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# Penguins as bioindicators of mercury contamination in the southern Indian Ocean: geographical and temporal trends☆

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ABSTRACT

Penguins have been recently identified as useful bioindicators of mercury (Hg) transfer to food webs in the Southern Ocean over different spatial and temporal scales. Here, feather Hg concentrations were measured in adults and chicks of all the seven penguin species breeding in the southern Indian Ocean, over a large latitudinal gradient spanning Antarctic, subantarctic and subtropical sites. Hg was also measured in feathers of museum specimens of penguins collected at the same sites in the 1950s and 1970s. Our aim was to evaluate geographical and historical variations in Hg transfer to penguins, while accounting for feeding habits by using the stable isotope technique ($\delta^{13}C$, habitat; $\delta^{15}N$, diet/trophic level). Adult feather Hg concentrations in contemporary individuals ranged from 0.7 ± 0.2 to 5.9 ± 1.9 μg $g^{-1}$ dw in Adélie and gentoo penguins, respectively. Inter-specific differences in Hg accumulation were strong among both adults and chicks, and mainly linked to feeding habits. Overall, penguin species that feed in Antarctic waters had lower feather Hg concentrations than those that feed in subantarctic and subtropical waters, irrespective of age class and dietary group, suggesting different Hg incorporation into food webs depending on the water mass. While accounting for feeding habits, we detected different temporal variations in feather Hg concentrations depending on species. Notably, the subantarctic gentoo and macaroni penguins had higher Hg burdens in the contemporary rather than in the historical sample, despite similar or lower trophic levels, respectively. Whereas increases in Hg deposition have been recently documented in the Southern Hemisphere, future monitoring is highly needed to confirm or not this temporal trend in penguins, especially in the context of actual changing Hg emission patterns and global warming.



## 1. Introduction

Mercury (Hg) is a highly-toxic nonessential metal of global concern. Under its inorganic form, Hg is highly volatile, and can be transported over inter-continental distances (UNEP, 2013). Atmospheric deposition is the main input of Hg to the open ocean (e.g., Mason et al., 2012; Driscoll et al., 2013). Hence, Hg is widely distributed in oceanic waters, with the concentrations of the different chemical species varying horizontally and vertically depending on a multitude of biotic and abiotic factors (Fitzgerald et al., 2007). Under the organic form (methyl-Hg, Me–Hg), Hg bioaccumulates in the tissues of marine organisms and biomagnifies up food webs (Fitzgerald et al., 2007; Driscoll et al., 2013), exerting deleterious effects such as endocrine disruption and neurodevelopmental impairment in apex predators (e.g., Wolfe et al., 1998; Dietz et al., 2013; Tartu et al., 2013). Anthropogenic perturbations to the global Hg cycle have tripled the total Hg content of surface oceanic waters compared to pre-anthropogenic conditions, and also significantly increased total Hg concentration in intermediate and deep waters (Driscoll et al., 2013; Lamborg et al., 2014). In the Northern Hemisphere, growing oceanic Hg concentrations have been associated to increasing Hg bioaccumulation in marine biota, such as marine mammals and

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seabirds (Monteiro and Furness, 1997, Braune et al., 2005; Bond et al., 2015). Comparatively less information is available on Hg concentrations and transfer to food webs in oceanic waters of the Southern Hemisphere (but see Thompson et al., 1993; Frias et al., 2012; Brasso et al., 2015). This is particularly true for the southern Indian Ocean, where studies on bioaccumulation in biota are increasing (e.g., Bocher et al., 2003; Carravieri et al., 2014a; Fontaine et al., 2015), while, surprisingly, there is still limited information on seawater Hg distribution and speciation (Cossa et al., 2011; Lamborg et al., 2014), and no data on temporal trends.

Seabirds have been used extensively as bioindicators of Hg contamination of their food webs (Furness and Camphuysen, 1997). Like other apex predators, seabirds are mainly exposed to Hg through food ingestion, and feeding ecology has been shown to be the main driver of between- and within-species variations of Hg concentration in their tissues (Becker et al., 2002; Bearhop et al., 2000; Carravieri et al., 2014a, b). After absorption by the gut, Hg contained in prey is highly assimilated in internal tissues, mainly the liver, kidney and muscle (Walker et al., 2012), and it is efficiently excreted through the moult over a regular basis (Furness et al., 1986; Monteiro and Furness, 2001). Feather Hg concentrations constitute thus a pertinent proxy of the Hg body burden (Thompson et al., 1998), and are commonly used for seabird Hg biomonitoring over the short- and long-term (Burger and Gochfeld, 2004). Recent studies of our group using seabirds suggest that Hg food web transfer to predators has a latitudinal trend in the southern Indian Ocean, increasing from Antarctic, through subantarctic, to subtropical waters (Blévin et al., 2013; Carravieri et al., 2014b; Goutte et al. 2014). This trend should however be confirmed by multi-sites and multi-species studies, and discussed in the light of the pioneer data on Me–Hg distribution in Southern Ocean waters (Cossa et al., 2011; Lamborg et al., 2014). Moreover, only one previous study has evaluated historical variations in Hg concentrations in a single seabird species in the southern Indian Ocean (Scheifler et al., 2005), and there is urgent need to investigate long-term temporal trends in this remote oceanic region.

Penguins represent the greatest seabird biomass in the Southern Ocean (Williams, 1995) and are particularly pertinent as bioindicator species of Hg food web contamination. Indeed, penguins are less dispersive than flying seabird species, and some populations from the southern Indian Ocean have almost constant trophic niches over the short- (breeding period) to long-term (wintering) (e.g., Thiébot et al., 2011a, b; 2012). Furthermore, penguins moult annually their entire plumage over a short-period, while fasting ashore (Williams, 1995; Cherel et al., 1994), reducing within-individual variations of Hg concentrations in their feathers (Brasso et al., 2013; Carravieri et al., 2014c). By using penguins as bioindicators, and as a companion investigation to Carravieri et al. (2013), the main aim of this study was to describe spatio-temporal variations in Hg transfer to these avian predators at different latitudes of the southern Indian Ocean. To this end, feather Hg has been measured in all penguin species breeding in the French Austral Territories (TAAF) over a large geographical range, from Antarctica to the subtropics, during the same breeding season in 2006–2007 (Table 1). Moreover, feathers were obtained from museum specimens of penguins collected at the same sites during the 1950s to the 1970s. Potential spatio-temporal variations in feeding ecology have been taken into account using stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$), which are known proxies of feeding habitat and trophic position, respectively (Vanderklift and Ponsard, 2003; Newsome et al., 2007). Hg and stable isotopes have been measured in feathers from both adults and chicks at each site. Chicks were expected to show lower feather Hg concentrations than adults, because of their shorter period of exposure. Given the previous results on the latitudinal differences in Hg transfer to predators in the southern Indian Ocean (Blévin et al., 2013; Carravieri et al., 2014b; Goutte et al., 2014), we expected increasing Hg concentrations in the feathers of penguin populations breeding from high to low latitudes. Finally, given the increasing trends of Hg deposition in the Southern Hemisphere (e.g., Hermanns and Biester, 2013) and of Hg bioaccumulation in marine animals (e.g., Vo et al., 2011; Bond et al., 2015), we expected feather Hg concentrations of contemporary penguins to be higher than those of museum specimens from the 50s and 70s.

## 2. Material and methods

### 2.1. Study site, species and field collections

Fieldwork was conducted at three sites of the French Southern and Antarctic Territories, that are representative of different water masses, namely Adélie land (66°40′S, 140°01′E) in Antarctica, Southern Ocean, the Crozet Islands (46°26′S, 51°45′E) in the subantarctic zone *sensus lato* (between the Polar and the Subtropical Fronts, Southern Ocean), and Amsterdam Island (37°50′S, 77°31′E) in the subtropics (north of the Subtropical Front, Indian Ocean). We define the Southern Ocean as the water masses south of the Subtropical Front (Pollard et al., 2002). For simplicity, we use the term "southern Indian Ocean" when referring to the whole region studied. All the seven penguin species breeding at these sites were sampled: emperor *Aptenodytes forsteri* and Adélie *Pygoscelis adeliae* penguins at Adélie land; king *Aptenodytes patagonicus*, macaroni *Eudyptes chrysolophus*, southern rockhopper *Eudyptes chrysocome filholi* and gentoo penguins *Pygoscelis papua* at Crozet Islands; and northern rockhopper penguins *Eudyptes moseleyi* at Amsterdam Island.

Penguin moult involves two distinct processes, with new feather synthesis and old feather loss overlapping in mid-moult (Cherel et al., 1994). Thus, for the contemporary sample, both new and old feathers from the same individual adult penguins were simultaneously collected in mid-moult, in order to evaluate potential inter-annual variation of adult penguins Hg exposure at the individual scale. Old and new feathers refer to moults that occurred during the 2005–2006 and 2006–2007 austral summers (hereafter called 2006 and 2007), respectively. Emperor penguin feathers were collected on breeding, not moulting birds, because, unlike other penguins, adult emperor penguins do not moult at the breeding sites. Inter-annual variations in feather Hg content were thus evaluated in six species only. Feathers (2007 moult) were also sampled from chicks at fledging (i.e. at the end of the breeding season). Historical feather samples (from 1950 to 1977) were obtained from specimens held in the ornithological collection of the Muséum National d'Histoire Naturelle of Paris (France). Feathers were taken only when complete capture information was present with a particular study specimen. Between 6 and 10 body feathers per individual (or museum specimen) were collected and stored dry in sealed plastic bags until analysis at the University of La Rochelle, France.

### 2.2. Sample analyses

Prior to chemical analysis, feathers were cleaned to remove surface lipids and contaminants as previously described (Carravieri et al., 2013). Since almost all Hg is under the organic form in feathers, total Hg approximates the amount of feather Me–Hg (Bond and Diamond, 2009; Thompson and Furness, 1989). Total Hg was also quantified in feathers of museum specimens, because Hg-containing preservatives were not used at the Muséum National d'Histoire Naturelle of Paris at the time the museum specimens were collected, avoiding a potential contamination (Vo et al., 2011).