



# Feather mercury concentrations in Southern Ocean seabirds: Variation by species, site and time<sup>☆</sup>



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## ABSTRACT

We studied mercury contamination in 25 seabird species breeding along a latitudinal gradient across the Southern Ocean, from Gough Island (40°S) through Marion Island (47°S) to Byers Peninsula (63°S). Total mercury concentrations in body feather samples of adults caught at breeding colonies from 2008 to 2011 were determined. Krill (*Euphausia* spp.) and other zooplankton consumers had low mercury concentrations (gentoo penguin *Pygoscelis papua*, chinstrap penguin *Pseudomonas Antarctica*, common diving petrel *Pelecanoides urinatrix*, broad-billed prion *Pachyptila vittata*; mean levels 308–753 ng g<sup>-1</sup>), whereas seabirds consuming squid or carrion had high mercury concentrations (ascending order: Kerguelen petrel *Aphrodroma brevirostris*, southern giant petrel *Macronectes giganteus*, soft-plumaged petrel *Pterodroma mollis*, sooty albatross *Phoebastria fusca*, Atlantic petrel *Pterodroma incerta*, northern giant petrel *Macronectes halli*, great-winged petrel *Pterodroma macroptera*; 10,720–28038 ng g<sup>-1</sup>). The two species with the highest mercury concentrations, northern giant petrels and great-winged petrels, bred at Marion Island. Among species investigated at multiple sites, southern giant petrels had higher mercury levels at Marion than at Gough Island and Byers Peninsula. Mercury levels among Byers Peninsula seabirds were low, in two species even lower than levels measured 10 years before at Bird Island, South Georgia. Replicate measurements after about 25 years at Gough Island showed much higher mercury levels in feathers of sooty albatrosses (by 187%), soft-plumaged petrels (53%) and Atlantic petrels (49%). Concentrations similar to the past were detected in southern giant petrels at Gough and Marion islands, and in northern giant petrels at Marion. There were no clear indications that timing of moult or migratory behavior affected mercury contamination patterns among species. Causes of inter-site or temporal differences in mercury contamination could not be verified due to a lack of long-term data related to species' diet and trophic levels, which should be collected in future together with data on mercury contamination.

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## 1. Introduction

In our changing world where human activities expand to the most remote places of the earth, environmental pollution is an increasing hazard. Within the wide spectrum of toxic substances both natural and artificial, mercury (Hg), a non-essential metal, is of

particular concern (UNEP, 2013). Some Hg derives from natural sources, linked to volcanic and geothermal activities, and it is widely distributed due to its ability to remain in a gaseous form and be carried with air masses (Ebinghaus et al., 2002; Fitzgerald and Lamborg, 2003). Human activities, such as coal burning, have increased the amount of mercury cycling among land, atmosphere and ocean by a factor of three to five, despite some areas of uncertainty in the global biogeochemical cycle of mercury still remain (Selin, 2009). Global emissions of mercury decreased from 1990 to 2007 in Europe and North America but increased in Asia to 56% of all anthropogenic emissions (Fitzgerald and Lamborg, 2003; Driscoll et al., 2013). Mercury dynamics involve transport and

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deposition as principal pathways for Hg to oceanic surface waters. This highly dynamic process through air-sea exchange plays a role in the redistribution of Hg across the Earth's surface (Lamborg et al., 1999). In this respect, emitted Hg may be deposited anywhere in its hemisphere of origin, but also transported between hemispheres, although in a less efficient manner (Driscoll et al., 2013). Though inputs in the Northern Hemisphere have declined in recent decades (Mason et al., 2012; Burgess et al., 2013; Driscoll et al., 2013), most industrial activity still occurs in northern regions (UNEP, 2013), and therefore concentrations are generally lower in the Southern Hemisphere (by 30% in the air, Driscoll et al., 2013). Anyway, the high summer concentrations of Hg in South Polar air and biota raises the concern that Antarctica may become an important sink in the global Hg cycle, especially in view of possible changes in sea ice coverage and increasing anthropogenic emissions of Hg in the Southern Hemisphere (Bargagli, 2008). Further, once in water, Hg is both methylated leading to methylmercury ( $\text{CH}_3\text{Hg}$ ) which is highly toxic to biota (Driscoll et al., 2013; UNEP, 2013) or demethylated by UV light (in the euphotic area; Blum et al., 2014). Methylated Hg is ubiquitous in the open ocean (Mason and Sullivan, 1999; Lamborg et al., 2014); concentrations are biomagnified through the food web, reaching levels in marine top predators several orders of magnitude higher than those in the water.

In this regard, seabirds are excellent bioindicators to monitor Hg in marine ecosystems because their high trophic positions in marine food webs reflect the hazards of Hg to marine ecosystems and humans better than abiotic samples (e.g. Burger, 1993; Furness, 1993; ICES, 1999; Becker and Dittmann, 2009; Dittmann et al., 2012; Helgason et al., 2008; Braune et al., 2014). Hg is toxic, influencing endocrine-related mechanisms including accumulation and specific cytotoxicity in endocrine tissues, and interactions with sex hormones affecting enzymes within the steroidogenesis pathway (Tan et al., 2009). Sublethal effects of Hg on birds include adverse impacts on blood and tissue chemistry, metabolism, growth, development, reproduction and behavior (Eisler, 1987; Boening, 2000). To correctly interpret their levels, however, we need to understand both the main uptake and excretion pathways of Hg in birds. As a decontamination procedure, Hg from prey is either inactivated in the liver or is excreted into feathers during moult (Muirhead and Furness, 1988; Kim et al., 1996) or into eggs (e.g. Lewis et al., 1993). The chemical form of Hg in seabird feathers is almost entirely methylmercury (Braune and Gaskin, 1987; Thompson and Furness, 1989). Given their non-destructive collection, feathers have been widely used as an effective index of seabird contamination with Hg (e.g. Lock et al., 1992; Thompson et al., 1992, 1993; Burger and Gochfeld, 2000a, 2000b; Becker et al., 2002; Kojadinovic et al., 2007; Elliott and Elliott, 2013; Carravieri et al., 2014b).

The uptake of Hg in seabirds is dependent on a variety of factors, including diet (Monteiro et al., 1998; Burger and Gochfeld, 2000a,b; Becker et al., 2002; Bocher et al., 2003; Kojadinovic et al., 2007; Anderson et al., 2009), prey size (Croxall and Prince, 1980; Xavier and Croxall, 2007), habitat use and seasonal movements (Kojadinovic et al., 2007; Anderson et al., 2009; Hipfner et al., 2011; Tavares et al., 2013; Carravieri et al., 2014a), species-specific life-history traits such as longevity and gender (Becker et al., 2002; Tavares et al., 2013; Carravieri et al., 2014a), behavioural and physiological traits such as constraints on the elimination of mercury from the body due to slow moult patterns and duration (Muirhead and Furness, 1988; Stewart et al., 1999; Tavares et al., 2013), and differences in Hg detoxification (Muirhead and Furness, 1988; Bocher et al., 2003). Furthermore, Hg levels in feathers formed during the non-breeding season appear to be more strongly governed by species effects (such as moult schedule) than

by trophic relationships across taxa (Anderson et al., 2009).

Although atmospheric deposition, the main source of inorganic mercury to open ocean systems, occurs in all ocean basins, inputs of anthropogenic mercury into the ocean are spatially variable (Mason et al., 2012), leading to the need to understand spatial variability of Hg in marine biota. In the Southern Ocean, feathers or blood have been used to monitor Hg levels in seabird communities such as those at South Georgia (Becker et al., 2002; Anderson et al., 2009; Tavares et al., 2013) and other areas (Blévin et al., 2013; Carravieri et al., 2014b; Goutte et al., 2014a,b), but spatial coverage of Southern Ocean and surrounding marine areas' Hg contamination in seabirds is generally poor. Moreover, we need to assess temporal trends in Hg, since biological exposure in the upper ocean may respond slowly to atmospheric deposition, and bioaccumulation into oceanic food chains may take years to decades (Mason et al., 2012). In the 1980s, high Hg concentrations recorded in some Southern Ocean albatrosses and petrels were attributed to their scavenging behavior and physiological peculiarities related to Hg excretion, but it was suggested to ultimately derive from naturally high "background" Hg concentrations within Southern Ocean food chains (Thompson et al., 1993; Anderson et al., 2009). In the 1990s, Becker et al. (2002) reported elevated Hg concentrations in a seabird community breeding at South Georgia. They hypothesised that this could result from on-going Hg pollution by industrial and agricultural emissions originating mainly from the Northern Hemisphere. However, no consistent results on temporal changes have been produced for Antarctic seabirds, so these hypotheses need further evaluation.

In this paper we provide comprehensive recent data and review existing literature on Hg concentrations in feathers of 25 seabird species sampled across a large-scale (5900 km) longitudinal gradient in three very different marine regions, the Southern Ocean, the temperate South Atlantic Ocean and the sub-Antarctic Indian Ocean. Our main purpose is to (1) interpret Hg contamination patterns among the species in relation to trophic position and diets, (2) expand current geographic coverage to understand spatial differences in Hg levels in seabirds, and (3) investigate temporal changes after 25 years in Hg concentrations in some of these seabird species.

## 2. Materials and methods

### 2.1. Study areas

Byers Peninsula (62°38'S, 61°50'W) is an Antarctic Specially Protected Area (ASPA No. 126) situated on Livingston Island in South Shetlands, about 500 km south of the Antarctic Convergence (Fig. 1). Byers Peninsula has been one of the largest ice-free areas in the Antarctic Peninsula over at least the last 3000 years (Björck et al., 1991), which allows a relatively large number of seabirds to breed there compared to other Antarctic localities. Gil-Delgado et al. (2013) estimated populations of 2793 southern giant petrels *Macronectes giganteus*, 3746 Antarctic terns *Sterna vittata*, 1884 kelp gulls *Larus dominicanus*, 60–91 sub-Antarctic skuas *Stercorarius antarcticus*, 4200 pairs of gentoo penguin *Pygoscelis papua* and 50 pairs of chinstrap penguin *Pseudomonas antarctica*.

Sub-Antarctic Marion Island (46°54'S, 37°44'E), the larger of the two Prince Edward Islands (Fig. 1), lies between the Subtropical Convergence and the Antarctic Convergence (300 km north). It is downstream from the Indian Ocean Ridge, which creates a diverse range of oceanographic habitats resulting in some of the most productive marine regions of Earth. The Prince Edward Islands are home to 28 breeding species of seabirds, several of which are listed as threatened (Ryan et al., 2009; Taylor et al., 2011). Marion Island alone supports some 0.8–1.0 million pairs of seabirds (Ryan and

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