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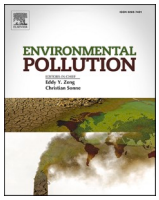

Dynamics of mercury contamination within the albatross and petrel community at South Georgia

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ABSTRACT

At the subantarctic islands of South Georgia, albatrosses and petrels occupy a range of trophic niches, from zooplanktivore to top predator. Interspecific variation in mercury (Hg) contamination is therefore expected to be large within this community, as diet is the main exposure pathway. This study compared total Hg (THg) concentrations and stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) in feathers of >250 chicks belonging to eight albatross and petrel species at South Georgia during three years (2018-2020). Generally, zooplanktivorous species (Antarctic prion *Pachyptila desolata*, blue petrel *Halobaena caerulea*) and the wandering albatross *Diomedea exulans* (top predator) were least and most contaminated, respectively. However, the order of increasing THg concentrations among giant petrels *Macronectes* spp. and pelagic generalist species varied annually, likely reflecting shifts in diet or distribution given the diversity of alternative foraging habitats. Accounting for species effects, THg was positively associated with $\delta^{15}N$ in all years, and with $\delta^{13}C$ in two years, indicating that contamination increased with trophic position and generally, but not always, varied along a foraging habitat or latitudinal gradient. Lastly, pelagic generalists and northern giant petrels *M. halli*, but neither zooplanktivores nor wandering albatrosses, were more contaminated at Kerguelen than South Georgia, potentially reflecting dietary differences, more complex food chains and a reduced role of Antarctic krill *Euphausia superba* in the pelagic foodweb of the southern Indian Ocean. Overall, this study highlights the drivers of variation among species, years and regions in THg concentrations, and the need for further work to predict future trends.

1. Introduction

Mercury (Hg) contamination of marine foodwebs is a widespread environmental issue that can negatively impact biodiversity and ecosystem functioning (Alava et al., 2017; Sigmund et al., 2023). Hg is naturally present in the environment owing to processes such as the weathering of rocks, volcanism and geothermal activity (Schneider et al., 2023). Nonetheless, human inputs, including from coal combustion and gold mining, have greatly increased environmental Hg levels (Pirrone et al., 2010; Outridge et al., 2018; Streets et al., 2019). On a global scale, emissions from anthropogenic activities have increased the amount of Hg in the atmosphere by approximately 450% above natural conditions (Outridge et al., 2018), with a three-fold increase at the ocean surface (Lamborg et al., 2014). Hg is predominantly released to the atmosphere in its gaseous elemental form (Hg^0), where it persists for several months to a year and hence can be transported over hemispheric to global scales (Fisher et al., 2023; Schneider et al., 2023). Accordingly, marine foodwebs in remote areas, such as in the subantarctic and Antarctic, are still exposed to Hg despite their distance from industrial pollution sources (Cusset et al., 2023; Gimeno et al., 2024; Dastoor et al., 2022; Søndergaard et al., 2025). In the marine environment, methylation of inorganic Hg (iHg) by microorganisms produces methyl-Hg (MeHg) (Blum et al., 2013; Podar et al., 2015), which is a neurotoxin that bioaccumulates within organisms and biomagnifies through foodwebs (Lavoie et al., 2013; Seco et al., 2021; Matias et al., 2022). These processes can lead to long-lived marine predators (including marine mammals, large predatory fishes and seabirds) accumulating high Hg concentrations in their tissues via their diets (Chételat et al., 2020; Okado et al., 2026), with potential repercussions for their health and reproduction (Chastel et al., 2022; Carrasco, 2025).

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Procellariiform seabirds (albatrosses and petrels), many of which breed in the subantarctic, are among the longest lived vertebrates (Froy et al., 2013). Moreover, these species often feed at high trophic levels, consuming varying proportions of cephalopods, fish, crustacea, carrion and gelatinous zooplankton (Cherel and Klages, 1998; Mills et al., 2020a, 2021). As a result, albatrosses and large petrels can accumulate very high concentrations of Hg (Bustamante et al., 2016; Mills et al., 2024; Rewi et al., 2024). In particular, albatrosses are generally regarded as the most contaminated of all avian families in terms of Hg concentrations in feathers (Cherel et al., 2018), and exhibit extremely high concentrations in internal tissues such as the liver (Muirhead and Furness, 1988; Stewart et al., 1999). Albatrosses and petrels often congregate to breed in large, multispecies assemblages at a limited number of suitable sites (particularly offshore islands), and coexistence is facilitated by interspecific differences in timing of breeding, feeding areas, diving depths and diets (Croxall and Prince, 1980; Croxall et al., 1997; Moreno et al., 2016). Additionally, variation in resource use may also occur within species, driven by factors such as sex, age, breeding status and individual preference (Phillips et al., 2011, 2017). Ultimately, this variation in feeding ecology determines the trophic structure of breeding seabird communities (Croxall and Prince, 1980; Croxall et al., 1997; Moreno et al., 2016), but is also central in determining the relative Hg concentrations among species, as diet is the main exposure pathway (Becker et al., 2002, 2016; Anderson et al., 2009; Chételat et al., 2020).

This study focuses on Hg contamination of albatross and petrel chicks at the subantarctic islands of South Georgia (~300 km south of the Antarctic Polar Front, APF), where there is a large and diverse breeding assemblage (Croxall and Prince, 1980; Moreno et al., 2016). These species occupy a range of trophic niches at South Georgia, from zooplanktivores to top predator, and exploit different marine habitats, from inshore to highly pelagic waters (Croxall and Prince, 1980; Croxall et al., 1997; Moreno et al., 2016). Besides a single comparison of giant petrel *Macronectes* spp. chicks, all previous studies of Hg contamination of seabirds at South Georgia have focused on adults (Becker et al., 2002, 2016; Anderson et al., 2009; Mills et al., 2024, 2025a). However, analysing Hg concentrations in the tissues of chicks has several advantages over other age classes (Blévin et al., 2013; Carravieri et al., 2014a, 2014b). (i) Pre-fledging chicks obtain all their food from parents that feed within the waters around the colony due to the central-place foraging constraint. Hg concentrations in chick feathers therefore reflect contamination of local foodwebs during a well-defined period (chick-rearing). (ii) Seabird diets and at-sea distributions are generally well-characterised during chick-rearing, given their accessibility for tracking-device deployment and diet sampling at this time (e.g., of stomach contents). (iii) Maternal transfer via the egg contributes very little of the total Hg (THg = iHg + MeHg) in the feathers of well-grown chicks (Stewart et al., 1997; Blévin et al., 2013). (iv) Stable isotope analysis of blood and feathers has emerged as the primary method of inferring albatross diets (McInnes et al., 2016), and the integration periods for THg and stable isotopes in chick feathers are similar (Bond, 2010).

Here, the following hypotheses are tested to investigate the possible drivers of intra- and interspecific variation in THg concentrations (**H1-H3**). First, blood THg concentrations of breeding adults of species sampled in a single year in the early 2000s increased with trophic position (Anderson et al., 2009). Hence, the same pattern of an increase in THg concentrations of chicks from zooplanktivorous species to carrion feeders, pelagic generalists and the top predator was expected here (**H1**). Second, there is little evidence for annual changes in the trophic structure of the albatross and petrel community at South Georgia (Moreno et al., 2016). Therefore, given the link between diet and Hg contamination, the hypothesis was that the order of least to most contaminated species would remain consistent among years (**H2**). Finally, THg concentrations were expected to be lower than in seabirds at the Kerguelen Islands in the southern Indian Ocean (Blévin et al., 2013), reflecting changes in diet associated with regional differences in foodweb structure and composition. In particular, Antarctic krill *Euphausia superba* is of less importance in the foodwebs of the southern Indian Ocean compared to the southwest (SW) Atlantic Ocean sector of the Southern Ocean, where it is the dominant mid-trophic-level species (Atkinson et al., 2019; McCormack et al., 2020) (**H3**).

2. Materials and methods

2.1. Study site, species and feather sampling

This study focused on the albatross and petrel community at Bird Island, South Georgia (54°00′S, 38°03′W). South Georgia lies south of the APF on the Scotia Arc in the SW Atlantic Ocean sector of the Southern Ocean. Feather sampling of albatross and petrel chicks was carried out over three consecutive breeding seasons (2017/18, 2018/19 and 2019/20; referred to as 2018, 2019 and 2020, respectively). Following previous studies at Bird Island (Moreno et al., 2016; Mills et al., 2025a), during each season, fully-grown feathers were sampled from the lower back of well-developed chicks that were within 1-2 weeks of fledging. Given that mean laying and hatching dates of albatrosses and petrels are consistent among years at Bird Island (Brown et al., 2015; Keogan et al., 2018), chicks were sampled at a broadly similar age and size in each year. Feathers were then stored dry at ambient temperature in labelled and sealed envelopes prior to analysis. Chicks of the following species were sampled: Antarctic prion *Pachyptila desolata* (n = 18), blue petrel *Halobaena caerulea* (n = 32), black-browed albatross *Thalassarche melanophris* (n = 36), grey-headed albatross *T. chrysostoma* (n = 36), white-chinned petrel *Procellaria aequinoctialis* (n = 35), southern giant petrel *M. giganteus* (n = 35), northern giant petrel *M. halli* (n = 34) and wandering albatross *Diomedea exulans* (n = 36) (Table 1).

Although the foraging areas of some species at South Georgia are wider during the incubation period, all those included in this study feed mainly at, or south, of the APF in the SW Atlantic sector of the Southern Ocean while rearing chicks. The only exceptions are wandering albatrosses and female northern giant petrels, which also feed on the Patagonian Shelf or in subtropical waters (Navarro et al., 2013; Phillips et al., 2011; Tancell et al., 2016). Based on previous diet analyes (Moreno et al., 2016), the study species can be assigned to the following trophic guilds: (i) zooplanktivores (Antarctic prion, blue petrel); (ii) pelagic generalists (white-chinned petrel, black-browed albatross, grey-headed albatross); (iii) carrion feeders (southern giant petrel, northern giant petrel); and (iv) top predator (wandering albatross). Breeding seasons of all species are partly or entirely during the austral summer, with most laying in October-December and chicks fledging from February-May (Croxall and Prince, 1980). Wandering albatrosses differ, as laying is from December to early January, and chicks fledge in the following November to December (Croxall and Prince, 1980).

2.2. Total mercury determinations

MeHg comprises >90% of the THg in albatross and petrel feathers (Renedo et al., 2017). Once feathers are grown, THg concentrations remain fixed (Crewther et al., 1965; Appelquist et al., 1984). Chick feathers were prepared and analysed following Mills et al. (2025a). Feathers were cleaned using chloroform:methanol solution (2:1 v/v) and ultrapure water and then dried at 40°C in an oven for 48 h. Three feathers from each chick were homogenised into a very fine powder by cutting them with stainless steel scissors. Determinations of THg concentrations in chick feathers were made at the laboratory Littoral Environnement et Sociétés (LIENSs) at La Rochelle Université (La Rochelle, France) with an Advanced Mercury Analyser spectrophotometer (Altec® AMA-254). Each sample was analysed two or three times to ensure that the relative standard deviations among replicates remained <10% in all cases. Average values were used in statistical analyses.

Table 1
Mean (±SD) total mercury (THg) concentrations (μg g^{-1} dw) and stable isotope values of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) of chick feathers of albatrosses and petrels at Bird Island, South Georgia (2018-2020). Study species were Antarctic prion *Pachyptila desolata*, blue petrel *Halobaena caerulea*, black-browed albatross *Thalassarche melanophris*, grey-headed albatross *T. chrysostoma*, northern giant petrel *Macronectes halli*, southern giant petrel *M. giganteus*, wandering albatross *Diomedea exulans* and white-chinned petrel *Procellaria aequinoctialis*.

Feeding guild	Species	Year	n	THg (μg g^{-1} dw)	$\delta^{15}N$	$\delta^{13}C$
Zooplanktivore	Antarctic prion	2018	3	0.41 ± 0.33	10.5 ± 1.0	−23.6 ± 0.1
		2019	12	0.20 ± 0.07	10.2 ± 0.5	−22.8 ± 0.4
		2020	3	0.21 ± 0.04	10.6 ± 0.8	−22.7 ± 0.3
	Blue petrel	2018	11	0.74 ± 0.32	9.9 ± 0.4	−24.3 ± 0.5
		2019	10	1.18 ± 0.55	10.0 ± 0.5	−23.9 ± 0.4
		2020	11	0.71 ± 0.11	10.4 ± 0.3	−23.6 ± 0.4
Pelagic generalist	White-chinned petrel	2018	12	1.37 ± 0.47	12.5 ± 0.7	−22.2 ± 0.9
		2019	12	1.71 ± 0.45	12.4 ± 0.8	−21.9 ± 1.1
		2020	11	1.14 ± 0.32	12.0 ± 0.6	−21.8 ± 0.8
	Black-browed albatross	2018	12	1.28 ± 0.31	13.1 ± 0.6	−23.0 ± 0.4
		2019	12	1.65 ± 0.40	12.1 ± 0.7	−22.0 ± 0.5
		2020	12	1.83 ± 0.73	12.4 ± 1.0	−21.2 ± 0.9
	Grey-headed albatross	2018	12	1.49 ± 0.43	12.1 ± 0.4	−23.6 ± 0.3
		2019	12	2.04 ± 0.90	12.2 ± 0.6	−21.8 ± 0.5
		2020	12	1.83 ± 0.44	12.4 ± 0.3	−20.5 ± 1.0
Carrion feeder	Northern giant petrel	2018	12	3.02 ± 0.89	13.1 ± 0.4	−20.9 ± 0.6
		2019	11	2.20 ± 0.71	12.6 ± 0.4	−20.9 ± 0.4
		2020	11	1.90 ± 0.38	12.9 ± 0.2	−20.7 ± 0.4
	Southern giant petrel	2018	12	2.03 ± 0.44	13.2 ± 0.3	−20.9 ± 0.4
		2019	12	1.87 ± 0.80	12.4 ± 0.2	−21.1 ± 0.5
		2020	11	2.17 ± 0.58	12.6 ± 0.2	−20.8 ± 0.5
Top predator	Wandering albatross	2018	12	3.95 ± 0.77	14.8 ± 0.2	−21.6 ± 0.4
		2019	12	4.60 ± 0.95	15.1 ± 0.2	−20.5 ± 0.4
		2020	12	6.14 ± 1.68	15.3 ± 0.4	−20.7 ± 0.7

Analytical accuracy and precision were assessed using certified reference materials (CRMs), including lobster hepatopancreas TORT-3 [certified THg concentration: 0.29 ± 0.02 μg g^{-1} dry weight (dw), from National Research Centre Canada (NRC)] and dogfish liver DOLT-5 (0.44 ± 0.18 μg g^{-1} dw, from NRC). CRM masses were altered such that they had similar quantities of Hg as in the chick feather samples. CRMs were analysed at the start and end of each analytical cycle and for every 10 samples. Measured THg concentrations (means ± standard deviations) of TORT-3 and DOLT-5 were 0.30 ± 0.01 μg g^{-1} dw (n = 42) and 0.42 ± 0.01 μg g^{-1} dw (n = 9). These values corresponded to recoveries of 102.5 ± 1.9% and 94.8 ± 0.8% for TORT-3 and DOLT-5, respectively. Procedural blanks were analysed at the start of each analytical run. The limit of quantification (LoQ) for the AMA is 0.1 ng. Chick feather THg concentrations are reported in μg g^{-1} dw.

2.3. Stable isotope analysis

Stable isotopes of carbon (^{13}C:^{12}C, expressed as $\delta^{13}C$ values in per mil units, ‰) and nitrogen (^{15}N:^{14}N, $\delta^{15}N$) are considered to serve as proxies for feeding habitats (carbon sources) and trophic positions, respectively (Inger and Bearhop, 2008; Karnovsky et al., 2012). In feathers of seabird chicks, $\delta^{13}C$ and $\delta^{15}N$ values reflect those of prey delivered by parents (Inger and Bearhop, 2008). Following Mills et al. (2025a), subsamples of approximately 0.3 mg of homogenised feather samples (as analysed above) were weighed into 6 × 4 mm tin capsules using a microbalance. Stable isotope analyses of carbon and nitrogen of bulk chick feather samples were conducted using a continuous flow isotope ratio mass spectrometer (Delta-V Plus with a Conflo IV Interface, Thermo Scientific, Bremen, Germany) coupled to an elemental analyser (Flash 2000 or Flash IRMS EA Isolink CN, Thermo Scientific, Milan, Italy) at LIENSs. Results are reported in the conventional δ notation in per mil (‰) units relative to the international standards Vienna PeeDee Belemnite (VPDB) and atmospheric N_2 (AIR) for carbon and nitrogen, respectively. Measurement errors associated with replicate measurements of reference materials (USGS61 and USGS63) were ±0.20 ‰ for $\delta^{13}C$ and $\delta^{15}N$ values.

2.4. Data analysis

R version 4.4.0 was used for all statistical analyses (R Core Team, 2024). THg concentrations were $\log_{10}$ transformed prior to analysis to reduce positive skew and improve homoscedasticity. First, a Generalised Linear Model (GLM) with a Gaussian error distribution and identity link function was used to assess variation in THg concentrations in relation to species, year and their interaction. Likelihood ratio tests were used to assess the significance of model terms. Model assumptions were evaluated using visual inspection of residual diagnostics. Within-year pairwise comparisons among species were conducted using Holm-adjusted post-hoc tests of estimated marginal means (Lenth and Piaskowski, 2025). Results were summarised with compact letter displays, whereby species sharing letters within a given year were not significantly different at α = 0.05 (Fig. 1). Second, relationships between THg concentrations and stable isotope values were examined within each year to investigate potential influences of trophic position and foraging habitat. THg concentrations ($\log_{10}$ transformed) were modelled in relation to $\delta^{15}N$ or $\delta^{13}C$ using separate GLMs (Gaussian error distribution and identity link function) fitted for each year. Species was included as a factor in all models to account for interspecific differences in THg concentrations. Separate GLMs were used for $\delta^{15}N$ and $\delta^{13}C$ values as these were strongly correlated within years (Pearson's correlation, $r > 0.68$ in all cases), hence the inclusion of both terms in a single model would introduce multicollinearity. Residual diagnostics were again inspected to confirm model assumptions. Finally, for species with available data (all but southern giant petrels and grey-headed albatrosses), chick feather THg concentrations at South Georgia were compared with those reported by Blévin et al. (2013) for the Kerguelen Islands (determined using the same methodology in the same laboratory as this study) using Welch's independent-samples t-tests based on published means, standard deviations and sample sizes. The ggplot2 package in R was used to visualise the data throughout (Wickham, 2016).

3. Results

THg concentrations were determined in feathers of 262 chicks of eight species of albatrosses and petrels at Bird Island (Table 1).

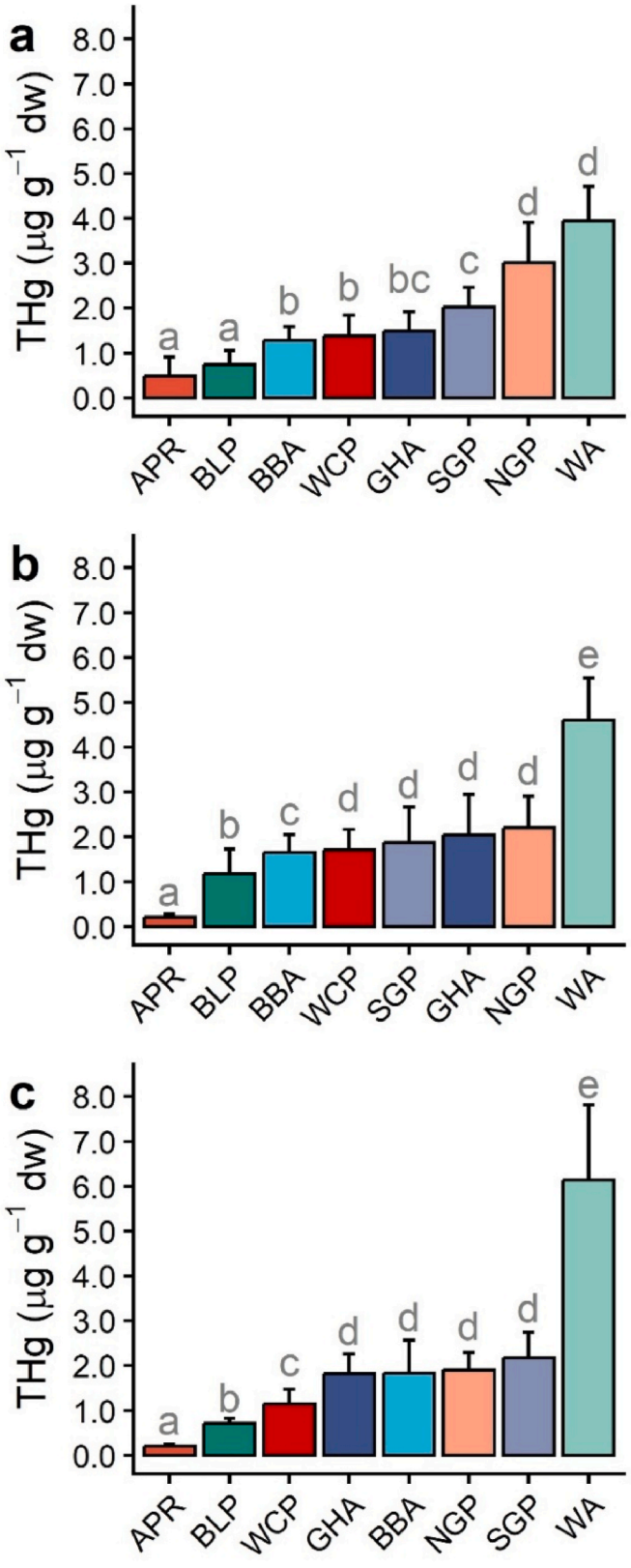

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Fig. 1. Mean (±SD) total mercury (THg) concentrations (µg g^{-1} dw) in chick feathers of albatrosses and petrels at Bird Island, South Georgia, in (**a**) 2018, (**b**) 2019 and (**c**) 2020. Species are ordered by mean THg concentrations within each year. Species are abbreviated on the x-axis as: APR = Antarctic prion *Pachyptila desolata*; BLP = blue petrel *Halobaena caerulea*; WCP = white-chinned petrel *Procellaria aequinoctialis*; BBA = black-browed albatross *Thalassarche melanophris*; GHA = grey-headed albatross *T. chrysostoma*; SGP = southern giant petrel *Macronectes giganteus*; NGP = northern giant petrel *M. halli*; and WA = wandering albatross *Diomedea exulans*. Species sharing the same letter were not significantly different according to post-hoc comparisons within years (Holm-adjusted $p < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Concentrations ranged from 0.10 µg g^{-1} dw (an Antarctic prion sampled in 2019) to 8.82 µg g^{-1} dw (a wandering albatross sampled in 2020). The GLM explaining variation in THg concentrations (log_{10} transformed) included a significant species × year interaction ($\chi^2 = 69.7$, $p < 0.001$), indicating that interspecific differences depended upon the year. Pairwise comparisons showed that zooplanktivorous species (Antarctic prions and blue petrels) consistently exhibited the lowest mean concentrations, and wandering albatrosses showed the highest in every year (though concentrations were similar to northern giant petrels in 2018) (Fig. 1). Giant petrels generally displayed intermediate to high mean concentrations. However, regarding the order of increasing concentrations, giant petrels and the pelagic generalists shifted from year to year (Fig. 1). Results of all post-hoc comparisons within each year are in Fig. 1. Accounting for species differences, THg concentrations (log_{10} transformed) were positively associated with $\delta^{15}N$ in 2018 (GLM, $\chi^2 = 6.74$, $p < 0.01$), 2019 ($\chi^2 = 8.44$, $p < 0.01$) and 2020 ($\chi^2 = 40.3$, $p < 0.001$), corresponding to increases of approximately 21% (slope ± SE, 0.08 ± 0.03), 22% (0.09 ± 0.03) and 36% (0.14 ± 0.02) per 1 ‰ in $\delta^{15}N$, respectively (Fig. 2). There were also significant positive relationships between THg and $\delta^{13}C$ in 2019 and 2020 ($\chi^2 = 9.18$, $p < 0.01$ and $\chi^2 = 12.03$, $p < 0.001$, respectively), but not in 2018 ($\chi^2 = 2.86$, $p = 0.09$) (Fig. 2).

THg concentrations in chick feathers were significantly lower at South Georgia than at the Kerguelen Islands in black-browed albatrosses ($t = -5.43$, $p < 0.001$), northern giant petrels ($t = -9.52$, $p < 0.001$) and white-chinned petrels ($t = -2.50$, $p < 0.05$). THg concentrations were not significantly different in Antarctic prions ($t = 0.83$, $p = 0.41$), blue petrels ($t = 0.28$, $p = 0.78$) or wandering albatrosses between sites ($t = 0.87$, $p = 0.39$) (Fig. 3).

4. Discussion

This study provides a comprehensive assessment of Hg exposure to seabird chicks at South Georgia, a globally important breeding site, and extends previous work that was limited to chicks of a few species or to adults (Becker et al., 2002, 2016; Anderson et al., 2009; Mills et al., 2024, 2025a). Studies of Hg contamination in seabird communities based on sampling of adults are potentially complicated by the long accumulation period between moults and the diversity of migration strategies among species, which can include extensive periods spent in distinct water masses (Stewart et al., 1999; Anderson et al., 2009; Carravieri et al., 2014a; Mills et al., 2024). By comparison, the THg concentrations measured in this study of chicks are indicative of contamination within the SW Atlantic sector of the Southern Ocean during a well-defined period, since all species mainly forage in this region while rearing chicks (Navarro et al., 2013; Phillips et al., 2011; Tancell et al., 2016).

4.1. Relative THg concentrations across years

The highest and lowest THg concentrations were always in wandering albatrosses and the zooplanktivores (Antarctic prions and blue petrels), respectively, and there was a 90-fold difference between the

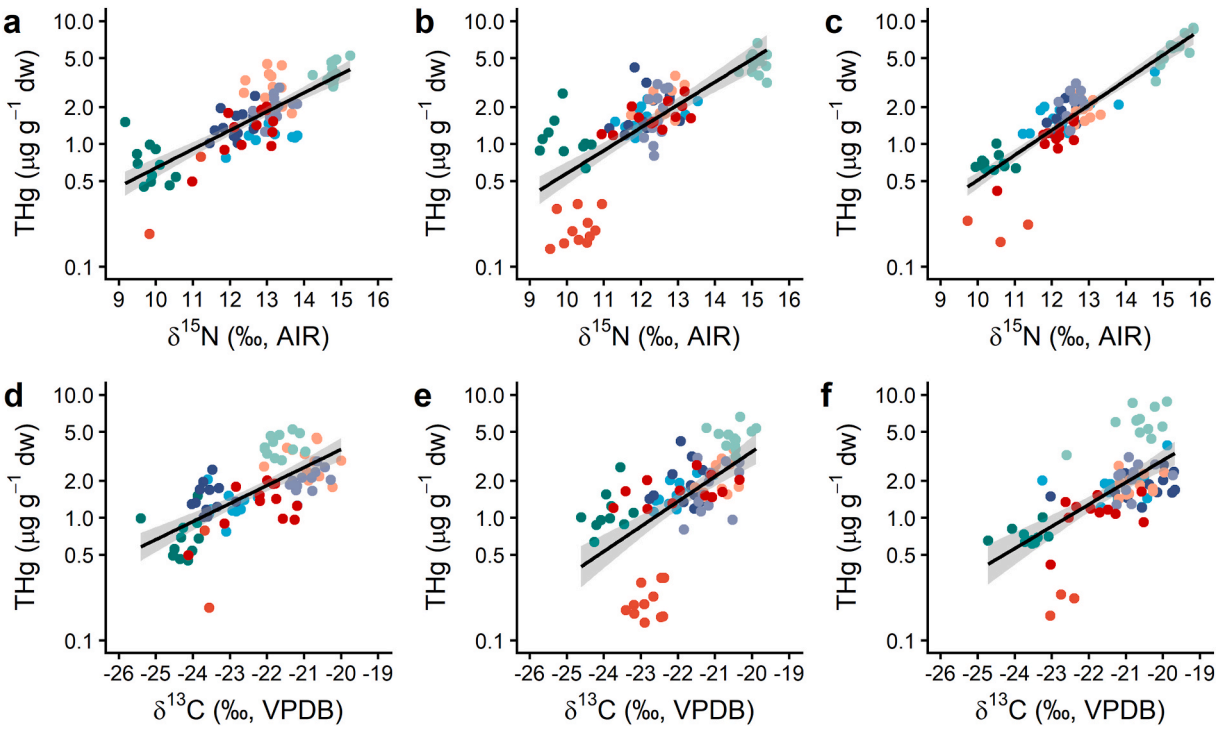

Fig. 2. Relationships between total mercury (THg) concentrations (µg g^{-1} dw) and stable isotope values (‰) of nitrogen (δ^{15}N) and carbon (δ^{13}C) in chick feathers of albatrosses and petrels at Bird Island, South Georgia, in 2018, 2019 and 2020 (**a-c** and **d-f**, respectively). Solid lines represent model-adjusted predictions from Gaussian GLMs accounting for species identity, and shaded areas indicate 95% confidence intervals. THg concentrations are shown on a log-scaled y-axis. Points are coloured by species identity as indicated in Fig. 1.

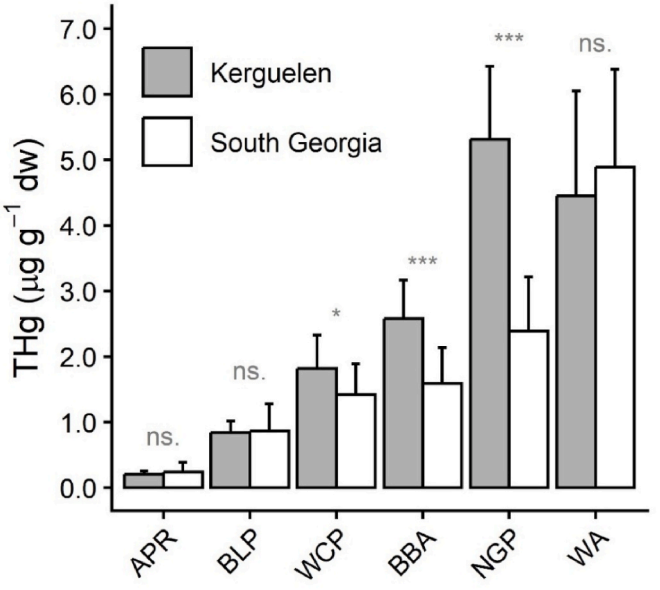

Fig. 3. Mean (±SD) total mercury (THg) concentrations (µg g^{-1} dw) of seabird chick feathers sampled at Bird Island, South Georgia (2018-2020; this study), and at the Kerguelen Islands in the mid-2000s (Blévin et al., 2013). Species on the x-axis are abbreviated as follows: APR = Antarctic prion *Pachyptila desolata*; BLP = blue petrel *Halobaena caerulea*; WCP = white-chinned petrel *Procellaria aequinoctialis*; BBA = black-browed albatross *Thalassarche melanophris*; NGP = northern giant petrel *Macronectes halli*; and WA = wandering albatross *Diomedea exulans*. Statistically significant differences between the two sites are indicated above each column.

least and most contaminated individual (an Antarctic prion and wandering albatross chick, respectively). This corroborates an analysis of THg in blood and feathers of breeding adults in a single year in the early 2000s (Anderson et al., 2009), providing some support for **H1**. However, a key finding of this study was the significant species × year interaction and pairwise comparisons, which indicated that the order of least to most contaminated species was not consistent across years (Fig. 1), refuting **H2**. Indeed, the order of those species with intermediate THg concentrations, which included the pelagic generalists (black-browed albatrosses, grey-headed albatrosses and white-chinned petrels) and giant petrels, shifted from one year to the next (Fig. 2). This result indicates that caution should be exercised when interpreting interspecific differences in pollutant exposure from single season studies of seabird communities.

The low THg concentrations in chicks of zooplanktivorous species were largely related to their low trophic positions, and hence lower biomagnification. This is reflected in the interspecific differences in δ^{15}N values compared to other trophic guilds (Fig. 4). Comparisons between Antarctic prions and blue petrels, however, are somewhat more complicated. THg concentrations were significantly higher in blue petrels in two of the three years (Fig. 1), but they exhibited lower δ^{13}C and δ^{15}N values than Antarctic prions (Fig. 4). THg concentrations in blood were also higher in breeding adult blue petrels than Antarctic prions in one of two previous studies (Anderson et al., 2009; Quillfeldt et al., 2022). Moreover, concentrations were significantly higher in muscle, kidney and liver of blue petrels than Antarctic prions at Kerguelen (Bocher et al., 2003). The apparent inconsistency between THg concentrations and stable isotope values here seems to relate partly to diet, as analyses of regurgitates from the mid-1970s to mid-1990s show that crustacea, especially Antarctic krill, are the main prey of the two species, but blue petrels consume more fish and fewer copepods than Antarctic prions (Prince, 1980; Reid et al., 1997). The greater use by blue petrels of higher latitude waters, where isotopic baseline values are lower, likely also has an influence (Navarro et al., 2013; Quillfeldt et al., 2022).

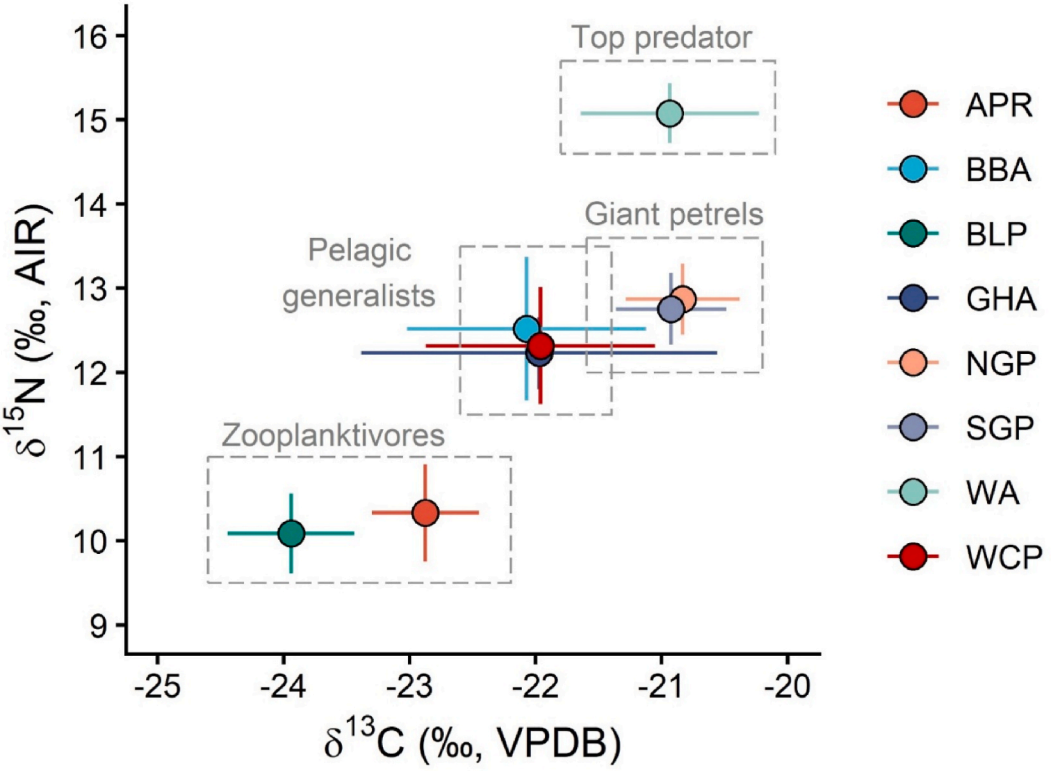

Fig. 4. Mean (±SD) stable isotope values (‰) of carbon (δ^{13}C) and nitrogen (δ^{15}N) in chick feathers of albatrosses and petrels at Bird Island, South Georgia sampled in 2018-2020. Species are abbreviated as follows: APR = Antarctic prion *Pachyptila desolata*; BLP = blue petrel *Halobaena caerulea*; WCP = white-chinned petrel *Procellaria aequinoctialis*; BBA = black-browed albatross *Thalassarche melanophris*; GHA = grey-headed albatross *T. chrysostoma*; SGP = southern giant petrel *Macronectes giganteus*; NGP = northern giant petrel *M. halli*; and WA = wandering albatross *Diomedea exulans*. Grey boxes and text indicate feeding guilds (Moreno et al., 2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

In contrast, wandering albatrosses were consistently the most contaminated species in this study, although THg concentrations were not significantly different from northern giant petrel chicks in 2018 (Fig. 1). High Hg concentrations of wandering albatross chicks are related to their high trophic positions, confirmed by their high δ^{15}N values (Fig. 4), as this species is the top predator within the procellariiform community at South Georgia (Moreno et al., 2016). Stomach contents analyses indicate that wandering albatrosses feed primarily on large cephalopods and fish, including Patagonian toothfish *Dissostichus eleginoides* and blue antimora *Antimora rostrata* (Ceia et al., 2012; Xavier et al., 2004), and hence they occupy a trophic position where biomagnification is expected to be greatest.

Anderson et al. (2009) found that blood THg concentrations of adult pelagic generalists were higher than giant petrels. In this study, however, the order of low to high THg concentrations among pelagic generalists and giant petrels differed among years. Northern and southern giant petrel chicks had similar mean THg concentrations in 2019 and 2020, but not 2018. Diet composition was similar in the two giant petrel species at South Georgia in the mid-2010s: approximately half the diet by mass was penguins, and the remainder was largely Antarctic fur seal *Arctocephalus gazella* carrion, other seabirds and Antarctic krill (Mills et al., 2021). Hg contamination of giant petrel chicks was positively associated with a shift away from carrion consumption (connected with the decreasing size and productivity of the Antarctic fur seal population) and towards consumption of prey from lower trophic levels during the 2010s (Mills et al., 2025a). In 2018, THg concentrations in northern giant petrel and wandering albatross chicks were not significantly different, reflecting higher concentrations in the former and lower in the latter than in 2019 and 2020 (Fig. 1). The inference from Mills et al. (2025a), as well as the higher δ^{15}N (Fig. 4), is that northern giant petrels likely consumed a greater proportion of penguins and Antarctic fur seal carrion versus low-trophic-level prey (which have lower Hg concentrations) in 2018. By comparison, lower δ^{13}C and δ^{15}N values in 2018 than other years in wandering albatrosses likely indicates a partial shift in the foraging distribution. Once chicks can be left alone at the nest, wandering albatrosses feed over an extensive area, from Antarctic to subtropical waters (Xavier et al., 2004; Warwick-Evans et al., 2025). Annual variation in the relative use of different water masses such as increased use of more southerly waters (with lower isotopic baseline values), and greater consumption of Antarctic prey, which tend to show lower THg concentrations (Seco et al., 2020, 2021), might well explain the isotopic shift and lower THg concentrations in 2018.

THg concentrations in chicks of the three pelagic generalist species also varied considerably, and in some years were not significantly different from one or both species of giant petrels (Fig. 1). Despite broadly similar stable isotope values (Fig. 4), there are marked differences in diet composition and at-sea distributions among the pelagic generalists. Additionally, they have very large potential foraging ranges during chick-rearing, which could influence annual exposure levels. Cephalopods are the most important component of grey-headed albatross chick diets at South Georgia (Mills et al., 2020a). Adults primarily feed at the APF while rearing chicks, with additional use by some individuals of waters in the central Scotia Sea, the shelf and shelf-slope waters of the South Scotia Arc, extending from the South Orkney Islands to the Antarctic Peninsula (Xavier et al., 2003; Phillips et al., 2004). In contrast, black-browed albatross chicks are fed equal proportions of Antarctic krill and fish, cephalopods are less important (Mills et al., 2020a). During chick-rearing, the feeding distributions of adults are mainly concentrated over neritic shelf and shelf-slope waters around South Georgia, Shag Rocks and the Scotia Arc (Phillips et al., 2004). Some individuals also feed in the waters at the APF, parts of the central Scotia Sea, southeast of the South Sandwich Islands and in the Weddell

Sea, but these areas are of less importance at the population-level (Phillips et al., 2004). Nonetheless, in any one season, Antarctic krill, fish or cephalopods may predominate in the diets of these species (Mills et al., 2020a), with potential repercussions for annual variation in Hg contamination. Finally, white-chinned petrels consume a higher proportion of Antarctic krill (~40-50% in studies in the 1980s and 1990s), and in chick-rearing, feed over a very extensive region that includes areas used by black-browed and grey-headed albatrosses as well as the Patagonian Shelf (Croxall et al., 1995; Berrow and Croxall, 1997; Berrow et al., 2000a).

4.2. Trophic drivers of contamination

Accounting for the effect of species, THg concentrations were positively related to $\delta^{15}N$ in all three years, and to $\delta^{13}C$ in 2019 and 2020 (Fig. 2). Typically, $\delta^{15}N$ is used as a proxy for trophic position (Inger and Bearhop, 2008). Hence, allowing for some uncertainty related to potential annual variation in $\delta^{15}N$ baselines in different feeding areas (Elliott et al., 2021), this indicates that chicks that were fed higher trophic level prey were more contaminated with Hg. This is consistent with the biomagnification process (i.e., increasing concentrations with trophic level). In the South Georgia and Scotia Sea marine ecosystems, Hg concentrations increase from particulate organic matter and zooplankton through to cephalopods, myctophid and notothenioid fish, and finally predators, including marine mammals and seabirds (Seco et al., 2021). Feather $\delta^{13}C$ values mainly reflect differences in foraging habitat and water mass rather than trophic level (Phillips et al., 2009), and were positively associated with THg in two study years, suggesting that exposure varied along a habitat or latitudinal gradient as well as with trophic position. However, since $\delta^{13}C$ and $\delta^{15}N$ were strongly correlated within years, relationships with $\delta^{13}C$ also likely reflect, at least in part, covariation with trophic position (Fig. 4). Together, these results imply that changes in the structure and dynamics of foodwebs may influence Hg concentrations of seabirds at South Georgia via changes in their diets (Mills et al., 2025a). For instance, Antarctic krill comprises approximately one third of the combined prey consumption of the breeding procellariiform seabird community at South Georgia (Moreno et al., 2016). Seco et al. (2021) hypothesised that in years when the local abundance of Antarctic krill is low, seabirds at South Georgia utilise different trophic pathways, with a corresponding increase in Hg exposure. Importantly, Antarctic krill densities around South Georgia show high variation from year-to-year (Fielding et al., 2014; Trathan et al., 2022), and the distribution of Antarctic krill has contracted towards the Antarctic continent, reducing densities at South Georgia (Atkinson et al., 2019). As such, there is a pressing need for further research on the links between Antarctic krill availability, seabird diets and pollutant exposure.

4.3. Comparison with the Kerguelen Islands

Comparable data on Hg contamination were available from the Kerguelen Islands for all study species except southern giant petrels and grey-headed albatrosses (Blévin et al., 2013). THg concentrations in chicks of Antarctic prions, blue petrels and wandering albatrosses did not differ between the two regions (sampled in 2008, 2003 and 2005 at Kerguelen, respectively). However, chicks of white-chinned petrels, black-browed albatrosses and northern giant petrels were more contaminated at the Kerguelen Islands (all sampled in 2005) (Fig. 3). Hence, there was mixed support for **H3**. Notably, northern giant petrels had the highest THg concentrations in the community at Kerguelen (Blévin et al., 2013). Moreover, blood THg concentrations of breeding adult brown skuas *Stercorarius antarcticus lonnbergi* are also higher at Kerguelen than South Georgia (Mills et al., 2025b). As stated in **H3**, geographic differences in diet, potentially related to the reduced role of Antarctic krill in the southern Indian Ocean (McCormack et al., 2020), may explain these results. For instance, Antarctic krill is an important component of black-browed albatross diets at South Georgia (Mills et al., 2020a), but crustacea are unimportant at the Kerguelen Islands, and adults instead feed mainly on fish (73%), as well as penguin carrion (14%) and cephalopods (10%) (Cherel et al., 2000). Though there are no published diet data from Kerguelen in the chick-rearing period, northern giant petrels likely consume elephant seal *Mirounga leonina* and king penguin *Aptenodytes patagonicus* carrion, as well as other prey (Ridoux, 1994; Thiers et al., 2014), and these first two species have moderate to high THg concentrations (Cipro et al., 2017; Carravieri et al., 2020; Barragán-Barrera et al., 2024). An additional hypothesis would be that environmental Hg exposure is generally higher at Kerguelen, which lies at a lower latitude than South Georgia (49°S vs 54°S) in close proximity to the APF. There is a latitudinal trend in Hg contamination of seabird species in the Southern Hemisphere, increasing from those that feed in Antarctic waters to those that use subantarctic and subtropical waters (Carravieri et al., 2016, 2017). This trend may be related to enhanced Hg methylation and vertical advection from the mesopelagic zone towards the surface at lower latitudes (Renedo et al., 2020). Such differences in Hg cycling at large spatial scales and the implications for Hg exposure and consequences for health are largely unexplored (Ibañez et al., 2024; Mills et al., 2020b). More generally, establishing causal links between pollutant exposure and population processes for albatrosses and petrels at South Georgia is important from a conservation-perspective, as several species have undergone steep long-term population declines (Berrow et al., 2000b; Mackley et al., 2025).

CRediT authorship contribution statement

William F. Mills: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Paco Bustamante:** Writing – review & editing, Investigation. **Richard A. Phillips:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Ethics statement

All handling and body feather sampling of all seabird chicks during the fieldwork for this study was approved by the British Antarctic Survey Animal Welfare and Ethics Review Body and was carried out under permits from the Government of South Georgia and the South Sandwich Islands.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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