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Seasonal variation of mercury contamination in Arctic seabirds: a pan- arctic assessment

Authors: Céline Albert^a, Hálf dán Helgi Helgason^b, Maud Brault-Favrou^a, Gregory J. Robertson^c, Sébastien Descamps^b, Françoise Amélineau^{b,d}, Jóhannis Danielsen^e, Rune Dietz^f, Kyle Elliott^g, Kjell Einar Erikstad^h, Igor Eulaers^f, Alexey Ezhovⁱ, Michelle G. Fitzsimmons^c, Maria Gavrilov^{j,k}, Elena Golubova^l, David Grémillet^{d,m,n}, Scott Hatch^o, Nicholas P. Huffeldt^f, Dariusz Jakubas^p, Alexander Kitaysky^q, Yann Kolbeinsson^r, Yuri Krasnovⁱ, Svein-Håkon Lorentsen^s, Erlend Lorentzen^b, Mark L. Mallory^t, Benjamin Merkel^b, Flemming Ravn Merkel^{f,u}, William Montevecchi^v, Anders Mosbech^f, Bergur Olsen^e, Rachael A. Orben^w, Allison Patterson^g, Jennifer Provencher^x, Christine Plumejeaud^a, Isabeau Pratte^t, Tone Kristin Reiertsen^h, Heather Renner^y, Nora Rojek^y, Marc Romano^y, Hallvard Strøm^b, Geir Helge Systad^z, Akinori Takahashi^{aa}, Jean-Baptiste Thiebot^{aa}, Thorkell Lindberg Thórarinsson^r, Alexis P. Will^q, Katarzyna Wojczulanis-Jakubas^p, Paco Bustamante^{a,ab}, Jérôme Fort^a

Institutions:

^a Littoral, Environnement et Sociétés (LIENSs), UMR 7266 CNRS-La Rochelle Université, 2 Rue Olympe de Gouges, FR-17000, La Rochelle, France

^b Norwegian Polar Institute, Framcentre, Hjalmar Johansens Gate 14, NO-9296 Tromsø

^c Wildlife Research Division, Environment Climate Change Canada, 6 Bruce Street, Mount Pearl NL A1N 4T3, Canada

^d Centre d'Ecologie Fonctionnelle et Evolutive (CEFE) UMR 5175, CNRS – Université de Montpellier – Université Paul-Valéry Montpellier – EPHE, Montpellier, France

- ^e The Faroese Marine Research Institute Nóatún 1, FO-100 Tórshavn Faroe Islands
- ^f Aarhus University, Department of Bioscience, Arctic Research Centre (ARC), Frederiksborgvej 399, PO Box 358, DK-4000 Roskilde, Denmark
- ^g Department of Natural Resource Sciences, McGill University, Ste Anne-de-Bellevue, QC H9X 3V9, Canada
- ^h Norwegian Institute for Nature Research (NINA) FRAM – High North Research Centre for Climate and the Environment PO Box 6606 Langnes NO-9296 Tromsø Norway
- ⁱ Murmansk Marine Biological Institute, 17 Vladimirskaia street, 183010 Murmansk, Russia
- ^j Association Maritime Heritage, RU – 199106, Icebreaker “Krassin”, The Lieutenant Schmidt emb., 23 Line, Saint-Petersburg, Russia
- ^k National Park Russian Arctic, RU-168000, Sovetskikh kosmonavtov ave., 57, Archangelsk, Russia
- ^l Laboratory of Ornithology, Institute of Biological Problems of the North, RU-685000, Magadan, Portovaya Str., 18, Russia
- ^m FitzPatrick Institute of African Ornithology, UCT, Rondebosch 7701 South Africa
- ⁿ Centre d’Etudes Biologiques de Chize’ (CEBC), UMR 7372-CNRS, La Rochelle Université, France
- ^o Institute for Seabird Research and Conservation, Anchorage 99516-3185, Alaska, USA
- ^p University of Gdańsk, Faculty of Biology, Dept. of Vertebrate Ecology and Zoology, Wita Stwosza 59, PL-80-308 Gdańsk, Poland
- ^q Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK 99775, USA
- ^r Northeast Iceland Nature Research Centre, Hafnarstétt 3, 640 Húsavík, Iceland
- ^s Norwegian Institute for Nature Research (NINA) Høgskoleringen 9, NO-7034 Trondheim, Norway
- ^t Acadia University, 33 Westwood Avenue, Wolfville, Nova Scotia, Canada, B4P 2R6
- ^u Greenland Institute of Natural Resources, P.O. Box 570, 3900 Nuuk, Greenland.
- ^v Psychology Department, Memorial University, St. John’s, Newfoundland A1M 2Y8, Canada
- ^w Department of Fisheries and Wildlife, Oregon State University, Hatfield Marine Science Center, 2030 SE Marine Science Dr., Newport, OR 97365, USA
- ^x Canadian Wildlife Service, Environment and Climate Change Canada, Place Vincent Massey, 351 St. Joseph Blvd, Hull, Quebec, K1A 0H3, Canada
- ^y U.S. Fish and Wildlife Service, Alaska Maritime Wildlife Refuge, Homer, Alaska, USA
- ^z Norwegian Institute for Nature Research (NINA) Thormøhlensgate 55 NO-5006 Bergen
- ^{aa} National Institute of Polar Research 10-3, Midori-cho, Tachikawa Tokyo 190-8518, Japan
- ^{ab} Institut Universitaire de France (IUF), 1 rue Descartes 75005 Paris, France

Abstract: Mercury (Hg) is a natural trace element found in high concentrations in top predators, including Arctic seabirds. Most current knowledge about Hg concentrations in Arctic seabirds relates to exposure during the summer breeding period when researchers can easily access seabirds at colonies. However, the few studies focused on winter have shown higher Hg concentrations during the non-breeding period than breeding period in several tissues. Hence, improving knowledge about Hg exposure during the non-breeding period is crucial to understanding the threats and risks encountered by these species year-round. We used feathers of nine migratory alcid species occurring at high latitudes to study bird Hg exposure during both the breeding and non-breeding periods. Overall, Hg concentrations during the non-breeding period were ~3 times higher than during the breeding period. In addition, spatial differences were apparent within and between the Atlantic and Pacific regions. While Hg concentrations during the non-breeding period were ~9 times and ~3 times higher than during the breeding period for the West and East Atlantic respectively, Hg concentrations in the Pacific during the non-breeding period were only ~1.7 times higher than during the breeding period. In addition, individual Hg concentrations during the non-breeding period for most of the seabird colonies were above $5.00 \mu\text{g g}^{-1}$ dry weight (dw), which is considered to be the threshold at which deleterious effects are observed, suggesting that some breeding populations might be vulnerable to non-breeding Hg exposure. Since wintering area locations, and migration routes may influence seasonal Hg concentrations, it is crucial to improve our knowledge about spatial ecotoxicology to fully understand the risks associated with Hg contamination in Arctic seabirds.

Key words: polar, top predators, metal, seasonal variation, feathers

Introduction

Concentrations of mercury (Hg), a naturally-occurring non-essential element, have increased in marine ecosystems over the last decades because of anthropogenic emissions (UNEP, 2013). In its methylated, toxic form (methyl-mercury, MeHg), Hg is considered a pollutant of concern for both wildlife and human health (Braune et al., 2012; Dietz et al., 2019, 2013; Tan et al., 2009; Wolfe et al., 1998), prevalent even in remote areas such as the polar regions (Albert et al., 2019; AMAP, 2018; Johansen et al., 2007; Provencher et al., 2014). Mercury is assimilated by organisms through their diet and biomagnifies through food webs (Morel et al., 1998). The highest concentrations are generally found in top predators, such as seabirds and marine mammals, with the latter often carrying even higher body burdens than seabirds (AMAP, 2005, 1998; Dietz et al., 2019, 2013, 1996). In turn, elevated Hg may be associated with physiological, behavioral or reproductive impacts, such as neurological deficiencies, immune disruption or lowered egg hatchability (Ackerman et al., 2016; Dietz et al., 2019), ultimately having long-term, deleterious effects on seabird population dynamics (Goutte et al., 2014a, 2014b). Spatial differences have been highlighted in numerous marine species with higher Hg concentrations found in the Canadian Arctic compared to the European Arctic (AMAP, 2018), but with large interspecies variation (Albert et al., 2019; AMAP, 2018). However, current knowledge about Hg concentrations in Arctic seabirds is restricted mostly to the breeding period (but see Fleishman et al., 2019; Fort et al., 2014), and little is known about the non-breeding period, which is mostly spent in areas outside the Arctic.

At the end of the breeding period, most Arctic seabirds leave their breeding site and migrate principally to southerly areas where conditions, including environmental Hg contamination, might differ from those encountered at their breeding areas. For example, little auks (or dovebies; *Alle alle*) had higher Hg concentrations during the non-breeding period spent east of Newfoundland than during the breeding period in East Greenland, negatively impacting their subsequent reproduction (Fort et al., 2014). Outside of the Arctic, common guillemots (or common murrelets, *Uria aalge*) have higher and increasing Hg concentrations while wintering in the North Sea compared to their breeding grounds (Joiris et al., 1997). In this context, to better understand the Hg contamination risk to Arctic seabirds, the concentrations of this element should be studied year-round and at multiple spatial scales.

The alcid family of seabirds (Charadriiformes: Alcidae) comprises the most numerous species in the Arctic, from the High to the sub-Arctic, and shows a circumpolar distribution. Some species are endemic to the Pacific Arctic, such as murrelets (*Brachyramphus*), auklets (Aethiini) and tufted puffins (*Fratercula cirrhata*). Others are endemic to the Atlantic Arctic, such as little auks and razorbills (*Alca torda*), or are common to both regions, such as black guillemots (*Cepphus grylle*), common guillemots and Brünnich's guillemots (or thick-billed murrelets; *Uria lomvia*) (Gaston and Jones 1998). Alcids feed on zooplankton (e.g. little auks, least auklets), fish (e.g. common guillemots) or both (e.g. Brünnich's guillemot), with diet potentially switching during or between seasons (Gaston and Jones, 1998). In the Arctic, most

alcids aggregate in large colonies for reproduction, then migrate to overwinter in open seas, generally farther south.

Alcids undergo two seasonal molts with important implications for their Hg contamination, as approximately 70% to 90% of the Hg body burden is excreted into growing feathers (Agusa et al., 2005; Braune, 1987; Honda et al., 1986). A partial molt (head, cheeks and neck) occurs after the non-breeding period in the spring leading to the nuptial plumage, and a total molt (body, head and wings) occurs after the breeding period, leading to winter plumage. Thus, Hg concentrations in head feathers mostly provide information about non-breeding exposure (from fall to early spring), while concentrations in body and wing feathers mostly provide information about contamination at the breeding sites (from early spring to fall) (Albert et al., 2019; Fort et al., 2014).

Here we focused on nine alcid species distributed around the Arctic, representing different marine foraging niches and ocean systems. More specifically, we used body and head feathers to investigate seasonal, spatial and interspecific variation in Hg contamination. We predicted higher Hg concentrations: i) in head feathers (i.e. non-breeding period) than in body feathers (i.e. breeding period); ii) in the western Atlantic as compared to other regions; and iii) in species feeding at higher trophic levels. We based these predictions on known foraging ecologies (Gaston and Jones, 1998) and previously documented patterns of Hg exposure in the Pacific, and West and East Atlantic. The northern Pacific has higher Hg deposition rates due high emissions from Asia (Selin et al., 2007), but levels in biota are more closely linked to

methylation rates by bacteria (Elliott and Elliott, 2016; Wang et al., 2018), which led us to expect high levels in the western Atlantic based on previous work (Albert et al., 2019; AMAP, 2018).

Material and methods

Sample collection

Body feathers and head feathers (hereafter BF and HF, respectively) were collected during the breeding period from ancient murrelets (*Synthliboramphus antiquus*), Brünnich's guillemots, common guillemots, crested auklets (*Aethia cristatella*), least auklets (*Aethia pusilla*), little auks, razorbills, rhinoceros auklets (*Cerorhinca monocerata*) and tufted puffins. Sampling took place at 28 breeding colonies from the North Atlantic to North Pacific and from the sub-Arctic to the High Arctic between 2015 to 2017 during the months of May to August ($n=1,331$, Fig. 1, Table 1, Table SI 1). Seabirds were captured during late incubation and chick-rearing with a noose pole, noose carpet, mist-net or by hand, handled for 5 - 10 min and released after sampling. In the Aleutian Islands and the Sea of Okhotsk, BF and HF were sampled from fresh carcasses.

Mercury analysis

Prior to chemical analysis, any external contaminants were removed by plunging feathers for 3 min in a 2:1 chloroform:methanol solution in an ultrasonic bath. Feathers were then rinsed twice in a methanol solution and dried at 45°C for 48 h. Analyses were then performed on a pool of

three homogenized feathers reduced to powder with stainless-steel scissors (Carravieri et al., 2014). Total Hg concentrations were measured on a subsample of 0.50 - 2.00 mg dry powder using an Advanced Mercury Analyzer spectrophotometer (Altec AMA 254) at the Littoral, Environnement et Sociétés laboratory (LIENSs, La Rochelle, France) as described in Chouvelon et al. (2009). Briefly, the samples were combusted under oxygen and the liberated Hg was analyzed by atomic absorption spectrophotometry. For each sample, analyses were repeated two or three times, until the relative standard deviation for the aliquots was <10%. Subsequently, the mean of the repeated Hg measurements was used for statistical analysis. To ensure the accuracy of measurements, certified reference materials (CRM) were analyzed every 15 samples. These included: CRM - lobster Hepatopancreas TORT-3 ; NRC, Canada; reference values were of $0.292 \pm 0.022 \mu\text{g g}^{-1}$ dry weight (dw) *SD*, mean measured $\pm SD = 0.296 \pm 0.002 \mu\text{g g}^{-1}$ dw, recovery = 101 % ; and lobster hepatopancreas TORT-2; $0.27 \pm 0.06 \mu\text{g g}^{-1}$ dw *SD*, mean measured = $0.26 \pm 0.01 \mu\text{g g}^{-1}$ dw *SD* , recovery = 96%. Masses of the CRMs (~10 mg) were adjusted to represent amounts of Hg similar to that in feather samples. In addition, blanks were run prior to the analyses and the detection limit was established at 0.05 ng. All values are given in dry weight unless otherwise noted.

Statistical analyses

To investigate seasonal Hg variations, we first classified seabird colonies into three regions: the Pacific, the East Atlantic and the West Atlantic (Fig. 1), following previous studies

and known differences in the ecology of seabirds across these regions (see Descamps et al., 2019). We used linear mixed models (R package “lme4”) (Bates et al., 2015) to examine patterns in Hg seasonality and how that varied among species or region. We considered all species in a first analysis. Subsequently, we examined only the two guillemot species, as these were the only two species sampled in all three regions. In each model, we always included the type of feather (representing the breeding or non-breeding period), plus the region and the species (1st analysis only) as fixed effects. Colonies and individuals were sampled for one to three breeding periods during the study period (2015-2017). Hence, to address the potential non-independence among Hg concentrations taken within years, within individuals, and within colonies, all three were treated as random effects. The full model followed the form: [Hg] ~ fixed effects (regions + species + type of feathers) + random effects (years + individuals + sampling sites). Hg concentrations were log_e-transformed to meet the parametric assumptions of normality and homoscedasticity of residual distribution, and to avoid impossible predicted values below zero. We used the Akaike Information Criterion (AIC, Burnham and Anderson, 2002) to compare models. As all Δ AIC values between two models differed by more than 2, the model with the lowest AIC was selected. Statistical analyses were performed with R version 3.4.3 (R Core Team, 2017) and maps were created with ArcGIS Pro version 2.5.0 (ESRI, 2019). Means are reported with standard deviation (mean \pm SD) unless otherwise noted.

Results

Mean Hg concentrations in alcid body and head feathers, by species and by breeding site are summarized in Table 1, illustrated in Fig. SI 2 (details per year in Table SI 1), and further summarized by species and region in Table 2 and Fig. SI 3. The mean Hg concentrations in alcid body and head feathers, by sampling site, are summarized in Fig. 2.

Hg contamination during the breeding period

Overall, the mean Hg concentration in alcid feathers during the breeding period was 1.20 ± 0.83 $\mu\text{g g}^{-1}$ dw. Regionally, the highest mean Hg concentration across all species during the breeding period was observed in the West Atlantic (1.70 ± 0.77 $\mu\text{g g}^{-1}$; median = 1.59 $\mu\text{g g}^{-1}$; range = 0.41 - 6.97 $\mu\text{g g}^{-1}$), followed by the Pacific (1.55 ± 1.37 $\mu\text{g g}^{-1}$; median = 0.95 $\mu\text{g g}^{-1}$; range = 0.32 - 6.99 $\mu\text{g g}^{-1}$) and the East Atlantic (0.75 ± 0.26 $\mu\text{g g}^{-1}$; median = 0.71 $\mu\text{g g}^{-1}$; range = 0.28 - 2.29 $\mu\text{g g}^{-1}$ – Fig. SI 4A). The lowest mean species Hg concentration during the breeding period was measured in crested auklets (1.00 ± 0.51 $\mu\text{g g}^{-1}$) and the highest were observed in rhinoceros auklets (3.47 ± 1.63 $\mu\text{g g}^{-1}$ – Fig. SI 5A).

Hg concentrations during the non-breeding period

Mean alcid Hg concentration in feathers during the non-breeding period was 3.60 ± 2.40 $\mu\text{g g}^{-1}$, three times the mean concentration in the breeding period. The highest mean Hg concentrations during the non-breeding period were observed in the West Atlantic (5.42 ± 2.52

$\mu\text{g g}^{-1}$; median = $5.21 \mu\text{g g}^{-1}$; range = $1.21\text{-}15.44 \mu\text{g g}^{-1}$) followed by the Pacific ($2.64 \pm 2.07 \mu\text{g g}^{-1}$; median = $2.06 \mu\text{g g}^{-1}$; range = $0.26\text{-}11.65 \mu\text{g g}^{-1}$) and the East Atlantic ($2.52 \pm 1.46 \mu\text{g g}^{-1}$; median = $2.01 \mu\text{g g}^{-1}$; range = $0.47\text{-}8.77 \mu\text{g g}^{-1}$ – Fig. SI 4B). Mirroring the breeding period results, the lowest mean Hg concentration during the non-breeding period was measured in crested auklets ($1.45 \pm 0.58 \mu\text{g g}^{-1}$) while the highest observed was in rhinoceros auklets ($6.89 \pm 2.04 \mu\text{g g}^{-1}$ – Fig. SI 5B).

Hg seasonality

When testing for seasonal and species variation in Hg concentrations, the best-fit model included the interaction between species and season (AIC model with interaction = 2,433.08; AIC model without interaction = 2,667.68). This model indicated higher Hg concentrations during the non-breeding period, varying according to species. The largest seasonal differences occurred in Brünnich's guillemots (estimate \pm SD = $1.15 \pm 0.68 \mu\text{g g}^{-1}$), common guillemots ($1.12 \pm 0.57 \mu\text{g g}^{-1}$), little auks ($0.82 \pm 0.62 \mu\text{g g}^{-1}$) and razorbills ($1.50 \pm 1.22 \mu\text{g g}^{-1}$); while no significant seasonal variation in Hg concentrations was found in ancient murrelets ($0.36 \pm 0.66 \mu\text{g g}^{-1}$), crested auklets ($0.41 \pm 0.69 \mu\text{g g}^{-1}$), least auklets ($0.23 \pm 0.70 \mu\text{g g}^{-1}$), rhinoceros auklets ($0.75 \pm 0.68 \mu\text{g g}^{-1}$) and tufted puffins ($0.29 \pm 0.66 \mu\text{g g}^{-1}$). When testing for seasonal differences among regions, the best-fit model included the interaction between season and region (AIC model with interaction = 2,643.84; AIC model without interaction = 2,815.64). This model indicated higher Hg concentrations during the non-breeding period, varying according

to region. The largest seasonal Hg difference was found in the West Atlantic ($1.13 \pm 0.63 \mu\text{g g}^{-1}$) and the East Atlantic ($1.13 \pm 0.73 \mu\text{g g}^{-1}$) followed by the Pacific ($0.57 \pm 0.73 \mu\text{g g}^{-1}$). The frequency of individual (per species and breeding colonies) below of above the toxicity threshold (Eisler, 1987) of $5.00 \mu\text{g g}^{-1}$ during the non-breeding period is represented in Fig. 3.

We tested for seasonal and spatial differences in Hg concentrations for Brünnich's and common guillemots, the two species sampled in all three regions. For Brünnich's guillemots, the best-fit model included an interaction between the type of feather and the region (AIC model with interaction= 943.16; AIC model without interaction = 1,014.28). This indicated that higher Hg concentrations occurred during the non-breeding period with variations being region-specific in this species. The largest seasonal difference in Brünnich's guillemots occurred in the West Atlantic (estimate \pm SD = $1.30 \pm 0.61 \mu\text{g g}^{-1}$), followed by the East Atlantic ($1.14 \pm 0.76 \mu\text{g g}^{-1}$) and the Pacific ($0.63 \pm 0.60 \mu\text{g g}^{-1}$). For common guillemots, similar results were found with contrasted seasonal differences in Hg concentrations across the three regions (AIC model with interaction= 363.37; AIC model without interaction = 379.03), and following the same pattern of largest differences in the West Atlantic ($1.12 \pm 0.60 \mu\text{g g}^{-1}$) and the East Atlantic: $1.12 \pm 0.55 \mu\text{g g}^{-1}$), followed by the smallest differences in the Pacific ($0.83 \pm 0.51 \mu\text{g g}^{-1}$).

Discussion

Limited data, from both blood and feather samples previously suggested considerable seasonal variation in seabird Hg concentrations, with higher contamination reported from the

non-breeding period when seabirds are often outside of Arctic regions (Fort et al., 2014; Joiris et al., 1997; Lavoie et al., 2014; Takahashi et al., 2020). In our study, we found clear seasonal differences in Hg concentrations for most study sites and species, confirming that higher Hg exposure occurred during the non-breeding period for some species. However, populations of ancient murrelets, crested and least auklets, and tufted puffins from the Pacific Region, in addition to the little auks from the northwest Atlantic (Thule, Greenland), presented low or no seasonal variation (BF : HF ratio >0.70) in their Hg concentrations. Non-breeding Hg contamination can be associated with negative effects during the following breeding season; birds with higher Hg concentrations subsequently had smaller eggs and experienced enhanced contamination during the breeding period (Fort et al., 2014, Lavoie et al., 2014). Further study is needed to assess the importance of effects on breeding driven by Hg contamination, especially for guillemots in the West Atlantic and rhinoceros auklets in the Pacific, as those populations have especially high levels of Hg. Four non-exclusive hypotheses could explain Hg seasonal variation in migratory species: 1) the occurrence of a dietary shift between seasons, 2) different food chain lengths in breeding versus non-breeding areas; 3) contrasting environmental contamination between sites; and/or 4) higher energy requirements (e.g. during storms, increased thermoregulatory costs) and thus enhanced food intakes during the winter period (Burke and Montevecchi, 2018; Dunn et al., 2020; Fort et al., 2009).

Seasonal and interspecific differences

As food represents the main pathway of Hg exposure for seabirds and other marine predators, their contamination is closely related to their diet and trophic position (Carravieri et al., 2018), with Hg concentrations increasing with trophic level. Therefore, seasonal dietary shifts towards higher trophic level prey or the use of longer food chains during the non-breeding period may lead to higher Hg concentrations (Braune et al., 2014). Nitrogen stable isotope ratios have been widely used to infer trophic level in Arctic marine systems (e.g. Hobson et al., 2002), including characterization of Hg biomagnification processes (Atwell et al., 1998; Campbell et al., 2005; Pomerleau et al., 2016). However, nitrogen stable isotopes in feathers reflect bird trophic status during the feather growth period only (which lasts a few weeks), while Hg concentrations represent their contamination during the intermolt period (lasting several months). Hence, using nitrogen stable isotopes in feathers to interpret Hg concentrations and their seasonal variations requires a stable diet through the inter-molt period (Bond, 2010). In addition, comparing stable isotope values at large spatial scales requires accurate information about spatial baseline variation (e.g. isoscapes) (Hobson et al., 2012), which is still largely missing for the non-breeding period and the Arctic and subarctic regions. Moreover, the diet of Arctic seabirds is generally well-documented during the breeding period but information about their winter diet is scarce, and only available for five of the nine studied species (Brünnich's and common guillemots, little auks, ancient murrelets, rhinoceros auklets) from a few wintering areas (see references below).

For most populations, higher Hg concentrations were found during the non-breeding period. This contrasts with reported dietary shifts towards lower trophic levels during that period for some species. For example, across their range Brünnich's guillemots feed on both fish and zooplankton during the breeding period (Gaston and Jones 1998). During the non-breeding period, they forage on lower trophic level prey (mostly invertebrates and fish in the Atlantic and mostly invertebrates in the Pacific, Gaston and Jones, 1998), although differences across sites might occur (Karnovsky et al., 2008; Linnebjerg et al., 2013; Moody and Hobson, 2007). Common guillemots (mostly feeding on fish) and razorbills (feeding on fish during summer and on a mixed diet of fish and zooplankton during winter) are known to have a constant diet or a switch to lower trophic level prey in winter, respectively (e.g. Huettmann et al., 2005; Lilliendahl, 2009; Lorentsen et al., 1999). Again, this contrasts with the higher Hg concentrations measured in the present study during the non-breeding period; we expected that feeding lower in the food web during the winter would result in lower Hg exposure.

A few studies investigated food web structure in the Arctic (e.g., Baffin Bay; Hobson and Welch, 1992; Linnebjerg et al., 2016) and subarctic marine systems (e.g., continental shelf off Newfoundland; Sherwood and Rose, 2005). These findings suggest slightly shortening food chain lengths toward southern locations. Again, this contrast with our finding of higher Hg contamination in birds during the non-breeding period, as they distribute more southerly at that time and we expected higher Hg uptake to result from longer food chains. Thus, our results suggest that other processes, besides diet shifts or differences in food web complexity, could

be operating. Alternatively, a larger food intake due to higher energy requirements during the cold season (Burke and Montevecchi, 2018; Fort et al., 2009) and/or less excretion of Hg in winter due to less plumage exchange/formation at this time of the year may explain the higher Hg accumulates measured in feathers grown during the non-breeding period/winter. Therefore, bird movements and distribution, both during summer and winter, are likely the dominant factor in driving seasonal patterns of Hg concentration in Arctic alcids.

Seasonal and spatial differences

Our results also highlight spatial differences in seabird Hg contamination during the non-breeding period, as reflected by HF measurements. Mean Hg concentrations were higher in seabird populations breeding in the Northwest Atlantic, which are likely overwintering in the Labrador Sea (Linnebjerg et al., 2018; McFarlane Tranquilla et al., 2014), compared to the Northeast Atlantic seabirds, overwintering farther east (Fort et al., 2013a). Such results are concurring with the higher Hg concentrations reported earlier in little auks overwintering off Newfoundland (Fort et al. 2014) and suggest a Hg hotspot in the Labrador Sea.

In only a few cases, we found low or no seasonal variation in Hg concentrations, suggesting a constant Hg contamination year-round. This occurred almost exclusively in Pacific species and populations (i.e. ancient murrelets, crested, least auklets) as well as in one little auk population breeding in northwest Greenland (Northwest Atlantic). This absence of seasonal variation in the Pacific region could be due to a similar exposure at both their breeding and non-

breeding sites, representing long distance and widely dispersed transport of mercury from Asia (Selin et al., 2006). It is unlikely that the similarity is due to a shared resident strategy of birds staying close to the breeding grounds year-round, as many of the Pacific auks at our study sites migrate long distances (Gaston et al., 2017; Takahashi et al., 2020) or remain in the region (Orben et al., 2015). Moreover, some of the Atlantic auks with large seasonal differences have been shown to be relatively resident (e.g. New foundland murre: McFarlane Tranquilla et al., 2014). Further investigations combining migratory movements and Hg contamination in Pacific seabirds are needed to understand seabird vulnerability to Hg in this region (see Fleishman et al., 2019). Northwest Greenland little auk population had higher Hg concentrations compared to other Arctic regions, a pattern also found in some other seabirds and marine top predators (Albert et al., 2019; AMAP, 2011) and might be explained by similar elevated concentrations at both their breeding areas and their non-breeding areas off Newfoundland (Fort et al., 2013a).

Finally, our results show spatial differences in bird Hg contamination and seasonal variation between the Pacific and Atlantic regions. Brünnich's and common guillemots, which are present in both regions, showed smaller seasonal differences and lower non-breeding Hg concentrations in the Pacific than in the Atlantic, suggesting differences in Hg environmental contamination between both regions. The Arctic Ocean is a sink for contaminants such as Hg, with inflows from both atmospheric and oceanic currents, as well as rivers (Sonke et al., 2018). Nevertheless, important outflows of Hg also occur from the Arctic to lower latitudes (AMAP, 2018). Because the Arctic is widely open to the Atlantic with more numerous, complex

atmospheric and oceanic fluxes than the Pacific region, oceanic outflows of Hg (e.g. through the Canadian Arctic Archipelagoes and Fram Strait) (see Outridge et al., 2008) could partly explain the higher concentrations in Hg found in species from the Western Atlantic region compared to the Pacific regions of the Arctic. Alternatively, food webs vary among Arctic and sub-Arctic (Murphy et al., 2016), with Chukchi food webs being based on benthic inputs (Whitehouse et al., 2014). Hg levels in Pacific seabirds are closely associated with the base of the food web (Elliott and Elliott 2016), and variation in food webs among ocean basins may be one cause of lower Hg levels in the Pacific relative to the Atlantic. For example, a recent survey comparing Pacific to Atlantic waters in the Canadian Arctic (where Hg levels are higher in predators in the Pacific) found that variation in Hg in top predators was associated with higher levels of methylation in the Pacific despite lower levels of total Hg (Wang et al. 2018). Clearly, food web processes that affect methylation of Hg are important for explaining region differences, and that study, which linked disparate predator information to a single ship-based transect, might be strengthened by similar pan-Arctic predator information such as that present in our study.

Inter-individual variability in non-breeding Hg concentration

In addition to species and population differences, our results showed high inter-individual variability in Hg concentrations during the non-breeding period. Arctic seabirds are central-place foragers, feeding mostly in the vicinity of their colony during the breeding period

(Cunningham et al., 2018; Jakubas et al., 2016; Linnebjerg et al., 2015). However, during the non-breeding period, many migrate towards the open seas to spend the winter within or outside the Arctic (McFarlane Tranquilla et al., 2013). Recent tracking studies highlight how individuals from the same population might engage in contrasting migratory tactics, and thus occupy very different wintering areas (Fort et al., 2013a; Frederiksen et al., 2016; Studholme et al., 2019) where exposure to Hg and other pollutants could be substantially different (Leat et al., 2013; Miller et al., 2020; Watanuki et al., 2015). For instance, Brünnich's guillemots breeding at Coats Island and at the Gannet Islands (Northwest Atlantic) adopt variable individual strategies, with wintering areas ranging from the Labrador Sea to Newfoundland (Frederiksen et al., 2016; McFarlane Tranquilla et al., 2013). This finding is consistent with higher inter-individual variability in Hg concentrations for non-breeding than for the breeding Brünnich's guillemots. In comparison, common guillemots from the same colonies showed lower inter-individual variability in their non-breeding distribution as individuals overwinter close to their breeding colonies off Newfoundland (Fort et al., 2013b; McFarlane Tranquilla et al., 2013). Similarly, this was reflected in our results by lower variability in Hg concentrations for that species. This inter-individual variation in both Hg concentrations and large-scale distribution supports the hypothesis that individual migratory tactics play an important role in Hg exposure and calls for further studies linking individual movements to contamination risks.

Hg toxicity and risks for non-breeding Arctic seabirds

There is limited information about Hg toxicity thresholds for seabird feathers. Nevertheless, Hg concentrations above 5.00 $\mu\text{g/g dw}$ in feathers are usually considered to be associated with deleterious health and reproductive effects (Eisler, 1987). In addition, elevated Hg contamination during the non-breeding period can exert carry-over effects on reproductive parameters in the following breeding season (e.g. Fort et al., 2014). Our results demonstrate that some populations of Arctic alcids had Hg values close to or above 5.00 $\mu\text{g/g dw}$. In total, 26% of the sampled individuals for which non-breeding Hg was measured exceeded this toxicity threshold. These include rhinoceros auklets breeding in the Gulf of Alaska, and common and Brünnich's guillemot populations breeding in the Northwest Atlantic. This latter region has previously been associated with elevated Hg risk in seabirds. For instance, the investigation of Hg concentrations in the blood of Brünnich's guillemot breeding at Coats Island (Canadian Arctic, Northwest Atlantic) showed that above ~90% of the sampled individuals were associated with at least a moderate risk (Dietz et al., 2019).

Hence, many seabird species and populations might be at high risk of Hg contamination that could negatively impact their reproduction, with potential long-term effects on population dynamics (Goutte et al., 2014a, 2014b). Population trajectories of different Arctic seabird populations vary spatially (e.g. Frederiksen et al., 2016), and the potential role played by environmental pollution on these patterns has been largely overlooked. Therefore, there is a

need to include exposure to pollutants, notably during the non-breeding period, in population dynamic studies and conservation programs.

Conclusion

The present study is the first to investigate seabird seasonal Hg contamination at a large, pan-Arctic scale. Our results demonstrate that the non-breeding period is critical for Hg contamination of piscivorous and planktivorous seabirds. This period might represent an important risk for these sensitive populations, especially those breeding in the West Atlantic Arctic, and to a lesser extent in the Pacific Arctic and the East Atlantic. This study demonstrates that close monitoring should be pursued to understand both short- and long-term implications of Hg exposure on seabird population dynamics. Our study also shows that higher non-breeding contamination most likely depends on both individual, population, and species-specific migratory strategies determining year-round spatial distributions. We therefore call for further studies linking non-breeding distribution of seabirds and Hg contamination at the individual and population scales. This would facilitate better understanding of which wintering areas are associated with higher Hg contamination and thus pose higher risks for Arctic seabirds. Further studies including energetic modelling are also required to better understand the role of increased energy requirements on Hg seasonal changes. Therefore, there is a need for more integrative spatial ecotoxicology studies at multiple scales, combining tracking technologies, Hg measurements, dietary investigations, and including a large range of colonies and species.

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Pictures credit: Ancient murrelet: Dr. A. Andreev, Brünnich's guillemot: S. Descamps, little auk, common guillemot and razorbill: C. Albert, crested auklet: A. Will, rhinoceros auklet: tufted puffin: K. Elliott, least auklet: M. Romano.

References

- Ackerman, J.T., Eagles-Smith, C.A., Herzog, M.P., Hartman, C.A., Peterson, S.H., Evers, D.C., Jackson, A.K., Elliott, J.E., Vander Pol, S.S., Bryan, C.E., 2016. Avian mercury exposure and toxicological risk across western North America: A synthesis. *Science of the Total Environment* 568, 749–769. <https://doi.org/10.1016/j.scitotenv.2016.03.071>
- Agusa, T., Matsumoto, T., Ikemoto, T., Anan, Y., Kubota, R., Yasunaga, G., Kunito, T., Tanabe, S., Ogi, H., Shibata, Y., 2005. Body distribution of trace elements in Black-tailed gulls from Rishiri Island, Japan: age-dependent accumulation and transfer to feathers and eggs. *Environmental Toxicology and Chemistry* 24, 2107. <https://doi.org/10.1897/04-617R.1>
- Albert, C., Renedo, M., Bustamante, P., Fort, J., 2019. Using blood and feathers to investigate large-scale Hg contamination in Arctic seabirds: A review. *Environmental Research* 177, 108588. <https://doi.org/10.1016/j.envres.2019.108588>
- AMAP, 2018. AMAP Assessment 2018: Biological Effects of Contaminants on Arctic Wildlife and Fish. Tromsø, Norway.
- AMAP, 2011. AMAP Assessment 2011: Mercury in the Arctic. Oslo, Norway.
- AMAP, 2005. AMAP Assessment 2002: Heavy metals in the Arctic. AMAP, Oslo.
- AMAP (Ed.), 1998. AMAP assessment report: Arctic pollution issues. Oslo, Norway.
- Atwell, L., Hobson, K.A., Welch, H.E., 1998. Biomagnification and bioaccumulation of mercury in an arctic marine food web: insights from stable nitrogen isotope analysis. *Canadian Journal of Fisheries and Aquatic Sciences* 55, 1114–1121. <https://doi.org/10.1139/cjfas-55-5-1114>
- Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting linear Mixed-Effects Models using {lme4}. *Journal of Statistical Software* 67, 1–48. <https://doi.org/10.18637/jss.v067.i01>
- Bond, A.L., 2010. Relationships between stable isotopes and metal contaminants in feathers are spurious and biologically uninformative. *Environmental Pollution* 158, 1182–1184. <https://doi.org/10.1016/j.envpol.2010.01.004>
- Braune, B.M., 1987. Comparison of total mercury levels in relation to diet and molt for nine species of marine birds. *Archives of Environmental Contamination and Toxicology* 16, 217–224. <https://doi.org/10.1007/BF01055802>
- Braune, B.M., Gaston, A.J., Hobson, K.A., Gilchrist, H.G., Mallory, M.L., 2014. Changes in food web structure alter trends of mercury uptake at two seabird colonies in the Canadian Arctic. *Environmental Science & Technology* 48, 13246–13252. <https://doi.org/10.1021/es5036249>
- Braune, B.M., Scheuhammer, A.M., Crump, D., Jones, S., Porter, E., Bond, D., 2012. Toxicity of methylmercury injected into eggs of thick-billed murres and arctic terns. *Ecotoxicology* 21, 2143–2152. <https://doi.org/10.1007/s10646-012-0967-3>
- Burke, C.M., Montevocchi, W.A., 2018. Taking the bite out of winter: common murres (*Uria aalge*) push their dive limits to surmount energy constraints. *Frontiers in Marine Science* 5. <https://doi.org/10.3389/fmars.2018.00063>
- Burnham, K.P., Anderson, D., 2002. *Model Selection and Multi-model Inference: A Practical Information-theoretic Approach.*, Springer, New-York. ed.
- CAFF, 2001. High and low Arctic terrestrial boundaries were defined by the Circumpolar Arctic Vegetation Mapping Project - Bioclimatic subzones (CAVM). <http://www.geobotany.uaf.edu/cavm/>. Sub Arctic boundary was defined by the Arctic Biodiversity Assessment (ABA).
- Campbell, L.M., Norstrom, R.J., Hobson, K.A., Muir, D.C.G., Backus, S., Fisk, A.T., 2005. Mercury and other trace elements in a pelagic Arctic marine food web (Northwater

- Polynya, Baffin Bay). *Science of The Total Environment* 351–352, 247–263. <https://doi.org/10.1016/j.scitotenv.2005.02.043>
- Carravieri, A., Bustamante, P., Churlaud, C., Fromant, A., Cherel, Y., 2014. Moulting patterns drive within-individual variations of stable isotopes and mercury in seabird body feathers: implications for monitoring of the marine environment. *Marine Biology* 161, 963–968. <https://doi.org/10.1007/s00227-014-2394-x>
- Carravieri, A., Fort, J., Tarroux, A., Cherel, Y., Love, O.P., Prieur, S., Brault-Favrou, M., Bustamante, P., Descamps, S., 2018. Mercury exposure and short-term consequences on physiology and reproduction in Antarctic petrels. *Environmental Pollution* 237, 824–831. <https://doi.org/10.1016/j.envpol.2017.11.004>
- Chouvelon, T., Warnau, M., Churlaud, C., Bustamante, P., 2009. Hg concentrations and related risk assessment in coral reef crustaceans, molluscs and fish from New Caledonia. *Environmental Pollution* 157, 331–340. <https://doi.org/10.1016/j.envpol.2008.06.027>
- Cunningham, J., Elliott, K., Cottenie, K., Hatch, S., Jacobs, S., 2018. Individual foraging location, but not dietary, specialization: implications for rhinoceros auklets as samplers of forage fish. *Marine Ecology Progress Series* 605, 225–240. <https://doi.org/10.3354/meps12761>
- Descamps, S., Ramírez, F., Benjaminsen, S., Anker-Nilssen, T., Barrett, R.T., Burr, Z., Christensen-Dalsgaard, S., Erikstad, K., Irons, D.B., Lorentsen, S., Mallory, M.L., Robertson, G.J., Reiertsen, T.K., Strøm, H., Varpe, Ø., Lavergne, S., 2019. Diverging phenological responses of Arctic seabirds to an earlier spring. *Global Change Biology* 25, 4081–4091. <https://doi.org/10.1111/gcb.14780>
- Dietz, R., Letcher, R.J., Desforges, J.-P., Eulaers, I., Sonne, C., Wilson, S., Andersen-Ranberg, E., Basu, N., Barst, B.D., Bustnes, J.O., Bytingsvik, J., Ciesielski, T.M., Drevnick, P.E., Gabrielsen, G.W., Haarr, A., Hylland, K., Jenssen, B.M., Levin, M., McKinney, M.A., Nørregaard, R.D., Pedersen, K.E., Provencher, J., Styriehave, B., Tartu, S., Aars, J., Ackerman, J.T., Rosing-Asvid, A., Barrett, R., Bignert, A., Born, E.W., Branigan, M., Braune, B., Bryan, C.E., Dam, M., Eagles-Smith, C.A., Evans, M., Evans, T.J., Fisk, A.T., Gamberg, M., Gustavson, K., Hartman, C.A., Helander, B., Herzog, M.P., Hoekstra, P.F., Houde, M., Hoydal, K., Jackson, A.K., Kucklick, J., Lie, E., Loseto, L., Mallory, M.L., Miljeteig, C., Mosbech, A., Muir, D.C.G., Nielsen, S.T., Peacock, E., Pedro, S., Peterson, S.H., Polder, A., Rigét, F.F., Roach, P., Saunes, H., Sinding, M.-H.S., Skaare, J.U., Søndergaard, J., Stenson, G., Stern, G., Treu, G., Schuur, S.S., Víkingsson, G., 2019. Current state of knowledge on biological effects from contaminants on arctic wildlife and fish. *Science of the Total Environment* 696, 133792. <https://doi.org/10.1016/j.scitotenv.2019.133792>
- Dietz, R., Riget, F., Johansen, P., 1996. Lead, cadmium, mercury and selenium in Greenland marine animals. *Science of the Total Environment* 186, 67–93. [https://doi.org/10.1016/0048-9697\(96\)05086-3](https://doi.org/10.1016/0048-9697(96)05086-3)
- Dietz, R., Sonne, C., Basu, N., Braune, B., O'Hara, T., Letcher, R.J., Scheuhammer, T., Andersen, M., Andreasen, C., Andriashek, D., Asmund, G., Aubail, A., Baagøe, H., Born, E.W., Chan, H.M., Derocher, A.E., Grandjean, P., Knott, K., Kirkegaard, M., Krey, A., Lunn, N., Messier, F., Obbard, M., Olsen, M.T., Ostertag, S., Peacock, E., Renzoni, A., Rigét, F.F., Skaare, J.U., Stern, G., Stirling, I., Taylor, M., Wiig, Ø., Wilson, S., Aars, J., 2013. What are the toxicological effects of mercury in Arctic biota? *Science of the Total Environment* 443, 775–790. <https://doi.org/10.1016/j.scitotenv.2012.11.046>
- Dunn, R.E., Wanless, S., Daunt, F., Harris, M.P., Green, J.A., 2020. A year in the life of a North Atlantic seabird: behavioural and energetic adjustments during the annual cycle. *Scientific Reports* 10. <https://doi.org/10.1038/s41598-020-62842-x>

- Eisler, R., 1987. Mercury hazards to fish, wildlife and invertebrates: a synoptic review. Washington DC: U.S. Fish & Wildlife Service Biological Report 85 (1.10) 63.
- Elliott, K.H., Elliott, J.E., 2016. Origin of sulfur in diet drives spatial and temporal mercury trends in seabird eggs from Pacific Canada 1968–2015. *Environmental Science & Technology* 50, 13380–13386. <https://doi.org/10.1021/acs.est.6b05458>
- Environmental Systems Research Institute (ESRI), 2019. ArcGIS Pro.
- Fleishman, A.B., Orben, R.A., Kokubun, N., Will, A., Paredes, R., Ackerman, J.T., Takahashi, A., Kitaysky, A.S., Shaffer, S.A., 2019. Wintering in the Western Subarctic Pacific increases mercury contamination of red-legged kittiwakes. *Environmental Science & Technology*. <https://doi.org/10.1021/acs.est.9b03421>
- Fort, J., Moe, B., Strøm, H., Grémillet, D., Welcker, J., Schultner, J., Jerstad, K., Johansen, K.L., Phillips, R.A., Mosbech, A., 2013a. Multicolony tracking reveals potential threats to little auks wintering in the North Atlantic from marine pollution and shrinking sea ice cover. *Diversity and Distributions* 19, 1322–1332. <https://doi.org/10.1111/ddi.12105>
- Fort, J., Porter, W.P., Grémillet, D., 2009. Thermodynamic modelling predicts energetic bottleneck for seabirds wintering in the northwest Atlantic. *Journal of Experimental Biology* 212, 2483–2490. <https://doi.org/10.1242/jeb.032300>
- Fort, J., Robertson, G.J., Grémillet, D., Traisnel, G., Bustamante, P., 2014. Spatial ecotoxicology: Migratory arctic seabirds are exposed to mercury contamination while overwintering in the Northwest Atlantic. *Environmental Science & Technology* 48, 11560–11567. <https://doi.org/10.1021/es504045g>
- Fort, J., Steen, H., Strøm, H., Tremblay, Y., Grønningsaeter, E., Pettex, E., Porter, W.P., Grémillet, D., 2013b. Energetic consequences of contrasting winter migratory strategies in a sympatric Arctic seabird duet. *Journal of Avian Biology* 44, 255–262. <https://doi.org/10.1111/j.1600-048X.2012.00128.x>
- Frederiksen, M., Descamps, S., Erikstad, K.E., Gaston, A.J., Gilchrist, H.G., Grémillet, D., Johansen, K.L., Kolbeinsson, Y., Linnebjerg, J.F., Mallory, M.L., McFarlane Tranquilla, L.A., Merkel, F.R., Montevecchi, W.A., Mosbech, A., Reiertsen, T.K., Robertson, G.J., Steen, H., Strøm, H., Thórarinnsson, T.L., 2016. Migration and wintering of a declining seabird, the thick-billed murre *Uria lomvia*, on an ocean basin scale: Conservation implications. *Biological Conservation* 200, 26–35. <https://doi.org/10.1016/j.biocon.2016.05.011>
- Gaston, A.J., Hashimoto, Y., Wilson, L., 2017. Post-breeding movements of Ancient Murrelet *Synthliboramphus antiquus* family groups, subsequent migration of adults and implications for management. *PLOS ONE* 12, e0171726. <https://doi.org/10.1371/journal.pone.0171726>
- Gaston, A.J., Jones, I.L., 1998. *The Auks*. Oxford University Press.
- Goutte, A., Barbraud, C., Meillere, A., Carravieri, A., Bustamante, P., Labadie, P., Budzinski, H., Delord, K., Cherel, Y., Weimerskirch, H., Chastel, O., 2014a. Demographic consequences of heavy metals and persistent organic pollutants in a vulnerable long-lived bird, the wandering albatross. *Proceedings of the Royal Society B: Biological Sciences* 281, 20133313–20133313. <https://doi.org/10.1098/rspb.2013.3313>
- Goutte, A., Bustamante, P., Barbraud, C., Delord, K., Weimerskirch, H., Chastel, O., 2014b. Demographic responses to mercury exposure in two closely related Antarctic top predators. *Ecology* 95, 1075–1086. <https://doi.org/10.1890/13-1229.1>
- Hobson, K.A., Van Wilgenburg, S.L., Wassenaar, L.I., Powell, R.L., Still, C.J., Craine, J.M., 2012. A multi-isotope ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^2\text{H}$) feather isoscape to assign Afrotropical migrant birds to origins. *Ecosphere* 3, art44. <https://doi.org/10.1890/ES12-00018.1>
- Hobson, K.A., Welch, H.E., 1992. Determination of trophic relationships within a high Arctic

- marine food web using $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analysis. *Marine Ecology Progress Series* 84, 9–18.
- Honda, K., Nasu, T., Tatsukawa, R., 1986. Seasonal changes in mercury accumulation in the black-eared kite, *Milvus migrans Lineatus*. *Environmental Pollution Series A, Ecological and Biological* 42, 325–334. [https://doi.org/10.1016/0143-1471\(86\)90016-4](https://doi.org/10.1016/0143-1471(86)90016-4)
- Huettmann, F., Diamond, A.W., Dalzell, B., Macintosh, K., 2005. Winter distribution, ecology and movements of razorbills *Alca torda* and other auks in the outer Bay of Fundy, Atlantic Canada. 11.
- Jakubas, D., Iliszko, L.M., Strøm, H., Darecki, M., Jerstad, K., Stempniewicz, L., 2016. Foraging behavior of a high-Arctic zooplanktivorous alcid, the little auk, at the southern edge of its breeding range. *Journal of Experimental Marine Biology and Ecology* 475, 89–99. <https://doi.org/10.1016/j.jembe.2015.11.010>
- Johansen, P., Mulvad, G., Pedersen, H.S., Hansen, J.C., Riget, F., 2007. Human accumulation of mercury in Greenland. *Science of the Total Environment* 377, 173–178. <https://doi.org/10.1016/j.scitotenv.2007.02.004>
- Joiris, C.R., Tapia, G., Holsbeek, L., 1997. Increase of organochlorines and mercury levels in common guillemots *Uria aalge* during winter in the southern North Sea. *Marine Pollution Bulletin* 34, 1049–1057. [https://doi.org/10.1016/S0025-326X\(97\)00085-4](https://doi.org/10.1016/S0025-326X(97)00085-4)
- Karnovsky, N., Hobson, K., Iverson, S., Hunt, G., 2008. Seasonal changes in diets of seabirds in the North Water Polynya: A multiple-indicator approach. *Marine Ecology Progress Series* 357, 291–299. <https://doi.org/10.3354/meps07295>
- Lavoie, R.A., Baird, C.J., King, L.E., Kyser, T.K., Friesen, V.L., Campbell, L.M., 2014. Contamination of mercury during the wintering period influences concentrations at breeding sites in two migratory piscivorous birds. *Environmental Science & Technology* 48, 13694–13702. <https://doi.org/10.1021/es502746z>
- Leat, E., Bourgeon, S., Magnusdottir, E., Gabrielsen, G., Grecian, W., Hanssen, S., Olafsdottir, K., Petersen, A., Phillips, R., Strøm, H., Ellis, S., Fisk, A., Bustnes, J., Furness, R., Borgå, K., 2013. Influence of wintering area on persistent organic pollutants in a breeding migratory seabird. *Marine Ecology Progress Series* 491, 277–293. <https://doi.org/10.3354/meps10455>
- Lilliendahl, K., 2009. Winter diets of auks in Icelandic coastal waters. *Marine Biology Research* 5, 143–154. <https://doi.org/10.1080/17451000802279636>
- Linnebjerg, J.F., Fort, J., Guilford, T., Reuleaux, A., Mosbech, A., Frederiksen, M., 2013. Sympatric breeding Auks shift between dietary and spatial resource partitioning across the annual cycle. *PLoS ONE* 8, e72987. <https://doi.org/10.1371/journal.pone.0072987>
- Linnebjerg, J.F., Frederiksen, M., Kolbeinsson, Y., Snaethórsson, A.Ö., Thórisson, B., Thórarinsson, T.L., 2018. Non-breeding areas of three sympatric auk species breeding in three Icelandic colonies. *Polar Biology* 41, 1951–1961. <https://doi.org/10.1007/s00300-018-2334-1>
- Linnebjerg, J.F., Hobson, K.A., Fort, J., Nielsen, T.G., Møller, P., Wieland, K., Born, E.W., Riget, F., Mosbech, A., 2016. Deciphering the structure of the West Greenland marine food web using stable isotopes ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$). *Marine Biology* 11.
- Linnebjerg, J.F., Reuleaux, A., Mouritsen, K.N., Frederiksen, M., 2015. Foraging Ecology of three sympatric breeding alcids in a declining colony in Southwest Greenland. *Waterbirds* 38, 143–152. <https://doi.org/10.1675/063.038.0203>
- Lorentsen, Svein-Håkon, Anker-Nilssen, T., Lorentsen, Svein-Hakon, 1999. Diet of common murre wintering in the Northern Skagerrak during 1988-1990: Variation with sex, age and season. *Waterbirds* 22, 80. <https://doi.org/10.2307/1521996>
- McFarlane Tranquilla, L., Montevecchi, W., Hedd, A., Fifield, D., Burke, C., Smith, P., Regular, P., Robertson, G., Gaston, A., Phillips, R., 2013. Multiple-colony winter habitat use by

- murre *Uria* spp. in the Northwest Atlantic Ocean: Implications for marine risk assessment. *Marine Ecology Progress Series* 472, 287–303. <https://doi.org/10.3354/meps10053>
- McFarlane Tranquilla, L.A., Montevecchi, W.A., Fifield, D.A., Hedd, A., Gaston, A.J., Robertson, G.J., Phillips, R.A., 2014. Individual winter movement strategies in two species of murre (*Uria* spp.) in the Northwest Atlantic. *PLoS ONE* 9, e90583. <https://doi.org/10.1371/journal.pone.0090583>
- Miller, A., Elliott, J.E., Wilson, L.K., Elliott, K.H., Drouillard, K.G., Verreault, J., Lee, S., Idrissi, A., 2020. Influence of overwinter distribution on exposure to persistent organic pollutants (POPs) in seabirds, ancient murrelets (*Synthliboramphus antiquus*), breeding on the Pacific coast of Canada. *Environmental Pollution* 259, 113842. <https://doi.org/10.1016/j.envpol.2019.113842>
- Moody, A.T., Hobson, K.A., 2007. Alcid winter diet in the Northwest Atlantic determined by stable isotope analysis. *Marine Ornithology* 35, 39–46.
- Morel, F.M.M., Kraepiel, A.M.L., Amyot, M., 1998. The chemical cycle and bioaccumulation of mercury. *Annual Review of Ecology and Systematics* 29, 543–566. <https://doi.org/10.1146/annurev.ecolsys.29.1.543>
- Murphy, E.J., Cavanagh, R.D., Drinkwater, K.F., Grant, S.M., Heymans, J.J., Hofmann, E.E., Hunt, G.L., Johnston, N.M., 2016. Understanding the structure and functioning of polar pelagic ecosystems to predict the impacts of change. *Proceedings of the Royal Society B: Biological Sciences* 283, 20161646. <https://doi.org/10.1098/rspb.2016.1646>
- Orben, R.A., Paredes, R., Roby, D.D., Irons, D.B., Shaffer, S.A., 2015. Body size affects individual winter foraging strategies of thick-billed murre in the Bering Sea. *Journal of Animal Ecology* 84, 1589–1599. <https://doi.org/10.1111/1365-2656.12410>
- Outridge, P.M., Macdonald, R.W., Wang, F., Stern, G.A., Dastoor, A.P., 2008. A mass balance inventory of mercury in the Arctic Ocean. *Environmental Chemistry* 5, 89. <https://doi.org/10.1071/EN08002>
- Pomerleau, C., Stern, G.A., Pućko, M., Foster, K.L., Macdonald, R.W., Fortier, L., 2016. Pan-Arctic concentrations of mercury and stable isotope ratios of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) in marine zooplankton. *Science of the Total Environment* 551–552, 92–100. <https://doi.org/10.1016/j.scitotenv.2016.01.172>
- Provencher, J.F., Mallory, M.L., Braune, B.M., Forbes, M.R., Gilchrist, H.G., 2014. Mercury and marine birds in Arctic Canada: effects, current trends, and why we should be paying closer attention. *Environmental Reviews* 22, 244–255. <https://doi.org/10.1139/er-2013-0072>
- R Core Team, 2017. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
- Selin, N.E., Jacob, D.J., Park, R.J., Yantosca, R.M., Strode, S., Jaeglé, L., Jaffe, D., 2007. Chemical cycling and deposition of atmospheric mercury: Global constraints from observations. *Journal of Geophysical Research* 112. <https://doi.org/10.1029/2006JD007450>
- Sherwood, G.D., Rose, G.A., 2005. Stable isotope analysis of some representative fish and invertebrates of the Newfoundland and Labrador continental shelf food web. *Estuarine, Coastal and Shelf Science* 63, 537–549. <https://doi.org/10.1016/j.ecss.2004.12.010>
- Sonke, J.E., Teisserenc, R., Heimbürger-Boavida, L.-E., Petrova, M.V., Maruszczak, N., Le Dantec, T., Chupakov, A.V., Li, C., Thackray, C.P., Sunderland, E.M., Tananaev, N., Pokrovsky, O.S., 2018. Eurasian river spring flood observations support net Arctic Ocean mercury export to the atmosphere and Atlantic Ocean. *Proceedings of the National Academy of Sciences* 201811957. <https://doi.org/10.1073/pnas.1811957115>
- Studholme, K., Hipfner, J., Domalik, A., Iverson, S., Crossin, G., 2019. Year-round tracking

- reveals multiple migratory tactics in a sentinel North Pacific seabird, Cassin's auklet. *Marine Ecology Progress Series* 619, 169–185. <https://doi.org/10.3354/meps12965>
- Takahashi, A., Thiebot, J., Will, A., Tsukamoto, S., Merkel, B., Kitaysky, A., 2020. Breeding together, wintering an ocean apart: foraging ecology of the northern Bering Sea thick-billed and common murres in years of contrasting sea-ice conditions. *Polar Science*, in press.
- Tan, S.W., Meiller, J.C., Mahaffey, K.R., 2009. The endocrine effects of mercury in humans and wildlife. *Critical Reviews in Toxicology* 39, 228–269. <https://doi.org/10.1080/10408440802233259>
- UNEP, 2013. *Global Mercury Assessment 2013: Sources, Emissions, Releases and Environmental Transport*. UNEP Chemicals Branch, Geneva, Switzerland.
- Wang, K., Munson, K.M., Beaupré-Laperrière, A., Mucci, A., Macdonald, R.W., Wang, F., 2018. Subsurface seawater methylmercury maximum explains biotic mercury concentrations in the Canadian Arctic. *Scientific Reports* 8. <https://doi.org/10.1038/s41598-018-32760-0>
- Watanuki, Y., Yamamoto, T., Yamashita, A., Ishii, C., Ikenaka, Y., Nakayama, S.M.M., Ishizuka, M., Suzuki, Y., Niizuma, Y., Meathrel, C.E., Phillips, R.A., 2015. Mercury concentrations in primary feathers reflect pollutant exposure in discrete non-breeding grounds used by Short-tailed Shearwaters. *Journal of Ornithology* 156, 847–850. <https://doi.org/10.1007/s10336-015-1205-6>
- Whitehouse, G.A., Aydin, K., Essington, T.E., Hunt, G.L., 2014. A trophic mass balance model of the eastern Chukchi Sea with comparisons to other high-latitude systems. *Polar Biology* 37, 911–939. <https://doi.org/10.1007/s00300-014-1490-1>
- Wolfe, M.F., Schwarzbach, S., Sulaiman, R.A., 1998. Effects of mercury on wildlife: A comprehensive review. *Environmental Toxicology and Chemistry* 17, 146–160. <https://doi.org/10.1002/etc.5620170203>

Table 1. Species and region- specific Hg concentrations (mean \pm SD; in $\mu\text{g g}^{-1}$ dw) measured in body feathers (BF – representing exposure during the breeding period) and head feathers (HF – representing exposure during the non-breeding period). Breeding: non-breeding period Hg concentrations (mean \pm SD BF : HF) calculated from individual values. BF : HF ratio are represented in Fig. SI 6 ; n = samples size

| Species | Region | Sampling site | GPS Coordinates | n | BF mean \pm SD | HF mean \pm SD | BF : HF |
|----------------------|---------------|---------------------------------|-------------------|-----------------|------------------|------------------|-----------------|
| Ancient murrelet | Pacific | Talan Island | 59.18°N, 149.05°E | 5 | 2.64 \pm 1.00 | 3.69 \pm 1.18 | 0.81 \pm 0.52 |
| Brünnich's guillemot | Pacific | Saint George | 56.59°N, 169.61°W | 10 | 0.90 \pm 0.20 | 3.42 \pm 1.10 | 0.29 \pm 0.11 |
| | | Saint Lawrence | 63.40°N, 170.17°W | 40 | 0.77 \pm 0.33 | 1.43 \pm 0.89 | 0.79 \pm 0.49 |
| | East Atlantic | Alkefjellet, Spitsbergen | 79.58°N, 18.51°E | 32 | 0.63 \pm 0.20 | 1.70 \pm 0.48 | 0.39 \pm 0.14 |
| | | Bjørnøya | 74.50°N, 18.96°E | 48 | 0.50 \pm 0.09 | 2.91 \pm 1.73 | 0.24 \pm 0.15 |
| | | Cape Flora, Franz Josef Land | 79.95°N, 50.09°E | 61 | 0.74 \pm 0.21 | 1.64 \pm 0.35 | 0.47 \pm 0.16 |
| | | Cape Gorodetskiy | 69.15°N, 35.95°E | 19 | 0.66 \pm 0.10 | 2.06 \pm 0.39 | 0.33 \pm 0.07 |
| | | Hornøya, N Norway | 70.39°N, 31.16°E | 59 | 0.75 \pm 0.20 | 2.45 \pm 1.08 | 0.34 \pm 0.13 |
| | | Isfjorden, Spitsbergen | 78.25°N, 15.51°E | 32 | 1.17 \pm 0.37 | 6.05 \pm 1.56 | 0.21 \pm 0.08 |
| | | Kara Gate, Novaya Zemlya | 71.42°N, 51.95°E | 40 | 0.64 \pm 0.20 | 1.65 \pm 0.52 | 0.41 \pm 0.13 |
| | | Oranskyi islands, Novaya Zemlya | 77.07°N, 67.64°E | 34 | 0.70 \pm 0.20 | 1.79 \pm 0.35 | 0.39 \pm 0.10 |
| | West Atlantic | Coats Island | 62.47°N, 83.10°W | 19 | 1.63 \pm 0.33 | 8.22 \pm 3.27 | 0.23 \pm 0.12 |
| | | Gannet Islands | 53.94°N, 56.56°W | 41 | 2.39 \pm 0.95 | 9.24 \pm 1.73 | 0.27 \pm 0.12 |
| | | Grimsey, Iceland | 66.54°N, 18.00°W | 11 | 1.52 \pm 0.24 | 5.56 \pm 1.04 | 0.28 \pm 0.08 |
| | | Jan Mayen | 71.03°N, 8.29°W | 65 | 1.63 \pm 0.32 | 5.70 \pm 1.77 | 0.32 \pm 0.14 |
| | | Kippaku | 73.73°N, 56.63°W | 20 | 1.79 \pm 0.44 | 7.38 \pm 2.32 | 0.26 \pm 0.07 |
| Langanes, Iceland | | 66.18°N, 15.99°W | 35 | 1.38 \pm 0.21 | 4.83 \pm 1.14 | 0.30 \pm 0.08 | |
| Thule, NW Greenland | | 77.47°N, 69.23°W | 17 | 2.62 \pm 0.72 | 8.14 \pm 2.73 | 0.35 \pm 0.12 | |
| Common guillemot | Pacific | Saint Lawrence | 63.40°N, 170.17°W | 36 | 0.59 \pm 0.17 | 1.42 \pm 0.63 | 0.48 \pm 0.21 |
| | East Atlantic | Bjørnøya | 74.50°N, 18.96°E | 48 | 0.67 \pm 0.13 | 1.95 \pm 0.55 | 0.37 \pm 0.12 |
| | | Cape Gorodetskiy | 69.58°N, 32.94°E | 40 | 0.64 \pm 0.14 | 1.79 \pm 0.42 | 0.37 \pm 0.08 |
| | | Hjelmsøya, N Norway | 71.11°N, 24.73°E | 58 | 0.85 \pm 0.20 | 2.85 \pm 0.94 | 0.32 \pm 0.10 |
| | | Sklinna | 64.74°N, 10.77°E | 20 | 0.94 \pm 0.35 | 3.17 \pm 0.90 | 0.31 \pm 0.10 |
| | | Faroës | 61.98°N, 6.65°W | 8 | 2.26 \pm 1.05 | 4.91 \pm 2.37 | 0.54 \pm 0.26 |
| | West Atlantic | Funk Island | 49.76°N, 53.18°W | 23 | 2.21 \pm 0.39 | 6.83 \pm 1.11 | 0.33 \pm 0.09 |
| | | Gannet Islands | 53.94°N, 56.56°W | 32 | 2.17 \pm 0.51 | 6.44 \pm 1.25 | 0.35 \pm 0.11 |
| | | Gull Island | 47.95°N, 53.04°W | 40 | 2.04 \pm 0.60 | 5.90 \pm 1.47 | 0.38 \pm 0.17 |
| | | Jan Mayen | 71.03°N, 8.29°W | 61 | 0.98 \pm 0.36 | 3.88 \pm 1.65 | 0.28 \pm 0.11 |
| Langanes, Iceland | | 66.18°N, 15.99°W | 37 | 1.11 \pm 0.39 | 3.70 \pm 0.92 | 0.31 \pm 0.10 | |

| | | | | | | | |
|-------------------|---------------|---------------------------------|--------------------------|----|-----------|-----------|-----------|
| Crested auklet | Pacific | Saint Lawrence | <i>63.40°N, 170.17°W</i> | 14 | 1.00±0.51 | 1.45±0.58 | 0.75±0.32 |
| Least auklet | Pacific | Saint George | <i>56.59°N, 169.61°W</i> | 10 | 1.58±1.22 | 2.38±1.29 | 0.72±0.35 |
| | | Saint Lawrence | <i>63.40°N, 170.17°W</i> | 20 | 2.56±1.13 | 2.75±1.01 | 0.96±0.31 |
| Little auk | East Atlantic | Bjørnøya | <i>74.50°N, 18.96°E</i> | 31 | 0.82±0.19 | 2.57±1.12 | 0.37±0.15 |
| | | Hooker Island, Franz Josef Land | <i>80.23°N, 53.02°E</i> | 67 | 0.81±0.21 | 1.73±0.92 | 0.57±0.26 |
| | | Hornsund, Spitsbergen | <i>76.97°N, 15.78°E</i> | 37 | 0.82±0.35 | 2.80±1.01 | 0.34±0.23 |
| | | Isfjorden, Spitsbergen | <i>78.25°N, 15.51°E</i> | 5 | 0.90±0.16 | 2.97±0.70 | 0.31±0.03 |
| | West Atlantic | Kap Hoegh, E Greenland | <i>70.72°N, 21.55°W</i> | 64 | 1.34±0.44 | 2.69±0.70 | 0.52±0.18 |
| | | Thule, NW Greenland | <i>77.47°N, 69.23°W</i> | 10 | 2.08±0.52 | 2.15±0.40 | 1.00±0.30 |
| Razorbill | East Atlantic | Hornøya, N Norway | <i>70.39°N, 31.16°E</i> | 39 | 0.79±0.31 | 4.68±1.54 | 0.20±0.14 |
| | West Atlantic | Gannet Islands | <i>53.94°N, 56.56°W</i> | 13 | 2.89±1.84 | 4.84±1.55 | 0.65±0.47 |
| Rhinoceros auklet | Pacific | Middleton | <i>59.44°N, 146.33°W</i> | 19 | 3.47±1.63 | 6.89±2.04 | 0.54±0.33 |
| Tufted puffin | Pacific | Aiktak Island | <i>54.18°N, 164.82°W</i> | 11 | 3.12±1.42 | 4.04±1.35 | 0.80±0.26 |

Table 2. Geographical variations in Hg concentrations (mean \pm SD - $\mu\text{g}\cdot\text{g}^{-1}$ dw) measured in body feathers (BF – representing exposure during the breeding period) and head feathers (HF – representing exposure during the non-breeding period). Breeding: non-breeding period Hg concentrations (mean \pm SD BF : HF) calculated from individual values ; n = samples size

| Species | Regions | n | Mean \pm SD BF | Mean \pm SD HF | BF : HF |
|----------------------|---------------|-----|------------------|------------------|-----------------|
| Ancient murrelet | Pacific | 5 | 2.64 \pm 1.00 | 3.69 \pm 1.18 | 0.81 \pm 0.52 |
| Brünnich's guillemot | Pacific | 50 | 0.80 \pm 0.31 | 1.83 \pm 1.23 | 0.69 \pm 0.49 |
| | East Atlantic | 325 | 0.72 \pm 0.27 | 2.45 \pm 1.61 | 0.36 \pm 0.16 |
| | West Atlantic | 208 | 1.83 \pm 0.67 | 6.84 \pm 2.55 | 0.29 \pm 0.12 |
| Common guillemot | Pacific | 36 | 0.59 \pm 0.17 | 1.42 \pm 0.63 | 0.48 \pm 0.21 |
| | East Atlantic | 166 | 0.76 \pm 0.23 | 2.37 \pm 0.90 | 0.34 \pm 0.11 |
| | West Atlantic | 201 | 1.60 \pm 0.74 | 5.03 \pm 1.88 | 0.33 \pm 0.14 |
| Crested auklet | Pacific | 14 | 1.00 \pm 0.51 | 1.45 \pm 0.58 | 0.75 \pm 0.32 |
| Least auklet | Pacific | 30 | 2.24 \pm 1.23 | 2.63 \pm 1.10 | 0.88 \pm 0.34 |
| Little auk | East Atlantic | 140 | 0.82 \pm 0.24 | 2.24 \pm 1.10 | 0.46 \pm 0.25 |
| | West Atlantic | 74 | 1.44 \pm 0.51 | 2.61 \pm 0.69 | 0.58 \pm 0.25 |
| Razorbill | East Atlantic | 39 | 0.79 \pm 0.31 | 4.68 \pm 1.54 | 0.20 \pm 0.14 |
| | West Atlantic | 13 | 2.89 \pm 1.84 | 4.84 \pm 1.55 | 0.65 \pm 0.47 |
| Rhinoceros auklet | Pacific | 19 | 3.47 \pm 1.63 | 6.89 \pm 2.04 | 0.54 \pm 0.33 |
| Tufted puffin | Pacific | 11 | 3.12 \pm 1.42 | 4.04 \pm 1.35 | 0.80 \pm 0.26 |

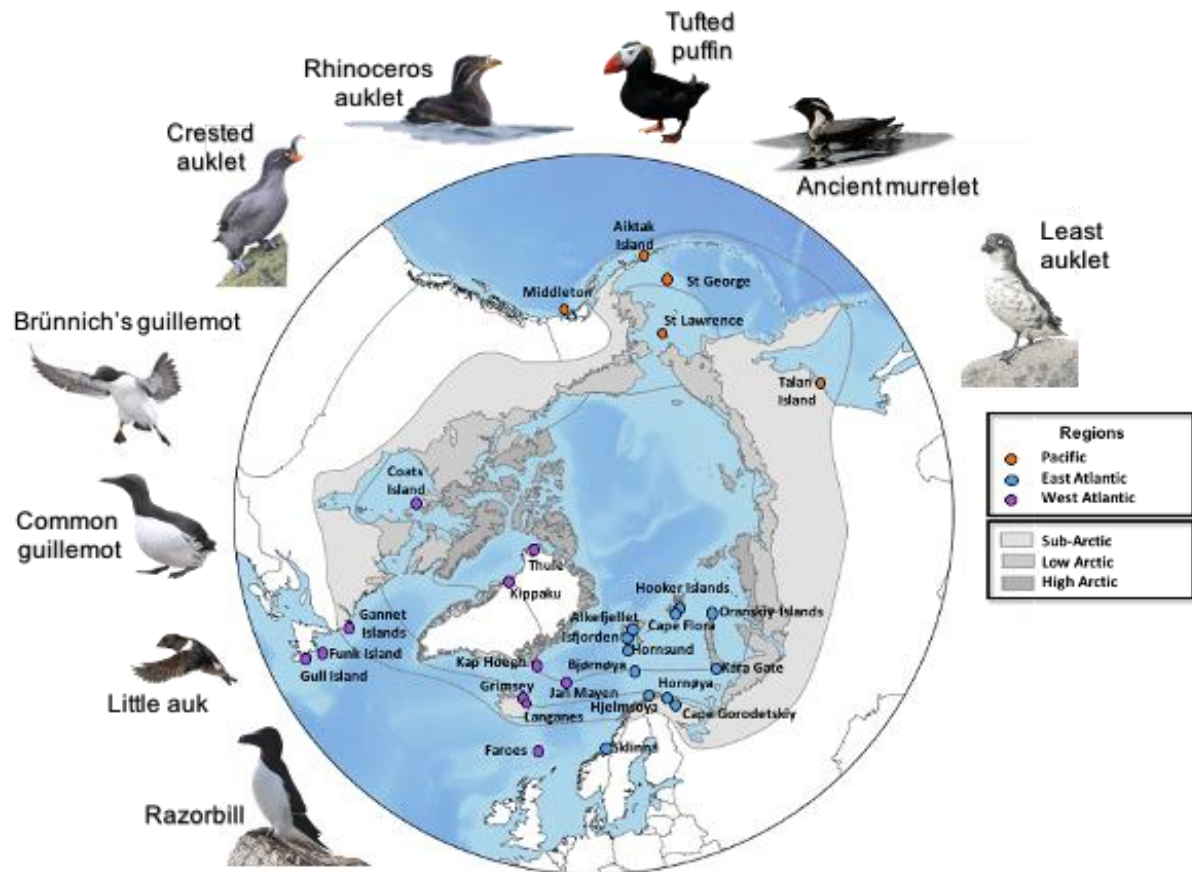


Figure 1. Location of the sampled breeding colonies locations of piscivorous and planktivorous alcids and sampling sites. The study sites were divided into three regions: Pacific (orange), East Atlantic (light blue), West Atlantic (purple). Colonies are colored based on the areas they belong to. Sub, Low and High Arctic are represented following the Conservation of Arctic Flora and Fauna delimitations (CAFF, 2001).

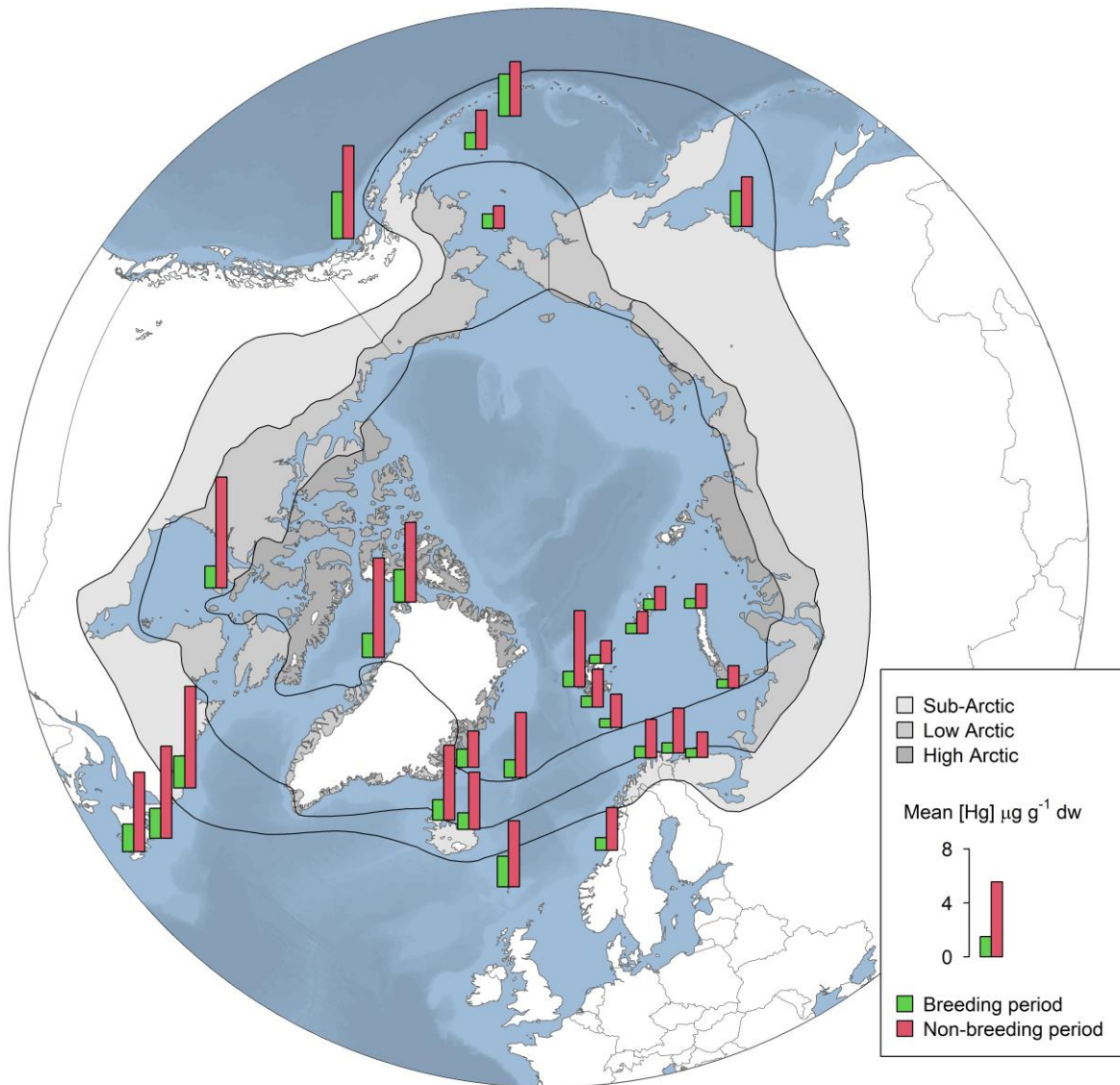


Figure 2. Hg concentrations during the breeding (body feathers - green) and non-breeding period (head feathers - red) for each study colony. Mean Hg concentrations and *SD* per species and colony are presented in Table 1 and Fig. SI 2. Sub, Low and High Arctic are represented following the Conservation of Arctic Flora and Fauna delimitations (CAFF, 2001).

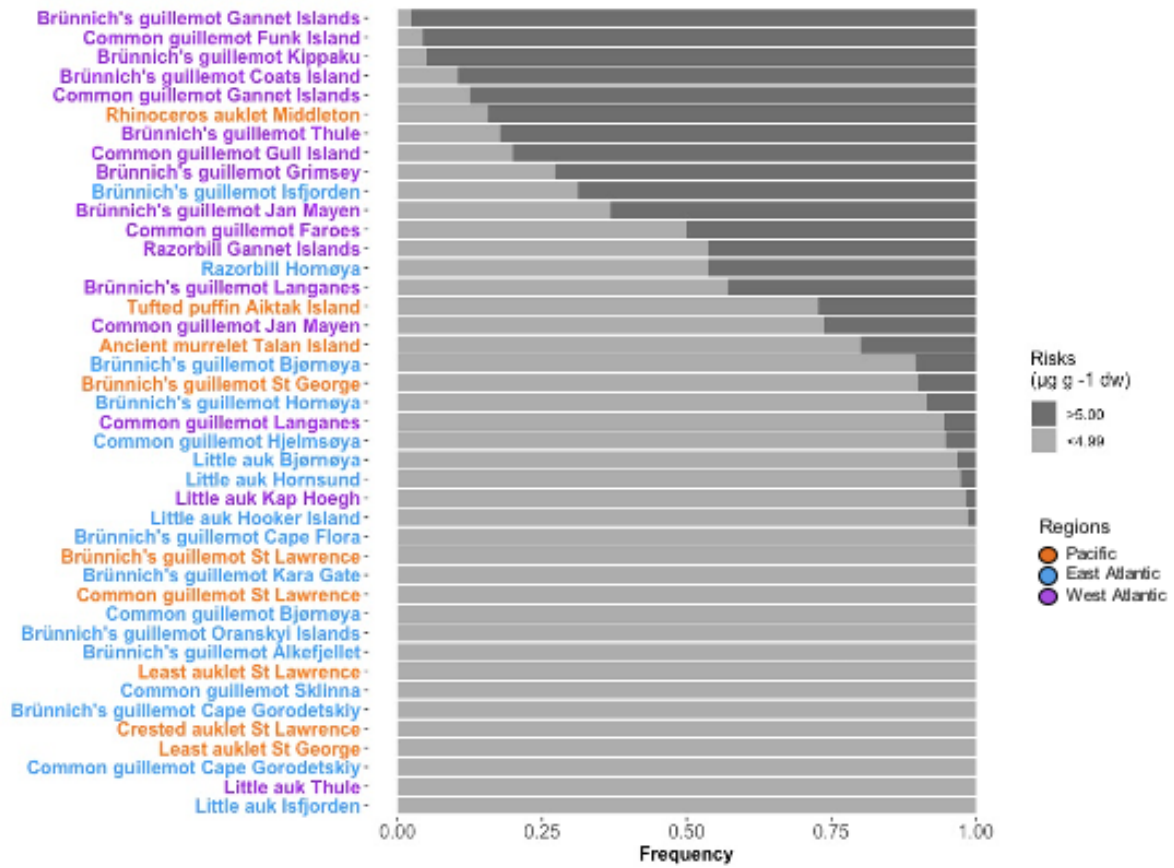


Figure 3. Frequency of individuals below (light grey) or above (dark grey) the toxicity threshold (Eisler, 1987) of 5.00 $\mu\text{g g}^{-1}$ dw in head feathers (representing exposure during the non-breeding season). The species and breeding colony names are colored by regions (see Fig. 1 - Pacific (orange), East Atlantic (light blue), West Atlantic (purple)). The sample size per species and colony can be found in Table 1.

Supplementary information

Table S1. Mean \pm SD Hg concentrations per species, regions, breeding sites, type of feathers (HF = Head Feathers, BF = Body feathers) and years.

| Species | Region | Breeding site | GPS Coordinates | Type of feathers | Mean \pm SD (n) | | | |
|--------------------|------------------|---------------------------------|-------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| | | | | | 2015 | 2016 | 2017 | Mean 2015-2017 |
| Ancient murrelet | Pacific | Talan Island | 59.18°N, 149.05°E | HF | NA | NA | 3.69 \pm 1.18 (5) | 3,69 \pm 1,18 (5) |
| | | | | BF | NA | NA | 2.64 \pm 1.00 (5) | 2,64 \pm 1.00 (5) |
| Brunnich guillemot | East Atlantic | Alkefjellet, Spitsbergen | 79.58°N, 18.51°E | HF | NA | 1.83 \pm 0.40 (17) | 1.54 \pm 0.53 (15) | 1,70 \pm 0,48 (32) |
| | | | | BF | NA | 0.63 \pm 0.22 (17) | 0.62 \pm 0.18 (15) | 0,63 \pm 0,20 (32) |
| | | Bjørnøya | 74.50°N, 18.96°E | HF | 2.84 \pm 1.69 (20) | 2.92 \pm 1.94 (18) | 3.03 \pm 1.59 (10) | 2,91 \pm 1,73 (48) |
| | | | | BF | 0.56 \pm 0.07 (20) | 0.44 \pm 0.07 (18) | 0.48 \pm 0.10 (10) | 0,50 \pm 0,09 (48) |
| | | Cape Flora, Franz Josef Land | 79.95°N, 50.09°E | HF | 1.60 \pm 0.43 (21) | 1.79 \pm 0.19 (20) | 1.51 \pm 0.35 (20) | 1,64 \pm 0,35 (61) |
| | | | | BF | 0.70 \pm 0.20 (21) | 0.77 \pm 0.19 (20) | 0.76 \pm 0.24 (20) | 0,74 \pm 0,21 (61) |
| | | Cape Gorodetskiy | 69.15°N, 35.95°E | HF | NA | NA | 2.06 \pm 0.39 (19) | 2.06 \pm 0.39 (19) |
| | | | | BF | NA | NA | 0.66 \pm 0.10 (19) | 0.66 \pm 0.10 (19) |
| | | Hornøya, N Norway | 70.39°N, 31.16°E | HF | 2.41 \pm 0.70 (20) | 2.28 \pm 1.28 (19) | 2.65 \pm 1.21 (20) | 2,45 \pm 1,08 (59) |
| | | | | BF | 0.78 \pm 0.24 (20) | 0.66 \pm 0.15 (19) | 0.80 \pm 0.17 (20) | 0,75 \pm 0,20 (59) |
| | | Isfjorden, Spitsbergen | 78.25°N, 15.51°E | HF | 5.71 \pm 1.33 (13) | 6.85 \pm 1.73 (11) | 5.50 \pm 1.39 (8) | 6,05 \pm 1,56 (32) |
| | | | | BF | 1.20 \pm 0.50 (13) | 1.26 \pm 0.29 (11) | 1.02 \pm 0.16 (8) | 1,17 \pm 0,37 (32) |
| | | Kara Gate, Novaya Zemlya | 71.42°N, 51.95°E | HF | 1.71 \pm 0.54 (20) | 1.58 \pm 0.51 (20) | NA | 1,65 \pm 0,52 (40) |
| | | | | BF | 0.71 \pm 0.19 (20) | 0.56 \pm 0.19 (20) | NA | 0,64 \pm 0,20 (40) |
| | | Oranskyi islands, Novaya Zemlya | 77.07°N, 67.64°E | HF | NA | 1.79 \pm 0.40 (16) | 1.79 \pm 0.32 (18) | 1,79 \pm 0,35 (34) |
| | | | | BF | NA | 0.64 \pm 0.20 (16) | 0.75 \pm 0.20 (18) | 0,70 \pm 0,20 (34) |
| Pacific | Saint George | 56.59°N, 169.61°W | HF | NA | NA | 3.42 \pm 1.10 (10) | 3.42 \pm 1.10 (10) | |
| | | | BF | NA | NA | 0.90 \pm 0.20 (10) | 0.90 \pm 0.20 (10) | |
| Pacific | Saint Lawrence | 63.40°N, 170.17°W | HF | NA | 1.40 \pm 0.92 (20) | 1.45 \pm 0.89 (20) | 1,43 \pm 0,89 (40) | |
| | | | BF | NA | 0.59 \pm 0.25 (20) | 0.96 \pm 0.31 (20) | 0,77 \pm 0,33 (40) | |
| West Atlantic | Coats Island | 62.47°N, 83.10°W | HF | 8.22 \pm 3.27 (19) | NA | NA | 8.22 \pm 3.27 (19) | |
| | | | BF | 1.63 \pm 0.33 (19) | NA | NA | 1.63 \pm 0.33 (19) | |
| | Gannet Islands | 53.94°N, 56.56°W | HF | 8.99 \pm 1.48 (17) | NA | 9.42 \pm 1.90 (24) | 9,24 \pm 1,73 (41) | |
| | | | BF | 2.86 \pm 1.24 (17) | NA | 2.06 \pm 0.47 (24) | 2,39 \pm 0,95 (41) | |
| | Grimsey, Iceland | 66.54°N, 18.00°W | HF | NA | NA | 5.56 \pm 1.04 (11) | 5,56 \pm 1,04 (11) | |
| | | | BF | NA | NA | NA | NA | |

| | | | | | | | | | |
|------------------|-------------------|---------------------|------------------|-------------------|----------------|----------------|----------------|----------------|----------------|
| | | | BF | NA | NA | 1.52±0.24 (11) | 1,52±0,24 (11) | | |
| | | Jan Mayen | 71.03°N, 8.29°W | HF | 5.41±1.26 (20) | 6.33±2.45 (25) | 5.21±0.70 (20) | 5,70±1,77 (65) | |
| | | | BF | 1.54±0.31 (20) | 1.84±0.25 (25) | 1.45±0.25 (20) | 1,63±0,32 (65) | | |
| | | Kippaku | 73.73°N, 56.63°W | HF | NA | 7.38±2.32 (20) | NA | 7.38±2.32 (20) | |
| | | | BF | NA | 1.79±0.44 (20) | NA | 1.79±0.44 (20) | | |
| | | Langanes, Iceland | 66.18°N, 15.99°W | HF | 4.57±1.19 (14) | 5.35±1.24 (12) | 4.53±0.69 (9) | 4,83±1,14 (35) | |
| | | | BF | 1.31±0.25 (14) | 1.48±0.17 (12) | 1.36±0.13 (9) | 1,38±0,21 (35) | | |
| | | Thule, NW Greenland | 77.47°N, 69.23°W | HF | 8.14±2.73 (17) | NA | NA | 8.14±2.73 (17) | |
| | | | BF | 2.62±0.72 (17) | NA | NA | 2.62±0.72 (17) | | |
| Common guillemot | East Atlantic | Bjørnøya | 74.50°N, 18.96°E | HF | 2.58±0.89 (5) | 1.80±0.30 (22) | 1.97±0.57 (21) | 1,95±0,55 (48) | |
| | | | | BF | 0.81±0.13 (5) | 0.70±0.13 (22) | 0.61±0.10 (21) | 0,67±0,13 (48) | |
| | | Cape Gorodetskiy | 69.58°N, 32.94°E | HF | NA | 1.84±0.47 (20) | 1.74±0.38 (20) | 1,79±0,42 (40) | |
| | BF | | | NA | 0.60±0.11 (20) | 0.68±0.16 (20) | 0,64±0,14 (40) | | |
| | | Hjelmsøya, N Norway | 71.11°N, 24.73°E | HF | 3.41±1.25 (19) | 2.50±0.61 (20) | 2.65±0.58 (19) | 2,85±0,94 (58) | |
| | BF | | | 0.93±0.16 (19) | 0.86±0.23 (20) | 0.75±0.18 (19) | 0,85±0,20 (58) | | |
| | | Sklinna | 64.74°N, 10.77°E | HF | NA | NA | 3.17±0.90 (20) | 3.17±0.90 (20) | |
| | BF | | | NA | NA | 0.94±0.35 (20) | 0.94±0.35 (20) | | |
| | | Pacific | Saint Lawrence | 63.40°N, 170.17°W | HF | NA | 1.27±0.37 (16) | 1.53±0.76 (20) | 1,42±0,63 (36) |
| | BF | | | | NA | 0.49±0.11 (16) | 0.67±0.16 (20) | 0,59±0,17 (36) | |
| | West Atlantic | Faroes | 61.98°N, 6.65°W | HF | NA | 5.51±2.77 (5) | 3.90±1.36 (3) | 4,91±2,37 (8) | |
| BF | | | | NA | 2.69±1.12 (5) | 1.55±0.32 (3) | 2,26±1,05 (8) | | |
| | | Funk Island | 49.76°N, 53.18°W | HF | NA | 6.83±1.11 (23) | NA | 6.83±1.11 (23) | |
| BF | | | | NA | 2.21±0.39 (23) | NA | 2.21±0.39 (23) | | |
| | | Gannet Islands | 53.94°N, 56.56°W | HF | 6.48±1.09 (12) | NA | 6.41±1.36 (20) | 6,44±1,25 (32) | |
| BF | | | | 2.25±0.58 (12) | NA | 2.12±0.48 (20) | 2,17±0,51 (32) | | |
| | | Gull Island | 47.95°N, 53.04°W | HF | NA | 5.20±1.56 (20) | 6.59±0.98 (20) | 5,90±1,47 (40) | |
| BF | | | | NA | 2.21±0.74 (20) | 1.87±0.35 (20) | 2,04±0,60 (40) | | |
| | | Jan Mayen | 71.03°N, 8.29°W | HF | 3.97±1.22 (19) | 4.59±2.08 (20) | 3.15±1.26 (22) | 3,88±1,65 (61) | |
| BF | | | | 0.99±0.36 (19) | 1.01±0.33 (20) | 0.94±0.41 (22) | 0,98±0,36 (61) | | |
| | Langanes, Iceland | 66.18°N, 15.99°W | HF | NA | 4.04±0.78 (18) | 3.37±0.93 (19) | 3,70±0,92 (37) | | |
| BF | | | NA | 1.13±0.29 (18) | 1.09±0.48 (19) | 1,11±0,39 (37) | | | |

| | | | | | | | | |
|---------------------|---------------------------------|-------------------------|--------------------------|----------------|----------------|----------------|----------------|----------------|
| Crested Auklet | Pacific | Saint Lawrence | <i>63.40°N, 170.17°W</i> | HF | NA | 1.38±0.80 (6) | 1.51±0.40 (8) | 1,45±0,58 (14) |
| | | | | BF | NA | 0.59±0.22 (6) | 1.31±0.45 (8) | 1.00±0,51 (14) |
| Least auklet | Pacific | Saint George | <i>56.59°N, 169.61°W</i> | HF | NA | NA | 2.38±1.29 (10) | 2.38±1.29 (10) |
| | | | | BF | NA | NA | 1.58±1.22 (10) | 1.58±1.22 (10) |
| Least auklet | | Saint Lawrence | <i>63.40°N, 170.17°W</i> | HF | NA | NA | 2.75±1.01 (20) | 2.75±1.01 (20) |
| | | | | BF | NA | NA | 2.56±1.13 (20) | 2.56±1.13 (20) |
| Little auk | East Atlantic | Bjørnøya | <i>74.50°N, 18.96°E</i> | HF | NA | 2.23±1.24 (10) | 2.74±1.05 (21) | 2,57±1,12 (31) |
| | | | | BF | NA | 0.84±0.24 (10) | 0.81±0.16 (21) | 0,82±0,19 (31) |
| | Hooker Island, Franz Josef Land | <i>80.23°N, 53.02°E</i> | HF | 1.64±0.98 (26) | 2.05±0.59 (19) | 1.56±1.03 (22) | 1,73±0,92 (67) | |
| | | | BF | 0.74±0.09 (26) | 0.89±0.26 (19) | 0.83±0.23 (22) | 0,81±0,21 (67) | |
| | Hornsund, Spitsbergen | <i>76.97°N, 15.78°E</i> | HF | NA | 2.85±1.00 (20) | 2.75±1.05 (17) | 2,80±1,01 (37) | |
| | | | BF | NA | 0.91±0.41 (20) | 0.71±0.20 (17) | 0,82±0,35 (37) | |
| | Isfjorden, Spitsbergen | <i>78.25°N, 15.51°E</i> | HF | NA | 2.81±0.34 (2) | 3.07±0.94 (3) | 2,97±0,70 (5) | |
| | | | BF | NA | 0.84±0.03 (2) | 0.94±0.20 (3) | 0,90±0,16 (5) | |
| | West Atlantic | Kap Hoegh, E Greeland | <i>70.72°N, 21.55°W</i> | HF | 3.06±0.86 (20) | 2.53±0.61 (20) | 2.51±0.48 (24) | 2,69±0,70 (64) |
| | | | | BF | 1.25±0.53 (20) | 1.44±0.41 (20) | 1.34±0.38 (24) | 1,34±0,44 (64) |
| Thule, NW Greenland | <i>77.47°N, 69.23°W</i> | HF | 2.15±0.40 (10) | NA | NA | 2.15±0.40 (10) | | |
| | | BF | 2.08±0.52 (10) | NA | NA | 2.08±0.52 (10) | | |
| Razorbill | East Atlantic | Hornøya, N Norway | <i>70.39°N, 31.16°E</i> | HF | NA | 4.89±1.47 (20) | 4.47±1.62 (19) | 4,68±1,54 (39) |
| | | | | BF | NA | 0.86±0.39 (20) | 0.71±0.19 (19) | 0,79±0,31 (39) |
| | West Atlantic | Gannet Islands | <i>53.94°N, 56.56°W</i> | HF | 4.84±1.55 (13) | NA | NA | 4,84±1,55 (13) |
| | | | | BF | 2.89±1.84 (13) | NA | NA | 2,89±1,84 (13) |
| Rhinoceros auklet | Pacific | Middleton | <i>59.44°N, 146.33°W</i> | HF | NA | NA | 6.89±2.04 (19) | 6.89±2.04 (19) |
| | | | | BF | NA | NA | 3.47±1.63 (19) | 3.47±1.63 (19) |
| Tufted puffin | Pacific | Aiktak Island | <i>54.18°N, 164.82°W</i> | HF | NA | NA | 4.04±1.35 (11) | 4.04±1.35 (11) |
| | | | | BF | NA | NA | 3.12±1.42 (11) | 3.12±1.42 (11) |

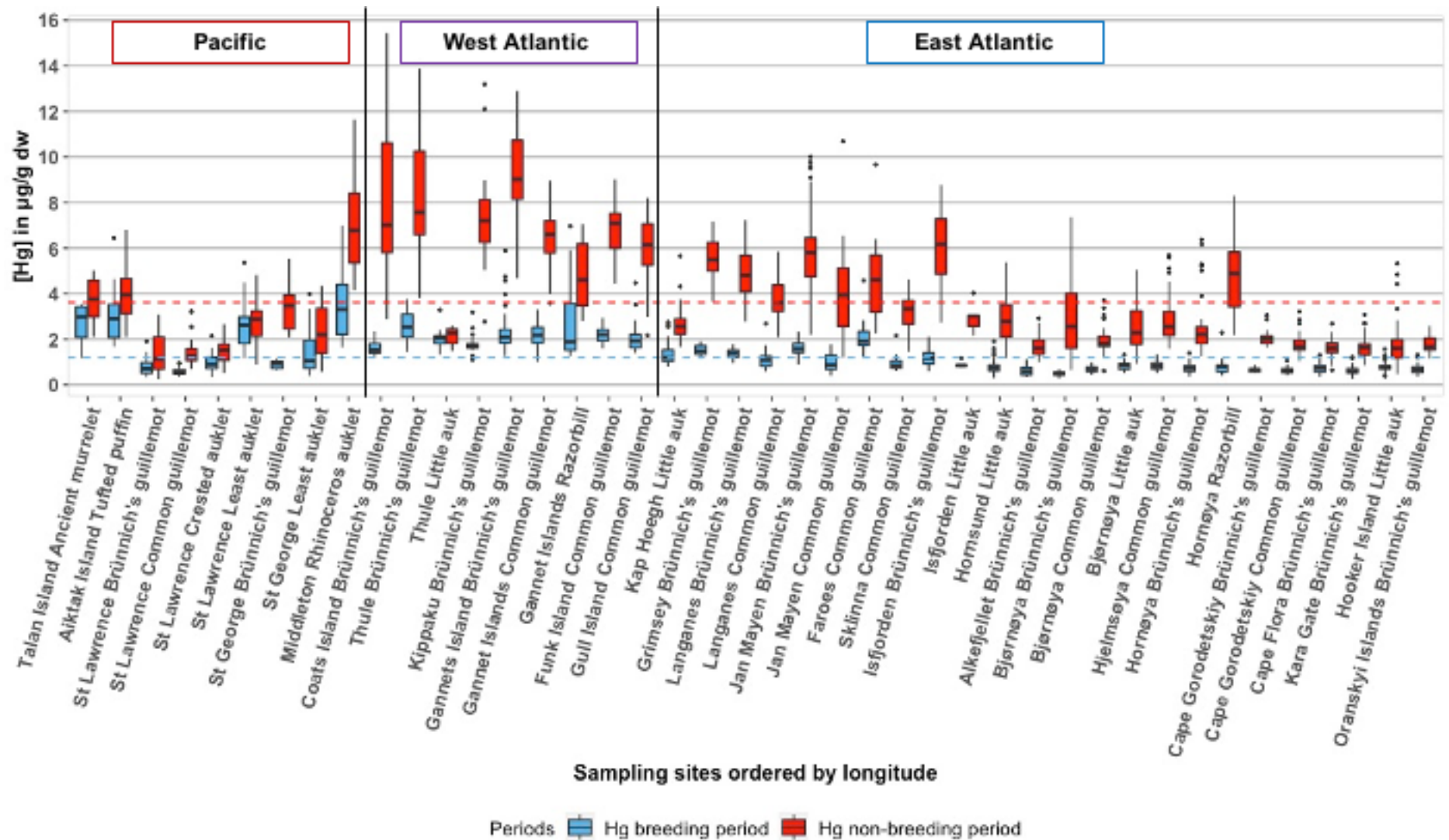


Figure S2. Mean Hg concentrations in Body Feathers (blue - representing the breeding period) and Head Feathers (red – representing the non-breeding period) for each study colony and species along a longitudinal gradient, from the Aleutian Islands to Talan Island. Mean Hg concentrations for BF ($1.20 \pm 0.83 \mu\text{g/g}$, blue) and HF ($3.56 \pm 2.37 \mu\text{g/g}$, blue) are represented by dashed lines. Mean Hg concentrations and SD per species are presented in Table 1 and SI Table1. Boxplots show the median (horizontal black line within the boxes), 1st and 3rd quartiles, the minimum (1st-1.5x interquartile range) and maximum (3rd-1.5x interquartile range) concentrations (lower and upper whiskers) and outliers.

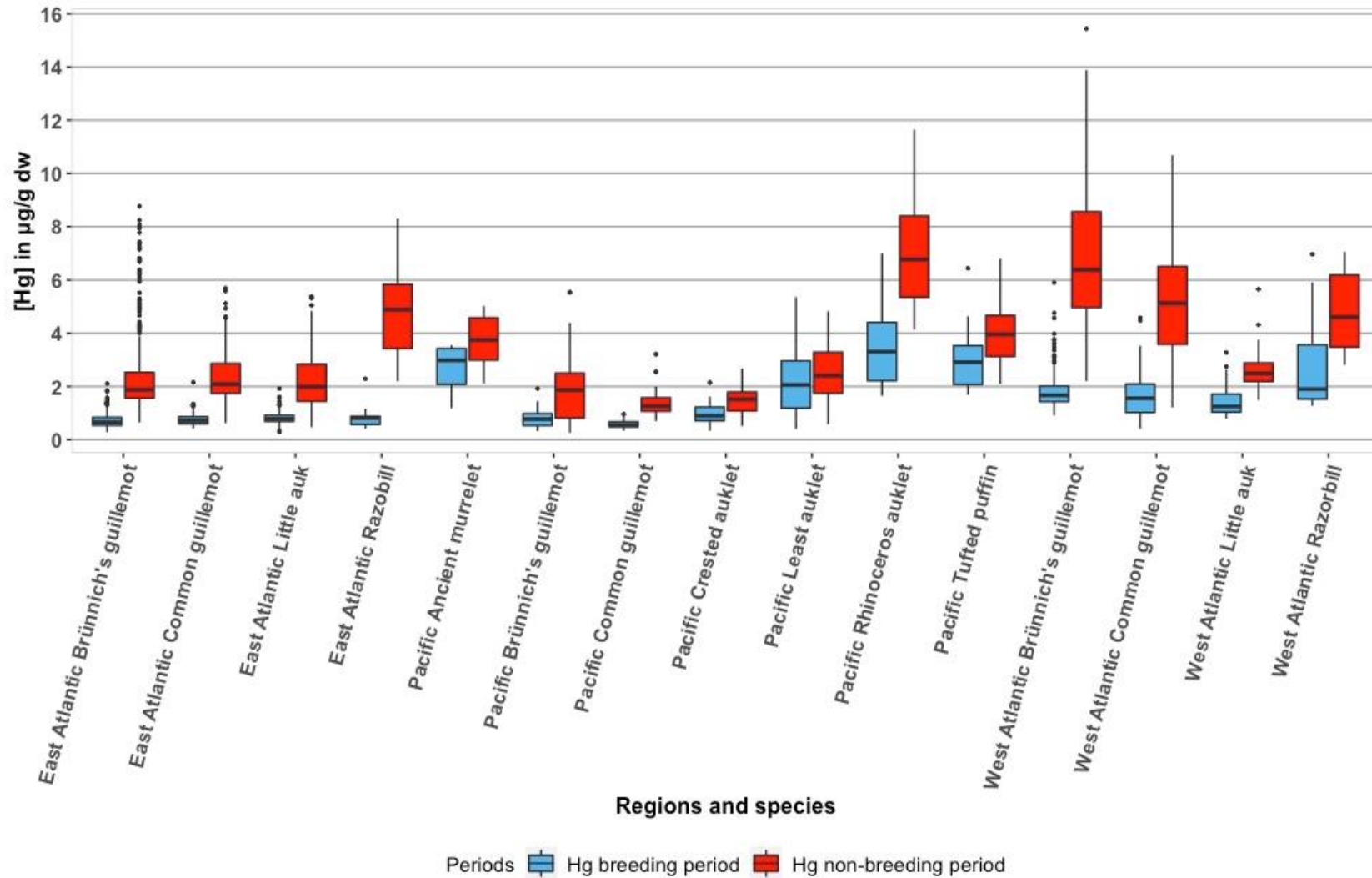


Figure S3. Mean Hg concentrations in Body Feathers (blue - representing the breeding period) and Head Feathers (red – representing the non-breeding period) for each region and species. Mean Hg concentrations and SD per species and regions are presented in Table 2. Boxplots show the median (horizontal black line within the boxes), 1st and 3rd quartiles, the minimum (1st-1.5x interquartile range) and maximum (3rd-1.5x interquartile range) concentrations (lower and upper whiskers) and outliers.

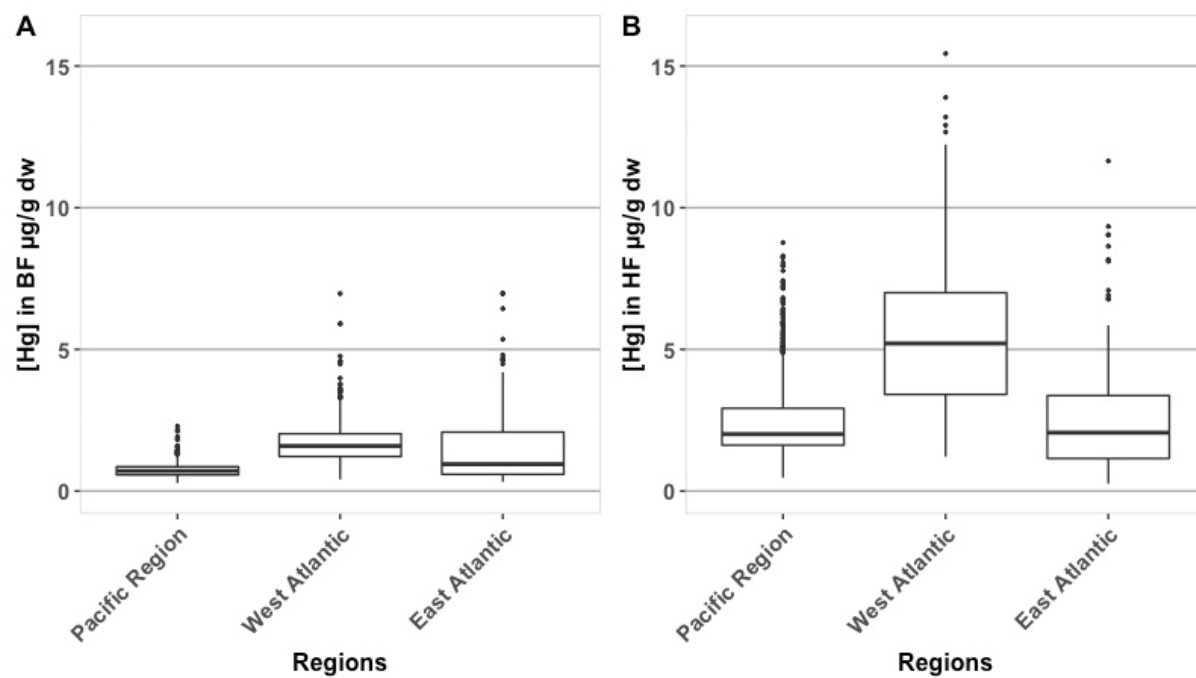


Figure S4. Representation of Hg concentrations ($\mu\text{g/g dw}$) in A) body feathers (BF – representing the breeding period), B) head feathers (HF – representing the non-breeding period) per regions.

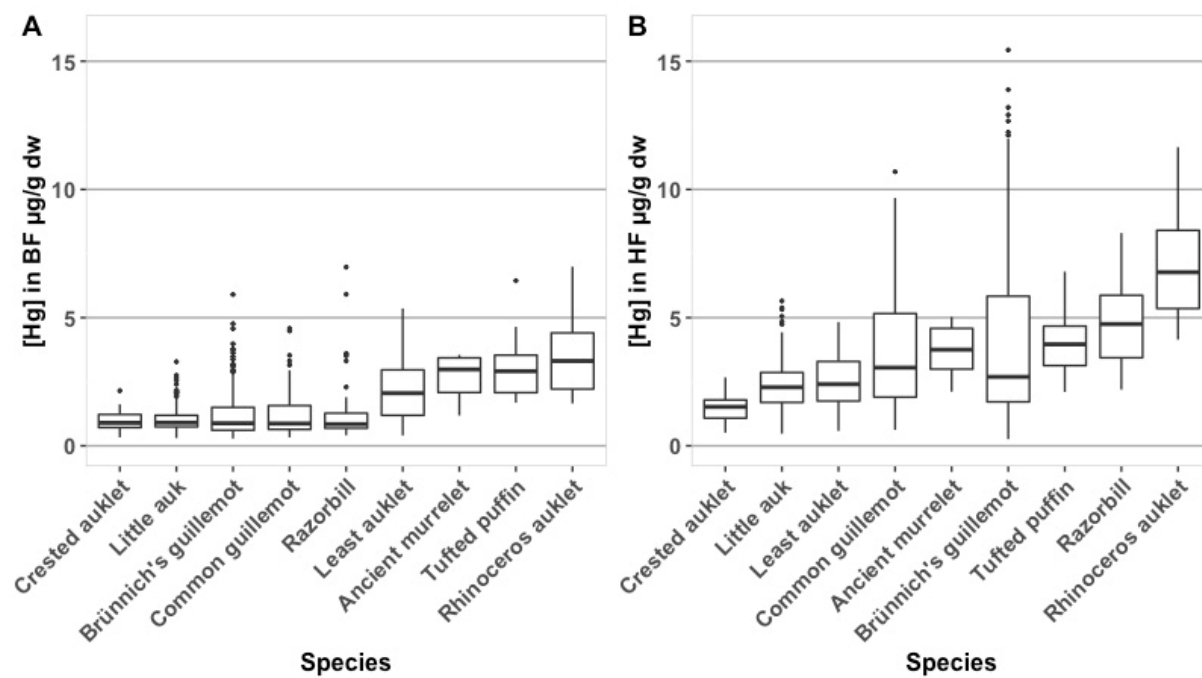


Figure S5. Representation of Hg concentrations ($\mu\text{g/g dw}$) in A) body feathers (BF – representing the breeding period), B) head feathers (HF – representing the non-breeding period) per species

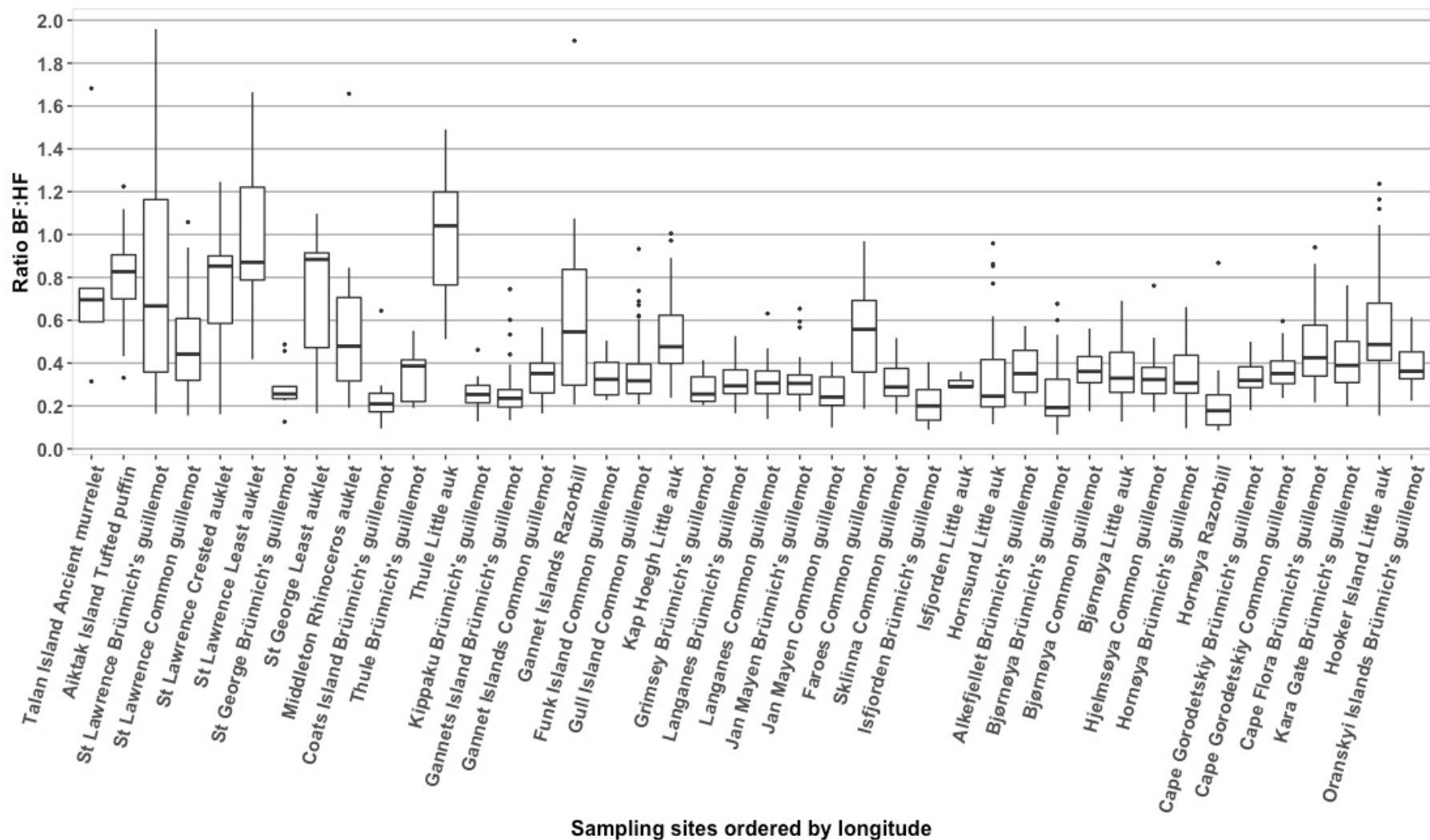


Figure S6. *Breeding : non-breeding period Hg concentrations.* Boxplots show the median (horizontal black line within the boxes), 1st and 3rd quartiles, the minimum (1st-1.5x interquartile range) and maximum (3rd-1.5x interquartile range) concentrations (lower and upper whiskers) and outliers.