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Penguins as bioindicators of mercury contamination in the Southern Ocean: Birds from the Kerguelen Islands as a case study

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HIGHLIGHTS

- Hg contamination was evaluated in 4 species of penguins at the Kerguelen Islands.
- Adults displayed significantly higher Hg levels than chicks in all species.
- Species and feeding habits (δ15N) were major determinants of Hg levels.
- Dietary specialisation was essential in explaining Hg levels in gentoo penguins.
- Penguins are reliable bioindicators of Hg contamination in the Southern Ocean.

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ABSTRACT

Seabirds have been used extensively as bioindicators of mercury (Hg) contamination in the marine environment, although information on flightless species like penguins remains limited. In order to assess the use of penguins as bioindicators of Hg contamination in subantarctic and Antarctic marine ecosystems, Hg concentrations were evaluated in the feathers of the four species that breed on the Kerguelen Islands in the southern Indian Ocean. Compared to other seabirds, adult Kerguelen penguins had low to moderate feather Hg concentrations, with an average ranging from 1.96 ± 0.41 μg g^{-1} dry weight in the southern rockhopper penguin to 5.85 ± 3.00 μg g^{-1} dry weight in the gentoo penguin. The species was a major determinant of Hg contamination, with feather Hg concentrations being lower in the oceanic species (king and crested penguins) than in the coastal one (gentoo penguin). In all species however, feather Hg concentrations were higher in adults than in chicks, reflecting the different periods of Hg bioaccumulation in the internal tissues of the two age classes. The relationship between adult penguin trophic ecology and Hg burdens was investigated using stable isotopes. Feeding habits (reflected by $\delta^{15}N$ values) had a greater effect on adult feather Hg concentrations when compared to foraging habitats (reflected by $\delta^{13}C$ values), indicating Hg biomagnification in Kerguelen neritic and oceanic waters. Dietary preferences were crucial in explaining individual feather Hg concentrations, as highlighted by intra-specific variation in Hg levels of gentoo penguins sampled at two different breeding sites of the archipelago. Penguins appear to reflect Hg bioavailability reliably in their foraging environment and could serve as efficient bioindicators of Hg contamination in the Southern Ocean on different spatial and temporal scales.

1. Introduction

While occurring naturally, mercury (Hg) is a pervasive environmental contaminant that negatively impacts humans and wildlife (Bond and Diamond, 2009; Scheuhammer et al., 2007). Over centuries a vast range of human activities have increased emissions to the atmosphere, modifying the cycling of Hg on the world scale (Fitzgerald et al., 2007; Selin, 2009). Aquatic environments, including marine ecosystems, are major repositories of natural and anthropogenic Hg. Hence, Hg is widely distributed in the World Ocean as a consequence of both long-range atmospheric transport and deposition (Ebinghaus et al., 2002; Fitzgerald et al., 1998). Despite being free of industrial sources of contamination and scarcely affected by local anthropogenic pollution, the Southern Ocean presents some unique features in the distribution of the different Hg species (Cossa et al., 2011), including elevated levels of contamination in some biota, especially top predators (Anderson et al., 2009; Bargagli et al., 1998; Muirhead and Furness, 1988). Indeed, Hg is known to bioaccumulate in the tissues of living organisms and to biomagnify within food webs, leaving top predators at risk of high contamination levels through food intake

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(Furness and Camphuysen, 1997; Morel et al., 1998). Top consumers include seabirds that have been identified as effective Hg sentinels in the marine environment (e.g., Burger and Gochfeld, 2004; Furness, 1993). In this context, seabird feathers have proved to be a valuable tissue, as they represent the main route of Hg excretion in birds (e.g., Braune and Gaskin, 1987; Monteiro and Furness, 1995) and can be easily collected during nesting from both chicks and breeding adults.

Previous investigations on Hg contamination of seabirds from the Southern Ocean essentially focused on flying species, mainly of the order Procellariiformes (Anderson et al., 2009; Becker et al., 2002; Bocher et al., 2003). By contrast, very little is known about the Hg exposure of diving seabirds like penguins (Bargagli et al., 1998; Becker et al., 2002; Scheifler et al., 2005). Penguins are less Hg contaminated than some other seabirds, but they present interesting ecological and practical advantages over flying species to investigate Hg contamination within Antarctic and subantarctic food webs. Firstly, unlike most albatrosses and petrels that disperse in northern waters during the nonbreeding period (BirdLife International, 2004), Antarctic and subantarctic penguins are restricted to the Southern Ocean all year long (Ballard et al., 2010; Thiebot et al., 2011a, 2011b, 2012). Penguins are thus truly representative of the level of contamination of Antarctic and subantarctic ecosystems. Secondly, depending on species, penguins forage at different depths of the water column, namely the epi-, meso-pelagic and benthic zones that are known to present heterogeneous Hg concentrations and Hg species distributions (Cossa et al., 2011; Fitzgerald et al., 2007; Thompson et al., 1998). Thirdly, penguins renew their whole plumage annually over a 2–4 week period on land (Adams and Brown, 1990; Cherel et al., 1994), thus contrasting with most other birds that present a prolonged, sequential moult leading to higher Hg concentrations in the earlier than in the later growing feathers (Furness et al., 1986). Hence, penguins appear to be good models to evaluate Hg contamination in their foraging environment, but this has yet to be proved conclusively.

The main objective of the present study was to assess the use of penguins as bioindicators of Hg contamination in marine ecosystems of the Southern Ocean. The following predictions were tested on the penguin assemblage from the subantarctic Kerguelen Islands where four species live in sympatry.

1) As already depicted in other seabirds (Anderson et al., 2009; Becker et al., 2002; Blévin et al., 2013), the diet and foraging ecology of penguins should play an important role in explaining feather Hg levels, because ingestion of food is the main route of Hg exposure in birds. As Kerguelen penguin species display contrasted feeding ecology (Table 1), feather Hg concentrations should show important inter-specific differences. The respective effects of habitats and diets were tested by using the isotopic niche as a proxy of the trophic niche of the species, with the ratios of stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) reflecting their foraging habitats and trophic positions, respectively. The isotopic method was already validated in the area, with seabird $\delta^{13}C$ values indicating their latitudinal foraging grounds and depicting offshore versus inshore consumers and their $\delta^{15}N$ values increasing with trophic level (Cherel and Hobson, 2007; Cherel et al., 2007, 2010; Jaeger et al., 2010). Taking into account the penguins' foraging ecology (Table 1), we make the following predictions. Firstly, feeding habitat ($\delta^{13}C$) should shape seabird Hg contamination, because Hg is not homogeneously distributed in marine ecosystems (Cossa et al., 2011; Hammerschmidt and Bowman, 2012). For example, benthic foragers should have higher feather Hg concentrations than pelagic foragers in relation to the substantial production of Me–Hg in coastal marine sediments (Fitzgerald et al., 2007). Secondly, penguins with the highest trophic positions ($\delta^{15}N$) should show the highest feather Hg concentrations, because Hg biomagnifies within marine food webs (e.g., Selin, 2009).
2) Between-year variation of Hg levels is an issue rarely investigated in seabirds. Taking into account that (i) penguin feeding habits are comparable in the breeding and non-breeding seasons (Thiebot et al., 2011a, 2011b, 2012); (ii) penguin feather Hg temporal integration is constant (one year); and (iii) the Kerguelen Islands are remote from anthropogenic Hg sources; no variation in feather Hg levels should be detected on a short temporal scale (two following years).
3) As already found in birds (Burger, 1993), Hg concentrations in the feathers should be higher in adult penguins than in chicks at fledging, mainly because: (i) the time interval of Hg accumulation is longer in adults than in chicks (~12 months of inter-moult period for adults and the 3–9 months of rearing period in chicks, depending on species) and (ii) Hg can bioaccumulate in internal tissues of long-lived animals over their whole life span.

The present article is the first exploratory step of a wider investigation on penguins as bioindicators of Hg contamination in the Southern Ocean. In the second step, we will focus on penguins breeding at different locations in order to highlight potential geographic

Table 1
Foraging ecology of penguins during the breeding and non-breeding periods at the Kerguelen Islands.

Species	Foraging habitat		Chick diet	References
Colony location	Breeding season (horizontal; vertical)	Non-breeding season (horizontal; vertical)		
King penguin				
Ratmanoff	Polar Frontal Zone (oceanic; epi-mesopelagic)	Unknown (likely in cold oceanic waters; epi-mesopelagic)	Pelagic fish	Bost et al. (2002), Cherel et al. (2010)
Macaroni penguin				
Cap Cotter	Eastwards off Kerguelen in the Polar Frontal Zone (oceanic; epipelagic)	Polar Frontal Zone (oceanic)	Pelagic crustaceans and fish	Cherel et al. (2010), Thiebot et al. (2011a, 2011b)
Southern rockhopper penguin				
Mayes, Morbihan Bay	Morbihan Bay (neritic; pelagic and benthic)	Subantarctic and Polar Frontal Zones (oceanic; epipelagic)	Pelagic crustaceans and fish	Tremblay and Cherel (2000, 2003), Cherel et al. (2010), Thiebot et al. (2012)
Gentoo penguin				
Ratmanoff (open sea)[a]	Eastwards off Kerguelen (neritic; benthic and pelagic);	Resident all year long	Benthic fish and pelagic crustaceans	Lescroël et al. (2004), Lescroël and Bost (2005)
Penn Island, Morbihan Bay (closed sea)	Morbihan Bay (coastal; pelagic)	Resident all year long	Pelagic crustaceans	Lescroël et al. (2004), Lescroël and Bost (2005)

[a] Cape Ratmanoff is close to Cape Estacade and diet of gentoo penguins is similar in both sites.