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Influence of migration range and foraging ecology on mercury accumulation in Southern Ocean penguins

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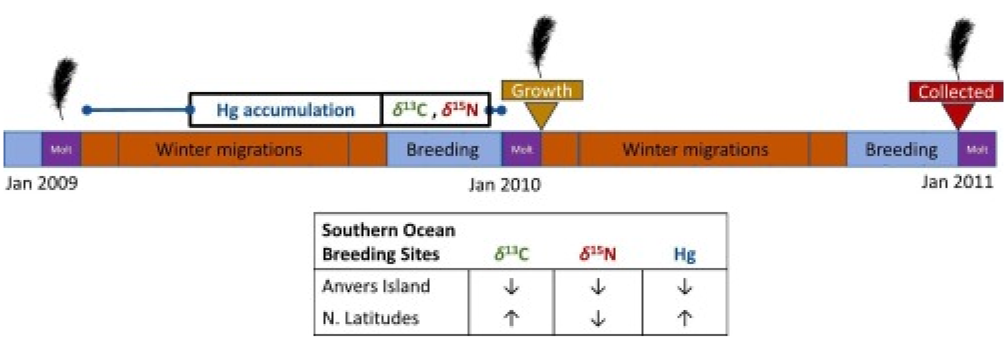
Highlights

- Anvers Island *Pygoscelis* penguin feather Hg, $\delta^{13}C$, and $\delta^{15}N$ were measured.
- Winter foraging likely contributes to relatively higher Hg in chinstrap penguins.
- Foraging ecology ($\delta^{13}C$) and diet ($\delta^{15}N$) were used to evaluate mercury accumulation.
- $\delta^{13}C$ was found to best explain feather Hg concentrations across the Southern Ocean.

Abstract

In order to evaluate mercury (Hg) accumulation patterns in Southern Ocean penguins, we measured Hg concentrations and carbon (δ^{13}C) and nitrogen (δ^{15}N) stable isotope ratios in body feathers of adult Adélie (*Pygoscelis adeliae*), gentoo (*Pygoscelis papua*), and chinstrap (*Pygoscelis antarctica*) penguins living near Anvers Island, West Antarctic Peninsula (WAP) collected in the 2010/2011 austral summer. With these and data from *Pygoscelis* and other penguin genera (*Eudyptes* and *Aptenodytes*) throughout the Southern Ocean, we modelled Hg variation using δ^{13}C and δ^{15}N values. Mean concentrations of Hg in feathers of Adélie ($0.09\pm0.05\,\mu g\,g^{-1}$) and gentoo ($0.16\pm0.08\,\mu g\,g^{-1}$) penguins from Anvers Island were among the lowest ever reported for the Southern Ocean. However, Hg concentrations in chinstrap penguins ($0.80\pm0.20\,\mu g\,g^{-1}$), which undertake relatively broad longitudinal winter migrations north of expanding sea ice, were significantly higher ($P<0.001$) than those in gentoo or Adélie penguins. δ^{13}C and δ^{15}N values for feathers from all three Anvers Island populations were also the lowest among those previously reported for Southern Ocean penguins foraging within Antarctic and subantarctic waters. These observations, along with size distributions of WAP krill, suggest foraging during non-breeding seasons as a primary contributor to higher Hg accumulation in chinstraps relative to other sympatric *Pygoscelis* along the WAP. δ^{13}C values for all Southern Ocean penguin populations, alone best explained feather Hg concentrations among possible generalized linear models (GLMs) for populations grouped by either breeding site ($AICc=36.9$, $w_i=0.0590$) or Antarctic Frontal Zone ($AICc=36.9$, $w_i=0.0537$). Although Hg feather concentrations can vary locally by species, there was an insignificant species-level effect ($w_i<0.001$) across the full latitudinal range examined. Therefore, feeding ecology at breeding locations, as tracked by δ^{13}C, control Hg accumulation in penguin populations across the Southern Ocean.

Graphical abstract



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Introduction

Mercury (Hg) is a global contaminant that is toxic to humans and wildlife (Tan et al., 2009). In the Southern Ocean, maximum concentrations of Hg typically occur at mesopelagic depths (Cossa et al., 2011; Mastromonaco et al., 2017) where Hg becomes associated with particulate organic matter (Sontag, 2018) and accumulates in krill (Séco et al., 2019; Sontag et al., 2019) and fish (Polito et al., 2016) prior to its accumulation by Southern Ocean predators, including seabirds (Polito et al., 2016; Renedo et al., 2018a; Chiang et al., 2021; Matias et al., 2022). While latitudinal variation of mercury accumulation in penguins (Brasso et al., 2015; Carravieri et al., 2016; Gimeno et al., 2024) and Southern Ocean flying birds has been well documented (Carravieri et al., 2014c; Thébault et al., 2021; Quillfeldt et al., 2023), few studies exist in which Hg concentrations in penguins were coupled with other biogeographical proxies (Renedo et al., 2018a) making it difficult to assess how geographical and ecological factors affect Hg accumulation across the wider Southern Ocean.

Penguins are a unique living record of the spatial trends of environmental contaminants including Hg (Ancora et al., 2002; Alvarez-Varas et al., 2018) because of their position in Southern Ocean food webs (Kokubun et al., 2015a; Carpenter-Kling et al., 2019) and wide geographic distribution (Biuw et al., 2010; Clucas et al., 2016). Variation of Hg accumulation in penguins with latitude (Carravieri et al., 2016) and within and among species across Antarctic, subantarctic, and subtropical populations (Brasso et al., 2015; Becker et al., 2016; Renedo et al., 2018b) may reflect distinct migratory patterns (Ballard et al., 2010, Hinke et al., 2019, Korczak-Abshire et al., 2021). Variation in penguin Hg accumulation also has been attributed to differences in local diet and foraging (Polito et al., 2011b; Polito et al., 2016), but the relative importance of local exposures vs. those that occur far from seasonal breeding habitats has not been assessed.

Much of the variation in Hg accumulation among penguin species and populations has been documented using penguin feathers (Brasso and Polito, 2013; Polito et al., 2016; Renedo et al., 2018b). During their annual molt, Hg accumulated in penguin body tissues throughout the previous year is excreted into the new set of feathers, as in other seabirds (Honda et al., 1986; Braune and Gaskin, 1987; Agusa et al., 2005; Renedo et al., 2021). However, a majority of penguin species are unique among birds in that they undergo a catastrophic annual molt at the end of their breeding season (Stonehouse, 1967) during which they fast while all feathers are replaced. Mercury in new penguin feathers therefore results from the deposition of Hg accumulated in body tissues since last molt, including the breeding and non-breeding seasons of the previous year (Renedo et al., 2021).

The annual-scale signal of dietary Hg recorded in feathers can be used in coordination with shorter-timescale accumulation of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotope values. $\delta^{13}C$ and $\delta^{15}N$ values provide a biogeochemical tracer in penguin feathers with weekly to monthly resolution of penguin foraging ecology (Ramos and Gonzalez-Solis, 2012; Renedo et al., 2018b). Using Hg, which represents accumulation on annual time scales, together with weekly-monthly resolution of $\delta^{13}C$ and $\delta^{15}N$ during the breeding season can provide a more detailed picture of penguin foraging throughout the year. Penguin foraging ecology has been examined using $\delta^{13}C$ and $\delta^{15}N$ values in penguin tissues, including penguin feathers (Cherel and Hobson, 2007; Lorrain et al., 2009; Hinke et al., 2015; Rosciano et al., 2016; Connan et al., 2019). $\delta^{15}N$ has been widely used to estimate penguin trophic position (Brasso et al., 2015), while $\delta^{13}C$ values reflect food sources and feeding locations (Stowasser et al., 2012; Carravieri et al., 2016). Little intra-individual variability in penguin feather $\delta^{13}C$ and $\delta^{15}N$ values occurs during feather formation (Polito et al., 2011a; Carravieri et al., 2014a). However, since $\delta^{13}C$ has lower discrimination factors relative to $\delta^{15}N$ in penguin tissues (Polito et al., 2011a), $\delta^{13}C$ is expected to be a better tracer of penguin foraging location.

$\delta^{13}C$ and $\delta^{15}N$ values in bird feathers are determined by the diet during the weeks to months prior to molt (Hobson and Clark, 1992; Cherel et al., 2005). While the somatic accumulation of Hg that is deposited in new feathers occurs over a longer period than that of C and N, much of the Hg in penguins may be accumulated during the period of hyperphagia (Renedo et al., 2018a) that occurs during the breeding season due to higher feeding rates prior to a 2–3 week fast during the molt in the austral autumn (Groscolas, 1978; Brown, 1986; Cherel et al., 1994). In gentoo and Adélie penguins, Hg isotope ratios in blood (short-term, current breeding season) and feather (long-term, previous breading season) tissues indicate that much of the Hg deposited in feathers from these species' that were collected prior to the molt of a breeding season (e.g. in Year 0), was accumulated during the previous austral summer immediately prior to that year's molt (e.g. in Year −1) at the time that the $\delta^{13}C$ and $\delta^{15}N$ values were also set (Renedo et al., 2018a). Thus, stable C and N isotope tracers may be used to identify sources of Hg in the penguin diet.

$\delta^{13}C$ and $\delta^{15}N$ values in feathers and blood suggest that chinstrap penguins occupy different trophic niches than gentoo penguins in the South Shetland Islands, north of the Antarctic Peninsula (Dimitrijevic et al., 2018). There, chinstrap penguins tend to consume slightly smaller krill that have higher concentrations of Hg relative to larger krill (Sontag et al., 2019). Other differences in population-level responses to environmental conditions among

Pygoscelis penguin species have been documented (Hinke et al., 2007), including longitudinal (east-west) winter migrations by chinstrap penguins north of expanding sea ice (Hinke et al., 2015). Greater extents of winter foraging by chinstrap relative to other *Pygoscelis* penguins can contribute to varying Hg accumulation among sympatric populations. Variations in penguin feather Hg concentrations have also been linked to population-level differences in trophic level (Brasso et al., 2015) and proximity to biological and physical Hg "hot spots" (Cusset et al., 2023). Differences in Hg accumulation in penguins from Antarctic, subantarctic, and subtropical populations have been linked to Southern Ocean water masses (Carravieri et al., 2016).

Our aim was to use $\delta^{13}C$ values to characterize the influence of latitude and Antarctic frontal zones to Hg accumulation in penguin populations across a wide geographic range of the Southern Ocean. The goals of this study were therefore to 1) examine how Hg concentrations in *Pygoscelis* penguins from the West Antarctic Peninsula (WAP) vary by species, breeding latitude and foraging strategies, and 2) examine broad geographical trends of Hg levels in Antarctic penguins across the Southern Ocean with respect to foraging location, diet, and polar frontal zones. To address these goals, we measured Hg concentrations and $\delta^{13}C$ and $\delta^{15}N$ values in adult feathers of Adélie, gentoo, and chinstrap penguins from populations that breed near Anvers Island at 65°S along the WAP in the austral summer (Fraser and Hofmann, 2003), and examined foraging strategies of sympatric *Pygoscelis* penguins from southern and northern (Hinke et al., 2015) colonies of the WAP region.

We then used our new results from Anvers Island penguin populations together with those from previously published reports for penguin populations from throughout the Southern Ocean in generalized linear models to assess the importance of penguin foraging location ($\delta^{13}C$) and diet ($\delta^{15}N$), the location of breeding sites with respect to latitude, and the positions of Antarctic frontal zones (Scheffer et al., 2012).

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Section snippets

Collection and mercury analysis of Pygoscelis penguin feathers

Pre-molt body feathers from three species of *Pygoscelis* penguins (*P. adeliae*, *P. papua*, and *P. antartica*) were collected during the 2010–2011 austral summer field season on three local islands (Humble (64°45′S, 64°05′W), Biscoe (64°48′S, 63°46′W), and Dream (64°43′S, 64°13′W)) near Anvers Island, WAP (Table 1). Feathers of Adélie penguins were collected from seasonal breeding populations living on Humble Island, while those of gentoo and chinstrap penguins were from Biscoe and Dream Islands,…

Mercury concentrations and summer diets of Pygoscelis penguins from Anvers Island and farther north along the West Antarctic Peninsula (WAP)

Concentrations of Hg in feathers of Adélie (0.09 $\mu g\,g^{-1}$) and gentoo (0.16 $\mu g\,g^{-1}$) penguins from Anvers Island were low and a factor of two to three lower than those of Adélie (0.32–0.35 $\mu g\,g^{-1}$) and gentoo (0.28–0.51 $\mu g\,g^{-1}$) penguins living near King George Island at the northern tip of the peninsula (Table 1). In contrast, Hg concentrations in feathers of chinstrap penguins from Anvers Island were 9 and 5 times higher ($P<0.001$) than those of neighboring populations of Adélie and gentoo…

Interspecies variations in mercury concentrations among penguins from the WAP

The concentrations of Hg in feathers of Anvers Island Adélie and gentoo penguins were some of the lowest for any species of penguin (0.09±0.05 and 0.16±0.08 $\mu g\,g^{-1}$, respectively) observed to date in the Southern Ocean (Gilmour et al., 2019). They are also much lower than Hg levels in feathers from Adélie adults in East Antarctica (0.7±0.20 $\mu g\,g^{-1}$), and gentoo penguins from the Crozet (46°S) and Kerguelen (49°S) archipelagos (5.90±1.91 and 5.85±0.85 respectively) (Carravieri et al.,…

Conclusions

Our analysis revealed a strong positive, nonlinear relationship between Hg concentrations in the feathers of seven species of Southern Ocean penguins and their $\delta^{13}C$ values (foraging habitat) while much weaker relationship was observed between Hg concentrations and $\delta^{15}N$ (diet) values. In addition, we found that the location of penguin breeding sites with respect to Antarctic Frontal Zones is an important geographical predictor of Hg concentrations in penguins throughout the Southern Ocean, as…

CRediT authorship contribution statement

Philip T. Sontag: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Linda V. Godfrey:** Writing – review & editing, Methodology. **William R. Fraser:** Writing – review & editing, Methodology, Investigation. **Jefferson T. Hinke:** Writing – review & editing, Resources, Data curation. **John R. Reinfelder:** Writing – review & editing, Supervision, Resources, Project administration.…

Declaration of competing interest

The authors declare no competing financial interests.…

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