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Mercury contamination of sympatric seabirds and associated health risks in an Antarctic ecosystem

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ABSTRACT

Antarctic marine ecosystems are located far from industrial pollution sources, yet mercury (Hg) contamination remains an important threat to regional biodiversity. Seabirds occupy mid- to high trophic positions in Antarctic food webs, and can show high levels of Hg contamination due to biomagnification. Here, total Hg (THg) concentrations and stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) were measured in red blood cells of brown skuas *Stercorarius antarcticus lonnbergi* (n = 44) and south polar skuas *S. maccormicki* (n = 50) at King George Island/Isla 25 de Mayo (South Shetland Islands) in the 2022/23 and 2023/24 breeding seasons. The objectives were to: (i) determine current levels of Hg contamination at King George Island and identify the underlying drivers (e.g., species, sex, year, $\delta^{13}C$ and $\delta^{15}N$); (ii) compare contaminant levels with other breeding sites; and (iii) examine potential Hg-associated health risks. At King George Island, south polar skuas had higher THg concentrations (mean ± SD, 3.85 ± 2.99 µg g^{-1} dw) than brown skuas (1.67 ± 1.25 µg g^{-1} dw), potentially due to their greater reliance on mesopelagic fish and carry-over effects from their non-breeding distributions. THg concentrations of males were higher than females, with deposition into eggs by females being the likeliest explanatory factor, and were positively related to $\delta^{15}N$, reflecting the biomagnification process. THg concentrations of brown skuas in this study were higher than at Hope Bay (Antarctic Peninsula), but lower than at South Orkney Islands (Antarctica), South Georgia and Kerguelen Islands (subantarctic). THg concentrations of the south polar skuas analysed here were higher than at Hope Bay and Adélie Land (Antarctic continent). Comparisons with toxicity benchmarks suggest that skuas are currently at low risk of Hg-associated health impacts at King George Island.

1. Introduction

Mercury (Hg) contamination of the world's oceans is a significant threat to marine biodiversity and wider ecosystem health (Sigmund et al., 2023). Indeed, owing to the adverse effects of Hg on humans and the environment more generally, a global agreement, the Minamata Convention on Mercury (www.mercuryconvention.org), aims to reduce and control Hg emissions and is ratified by > 150 countries (Evers et al., 2016). The amount of Hg entering the oceans has increased significantly due to human activities and Hg levels in surface waters are three times higher than in pre-industrial times (Lamborg et al., 2014; Outridge et al., 2018; Streets et al., 2019). At present, the most important anthropogenic contributor to environmental Hg levels is artisanal and small-scale gold mining, which is mostly concentrated in the Southern Hemisphere, but other important sources include the combustion of fossil fuels and production of non-ferrous metals (Fisher et al., 2023; Keane et al., 2023). Despite being located far from major anthropogenic emissions sources, and the continent being largely free of human activities, marine ecosystems in Antarctica are still impacted by Hg (Bestley et al., 2020; Cusset et al., 2023; Gimeno et al., 2024). This is in part because the

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dominant form of Hg emitted to the atmosphere (Hg^0, the gaseous elemental form) has a long residence time, which facilitates long range transport (over hemispheric to global scales) from its emissions sources, meaning that Hg can reach the polar regions and enter Antarctic food webs (Cusset et al., 2023; Fisher et al., 2023; Schneider et al., 2023; Gimeno et al., 2024). Additionally, Hg may be transported to Antarctic ecosystems by biovectors (e.g., migratory seabirds) (Wild et al., 2022), and there are potentially important natural sources of Hg in Antarctica (e.g., volcanic emissions and releases from sea ice), as well as local research stations, increasing tourist activities and shipping, all of which may provide local anthropogenic inputs of Hg (Mão de Ferro et al., 2014; Gionfriddo et al., 2016).

In aquatic environments, the methylation of inorganic Hg (iHg) by anaerobic microorganisms leads to the production of methyl-Hg (MeHg) (Regnell and Watras, 2019). MeHg is the most toxic form of Hg, and bioaccumulates within the tissues of organisms over time and biomagnifies along marine food chains (Seco et al., 2021a; Matias et al., 2022). Given that many seabirds are long-lived and occupy mid- to high trophic positions in Antarctic food webs, they can accumulate high Hg concentrations in their tissues via their food intake, which is the main route of Hg exposure (Bustamante et al., 2016; Cherel et al., 2018; Chételat et al., 2020; Mills et al., 2020, 2024a). Hg contamination can have a range of negative effects on seabirds, including for their physiology, neuroendocrine systems, immune status and behaviour (Tartu et al., 2013, 2015; Whitney and Cristol, 2017; Ibañez et al., 2024). For some species, Hg contamination is associated with reduced breeding success and can impact population dynamics (Goutte et al., 2014; Mills et al., 2020).

This study determined total Hg (THg = iHg + MeHg) concentrations in the blood of brown skuas *Stercorarius antarcticus lonnbergi* and south polar skuas *S. maccormicki* at King George Island/Isla 25 de Mayo, South Shetland Islands, Antarctica. These species have circumpolar breeding distributions in the Southern Hemisphere, although the former predominantly breeds on subantarctic islands, whereas breeding sites of the latter are mostly concentrated at higher latitudes, including on the Antarctic continent (Ritz et al., 2008). There are areas of breeding sympatry on the northern Antarctic Peninsula, South Shetland Islands and South Orkney Islands, where hybridisation between the two species regularly occurs (Ritz et al., 2008). Brown skuas and south polar skuas are both opportunistic feeders and consume a wide variety of prey through active predation, scavenging and kleptoparasitism (Reinhardt et al., 2000). However, when breeding in sympatry, analyses of regurgitated pellets indicate that brown skuas consume more penguin eggs and chicks, and south polar skuas feed to a greater extent at sea (Pietz, 1987; Graña Grilli and Montalti, 2012; de Almeida Reis et al., 2021; Morales et al., in review). This segregation in diet has typically been attributed to competitive exclusion by brown skuas, which are larger and considered to be more aggressive than south polar skuas (Pietz, 1987). At the South Shetland Islands, breeding allochrony (i.e., the earlier onset of breeding by brown skuas), and therefore the availability and accessibility of certain prey, may also contribute to these interspecific differences in diet (Morales et al., in review). The ecological differences between these species could result in differential dietary exposure to Hg, and hence the potential for associated health risks. Within this context, the objectives of this study were to: (i) determine current levels of Hg contamination of skuas at King George Island; (ii) compare contaminant levels with other breeding sites; (iii) investigate the biological and ecological drivers of varation in Hg concentrations (e.g., species, sex, year and feeding ecology); and (iv) assess the potential for Hg-associated health risks. Here, stable isotope values of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) were used to infer feeding habitats and trophic levels, respectively (Inger and Bearhop, 2008). Notably, brown skuas and south polar skuas are among the few seabird species for which Hg contamination has been shown to influence population dynamics (Goutte et al., 2014). Moreover, Hg concentrations in the blood of brown skuas are associated with adverse effects on the physiology, immune status and liver function at Hope Bay (Bahía Esperanza) on the Antarctic Peninsula, and with reduced egg volumes at that site (Ibañez et al., 2024).

2. Materials and methods

2.1. Study site and sample collection

This study focused on the breeding populations of brown skuas and south polar skuas at the Potter Peninsula, King George Island, South Shetland Islands (62°15′S, 58°40′W), during the 2022/23 and 2023/24 breeding seasons. King George Island is ~130 km from the northwestern edge of the Antarctic Peninsula (Fig. 1), and is the largest island of the South Shetland Islands archipelago. Both skua species are classified as Least Concern on the IUCN Red List; however, at the Potter Peninsula, breeding success (fledged chicks per active nest) of brown skuas (20 and 95 breeding pairs in 2022/23 and 2023/24) and south polar skuas (18 and 49 breeding pairs) is generally low, and has been declining since the mid-1980s (Krietsch et al., 2016; Gran;a Grilli et al., 2018; A.E. Ibañez, unpublished data). In December and January of each breeding season, active breeders of both species were caught directly from the nest or using a noose, and blood samples of ~2 mL were extracted from the brachial vein with 23-G needles and heparinized syringes. Blood samples were then kept at 4 °C for their return to the laboratory (within 6 h of sampling). Samples were then centrifuged (2000 rpm for 10 min) to isolate the cellular component, in which Hg preferentially partitions, which was then frozen at −20 °C prior to laboratory analyses (Tavares et al., 2013; Mills et al., 2022; Ibañez et al., 2022b, 2024). All birds were sampled during the incubation period, ~10–15 days after clutch completion (Mills et al., 2022; Ibañez et al., 2022b, 2024). Brown skuas and south polar skuas return to the Potter Peninsula in late September and early November and lay eggs in mid November and mid December, respectively (L.M. Morales, unpublished data). No birds were sampled more than once, although, in some cases, both members of a pair were sampled.

2.1.1. Molecular sexing

Brown skuas and south polar skuas exhibit female-biased sexual size dimorphism (SSD), such that female birds are larger and heavier than males (Furness, 1987; Phillips et al., 2002). Molecular sexing of all birds was undertaken at the Instituto de Investigaciones Marinas y Costeras (IIMyC, UNMdP-CONICET). Birds were sexed from blood samples via polymerase chain reaction amplification of part of two highly conserved genes (CHD) on the sex chromosomes (Fridolfsson and Ellegren, 1999).

2.2. Total Hg measurements

THg concentrations were determined in samples of red blood cells (hereafter "blood"), which were freeze-dried and homogenised before analysis. Hg has a half-life of 30–60 days in great skua *S. skua* blood (Bearhop et al., 2002; Albert et al., 2019), which is closely-related to the study species. THg in the blood of brown skuas and south polar skuas is mostly (>90 %) MeHg (Renedo et al., 2020), and concentrations were measured using an Advanced Mercury Analyser spectrophotometer (AMA-254 Altec®) at the laboratory Littoral Environnement et Sociétés (LIENSs; La Rochelle Université, La Rochelle, France), as previously described (Chouvelon et al., 2009). Samples were analysed in duplicate or triplicate (ranging from 0.17 to 3.38 mg dry weight [dw]), ensuring that relative standard deviations were <10 % (mean ± SD, 1.40 ± 0.01 %). The mean values of the replicate measurements were used in subsequent statistical analyses. A certified reference material (CRM; lobster hepatopancreas TORT-3, National Research Centre, Canada) with a certified THg concentration of 0.29 ± 0.02 $\mu g\ g^{-1}$ dw was analysed at the start of the sample runs, and then after every tenth sample to evaluate the accuracy and reproducibility of measurements. The mass of the CRM was adjusted to ensure an amount of Hg that was comparable to

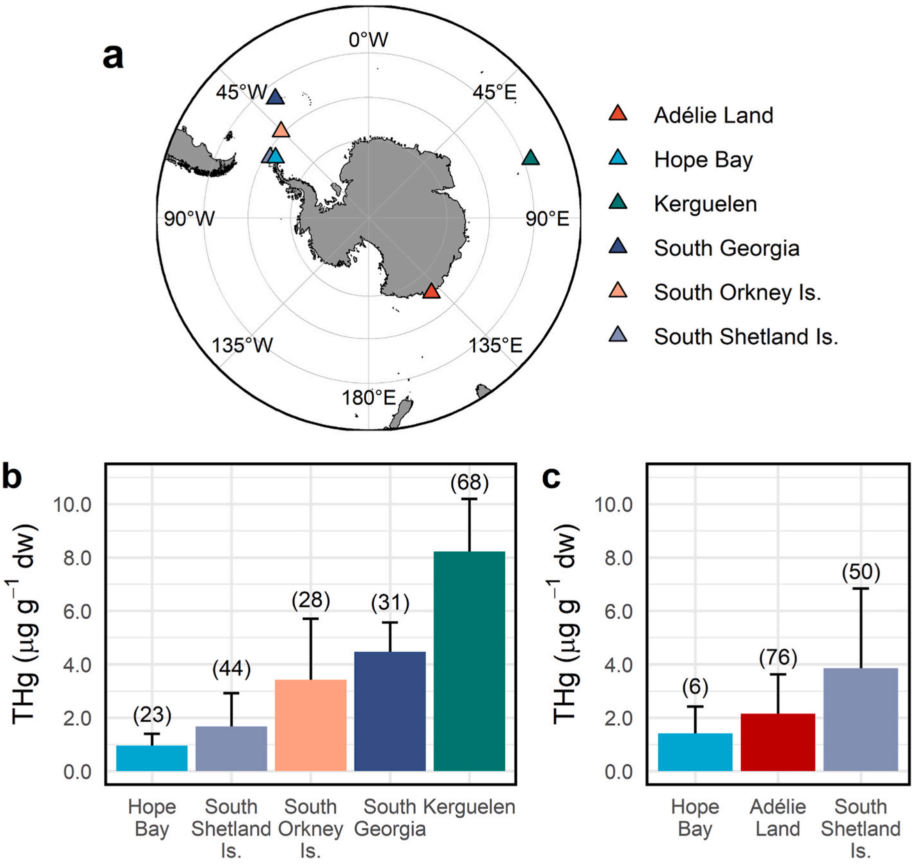

Fig. 1. **(a)** Breeding locations of brown skuas *Stercorarius antarcticus lonnbergi* and south polar skuas *S. maccormicki* at Adélie Land (Antarctica), Hope Bay/Bahía Esperanza (Antarctic Peninsula), Potter Peninsula, King George Island/Isla 25 de Mayo (South Shetland Islands), Signy Island (South Orkney Islands), Bird Island (South Georgia) and Mayes Island (Kerguelen archipelago). This figure was created using the ggOceanMaps package in R (Vihtakari, 2022). Mean (±SD) total mercury (THg) concentrations (μg g^{-1} dw) in red blood cells of adult **(b)** brown skuas and **(c)** south polar skuas from the Potter Peninsula (this study) in relation to those of the same species in other breeding locations in the Southern Ocean (Goutte et al., 2014; Mills et al., 2022; W.F. Mills, unpublished data). Sample sizes are indicated in parentheses above each column. All birds were sampled during incubation besides the brown skuas at Kerguelen and south polar skuas at Adélie Land which also included non-breeders and those sampled during brood guard. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

that in the blood samples. The measured value of the CRM was 0.30 ± 0.01 μg g^{-1} dw (n = 15) and therefore the recovery was 102.2 ± 0.9 %. Blanks were analysed at the beginning of each sample run. The AMA has a detection limit of 0.1 ng and THg concentrations are presented in μg g^{-1} dw.

2.3. *Stable isotope analysis*

Blood δ^{13}C and δ^{15}N values were determined for the same lyophilised blood samples as above, and have half-lives of 15.7 and 14.4 days in great skua blood, respectively (Bearhop et al., 2002). Hence, there is reasonable overlap with the half-life of Hg in the blood. Red blood cells do not typically require lipid extraction given their low lipid content, which is verified here by their low atomic C:N ratios (all <4.0) (Cherel et al., 2005). Subsamples of ~0.2 mg of blood were encapsulated in 6 × 4 mm tin capsules with a microbalance (Sartorius Cubis™). Stable isotope measurements were undertaken at the University of Reading's Chemical Analysis Facility (https://research.reading.ac.uk/chemical-analysis-facility) using a continuous flow-isotope ratio mass spectrometer coupled to a ThermoFisher™ DeltaV Advantage fitted with an Isolink CNSOH Temperature Conversion Elemental Analyzer (TC/EA) and smart function. Results are expressed as conventional δ values in per mil (‰) relative to the international standards Vienna PeeDee Belemnite (VPDB) and atmospheric N_2 (AIR) for carbon and nitrogen, respectively. Data were drift and stretch corrected using in-house (MethR [δ^{13}C = −27.5 ‰; δ^{15}N = −4.1 ‰], Reading Porcine Gelatin [δ^{13}C = −21.5 ‰; δ^{15}N = +5.0 ‰] and Reading Fish Skin [δ^{13}C = −15.6 ‰; δ^{15}N = +14.0 ‰]) and international standards (USGS61 [δ^{13}C = −35.05 ‰; δ^{15}N = −2.87 ‰], USGS62 [δ^{13}C = −14.79 ‰; δ^{15}N = +20.17 ‰] and USGS63 [δ^{13}C = −1.17 ‰; δ^{15}N = +37.83 ‰]). Each sample was analysed in triplicate and average values were used. Analytical errors were <0.20 ‰ for δ^{13}C and δ^{15}N based on repeated measurements of international and in-house standards.

To aid interpretation of the δ^{13}C and δ^{15}N values outlined above, stable isotope values of prey that are potentially available to both skua species during their pre-laying and incubation periods at King George Island were collated from the literature (Cipro et al., 2017; Polito et al., 2016; Graña Grilli et al., 2023; Quillfeldt et al., 2023). All prey were sampled from King George Island and surrounding waters, and included Adélie penguin *Pygoscelis adeliae* and gentoo penguin *P. papua* eggs (Cipro et al., 2017; Graña Grilli et al., 2023), Antarctic lanternfish *Electrona antarctica* (Polito et al., 2016), Antarctic krill *Euphausia superba* (Cipro et al., 2017; Graña Grilli et al., 2023), and Wilson's storm petrel *Oceanites oceanicus* and black-bellied storm petrel *Fregetta tropica* (Quillfeldt et al., 2023).

2.4. *Data analysis*

Data were analysed using R version 4.3.0 (R Core Team, 2023). THg concentrations were assessed for normality and homogeneity of variances (Shapiro-Wilk and Levene's tests, respectively), and were then log transformed. Linear mixed-effects models (LMMs) were used to investigate the biological and ecological drivers of variation in THg concentrations. Predictor variables in the LMMs were species, sex, breeding season, $\delta^{13}C$ values and $\delta^{15}N$ values. Two-way interactions between the species term and stable isotope values were also included. Nest identity was included as a random effect in all LMMs in order to account for non-independence between members of the same pair. Variance inflation factors (calculated using the car package in R) indicated no multicollinearity issues (all <3) (Fox and Weisberg, 2019). All possible combinations of fixed effects were computed and candidate models were ranked according to the Akaike Information Criterion, with a correction for small sample size (AICc), using the dredge function in the MuMIn package in R (Bartoń, 2020). The model(s) with lowest AICc value was considered to have received the most support and those within 2 AICc units (i.e., $\Delta AICc \leq 2.0$) of the best supported model were considered to be equally competitive (Burnham and Anderson, 2002). Model averaging was undertaken on this subset using the model.avg function in the MuMIn package (Burnham and Anderson, 2002). The direction of parameter estimates, standard errors (SEs) and 95 % confidence intervals (CIs) from model-averaged coefficients are reported. Fixed effects were considered statistically significant if 95 % CIs did not contain zero (Zuur et al., 2009). LMMs were fitted with the lme4 package and data were visualised with the ggplot2 package in R (Bates et al., 2015; Wickham, 2016).

2.4.1. *Comparisons with avian toxicity benchmarks*

To asssess potential Hg-associated health risks, blood THg concentrations of brown skuas and south polar skuas were compared to published avian Hg toxicity benchmarks (Ackerman et al., 2016). THg concentrations determined here were first converted to whole blood wet weight (ww) equivalents following established methods (Ackerman et al., 2020; Petalas et al., 2025), and assuming a 65 % moisture content (Carravieri et al., 2022). The percentage of individuals belonging to the following toxicity categories were calculated: (i) no risk (<0.2 μg g^{-1} ww); (ii) low risk (0.2–1.0 μg g^{-1} ww); (iii) moderate risk (1.0–3.0 μg g^{-1} ww); (iv) high risk (3.0–4.0 μg g^{-1} ww); and (v) severe risk (>4.0 μg g^{-1} ww) (Ackerman et al., 2016).

3. Results

3.1. *Drivers of Hg contamination*

Blood THg concentrations were determined for 44 brown skuas and 50 south polar skuas, with a minimum value of 0.36 μg g^{-1} dw (a male brown skua sampled in 2023) and maximum value of 17.45 μg g^{-1} dw (a female south polar skua sampled in 2024) (Table 1). Mean (±SD) THg concentrations of brown skuas (1.67 ± 1.25 μg g^{-1} dw) and south polar skuas (3.85 ± 2.99 μg g^{-1} dw) at King George Island are shown in relation to other breeding locations in Fig. 1. The highest-ranked LMM explained a large amount of variation in THg concentrations (conditional $R^2 = 0.62$), with the majority explained by fixed effects alone (marginal $R^2 = 0.48$). According to the highest-ranked models (Table 2), south polar skuas (estimate ± se, 0.37 ± 0.05 [95 % CIs, 0.26, 0.49]) had significantly higher blood THg concentrations than brown skuas (Fig. 1; Table 1). Males exhibited significantly higher concentrations (0.11 ± 0.04 [0.03, 0.20]) than females in both species (Fig. 1; Table 1). There was a significant positive relationship between THg concentrations and $\delta^{15}N$ values (0.12 ± 0.03 [0.07, 0.17]) (Fig. 2). Although breeding season (two-level factor) was included in the highest-ranked model (Table 2), the 95 % CIs overlapped with zero (−0.23, 0.02), and so there was no clear statistical effect. Neither $\delta^{13}C$ values nor interaction terms were included in the highest-ranked models.

Table 1
Mean (±SD) total mercury (THg) concentrations (μg g^{-1} dw) and stable isotope values of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) in red blood cells of breeding adult brown skuas *Stercorarius antarcticus lonnbergi* and south polar skuas *S. maccormicki* from the Potter Peninsula, King George Island (Isla 25 de Mayo), South Shetland Islands, Antarctica.

Species	Season	Sex	n	THg (μg g^{-1} dw)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Brown skua	**2022/23**	**Both**	**30**	**1.82 ± 1.44**	**−23.5 ± 1.3**	**10.9 ± 0.9**
Brown skua	2022/23	Female	17	1.61 ± 1.29	−23.5 ± 1.3	10.8 ± 1.0
Brown skua	2022/23	Male	13	2.10 ± 1.62	−23.6 ± 1.2	11.0 ± 0.9
Brown skua	**2023/24**	**Both**	**14**	**1.34 ± 0.64**	**−24.1 ± 0.5**	**11.0 ± 0.5**
Brown skua	2023/24	Female	8	1.30 ± 0.56	−24.1 ± 0.5	11.0 ± 0.5
Brown skua	2023/24	Male	6	1.40 ± 0.78	−24.2 ± 0.4	11.1 ± 0.5
South polar skua	**2022/23**	**Both**	**22**	**3.64 ± 2.05**	**−24.6 ± 0.5**	**10.7 ± 0.4**
South polar skua	2022/23	Female	12	2.67 ± 1.58	−24.4 ± 0.5	10.6 ± 0.4
South polar skua	2022/23	Male	10	4.81 ± 2.00	−24.8 ± 0.3	10.9 ± 0.3
South polar skua	**2023/24**	**Both**	**28**	**4.02 ± 3.59**	**−24.4 ± 0.7**	**11.1 ± 0.3**
South polar skua	2023/24	Female	14	4.13 ± 4.87	−24.2 ± 0.8	11.1 ± 0.3
South polar skua	2023/24	Male	14	3.91 ± 1.74	−24.7 ± 0.4	11.2 ± 0.3

Table 2
Model selection for variables explaining variation in log transformed total mercury (THg) concentrations (μg g^{-1} dw) in red blood cells of breeding adult brown skuas *Stercorarius antarcticus lonnbergi* and south polar skuas *S. maccormicki* from the Potter Peninsula, King George Island (Isla 25 de Mayo), South Shetland Islands, Antarctica. Models are ranked according to the Akaike Information Criterion with a correction for small sample size (AICc). The top five models are shown (according to differences in AICc from the top model, ΔAICc) and models with ΔAICc <2 were considered to be equally competitive and are shown in bold. All are linear mixed effects models with nest ID included as a random effect.

Model specification	df	logLik	AICc	ΔAICc	Weight
Species + Sex + $\delta^{15}N$ + Year	**7**	**3.91**	**7.5**	**0.00**	**0.39**
Species + Sex + $\delta^{15}N$	**6**	**2.57**	**7.8**	**0.33**	**0.33**
Species + Sex + $\delta^{15}N$ + Year + Species: $\delta^{15}N$	8	3.91	9.9	2.39	0.12
Species + Sex + $\delta^{15}N$ + Species: $\delta^{15}N$	7	2.69	9.9	2.44	0.11
Species + $\delta^{15}N$ + Year	6	0.70	11.6	4.08	0.05

3.2. *Avian toxicity benchmarks*

Comparisons with avian Hg toxicity benchmarks indicated that most brown skuas were either at no risk (46 %) or low risk (52 %) of toxicological effects, and far fewer individuals were at moderate risk (2 %). The majority of south polar skuas were classified as having a low (76 %) or moderate risk (16 %) of toxicological effects, with a minority of individuals at no risk (8 %). No birds were at high or severe risk.

4. Discussion

Hg contamination is an important threat to marine top predators in

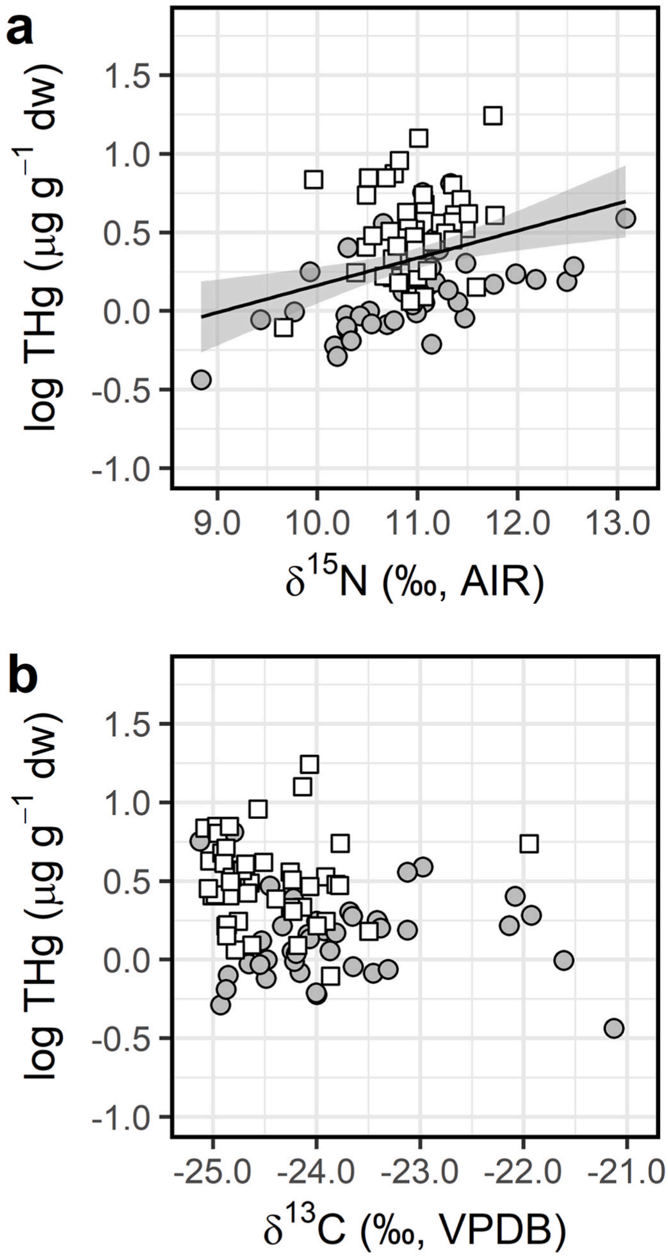

Fig. 2. Relationships between log transformed total mercury (THg) concentrations ($\mu g\ g^{-1}$ dw) and stable isotope values (‰) of **(a)** nitrogen ($\delta^{15}N$) and **(b)** carbon ($\delta^{13}C$) in red blood cells of breeding adult brown skuas *Stercorarius antarcticus lonnbergi* (circles) and south polar skuas *S. maccormicki* (squares) from the Potter Peninsula, King George Island/Isla 25 de Mayo, South Shetland Islands, Antarctica.

Antarctica (Bestley et al., 2020; Cusset et al., 2023; Gimeno et al., 2024), and seabirds that predate or scavenge other high trophic level organisms can accumulate high amounts of Hg (Chételat et al., 2020; Mills et al., 2022, 2024a,b, 2025). This study: (i) determined current Hg contamination levels of skuas at King George Island; (ii) compared Hg contamination with other breeding locations; (iii) investigated the factors driving variation in Hg concentrations; and (iv) examined the potential for toxicological effects. Due to the half-life of Hg in the blood and the timing of sampling, THg concentrations in this study primarily reflect contamination during the pre-laying and incubation periods, and potentially late migration, albeit to a lesser extent (Bearhop et al., 2000; Albert et al., 2019).

4.1. *Geographic differences in Hg contamination*

Blood THg concentrations of brown skuas at King George Island (this study) were significantly higher than the same species at Hope Bay (0.95 ± 0.45 $\mu g\ g^{-1}$ dw), but lower than those at the South Orkney Islands (3.42 ± 2.29 $\mu g\ g^{-1}$ dw) and South Georgia (4.47 ± 1.10 $\mu g\ g^{-1}$ dw) (Wilcoxon tests, all $p < 0.01$) (Mills et al., 2022) (Fig. 1). Additionally, south polar skuas at King George Island (this study) had significantly higher THg concentrations (Wilcoxon test, $p < 0.01$) than the same species at Hope Bay (1.41 ± 1.01 $\mu g\ g^{-1}$ dw) (W.F. Mills, unpublished data). Moreover, THg concentrations of brown skuas in this study were lower than at the Kerguelen Islands (8.22 ± 1.98 $\mu g\ g^{-1}$ dw) and THg concentrations of south polar skuas were higher than at Adélie Land (2.15 ± 1.48 $\mu g\ g^{-1}$ dw) (Goutte et al., 2014), though no raw data were available from those sites (Fig. 1). These geographic differences mirror the latitudinal trend in Hg contamination of seabirds that is regularly found in the Southern Hemisphere. Broadly, Hg contamination levels increase from birds feeding in Antarctic waters towards those exploiting subantarctic and subtropical waters (Carravieri et al., 2016, 2017; Renedo et al., 2020; Mills et al., 2022). One explanation for this pattern is greater efficiency of Hg methylation and increased vertical advection from the mesopelagic zone (i.e., ~200–1000 m below the surface) towards the surface in subtropical compared to subantarctic and Antarctic ecosystems (Renedo et al., 2020). Additionally, food chains in Antarctica may be shorter than in lower latitude ecosystems, and the associated differences in biomagnification could contribute to these spatial trends (Forero et al., 2005). Hg bioavailability may also vary among ocean basins; for instance, a meta-analysis of Hg contamination of penguins identified Hg hotspots and coldspots in the Indian and south Atlantic Oceans, respectively (Gimeno et al., 2024). Lastly, geographic differences in diet may also contribute to inter-site differences. For example, within the southwest Atlantic Ocean, the reliance of brown skuas on penguins as prey declines towards lower latitudes (Reinhardt et al., 2000), and during incubation, carrion and placentae of Antarctic fur seal *Arctocephalus gazella* are the most important food items at South Georgia (Phillips et al., 2004), whereas burrowing petrels are the most important prey to breeding brown skuas at Kerguelen Islands (Mougeot et al., 1998).

4.2. *Drivers of Hg contamination at King George Island*

4.2.1. *Interspecific differences*

South polar skuas exhibited higher THg concentrations than brown skuas in this study. Seabirds are mainly exposed to Hg via their food (Chételat et al., 2020), hence interspecific variation in diet is expected to contribute to differences in contamination. Skuas at the Potter Peninsula breed very close to breeding colonies of Adélie penguins (~1700 breeding pairs) and gentoo penguins (~6700 breeding pairs) (Albarrán et al., 2024). At King George Island, analyses of regurgitated pellets indicate that penguins are the most important prey for both species and that although incubating brown skuas consume more penguin eggs, south polar skuas consume a greater proportion of mesopelagic fish and select larger individual fish (de Almeida Reis et al., 2021; Morales et al., in review). The stable isotope data presented here are consistent with the consumption of penguin eggs and mesopelagic fish by skuas (alongside lower trophic level marine resources, e.g., Antarctic krill), and the more negative $\delta^{13}C$ values of south polar skuas likely reflects the greater proportion of mesopelagic fish in their diets (Fig. 2; Fig. 3). A minority of birds (mostly brown skuas) had low $\delta^{15}N$ and less negative $\delta^{13}C$ values, suggesting the use of alternative trophic pathways (e.g., inshore/coastal resources) (dashed rectangle; Fig. 3). Future stable isotope analyses of sulfur ($\delta^{34}S$) may help to better distinguish the different food sources of skuas.

Seabirds that consume mesopelagic prey have higher Hg burdens than those feeding in the epipelagic zone (0–200 m) due to enhanced Hg methylation rates in the low oxygen waters of the mesopelagic zone

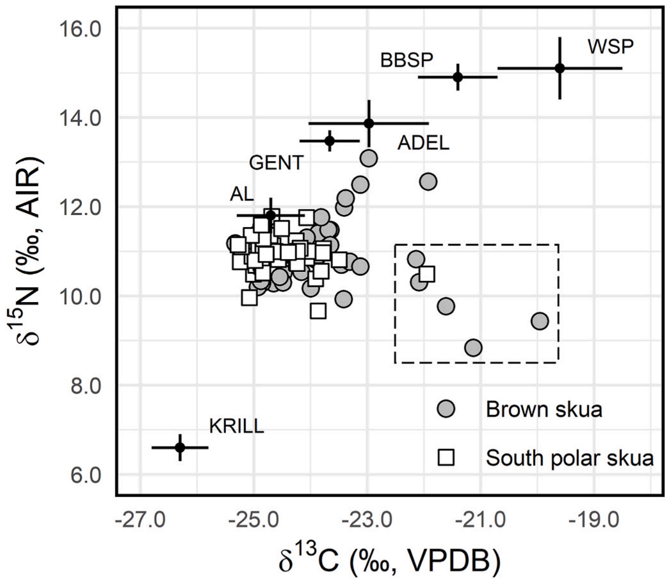

Fig. 3. Individual stable isotope values (‰) of carbon (δ^{13}C) and nitrogen (δ^{15}N) in red blood cells of breeding brown skuas *Stercorarius antarcticus lonnbergi* (circles) and south polar skuas *S. maccormicki* (squares) from the Potter Peninsula, King George Island (Isla 25 de Mayo), South Shetland Islands, Antarctica. Mean (±SD) δ^{13}C and δ^{15}N values of potential prey (lipid extracted) are also shown, including Antarctic krill *Euphausia superba* (KRILL), Antarctic lanternfish *Electrona antarctica* (AL), eggs of Adélie penguins *Pygoscelis adeliae* (ADEL) and gentoo penguins *P. papua* (GENT) and Wilson's storm petrel *Oceanites oceanicus* (WISP) and black-bellied storm petrels *Fregetta tropica* (BBSP) (Cipro et al., 2017; Polito et al., 2016; Graña Grilli et al., 2023; Quillfeldt et al., 2023). Trophic enrichment factors are applied to prey values following Graña Grilli et al. (2023). Dashed rectangle indicates individuals using an alternative trophic pathway (see text).

(Ochoa-Acuña et al., 2002; Choy et al., 2009). The Antarctic lanternfish is an abundant mesopelagic fish (that performs diel vertical migrations towards the surface at night) and is the most important fish prey to both skuas during the breeding period (Hahn et al., 2008; Morales et al., in review). THg concentrations in the muscle tissue of Antarctic lanternfish in the southwest Atlantic Ocean (0.22 ± 0.08 μg g^{-1} dw; Seco et al., 2021b) can be higher than in eggs of Adélie or gentoo penguins (0.08 ± 0.05 μg g^{-1} dw and 0.13 ± 0.04 μg g^{-1} dw, respectively) at the South Shetland Islands (Polito et al., 2016; Cipro et al., 2017), and blood THg concentrations of chicks of these penguin species (0.06 ± 0.03 μg g^{-1} dw and 0.08 ± 0.05 μg g^{-1} dw, respectively) (Souza et al., 2020), the latter being less available to south polar skuas due to breeding allochrony. However, a different study at King George Island found higher concentrations in Adélie (0.24 ± 0.16 μg g^{-1} dw) and gentoo penguin eggs (0.22 ± 0.32 μg g^{-1} dw) (Padilha et al., 2023). Antarctic lanternfish also show much higher Hg concentrations than epipelagic fish or Antarctic krill (Polito et al., 2016). Hence, it may be that while both species consume penguin eggs, the greater proportion of Antarctic lanternfish in south polar skua diets contributes to their higher contaminant levels. Brown skuas consume a wider range of resources (as evidenced by their wider isotopic niches; Fig. 3), and so may supplement the consumption of penguin eggs with prey that are less contaminated than mesopelagic fish. It is noteworthy, however, that black-bellied storm petrels *Fregetta tropica* at King George Island, which also feed on Antarctic lanternfish, also show high levels of Hg in their blood while incubating (2.46 ± 0.42 μg g^{-1} dw) (Hahn, 1998; Quillfeldt et al., 2023). South polar skuas, but not brown skuas, have also been recorded as feeding on other skuas at the Potter Peninsula, which could lead to higher THg concentrations (de Almeida Reis et al., 2021), though this is not necessarily supported by the stable isotope data in this study.

Another potential factor contributing to interspecific differences in contamination is carry-over effects of different distributions during late migration, given the timing of sampling and the half-life of Hg in skua blood (Bearhop et al., 2000). Brown skuas from King George Island spend the non-breeding period feeding on the Patagonian Shelf, Argentine Basin and to some degree on the southern Brazil Shelf (Krietsch et al., 2017); whereas most south polar skuas from King George Island undertake transequatorial migrations to the Northern Hemisphere (Kopp et al., 2011), where Hg exposure is higher. This may contribute to the higher THg concentrations of south polar skuas, including the high maximum value (17.45 μg g^{-1} dw) recorded here.

4.2.2. *Differences between sexes*

There was a significant effect of sex on blood THg concentrations, with male skuas exhibiting higher Hg concentrations than females at King George Island. Depuration of Hg into eggs offers a mechanism by which breeding females (and not males) are able to eliminate Hg and reduce their body burden (Robinson et al., 2012). It is probable that this accounts at least in part for the sex differences observed here. Additionally, trophic differences between males and females, and hence dietary exposure to Hg, may also contribute to this variation (Mills et al., 2022; Ibañez et al., 2022b). Both the study species show female-biased SSD (i.e., females are larger and heavier than males) (Phillips et al., 2002), which could conceivably influence their diet. However, mean δ^{13}C and δ^{15}N values are generally similar between sexes (Table 1), suggesting that diet composition is also similar. Indeed, at South Georgia, males and females are comparable during late incubation and early chick-rearing in their territorial attendance, foraging times and habitats (Carneiro et al., 2014). Also, a stable isotope study found no evidence for sex differences in foraging ecology of brown skuas during the breeding period at South Georgia (Anderson et al., 2009). There was also no evidence of sex differences in non-breeding distributions of brown skuas or south polar skuas (Kopp et al., 2011; Krietsch et al., 2017).

4.2.3. *Relationship with δ^{15}N values*

Blood THg concentrations of skuas were positively related to δ^{15}N values. The interaction between the species term and δ^{15}N values was not included in the highest ranked models, hence the slope of the relationship did not differ between species (Fig. 2). This relationship reflects Hg biomagnification through the food web at King George Island, such that birds consuming a greater proportion of high trophic level prey (with elevated δ^{15}N values) generally had higher THg concentrations. Broadly, δ^{15}N values are effective tracers of trophic level (Inger and Bearhop, 2008), and the stable isotope data suggest that higher δ^{15}N values are associated with the consumption of high trophic level resources that the skuas obtain on land (e.g., penguin eggs, storm petrels) compared to low trophic level prey obtained at sea (e.g., Antarctic krill) (Fig. 3). Hg bioaccumulation in these prey and biomagnification process in Southern Ocean food webs is well documented (Seco et al., 2021a; Ibañez et al., 2022a; Matias et al., 2022; Mills et al., 2022). Indeed, as stated above, penguins eggs and storm petrels can show high Hg concentrations at King George Island (Padilha et al., 2023; Quillfeldt et al., 2023), especially compared to epipelagic prey (Polito et al., 2016; Cipro et al., 2017). Mesopelagic fish show similar δ^{15}N values to epipelagic fish in the waters around King George Island (Polito et al., 2016), which likely contributes to the high variation in the relationship between THg and δ^{15}N values (given their relatively high THg concentrations), in addition to the slight mismatch in integration periods (Bearhop et al., 2000, 2002). Given their half-lives in skua blood, diets and feeding areas during the late migration period may have little influence on the isotope values here (Bearhop et al., 2002). There were no clear relationships with δ^{13}C values across the dataset (Fig. 2).

4.3. *Health implications of Hg contamination*

Comparisons with avian toxicity benchmarks indicate that at King George Island, most skuas are at low risk of Hg-associated health impacts. However, a substantial minority of brown skuas and south polar skuas were at no risk and moderate risk, respectively. These results indicate that Hg does not currently pose a significant threat to brown skuas, but may pose some threat to south polar skuas. However, Ibañez et al. (2024) found that immune markers (hematocrit, Immunoglobulin Y and albumin) and egg volumes were negatively associated with Hg contamination of brown skuas at Hope Bay, and alanine aminotransferase (an indicator of liver dysfunction) in that study was positively correlated with Hg contamination (Ibañez et al., 2024). This is despite the relatively low levels of contamination at that site, with the highest blood THg concentration being 2.33 μg g^{-1} dw (Ibañez et al., 2024). Additionally, the toxicity benchmarks do not account for selenium (Se) concentrations, which plays a protective role against Hg toxicity (Cuvin-Aralar and Furness, 1991; Eagles-Smith et al., 2018). Indeed, considering the Hg:Se molar ratio is important to fully understand the potential risks of Hg contamination to Antarctic seabirds (Cruz-Flores et al., 2024). Future studies focusing on Se concentrations and their influence on the toxic effects of Hg on skuas are required.

CRediT authorship contribution statement

William F. Mills: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Andrés E. Ibañez:** Writing – review & editing, Resources, Project administration, Methodology, Conceptualization. **Paco Bustamante:** Writing – review & editing, Investigation. **Juliette Waterman:** Writing – review & editing, Investigation. **Lara M. Morales:** Writing – review & editing, Resources. **Rocío Mariano-Jelicich:** Writing – review & editing, Resources. **Diego Montalti:** Writing – review & editing, Supervision. **Stuart Black:** Writing – review & editing, Supervision, Funding acquisition.

Ethics statement

All the relevant international, national and institutional guidelines related to the sampling, care and experimental use of animals in this study were followed, as established by Article III, Annex II of the Madrid Protocol, Law 24.216 (Taking, Harmful Intrusion and Introduction of Species), within the framework of the projects evaluated and approved by the Environment Office of the Instituto Antártico Argentino and the Dirección Nacional del Antártico (permit numbers: 2022-FEAMB-CT-GA-22 and 2023-FEAMB-CT-GA-26). The protocols for this study were evaluated and approved by the Institutional Committee for the Care and Use of Study Animals (CICUAE) of Natural Science and Museum Faculty (FCNyM-UNLP).

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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