06-7.94)	-19.2 $\pm$ 1.2	13.4 $\pm$ 0.8
White-chinned petrel	14	1.82 $\pm$ 0.51 (1.13-2.76)	-22.2 $\pm$ 0.7	11.3 $\pm$ 0.8
Grey petrel	16	3.16 $\pm$ 1.21 (1.59-5.70)	-19.9 $\pm$ 0.6	13.6 $\pm$ 0.4
White-headed petrel	10	1.54 $\pm$ 0.34 (1.07-1.99)	-22.0 $\pm$ 0.5	12.2 $\pm$ 0.2
Great-winged petrel	10	1.64 $\pm$ 0.48 (0.96-2.68)	-20.0 $\pm$ 0.4	12.9 $\pm$ 0.4
Kerguelen petrel	18	0.78 $\pm$ 0.17 (0.51-1.20)	-22.1 $\pm$ 0.5	11.7 $\pm$ 0.5
Blue petrel	13	0.84 $\pm$ 0.18 (0.58-1.14)	-21.8 $\pm$ 0.5	9.8 $\pm$ 0.5
Antarctic prion	10	0.21 $\pm$ 0.05 (0.16-0.31)	-21.5 $\pm$ 0.5	9.3 $\pm$ 0.4
Thin-billed prion	9	0.22 $\pm$ 0.09 (0.12-0.40)	-21.5 $\pm$ 0.5	9.1 $\pm$ 0.4
Common diving petrel	17	0.11 $\pm$ 0.02 (0.07-0.15)	-17.0 $\pm$ 0.5	12.1 $\pm$ 0.4
South Georgian diving petrel	3	0.08 $\pm$ 0.01 (0.07-0.08)	-21.2 $\pm$ 0.4	8.9 $\pm$ 0.2
Kerguelen shag	10	2.21 $\pm$ 1.06 (1.35-4.64)	-13.8 $\pm$ 1.0	14.0 $\pm$ 0.6
Subantarctic skua	22	5.15 $\pm$ 1.56 (2.40-7.93)	-21.8 $\pm$ 0.4	10.8 $\pm$ 0.3
Kelp gull	7	0.73 $\pm$ 0.38 (0.40-1.38)	-12.8 $\pm$ 0.7	13.4 $\pm$ 1.0

**Table 3**

AIC model ranking for feather Hg concentrations within the Kerguelen seabird community.

Model	AIC	$\Delta\text{AIC}^a$	$w_i^b$
$\delta^{15}\text{N}$ + species	73.99	0.00	0.51
$\delta^{13}\text{C} + \delta^{15}\text{N}$ + species	74.08	0.09	0.49
$\delta^{13}\text{C}$ + species	104.53	30.54	1.19e-07
species	104.66	30.67	1.12e-07
$\delta^{13}\text{C} + \delta^{15}\text{N}$	690.60	616.61	6.51e-135
$\delta^{13}\text{C} + \delta^{15}\text{N}$ + chick rearing duration	691.82	617.83	3.54e-135
$\delta^{15}\text{N}$ + chick rearing duration	764.87	690.88	4.85e-151
$\delta^{15}\text{N}$	777.57	703.58	8.48e-154
$\delta^{13}\text{C}$ + chick rearing duration	824.53	750.54	5.37e-164
chick rearing duration	826.53	752.54	1.98e-164
$\delta^{13}\text{C}$	855.65	781.66	9.42e-171
null	861.10	787.11	6.17e-172

<sup>a</sup> Scaled  $\Delta\text{AIC}$  ;  $\Delta\text{AIC} = 0.00$  is interpreted as the best fit to the data among the models.

<sup>b</sup> Weight of evidence interpreted as a proportion. Weights across all models sum to 1.00.

**Table 4**

An overall synthesis of feather Hg concentrations (mean  $\pm$  SD  $\mu\text{g}\cdot\text{g}^{-1}$  dry mass) in seabird chicks.

Species	Location	Type of feather	<i>n</i>	Hg	References
<b>Spheniscidae</b>					
Adelie penguin ( <i>Pygoscelis adeliae</i> )	Terra Nova Bay, Antarctica	not specified	11	0.37 $\pm$ 0.15	Bargagli et al., 1998
<b>Diomedidae</b>					
Wandering albatross ( <i>Diomedea exulans</i> )	Bird Island, South Georgia	body feather	10	3.31 $\pm$ 0.68	Becker et al., 2002
Laysan albatross ( <i>Phoebastria immutabilis</i> )	Midway Island	body feather	47	2.15 $\pm$ 0.12 <sup>a</sup>	Burger and Gochfeld, 2000
Black-footed albatross ( <i>Phoebastria nigripes</i> )	Midway Island	body feather	17	5.57 $\pm$ 0.36 <sup>a</sup>	Burger and Gochfeld, 2000
<b>Procellariidae</b>					
Barau's petrel ( <i>Pterodroma baraui</i> )	Reunion island	body feather	32	0.30 $\pm$ 0.07	Kojadinovic et al., 2007
Bonin petrel ( <i>Pterodroma hypoleuca</i> )	Midway Island	body feather	20	3.87 $\pm$ 0.32 <sup>a</sup>	Burger and Gochfeld, 2000
Sooty shearwater ( <i>Puffinus griseus</i> )	New-Zealand	body feather	4	0.80 $\pm$ 0.80	Lock et al., 1992
Audubon's shearwater ( <i>Puffinus lherminieri</i> )	Reunion Island	body feather	38	0.07 $\pm$ 0.01	Kojadinovic et al., 2007
	Aride Island, Seychelles archipelago	body feather	10	0.15 $\pm$ 0.03	Catry et al., 2008
	Aride Island, Seychelles archipelago	body feather	8	0.27 $\pm$ 0.06	Catry et al., 2008
Wedge-tailed shearwater ( <i>Puffinus pacificus</i> )	Aride Island, Seychelles archipelago	body feather	10	0.39 $\pm$ 0.05	Catry et al., 2008
<b>Phaethontidae</b>					
White-tailed tropicbird ( <i>Phaethon lepturus</i> )	Reunion Island	body feather	16	0.29 $\pm$ 0.02	Kojadinovic et al., 2007
	Aride Island, Seychelles archipelago	body feather	10	0.52 $\pm$ 0.11	Catry et al., 2008
	Aride Island, Seychelles archipelago	body feather	10	0.70 $\pm$ 0.10	Catry et al., 2008
Red-tailed tropicbird ( <i>Phaethon rubricauda</i> )	Midway Island	body feather	12	2.51 $\pm$ 0.28 <sup>a</sup>	Burger and Gochfeld, 2000
<b>Stercorariidae</b>					
Arctic skua ( <i>Stercorarius parasiticus</i> )	Shetland Island, Scotland	not specified	30	0.46 $\pm$ 0.22	Stewart et al., 1997
Great skua ( <i>Stercorarius skua</i> )	Shetland Island, Scotland	not specified	28	1.22 $\pm$ 0.38	Stewart et al., 1997
	Shetland Island, Scotland	body feather	29	2.16 $\pm$ 1.15	Bearhop et al., 2000
	St Kilda, Scotland	body feather	22	5.37 $\pm$ 1.29	Bearhop et al., 2000
<b>Laridae</b>					
Red-billed gull ( <i>Larus scopulinus</i> )	Kaikoura, New Zealand	body feather	27	2.02 $\pm$ 1.16	Furness et al., 1990

Black-headed gull ( <i>Larus ridibundus</i> )	Central region, Scotland	body feather	4	0.64 ± 0.09	Lewis and Furness, 1991
	Wadden sea, Germany	body feather	36	0.94 ± 0.45	Becker et al., 1994
Herring gull ( <i>Larus argentatus</i> )	Wadden sea, Germany	body feather	39	1.31 ± 0.62	Becker et al., 1994
	Wadden sea, Germany	body feather	39	1.27 ± 0.60	Becker et al., 1994
	Wadden sea	body feather	36	0.88 ± 0.53	Becker et al., 1994
Common tern ( <i>Sterna hirundo</i> )	Long Island, New-York	body feather	21	2.61 ± 2.55 <sup>a</sup>	Burger and Gochfeld, 1992
	Wadden sea, Germany	body feather	13	3.26 ± 0.70	Becker et al., 1994
	Wadden sea, Germany	body feather	13	3.00 ± 0.50	Becker et al., 1994
Sooty tern ( <i>Sterna fuscata</i> )	Lys Island	body feather	32	0.05 ± 0.03	Kojadinovic et al., 2007
	Aride Island, Seychelles archipelago	body feather	10	0.26 ± 0.05	Catry et al., 2008
White tern ( <i>Gygis alba</i> )	Midway Island	body feather	7	1.65 ± 0.18 <sup>a</sup>	Burger and Gochfeld, 2000
	Aride Island, Seychelles archipelago	body feather	10	0.21 ± 0.03	Catry et al., 2008
	Aride Island, Seychelles archipelago	body feather	10	0.40 ± 0.05	Catry et al., 2008
Brown noddy ( <i>Anous stolidus</i> )	Aride Island, Seychelles archipelago	body feather	10	0.27 ± 0.05	Catry et al., 2008
	Aride Island, Seychelles archipelago	body feather	10	0.37 ± 0.06	Catry et al., 2008
Lesser noddy ( <i>Anous tenuirostris</i> )	Aride Island, Seychelles archipelago	body feather	10	0.17 ± 0.03	Catry et al., 2008
	Aride Island, Seychelles archipelago	body feather	5	0.41 ± 0.17	Catry et al., 2008

<sup>a</sup> Values are mean ± SE.

Studies conducted on a too low number of individuals per species (n < 4) were not included here.

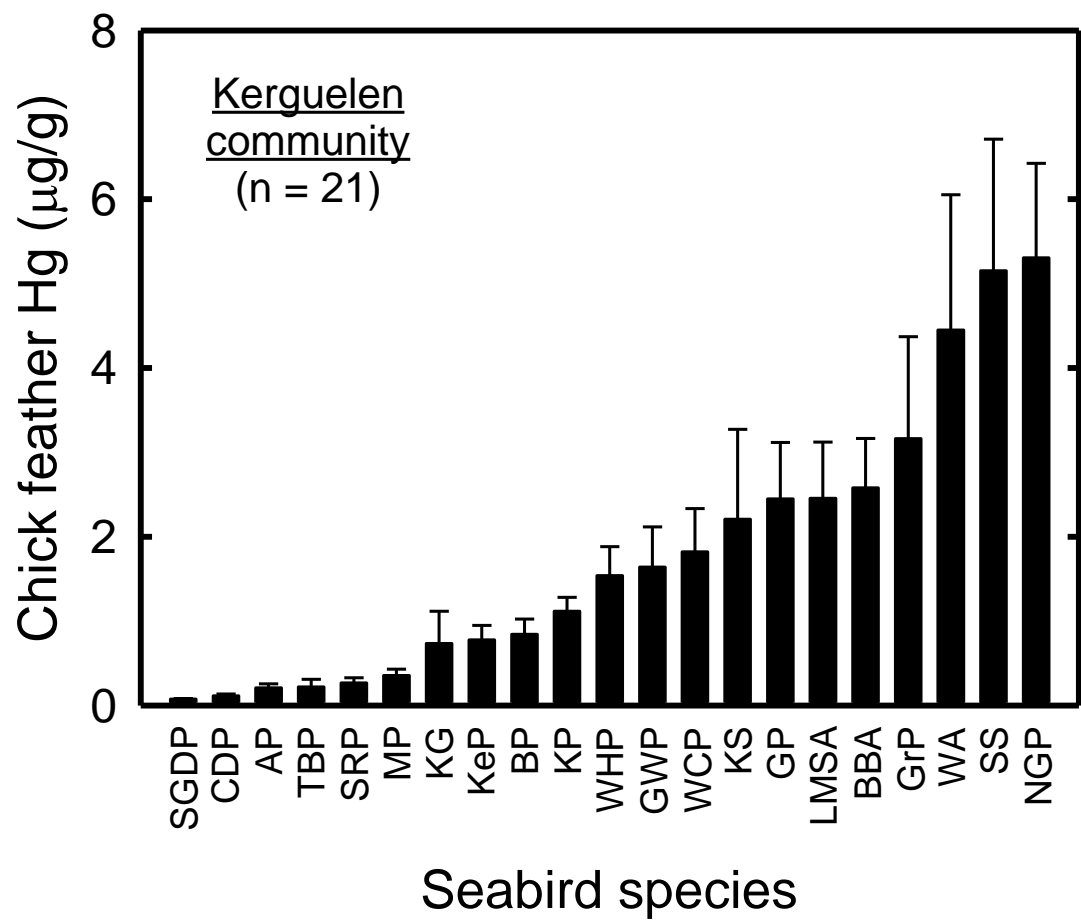


Fig. 1.

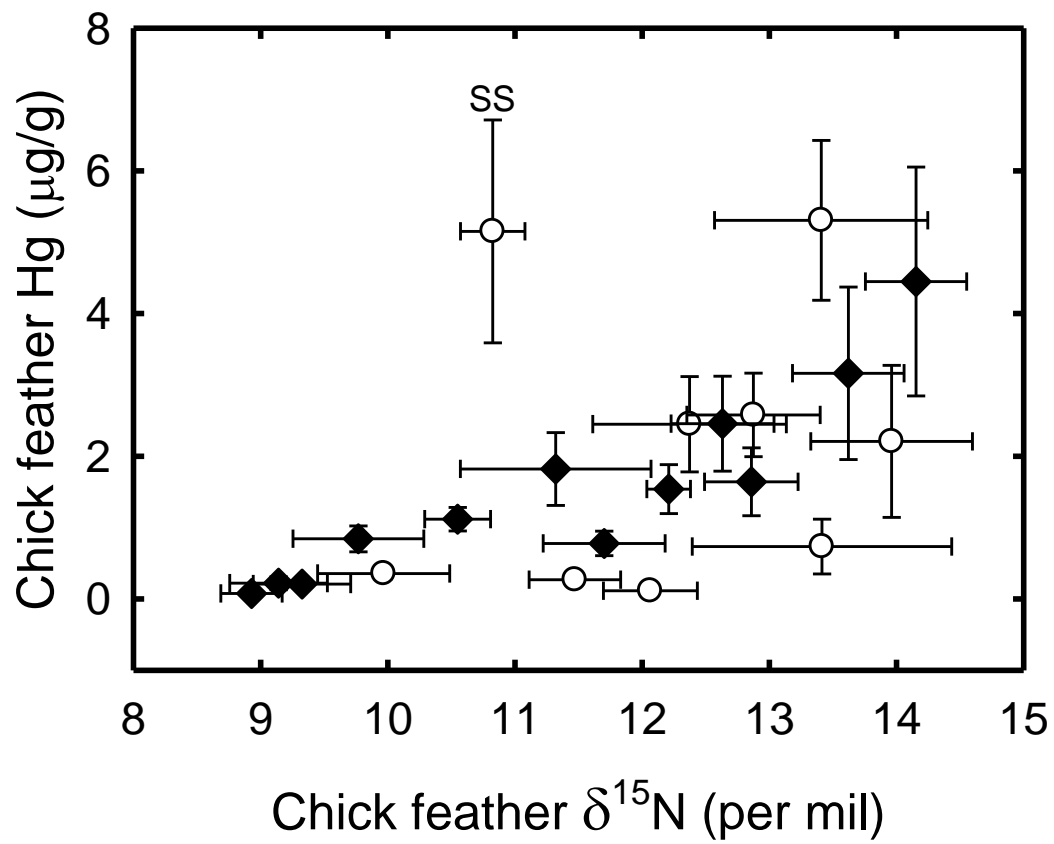
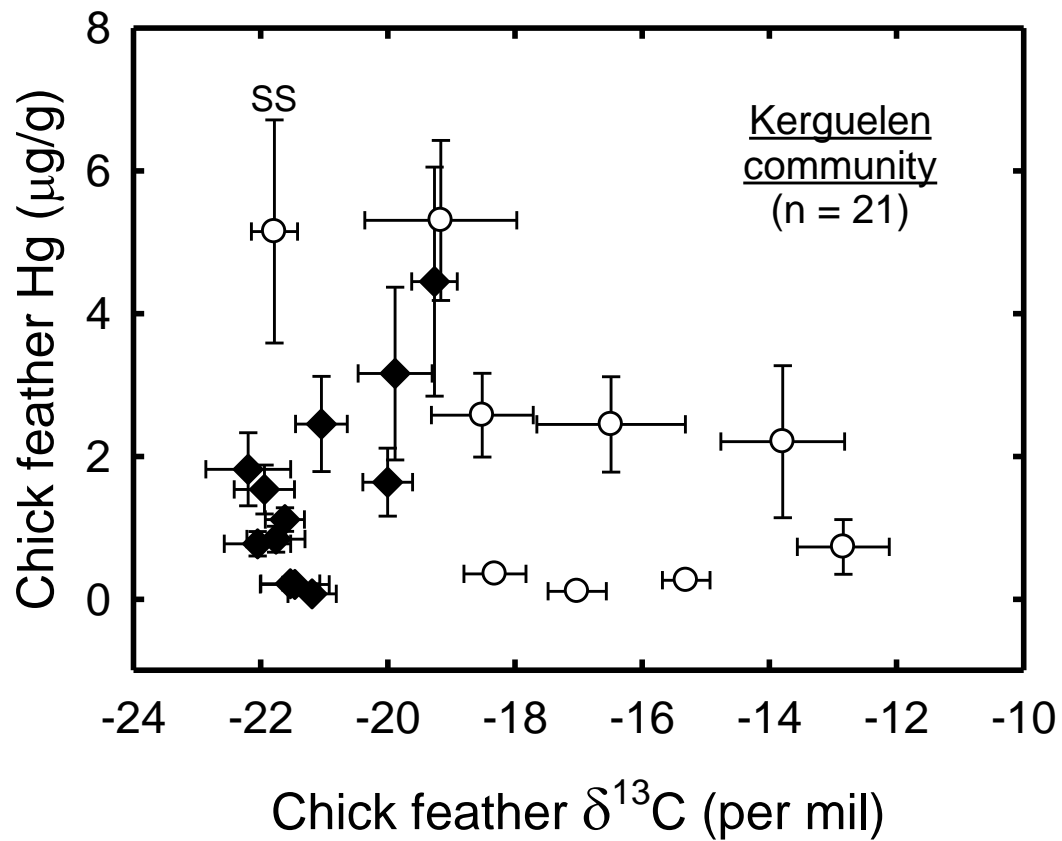


Fig. 2.



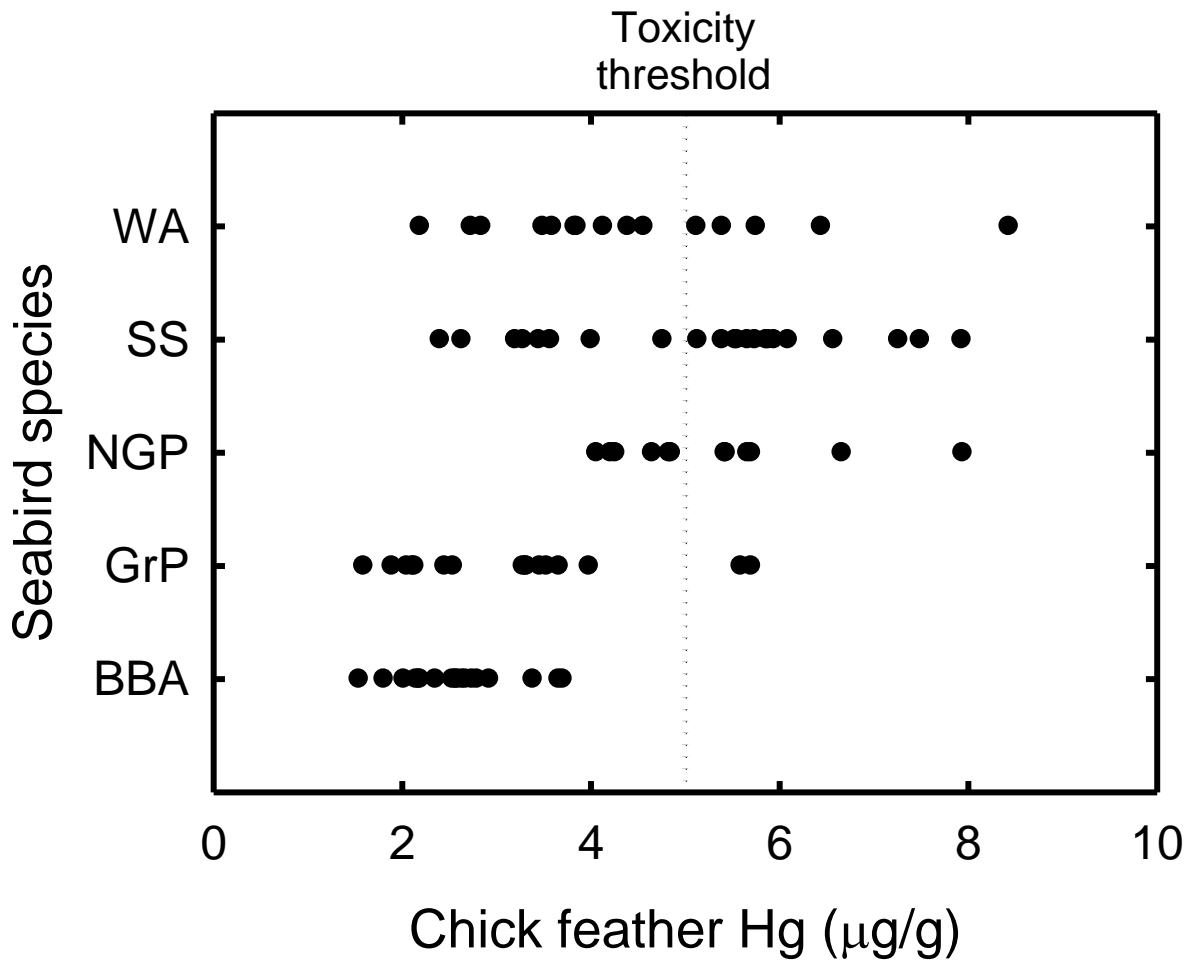


Fig. 3.