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Title:	Interannual variations in winter distribution impact individual seabird exposure to mercury
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2   mercury

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Running page head: Interannual variation in winter Hg concentrations

1   **Abstract:** 250 words

2   Migratory seabirds are exposed to various pollutants throughout their annual cycle.

3   Among them, mercury (Hg) is of particular concern given potentially large impacts on animals'

4   health. Recent studies suggest that winter is a critical period for seabirds when contamination

5   by Hg can be much higher than other times of year. However, individuals within and among

6   species can have different migration strategies that could affect their Hg exposure. Here, we

7   combined multi-year individual tracking data and Hg measurements from six Arctic seabird

8   species. We investigated whether inter-annual variations in individual winter contamination

9   with Hg was related to their fidelity to a wintering site over years. First, our results show that

10   Hg concentrations above toxicity threshold (i.e., 5 µg g $^{-1}$ dw in feathers) were observed in

11   variable proportions according to species. Second, our results show that individuals with high

12   fidelity to a wintering grounds had more similar Hg concentrations between years compared to

13   individuals with low fidelity, suggesting an effect of their migratory strategy on Hg

14   contamination. Further, we found that the directional change in wintering areas between years

15   influenced their Hg contamination, highlighting an additional effect of seabirds' winter

16   distribution. More specifically, individuals migrating to the northwest direction of a previous

17   wintering ground tend to be more contaminated compared to the eastern directions. Those

18   results confirm spatial differences in Hg concentration throughout the North-Atlantic Arctic

19   and an east-west gradient increase in Hg concentrations. This will nonetheless require more

20   large-scale ecotoxicological studies at smaller spatial resolution to confirm such a trend.

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1. Introduction

Mercury (Hg) is a highly toxic pollutant for humans and wildlife causing severe health impairments, even at low concentrations (e.g. Wolfe et al. 1998, Tan et al. 2009, Dietz et al. 2019). Even if Hg is naturally emitted by volcanoes or weathering of rocks (UNEP 2013), anthropogenic activities have been responsible for an increase in Hg concentrations in the environment since the industrial revolution (e.g. threefold increase in surface marine waters ; Lamborg et al. 2014). This pollutant is dramatically problematic in aquatic environments where it can easily transform into its toxic form (methylmercury – MeHg) by microorganisms (Hsu-Kim et al. 2013). This form is the most bioavailable to biota and is incorporated in food chains in which it biomagnifies (i.e., increase within trophic chains) making top predators the most contaminated species of their ecosystems. Hg is thus of major environmental concern worldwide, yet its spatial distribution is highly heterogeneous at the global scale (Zhang et al.

2020). Indeed, while Hg is mostly emitted in mid-Northern latitude, its physico-chemical characteristics allow it to be transported over large distances through atmospheric, oceanic or riverine currents and Hg is thus redistributed at the global scale (AMAP 2011, Sonke et al. 2018). As a consequence, Dietz et al. (2000) found that polar bears (*Ursus maritimus*) from Northwest Greenland had Hg concentrations approximately 10 times higher than individuals from Northeast Greenland. A negative latitudinal gradient in Hg concentrations has also been found in the southern hemisphere in 35 albatross populations (Cherel et al., 2018). Therefore, different spatial distributions can lead to highly different Hg exposure and contamination, potentially resulting in contrasting risks for individual health (Ackerman et al. 2016, Dietz et al. 2019). Among marine top predators, seabirds show some of the highest Hg concentrations (Atwell et al. 1998), with deleterious effects on behavior, physiology or reproduction reported in some species and populations. For example, amongst adult male black-legged kittiwakes (*Rissa tridactyla*) breeding in Svalbard, individuals with the highest Hg concentrations were more likely to neglect their eggs (Tartu et al. 2015). Similarly in birds, high Hg concentrations have been related to a reduction of hatchability and clutch size (Dietz et al. 2013, Ackerman et al. 2016), in addition to a decline in breeding success and population growth rate (Goutte et al. 2014). Understanding the relationship between seabird distributions and contamination by Hg is therefore important for the conservation of these species for which many populations are declining and deserve special attention (Croxall et al. 2012, Paleczny et al. 2015).

1   Seabirds are typically migratory species, many travelling hundreds to thousands of

2 kilometers every year to reach their wintering grounds (e.g. Egevang et al., 2010, Frederiksen

3 et al., 2016; McFarlane Tranquilla et al., 2014). However, these migratory strategies can be

4 highly variable between individuals, conditioning their winter distribution and thus potentially

5 their exposure to Hg. First, individuals from the same population can use contrasting wintering

6 areas, at relative distance from their breeding colonies (Quillfeldt et al., 2010). For instance,

7 red-legged kittiwakes (*Rissa brevirostris*) breeding at Saint George Island (Pribilof Islands –

8 Bering Sea) overwinter from the Eastern Bering Sea to the Sea of Okhotsk, with higher Hg

9 concentrations measured in individuals distributed in southern areas (Fleishman et al., 2019).

10 Second, each individual itself can change its migratory route between years and thus can have

11 contrasting fidelity to its wintering grounds. Hence, species can show high (e.g. common eiders

12 *Somateria mollissima*, atlantic puffin *Fratercula arctica*, european shags *Phalacrocorax*

13 *aristotelis*; Guilford et al. 2011, Petersen et al. 2012, Grist et al. 2014, Hanssen et al. 2016), low

14 (e.g. thin-billed prion *Pachyptila belcheri*; Quillfeldt et al. 2010) or variable (e.g. Brünnich's

15 *Uria lomvia* and common guillemots *Uria aalge*, northern fulmars *Fulmarus glacialis*; (Hatch

16 et al. 2010, McFarlane Tranquilla et al. 2014, Orben et al. 2015) individual fidelity to a

17 wintering ground. Together, these different migratory patterns and overwintering strategies

18 may affect the long-term exposure of seabirds to Hg and differentially impact their health,

19 reproduction and consequently their population dynamics (Vindenes et al. 2008). However, no

1   study has previously considered the link between consistency in winter distribution and

2   contamination with Hg.

3   By combining individual tracking data with Hg analyses and focusing on some of the

4   most abundant Arctic seabird species (black-legged kittiwake, Brünnich's guillemot, common

5   eider, common guillemot, little auk *Alle alle*, northern fulmar), we studied interannual fidelity

6   to wintering grounds and tested the hypothesis that this fidelity determines the consistency of

7   their Hg contamination. More specifically, we first predicted that species feeding at the highest

8   trophic levels during the non-breeding period (i.e., common guillemot, northern fulmar) have

9   higher Hg concentrations than species feeding at the lowest trophic levels (i.e., black-legged

10   kittiwake, Brünnich's guillemot, common eider, little auk). Then, we predicted that 1)

11   individuals with a low fidelity to a wintering ground from one year to the other show more

12   variable Hg contamination in comparison to faithful ones, 2) winter distribution affects Hg

13   contamination (Renedo et al. 2020), 3) species covering larger wintering areas (i.e., Brünnich's

14   guillemot, common guillemot, northern fulmar) experience more inter-individual variations in

15   Hg contamination than those distributed over more restricted wintering areas (i.e., common

16   eider, black-legged kittiwake, little auk).

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18   **2. Material and methods**

19   **2.1. Species, study sites and sampling collections**

From June 2014 to July 2016, adult black-legged kittiwakes (n = 13), Brünnich's guillemots (n = 65), common eiders (n = 22), common guillemots (n = 39), little auks (n = 6) and northern fulmars (n = 38) were equipped with light level geolocators (GLS – Global Location Sensor) during chick rearing at 17 breeding colonies widely distributed from Iceland to Russia (Fig. 1) and for two or three years (details in Table S1 and Fig. S1). Geolocators were retrieved in each subsequent breeding seasons (details in Table S2). After retrieval, seabirds were re-equipped in order to have at least their winter distribution for two years. Geolocators are low-weight instrument that record ambient light-levels over multiple years, which later can be converted into geographical locations (Wilson et al. 1992). However, the positional precision derived from light-level data is considered low (Lisokvski et al. 2012), and is mostly suited for studies of large-scale movements and distribution such as seabird migrations. The distribution extracted from the geolocators deployed in June 2014 - July 2014, June - July 2015 and June - July 2016 represent November 2014 - January 2015 (winter$_t$), November 2015 – January 2015 (winter$_{t+1}$) and November 2016 – January 2017 (winter$_{t+2}$), respectively (see Fig. 2).

In order to investigate individual Hg contamination during winter (i.e., non-breeding) periods, feathers were collected at the retrieval of geolocators (Fig. 2). Feathers are useful tissues to monitor Hg contamination during the winter period in seabirds (Albert et al., 2019). Indeed, during the plumage synthesis (molt), a large proportion of the Hg accumulated in internal organs since the last molt, but also Hg from the current diet, is excreted into the feathers (Honda et al. 1986, Braune 1987, Agusa et al. 2005) (Fig. 2). Hence, feathers inform about Hg

1   accumulated by an individual between two molting sequences, and specifically during the non-

2   breeding period according to selected feathers and molting pattern (see Albert et al, 2019). For

3   example, alcids and larids undergo a rapid total molt at the end of the breeding period (during

4   September or October) resulting in the winter plumage and a partial molt (cheek, neck, throat

5   in alcids, neck and back in larids) at the end of the winter period (during March or April)

6   resulting in the nuptial plumage (Gaston & Jones 1998, Cramp & Simmons 1983). Female

7   common eiders undergo a total molt at the end of the winter period and a partial molt at the end

8   of the breeding period (Baldassarre 2015, Goudie et al. 2020). Hence, head, back and belly

9   feathers provide information on Hg contamination specifically during the winter period in

10   alcids, black-legged kittiwakes and common eiders, respectively. Northern fulmars undergo

11   one total molt per year at the end of the breeding period, lasting from mid-August to late

12   October (Grissot et al. 2020). Recent studies indicated that Hg concentrations in fulmar body

13   feathers reflect inter-individual variations in Hg contamination during the non-breeding period

14   (Quinn et al. 2016). Therefore, body feathers (i.e., belly) were used to assess Hg contamination

15   during the non-breeding period for northern fulmars.

16   Therefore, at the retrieval of geolocators, we collected head feathers from Brünnich's

17   guillemots, common guillemots and little auks, and body feathers on black-legged kittiwakes

18   (back feather), common eiders (belly feather), and northern fulmars (belly feather) representing

19   Hg contamination during the preceding non-breeding period (Fig. 2). Feathers were stored in

20   plastic bags at ambient temperature until Hg analyses.

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2   **2.2.Spatial analyses**

3   The geolocators data were first converted into positional data by identifying the timing of

4   twilights, using a threshold method, from which we estimated two daily latitudes from the

5   length of the night and day, and two daily longitudes from time of apparent midnight and noon,

6   following procedures described in Merkel et al. (2016) and Bråthen et al. (2020). Since the

7   geolocation approach requires light to estimate seabird positions, for individuals located above

8   70 degrees north, positions could not be obtained for days or weeks around winter solstice

9   because of an apparent absence of daylight above this latitude (details in Table S3 and Fig. S2).

10   The timing of Arctic seabird molt and migration can vary slightly between breeding

11   sites (Frederiksen et al. 2012, Fort et al. 2013a). Nonetheless, to allow for inter-population

12   comparisons, and based on the knowledge about when seabirds are on their wintering ground

13   (Fort et al. 2012, 2013a, Frederiksen et al. 2016) we homogenized the winter period within

14   species. Therefore, we considered that seabirds were at their wintering ground from November

15   to January for black-legged kittiwakes (Frederiksen et al. 2012), Brünnich's and common

16   guillemots (Fort et al. 2013b, Frederiksen et al. 2016, Merkel et al. 2019), common eiders

17   (Hanssen et al. 2016), and little auks (Fort et al. 2012). As northern fulmars have been observed

18   returning back to their colonies as early as January in the literature (Macdonald 1980) and in

19   our dataset, the non-breeding period was defined from November to December in this species.

1 We then calculated a median winter position (i.e., median latitude and median longitude) for

2 each individual for each year, to be used in further analyses.

3 **2.3. Hg analyses**

4 Prior to Hg analyses, feathers were cleaned to remove external contamination. Feathers were

5 plunged into a 2:1 chloroform:methanol solution for three minutes in an ultrasonic bath, rinsed

6 twice in a methanol solution and dried at 45°C for 48 hours. Hg analyses were performed on a

7 ~ 0.20 – 1.00 mg subsample of a pool of three homogenized feathers, using an Advanced

8 Mercury Analyser spectrophotometer (Altec AMA 254 – detection limit of 0.05 ng). The

9 analysis of each sample was repeated (two to three times) until the relative standard deviation

10 for two subsamples was <10 %. Mean concentration for these two subsamples was then used

11 for statistical analyses. Prior to Hg analyses, blanks were run and, to ensure the accuracy of

12 measurements, certified reference materials (lobster Hepatopancreas TORT-3; NRC, Canada;

13 reference values were of 0.29 ± 0.02 µg g^{-1} dry weight (dw) SD, mean measured $\pm SD = 0.30 \pm$

14 0.002 µg g^{-1} dw, recovery $= 102.0 \pm 1.5$ %; and lobster hepatopancreas TORT-2; 0.27 ± 0.06

15 µg g^{-1} dw SD, mean measured $= 0.26 \pm 0.01$ µg g^{-1} dw SD, recovery $= 97.3 \pm 1.0$%) were used

16 every fifteen samples. Hg concentrations are expressed in µg g^{-1} dry weight (dw).

17 **2.4. Statistical analyses**

18 Variations in Hg concentrations (hereafter [Hg]) in the different species were analyzed

19 as a function of seabird fidelity to a wintering ground. To do so, the difference in [Hg] between

20 winters (i.e. delta [Hg], hereafter Δ [Hg]) as well as the distance (in km) between individual

1   winter median positions was determined at the individual scale. As some individuals have been

2   tracked in two non-consecutive years, the variations (Δ [Hg] and distance) have been studied

3   between winter $_t$ – winter $_{t+1}$, winter $_t$ – winter $_{t+2}$, winter $_{t+1}$ – winter $_{t+2}$. Phillips and colleagues

4   (2004) showed that the accuracy of seabird positions using light levels geolocators is 186 ± 114

5   (SD) km. Given this accuracy, the scale of the study area, and although the different study

6   species can be more or less mobile during winter, we considered the limit of 372 km to

7   discriminate individuals with high or low fidelity to a wintering ground. Based on this,

8   individual seabirds fell into the "high fidelity" group when the difference between two winter

9   median positions were < 372 km apart. Conversely, seabirds were considered to belong to the

10   "low fidelity" group when they wintered in distinctly different geographical areas between

11   years (i.e. winter median positions > 373 km apart). To ensure the defined threshold of 372 km

12   did not significantly affect our results and conclusions, the same analyses were performed using

13   thresholds of 200, 300, 350, 450 and 500 km (Table S4).

14   We performed Linear Mixed Models (LMMs) (R package "lme4") (Bates et al., 2015)

15   to investigate differences in Δ [Hg] (using absolute values) between low and high-fidelity

16   groups and species. To take into account the non-independence in our data (i.e., repeated Δ [Hg]

17   measures for 36 individuals), we included the bird identity (i.e., Bird ID) as a random factor.

18   The full model (Table 2 – LMM1) was: Δ [Hg] ~ fidelity (Low/High) + species + fidelity

19   (Low/High) * species + (1| Bird ID). We used a square root transformation for Δ [Hg] to meet

20   the parametric assumptions of normality and homoscedasticity of residual distribution. In a

1   second step, we considered the low fidelity group only and used the longitude and latitude of

2   seabird winter median positions during the different winters to determine the direction from the

3   previous to the newly used wintering ground (North-West, North-East, South-West or South-

4   East). As we were interested in the direction of migration and the variation of Δ [Hg] (i.e.,

5   decreasing or increasing depending on the direction), we worked on Δ [Hg] raw values.

6   Therefore, we used Linear Mixed Models (LMMs) to test if Δ [Hg] changed depending on

7   overwintering area (i.e., direction), distances (in km) and species. The individual identity was

8   added as a random effect to take into account the non-independence in our data (i.e., repeated

9   Δ [Hg] measures). The full model was (Table 2 – LMM2): Δ [Hg] ~ direction (North-West,

10   North-East, South-West or South-East) + distance (in km) + species + direction * species +

11   distance * species + (1| Bird ID). Residuals from this model were normally distributed and

12   homoscedastic, thus no transformation of Δ [Hg] was needed. The common eiders were not

13   added to this analysis as all individuals showed high fidelity to their wintering grounds. Finally,

14   we tested [Hg] differences between species using mixed models, with the full model being [Hg]

15   ~ species + (1| Bird ID). We used the Akaike's information criteria (AIC) to select the best

16   model (Burnham & Anderson 2002). If the difference in AIC between two models is <2, the

17   models are considered to have equal statistical support and in case of nested models, the

18   simplest (i.e., most parsimonious) was preferred. All statistical analyses were performed with

19   R (version 4.0.3) and RStudio version 1.3.1093 (R Core Team 2017).

20

3. Results

Our results showed a variation in Hg concentrations between species with the highest mean concentration for the Brünnich's guillemots followed by the black-legged kittiwakes, common guillemots, little auks and northern fulmars. The common eiders presented the lowest mean Hg concentrations (Table 1, Fig. S3).

Our results indicate that Δ [Hg] varied among species and fidelity (i.e., low or high) for their wintering ground. Indeed, our model selection indicates that the best model included these two variables, without interaction (Table 2) with the variation of Δ [Hg] impacted by the species ($F_{5,193.96} = 3.70$; $p = 0.003$) and their fidelity to a wintering ground ($F_{1,252.92} = 6.10$; $p = 0.014$). More specifically, the Δ [Hg] decrease from low (intercept = 1.11 ± 0.12 µg g^{-1} dw) to high fidelity (estimate = 0.97 ± 0.06 µg g^{-1} dw). The lack of interaction between the fidelity and the species suggested that the difference between low and high fidelity is the same for all species, except common eiders which only present individuals with high fidelity to a wintering ground (Table 1, Figs. 3 & S4). Indeed, seabirds with low fidelity presented higher variation of Δ [Hg] compared to seabirds with high fidelity to a wintering ground. The results were similar when considering other thresholds (Table S4). Black-legged kittiwakes, common guillemots and little auks (species for which only two years of tracking information were available) presented an equal number of individuals with either a low or a high fidelity to a wintering ground. Most of the Brünnich's guillemots were faithful to a wintering ground, while most of the northern fulmars showed low fidelity (Table 1).

1   Within the low fidelity group, our results indicate that Δ [Hg] varied among direction,

2   distances and species. Indeed, our model selection indicates that the model with the lowest

3   AICc includes the direction, distance and interaction between distance and species. This

4   interaction decreased the model AICc by less than 2 units and seems mostly driven by a

5   difference between the common guillemot and little auk and all the other species (Fig. 4, Fig.

6   S5). More specifically, the Δ [Hg] significantly decreased with the distance for the common

7   guillemot, little auk and northern fulmar, compared to the other species (Fig. S6). This result is

8   supported by a lower AIC (AIC = 357.68) for a model where species is under two modalities

9   (Species 1 = common guillemots + little auks + northern fulmars *versus* Species 2 = black-

10   legged kittiwakes + Brünnich's guillemots). The model also indicates that the Δ Hg variation

11   was the highest when individuals changed their winter distribution to the northwest direction

12   and the lowest when individuals changed to the southeast direction, and these effects were

13   similar among species (i.e., the interaction between direction and species was not selected;

14   Table 2).

15   **4. Discussion**

16   Seabirds can adopt different non-breeding strategies and show contrasting fidelity to their

17   wintering sites, at species, population and individual scales (Hatch et al. 2010, McFarlane

18   Tranquilla et al. 2014, Orben et al. 2015, Hanssen et al. 2016, Merkel et al. 2020). Hence, while

19   some seabirds use the same wintering ground every year, others change and occupy different

20   places from one year to the other. Such different strategies can have large effects on their

1   exposure to environmental stressors, particularly pollutants, which could in turn impact their

2   contamination level, body condition, reproduction and ultimately their population dynamics.

3   By combining for the first time the use of tracking devices on multiple species with Hg analyses,

4   we demonstrated that inter-annual fidelity of individuals to wintering areas affect their

5   contamination level, with a major effect of the location of these areas in the North Atlantic and

6   sub-Arctic.

7   Interannual changes in Hg contamination might be driven by several non-exclusive factors,

8   including different diets, changing migratory strategies between years (i.e., resident *vs*

9   migrating, fidelity to wintering sites) or different regions used during winter in the North-

10   Atlantic Arctic. Hg concentrations in Arctic seabirds, like in other predators, are closely related

11   to their diet. For example, previous studies found that Hg concentrations increased in sub-

12   Antarctic seabirds, from those feeding at low trophic levels (i.e. on crustaceans) to those feeding

13   at higher trophic levels (i.e. on fish, squid and carrion consumers) (Carravieri et al. 2014).

14   During winter, common guillemots and northern fulmars generally feed on relatively high

15   trophic levels (mainly fish; Erikstad 1990, Gaston & Jones 1998) compared to Brünnich's

16   guillemots, black-legged kittiwakes, little auks, (mainly zooplankton; Karnovsky et al. 2008,

17   Fort et al. 2010, Frederiksen et al. 2012, Reiertsen et al. 2014, Gaston & Jones 1998) or common

18   eiders (bivalves; Goudie et al. 2020). Therefore, higher Hg concentrations, if explained by diet

19   differences only, should be expected in common guillemots and northern fulmars, followed by

20   Brünnich's guillemots, black-legged kittiwakes, little auks and then common eiders. However,

1   our results showed a different contamination pattern, with values consistent with the existing

2   knowledge (Albert et al., 2019). Indeed, we found that the Brünnich's guillemots had the

3   highest mean Hg concentrations, followed by black-legged kittiwakes, little auks, common

4   guillemots and northern fulmars being more contaminated than the common eiders (Table 1).

5   Additionally, our results showed that Hg concentrations above 5 µg g $^{-1}$ dw in feathers, the

6   threshold above which the first deleterious effects are observed in birds (Eisler, 1987), were

7   observed in variable proportions according to the species with 2% in northern fulmars, 4% in

8   common guillemots, 15% in black-legged kittiwakes and 37% in Brünnich's guillemots.

9   Altogether, these results suggest an interspecies variation in Hg toxicity and that interannual

10   variations in winter Hg contamination cannot be explained by the diet alone, but potentially by

11   seabird movements and distribution.

12   Our study focused on six species breeding at 17 different colonies, showing contrasting

13   fidelity to their wintering grounds. The common eider was the only species for which all

14   individuals showed a high fidelity to their wintering grounds, overwintering year after year in

15   the same areas. This is the case for both eiders breeding in the Low Arctic and resident year-

16   round, and populations from the High Arctic migrating to southernly, but constant, locations

17   during winter (Bustnes & Erikstad 1993, Hanssen et al. 2016). As a consequence, all individual

18   common eiders in this study showed similar constant and low Hg concentrations from one year

19   to the other. The five other study species encompassed individuals with low or high fidelity to

20   their wintering grounds (Table 1). Accordingly, seabirds with low inter-annual fidelity had a

higher Δ [Hg] mean than individuals with high inter-annual fidelity (Figs. 2 and A1),

confirming an effect of adopted migratory movements on seabird winter Hg contamination, and

suggesting spatial variations over the North-Atlantic Arctic.

In addition, in individuals experiencing low fidelity to a wintering ground, we found

that while the effect of the direction was similar between species, the effect of the distance was

not. More specifically, regardless of the species, our results indicated that Hg concentrations

tended to be higher when individuals migrated northwest of their previous wintering ground.

In comparison, Hg concentrations tended to be lower when migrating in the three other

directions (Figs. 3, Fig. S2). We found that when the distance to their previous wintering ground

increased, Hg concentrations decreased for common guillemots, little auks and northern

fulmars, and increased for black-legged kittiwakes and Brünnich's guillemots. Overall, this

supports the hypothesis of a heterogeneous distribution of Hg in the marine environment at

large spatial scale. In the present study, wintering Brünnich's guillemots and northern fulmars

covered a large part of the North-Atlantic, while common guillemots, black-legged kittiwakes

and little auks were distributed over a part of it only (Fig. 1, Fig. S1). With such a large-scale

study, seabirds found on the eastern (or western) areas for the first year of our assessment had

more chance to migrate in the western (or eastern) areas the following years and such a point

was not possible to incorporate into the statistical analysis. But despite these spatial differences,

our results showed that their Hg concentrations varied the same way between years according

to changes in their distribution and directions, strengthening our interpretation. We therefore

1   believe that our results confirm the role of seabird winter movements and distribution on their

2   contamination to Hg and highlight spatial differences in Hg concentrations through the North-

3   Atlantic Arctic, with an increasing east-west gradient. Previous studies on the Arctic wildlife

4   also suggested a positive east-west Hg gradient during spring and summer (breeding period),

5   with species distributed in the Canadian Arctic being more contaminated than those in the

6   European Arctic (Provencher et al. 2014, AMAP 2018, Albert et al. 2019). The present data set

7   covers a large but fragmented part of the North-Atlantic Arctic. But a more precise dataset

8   could allow us to confirm and extend such a trend in the North-Atlantic Arctic.

9   Seabirds are exposed to various environmental threats during the winter period (e.g. oil

10   spills, storms, contaminants; Frederiksen et al. 2012, Petersen et al. 2012, Fort et al. 2014,

11   Guéry et al. 2017) which might impact their condition, survival or subsequent reproduction

12   (Votier et al. 2005, Mesquita et al. 2015, Anker-Nilssen et al. 2016). The large-scale distribution

13   of Hg in the marine environment is assumed to be relatively stable over years (Mason et al.

14   1998). Hence, high fidelity to their wintering ground likely expose seabirds to repeated threats

15   and constant pollution issues associated to this specific area (e.g. human industries), possibly

16   impacting their short-term survival and reproduction with long-term impacts on their

17   population dynamics (Guéry et al. 2017, 2019). On the other hand, seabirds wintering

18   constantly in an area with low level of such threats might only be exposed to limited acute

19   pollution events, which could have severe effects on their survival and subsequent reproduction

20   but limited long-term impacts on their populations. Conversely, seabirds with low fidelity to

wintering grounds and winter distribution will exploit contrasting wintering environments with

different Hg concentrations years after years (Quillfeldt et al., 2010) which might lower long-

term risks associated with Hg contamination. Therefore, the inter-individual variability in Hg

concentrations depending on their winter ground fidelity should be taken into account while

studying population dynamic of migratory species as it could have large effects on the survival,

reproduction and subsequently on population dynamics.

Our study demonstrates that individual migratory strategy and the consistency of

occupied wintering grounds affect their exposure to Hg and likely of other contaminants. Given

the high diversity of areas used by single individuals over two to three winters only, we urge to

extend ecotoxicological studies investigating seabird winter contamination and its impacts in

order to consider these interannual variations and fully apprehend the risks that Hg and other

pollutants represent for seabirds and other marine organisms.

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Table 1. Difference in Hg concentrations (mean ± *SD* Δ[Hg] in μg/g dw, absolute value) within low and high fidelity group (consistency in wintering grounds used, see methods for details), in addition to the mean [Hg] ± *SD* per species (pool of winter $_{t,t+1}$ and $_{t+2}$; details are summarized in Table S1). The sample size represents the number of individuals presenting a high or a low fidelity to a wintering ground between winter. 17 individuals (i.e., 7 Brünnich's guillemots, 6 common guillemots and 4 northern fulmars) with low fidelities have been found to have either low fidelity for all the interannual observations of the present study, either low fidelity for two inter-years and high fidelity for two other inter-years. Therefore, those birds have been added to both groups. ND: no data available.

Species	|Δ[Hg]| in High fidelity group (n)	Range	|Δ[Hg]| in Low fidelity group (n)	Range	Mean [Hg] ± SD (n)	Nb of individual with high fidelity	Nb of individual with low fidelity	Nb of individual with both fidelities	Total sample size (i.e., number of individuals)
Black-legged kittiwakes	1.03 ± 0.98 (5)	0.39 - 2.71	1.48 ± 0.91 (8)	0.02 - 2.82	3.10 ± 1.67	5	8	0	13
Brünnich's guillemots	1.00 ± 0.89 (47)	0.00 - 3.79	1.31 ± 1.22 (25)	0.07 - 4.64	4.09 ± 2.24	40	18	7	65
Common eiders	0.27 ± 0.28 (22)	0.03 - 1.23	ND	ND	0.81 ± 0.29	22	0	0	22
Common guillemots	0.68 ± 0.76 (24)	0.07 - 3.73	1.23 ± 0.86 (21)	0.04 - 2.95	2.73 ± 1.18	18	15	6	39
Little auks	1.26 ± 0.93 (3)	0.37 - 2.22	1.17 ± 1.21 (3)	0.15 - 2.50	2.93 ± 1.23	3	3	0	6
Northern fulmars	0.81 ± 0.74 (17)	0.14 - 2.78	0.97 ± 0.81 (25)	0.01 - 3.37	2.34 ± 1.16	13	21	4	38

Table 2. AIC model ranking for winter [Hg] within species and individuals with low fidelity to their wintering ground from one year to the other. The LMM results are presented in a decreasing order, from the best model (lowest AIC and Δ AIC) explaining variations in Δ [Hg]. The table includes the AICc, the Δ AICc and the AIC weight. Individuals (Bird ID) were added as a random effect.

Variable	Model	Number of parameters	AICc	Δ AICc	AIC Weight
LMM 1					
|Δ [Hg]|	~ fidelity + species + (1|Bird ID)	10	287.20	0.00	0.82
	~ species + (1|Bird ID)	9	290.97	3.77	0.13
	~ fidelity * species + (1| Bird ID)	14	294.02	6.83	0.03
	~ fidelity + (1| Bird ID)	5	294.39	7.19	0.02
	~ 1	4	302.58	15.38	0.00
LMM 2					
Δ [Hg]	~ direction + distance * species + (1|Bird ID)	16	362.88	0.00	0.52
	~ direction + distance + species + (1|Bird ID)	12	364.22	1.34	0.27
	~ direction * species+ (1|Bird ID)	20	366.42	3.54	0.09
	~ direction * species + distance + (1|Bird ID)	21	367.70	4.82	0.05
	~ direction * species + distance * species + (1|Bird ID)	24	368.01	5.13	0.04
	~ direction + species + (1|Bird ID)	11	368.65	5.76	0.03
	~ direction + distance + (1|Bird ID)	8	372.90	10.02	0.00
	~ direction + (1|Bird ID)	7	378.83	15.95	0.00
	~ distance + species + (1|Bird ID)	8	380.36	17.48	0.00
	~ distance * species + (1|Bird ID)	13	380.47	17.59	0.00
	~ species + (1|Bird ID)	8	380.73	17.85	0.00
	~ distance + (1|Bird ID)	5	385.98	23.10	0.00
	~1	4	387.74	24.86	0.00

Captions of Figures:

Fig. 1. Winter distribution of black-legged kittiwakes, Brünnich's guillemots, common eiders, common guillemots, little auks (median position from November to January) and northern fulmars (median position from November to December). Sampling sites (Table S1) are identified by (▲). Details per species are presented in Fig. S1.

Fig. 2. Schematic representation of i) [Hg] into internal organs along the time and during periods of the annual cycle ($_t$ and $_{t+1}$), ii) distribution (from geolocators) for winter $_t$ and $_{t+1}$ and iii) [Hg] measured in feathers representing the non-breeding period for winter $_t$ and $_{t+1}$. This schematic representation is based on the samples of 2015 and 2016.

Fig. 3. Δ [Hg] (absolute – see methods) between one year and the other for seabirds with low (> 372 km) or high fidelity (< 372 km) for their wintering grounds. Each species is represented by a specific color (see legend). The mean Δ [Hg] is represented by a red dotted line (detailed boxplot per species is provided in Fig. S1). Boxplots show the median (horizontal black line within the boxes), 1st and 3rd quartiles, the minimum (1st-1.5x interquartile range) and maximum (3dt-1.5x interquartile range) concentrations (lower and upper whiskers) and outliers.

Fig. 4. Δ [Hg] in the fourth different directions (NE=North-East, NW=North-West, SE=South-East, SW=South-West) in species and individuals with low fidelity to their wintering grounds. The mean Δ [Hg] is represented by a red dotted line. The zero axis is represented by a black dotted line (detailed boxplot per species is in Fig. S4). Boxplots show the median (horizontal black line within the boxes), 1st and 3rd quartiles, the minimum (1st-1.5x interquartile range) and maximum (3dt-1.5x interquartile range) concentrations (lower and upper whiskers) and outliers.

Fig. 1

Fig. 2

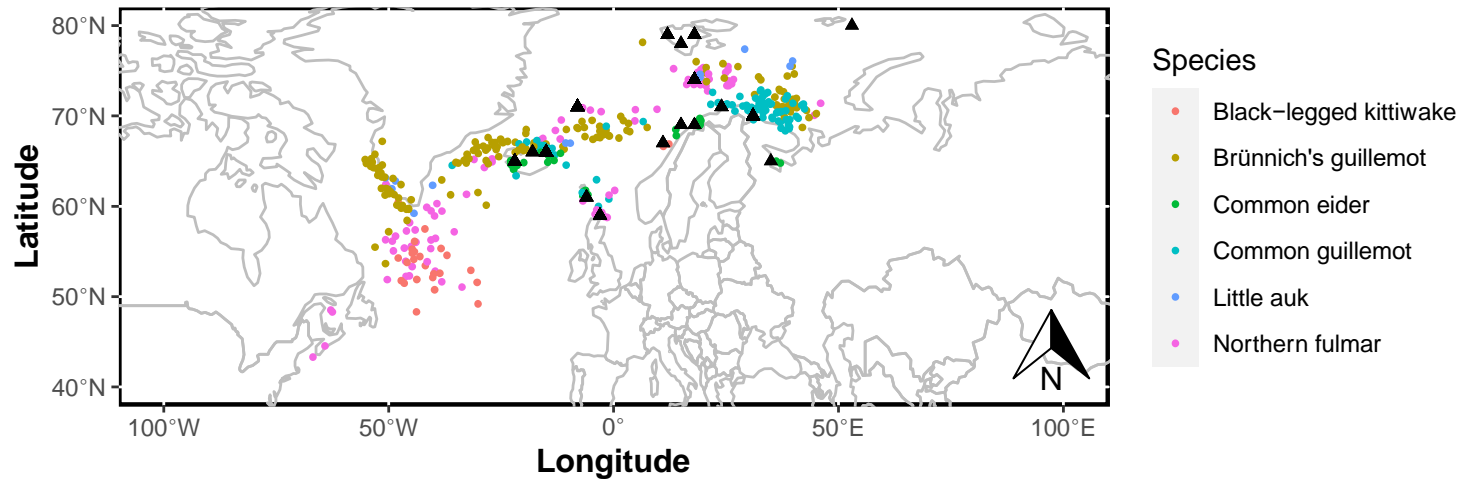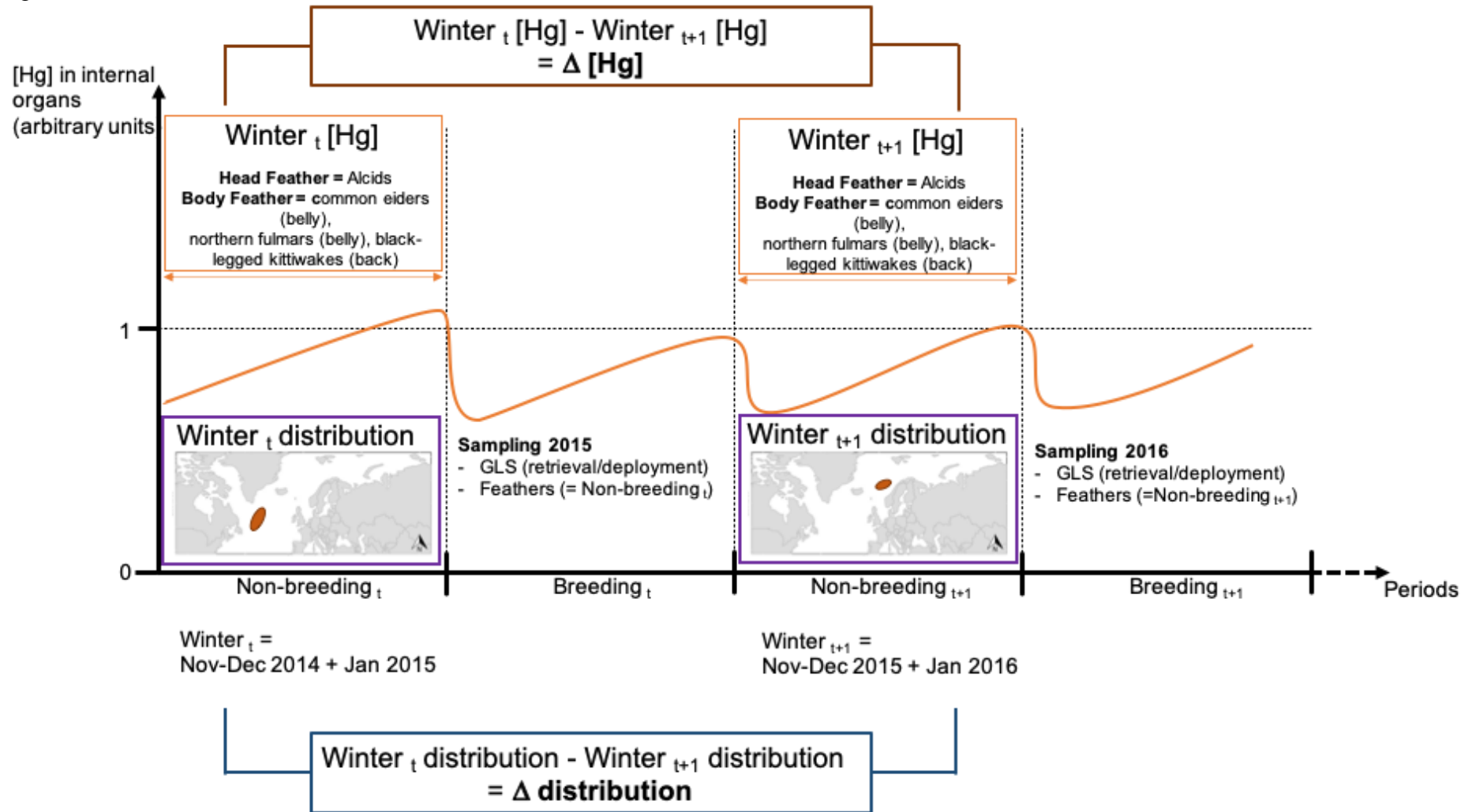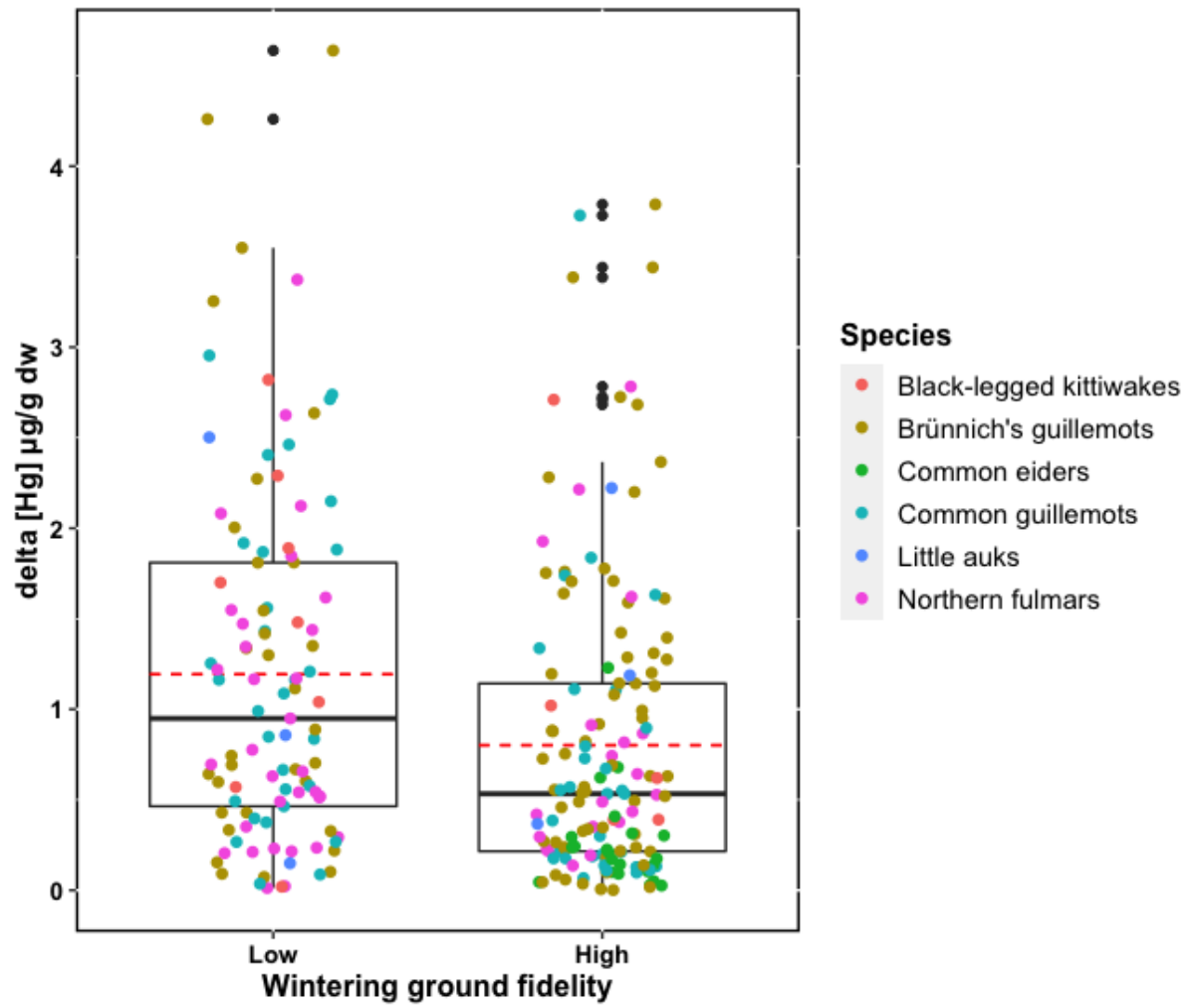Winter $_t$ [Hg] - Winter $_{t+1}$ [Hg]
= Δ [Hg]

[Hg] in internal organs (arbitrary units

Winter $_t$ [Hg]

Head Feather = Alcids
Body Feather = common eiders (belly),
northern fulmars (belly), black-legged kittiwakes (back)

Winter $_{t+1}$ [Hg]

Head Feather = Alcids
Body Feather = common eiders (belly),
northern fulmars (belly), black-legged kittiwakes (back)

1

Winter $_t$ distribution

Sampling 2015
- GLS (retrieval/deployment)
- Feathers (= Non-breeding $_t$)

Winter $_{t+1}$ distribution

Sampling 2016
- GLS (retrieval/deployment)
- Feathers (=Non-breeding $_{t+1}$)

0

Non-breeding $_t$ | Breeding $_t$ | Non-breeding $_{t+1}$ | Breeding $_{t+1}$ | Periods

Winter $_t$ =
Nov-Dec 2014 + Jan 2015

Winter $_{t+1}$ =
Nov-Dec 2015 + Jan 2016

Winter $_t$ distribution - Winter $_{t+1}$ distribution
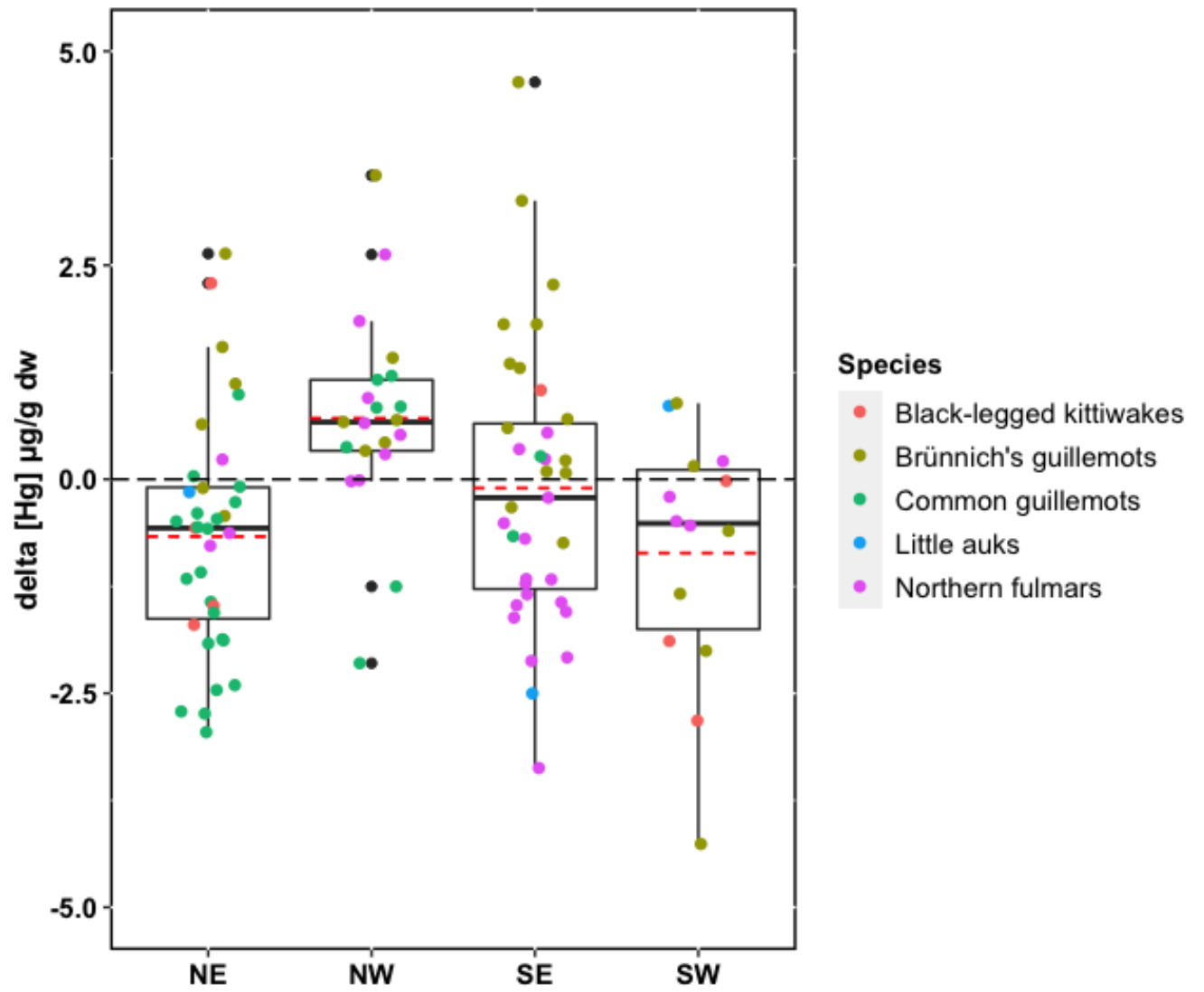= Δ distribution

30

Fig. 3

Fig. 4

1   **Title:** Interannual variations in winter distribution impact individual seabird exposure to

2   mercury

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Running page head: Interannual variation in winter Hg concentrations

1   **Abstract:** 250 words

2   Migratory seabirds are exposed to various pollutants throughout their annual cycle.

3   Among them, mercury (Hg) is of particular concern given potentially large impacts animals'

4   health. Recent studies suggest that winter is a critical period for seabirds when contamination

5   by Hg can be much higher than other times of year. However, individuals within and among

6   species can have different migration strategies that could affect their Hg exposure. Here, we

7   combined multi-year individual tracking data and Hg measurements from six Arctic seabird

8   species. We investigated whether inter-annual variations in individual winter contamination

9   with Hg was related to their fidelity to a wintering site over years. First, our results show that

10   Hg concentrations above toxicity threshold (i.e., 5 µg g $^{-1}$ dw in feathers) were observed in

11   variable proportions according to species. Second, our results show that individuals with high

12   fidelity to a wintering grounds had more similar Hg concentrations between years compared to

13   individuals with low fidelity, suggesting an effect of their migratory strategy on Hg

14   contamination. Further, we found that the directional change in wintering areas between years

15   influenced their Hg contamination, highlighting an additional effect of seabirds' winter

16   distribution. More specifically, individuals migrating to the northwest direction of a previous

17   wintering ground tend to be more contaminated compared to the eastern directions. Those

18   results confirm spatial differences in Hg concentration throughout the North-Atlantic Arctic

19   and an east-west gradient increase in Hg concentrations. This will nonetheless require more

20   large-scale ecotoxicological studies at smaller spatial resolution to confirm such a trend.

1. **Introduction**

Mercury (Hg) is a highly toxic pollutant for humans and wildlife causing severe health impairments, even at low concentrations (e.g. Wolfe et al. 1998, Tan et al. 2009, Dietz et al. 2019). Even if Hg is naturally emitted by volcanoes or weathering of rocks (UNEP 2013), anthropogenic activities have been responsible for an increase in Hg concentrations in the environment since the industrial revolution (e.g. threefold increase in surface marine waters ; Lamborg et al. 2014). This pollutant is dramatically problematic in aquatic environments where it can easily transform into its toxic form (methylmercury – MeHg) by microorganisms (Hsu-Kim et al. 2013). This form is the most bioavailable to biota and is incorporated in food chains in which it biomagnifies (i.e., increase within trophic chains) making top predators the most contaminated species of their ecosystems. Hg is thus of major environmental concern worldwide, yet its spatial distribution is highly heterogeneous at the global scale (Zhang et al.

2020). Indeed, while Hg is mostly emitted in mid-Northern latitude, its physico-chemical characteristics allow it to be transported over large distances through atmospheric, oceanic or riverine currents and Hg is thus redistributed at the global scale (AMAP 2011, Sonke et al. 2018). As a consequence, Dietz et al. (2000) found that polar bears (*Ursus maritimus*) from Northwest Greenland had Hg concentrations approximately 10 times higher than individuals from Northeast Greenland. A negative latitudinal gradient in Hg concentrations has also been found in the southern hemisphere in 35 albatross populations (Cherel et al., 2018). Therefore, different spatial distributions can lead to highly different Hg exposure and contamination, potentially resulting in contrasting risks for individual health (Ackerman et al. 2016, Dietz et al. 2019). Among marine top predators, seabirds show some of the highest Hg concentrations (Atwell et al. 1998), with deleterious effects on behavior, physiology or reproduction reported in some species and populations. For example, amongst adult male black-legged kittiwakes (*Rissa tridactyla*) breeding in Svalbard, individuals with the highest Hg concentrations were more likely to neglect their eggs (Tartu et al. 2015). Similarly in birds, high Hg concentrations have been related to a reduction of hatchability and clutch size (Dietz et al. 2013, Ackerman et al. 2016), in addition to a decline in breeding success and population growth rate (Goutte et al. 2014). Understanding the relationship between seabird distributions and contamination by Hg is therefore important for the conservation of these species for which many populations are declining and deserve special attention (Croxall et al. 2012, Paleczny et al. 2015).

1   Seabirds are typically migratory species, many travelling hundreds to thousands of

2   kilometers every year to reach their wintering grounds (e.g. Egevang et al., 2010, Frederiksen

3   et al., 2016; McFarlane Tranquilla et al., 2014). However, these migratory strategies can be

4   highly variable between individuals, conditioning their winter distribution and thus potentially

5   their exposure to Hg. First, individuals from the same population can use contrasting wintering

6   areas, at relative distance from their breeding colonies (Quillfeldt et al., 2010). For instance,

7   red-legged kittiwakes (*Rissa brevirostris*) breeding at Saint George Island (Pribilof Islands –

8   Bering Sea) overwinter from the Eastern Bering Sea to the Sea of Okhotsk, with higher Hg

9   concentrations measured in individuals distributed in southern areas (Fleishman et al., 2019).

10   Second, each individual itself can change its migratory route between years and thus can have

11   contrasting fidelity to its wintering grounds. Hence, species can show high (e.g. common eiders

12   *Somateria mollissima*, atlantic puffin *Fratercula arctica*, european shags *Phalacrocorax*

13   *aristotelis*; Guilford et al. 2011, Petersen et al. 2012, Grist et al. 2014, Hanssen et al. 2016), low

14   (e.g. thin-billed prion *Pachyptila belcheri*; Quillfeldt et al. 2010) or variable (e.g. Brünnich's

15   *Uria lomvia* and common guillemots *Uria aalge*, northern fulmars *Fulmarus glacialis*; (Hatch

16   et al. 2010, McFarlane Tranquilla et al. 2014, Orben et al. 2015) individual fidelity to a

17   wintering ground. Together, these different migratory patterns and overwintering strategies

18   may affect the long-term exposure of seabirds to Hg and differentially impact their health,

19   reproduction and consequently their population dynamics (Vindenes et al. 2008). However, no

study has previously considered the link between consistency in winter distribution and contamination with Hg.

By combining individual tracking data with Hg analyses and focusing on some of the most abundant Arctic seabird species (black-legged kittiwake, Brünnich's guillemot, common eider, common guillemot, little auk *Alle alle*, northern fulmar), we studied interannual fidelity to wintering grounds and tested the hypothesis that this fidelity determines the consistency of their Hg contamination. More specifically, we first predicted that species feeding at the highest trophic levels during the non-breeding period (i.e., common guillemot, northern fulmar) have higher Hg concentrations than species feeding at the lowest trophic levels (i.e., black-legged kittiwake, Brünnich's guillemot, common eider, little auk). Then, we predicted that 1) individuals with a low fidelity to a wintering ground from one year to the other show more variable Hg contamination in comparison to faithful ones, 2) winter distribution affects Hg contamination (Renedo et al. 2020), 3) species covering larger wintering areas (i.e. Brünnich's guillemot, common guillemot, northern fulmar) experience more inter-individual variations in Hg contamination than those distributed over more restricted wintering areas (i.e., common eider, black-legged kittiwake, little auk).

2. Material and methods

2.1. Species, study sites and sampling collections

From June 2014 to July 2016, adult black-legged kittiwakes (n = 13), Brünnich's guillemots (n

= 65), common eiders (n = 22), common guillemots (n = 39), little auks (n = 6) and northern

fulmars (n = 38) were equipped with light level geolocators (GLS – Global Location Sensor)

during chick rearing at 17 breeding colonies widely distributed from Iceland to Russia (Fig. 1)

and for two or three years (details in Table S1 and Fig. S1). Geolocators were retrieved in each

subsequent breeding seasons (details in Table S2). After retrieval, seabirds were re-equipped in

order to have at least their winter distribution for two years. Geolocators are low-weight

instrument that record ambient light-levels over multiple years, which later can be converted

into geographical locations (Wilson et al. 1992). However, the positional precision derived from

light-level data is considered low (Lisokvski et al. 2012), and is mostly suited for studies of

large-scale movements and distribution such as seabird migrations. The distribution extracted

from the geolocators deployed in June 2014 - July 2014, June - July 2015 and June - July 2016

represent November 2014 - January 2015 (winter$_t$), November 2015 – January 2015 (winter$_{t+1}$)

and November 2016 – January 2017 (winter$_{t+2}$), respectively (see Fig. 2).

In order to investigate individual Hg contamination during winter (i.e. non-breeding)

periods, feathers were collected at the retrieval of geolocators (Fig. 2). Feathers are useful

tissues to monitor Hg contamination during the winter period in seabirds (Albert et al., 2019).

Indeed, during the plumage synthesis (molt), a large proportion of the Hg accumulated in

internal organs since the last molt, but also Hg from the current diet, is excreted into the feathers

(Honda et al. 1986, Braune 1987, Agusa et al. 2005) (Fig. 2). Hence, feathers inform about Hg

accumulated by an individual between two molting sequences, and specifically during the non-breeding period according to selected feathers and molting pattern (see Albert et al, 2019). For example, alcids and larids undergo a rapid total molt at the end of the breeding period (during September or October) resulting in the winter plumage and a partial molt (cheek, neck, throat in alcids, neck and back in larids) at the end of the winter period (during March or April) resulting in the nuptial plumage (Gaston & Jones 1998, Cramp & Simmons 1983). Female common eiders undergo a total molt at the end of the winter period and a partial molt at the end of the breeding period (Baldassarre 2015, Goudie et al. 2020). Hence, head, back and belly feathers provide information on Hg contamination specifically during the winter period in alcids, black-legged kittiwakes and common eiders, respectively. Northern fulmars undergo one total molt per year at the end of the breeding period, lasting from mid-August to late October (Grissot et al. 2020). Recent studies indicated that Hg concentrations in fulmar body feathers reflect inter-individual variations in Hg contamination during the non-breeding period (Quinn et al. 2016). Therefore, body feathers (i.e., belly) were used to assess Hg contamination during the non-breeding period for northern fulmars.

Therefore, at the retrieval of geolocators, we collected head feathers from Brünnich's guillemots, common guillemots and little auks, and body feathers on black-legged kittiwakes (back feather), common eiders (belly feather), and northern fulmars (belly feather) representing Hg contamination during the preceding non-breeding period (Fig. 2). Feathers were stored in plastic bags at ambient temperature until Hg analyses.

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2.2.Spatial analyses

The geolocators data were first converted into positional data by identifying the timing of twilights, using a threshold method, from which we estimated two daily latitudes from the length of the night and day, and two daily longitudes from time of apparent midnight and noon, following procedures described in Merkel et al. (2016) and Bråthen et al. (2020). Since the geolocation approach requires light to estimate seabird positions, for individuals located above 70 degrees north, positions could not be obtained for days or weeks around winter solstice because of an apparent absence of daylight above this latitude (details in Table S3 and Fig. S2).

The timing of Arctic seabird molt and migration can vary slightly between breeding sites (Frederiksen et al. 2012, Fort et al. 2013a). Nonetheless, to allow for inter-population comparisons, and based on the knowledge about when seabirds are on their wintering ground (Fort et al. 2012, 2013a, Frederiksen et al. 2016) we homogenized the winter period within species. Therefore, we considered that seabirds were at their wintering ground from November to January for black-legged kittiwakes (Frederiksen et al. 2012), Brünnich's and common guillemots (Fort et al. 2013b, Frederiksen et al. 2016, Merkel et al. 2019), common eiders (Hanssen et al. 2016), and little auks (Fort et al. 2012). As northern fulmars have been observed returning back to their colonies as early as January in the literature (Macdonald 1980) and in our dataset, the non-breeding period was defined from November to December in this species.

1   We then calculated a median winter position (i.e., median latitude and median longitude) for

2   each individual for each year, to be used in further analyses.

3   **2.3. Hg analyses**

4   Prior to Hg analyses, feathers were cleaned to remove external contamination. Feathers were

5   plunged into a 2:1 chloroform:methanol solution for three minutes in an ultrasonic bath, rinsed

6   twice in a methanol solution and dried at 45°C for 48 hours. Hg analyses were performed on a

7   ~ 0.20 - 1 mg subsample of a pool of three homogenized feathers, using an Advanced Mercury

8   Analyser spectrophotometer (Altec AMA 254 – detection limit of 0.05 ng). The analysis of

9   each sample was repeated (two to three times) until the relative standard deviation for two

10   subsamples was <10 %. Mean concentration for these two subsamples was then used for

11   statistical analyses. Prior to Hg analyses, blanks were run and, to ensure the accuracy of

12   measurements, certified reference materials (lobster Hepatopancreas TORT-3 ; NRC, Canada;

13   reference values were of 0.29 ± 0.02 µg g^{-1} dry weight (dw) SD, mean measured $\pm SD = 0.30 \pm$

14   0.002 µg g^{-1} dw, recovery $= 102.0 \pm 1.5$ % ; and lobster hepatopancreas TORT-2; 0.27 ± 0.06

15   µg g^{-1} dw SD, mean measured $= 0.26 \pm 0.01$ µg g^{-1} dw SD , recovery $= 97.3 \pm 1.0\%$) were used

16   every fifteen samples. Hg concentrations are expressed in µg g^{-1} dry weight (dw).

17   **2.4. Statistical analyses**

18   Variations in Hg concentrations (hereafter [Hg]) in the different species were analyzed

19   as a function of seabird fidelity to a wintering ground. To do so, the difference in [Hg] between

20   winters (i.e. delta [Hg], hereafter Δ [Hg]) as well as the distance (in km) between individual

winter median positions was determined at the individual scale. As some individuals have been tracked in two non-consecutive years, the variations (Δ [Hg] and distance) have been studied between winter $_t$ – winter $_{t+1}$, winter $_t$ – winter $_{t+2}$, winter $_{t+1}$ – winter $_{t+2}$. Phillips and colleagues (2004) showed that the accuracy of seabird positions using light levels geolocators is 186 ± 114 (SD) km. Given this accuracy, the scale of the study area, and although the different study species can be more or less mobile during winter, we considered the limit of 372 km to discriminate individuals with high or low fidelity to a wintering ground. Based on this, individual seabirds fell into the "high fidelity" group when the difference between two winter median positions were < 372 km apart. Conversely, seabirds were considered to belong to the "low fidelity" group when they wintered in distinctly different geographical areas between years (i.e., winter median positions > 373 km apart). To ensure the defined threshold of 372 km did not significantly affect our results and conclusions, the same analyses were performed using thresholds of 200, 300, 350, 450 and 500 km (Table S4).

We performed Linear Mixed Models (LMMs) (R package "lme4") (Bates et al., 2015) to investigate differences in Δ [Hg] (using absolute values) between low and high-fidelity groups and species. To take into account the non-independence in our data (i.e., repeated Δ [Hg] measures for 36 individuals), we included the bird identity (i.e., Bird ID) as a random factor. The full model (Table 2 – LMM1) was: Δ [Hg] ~ fidelity (Low/High) + species + fidelity (Low/High) * species + (1| Bird ID)). We used a square root transformation for Δ [Hg] to meet the parametric assumptions of normality and homoscedasticity of residual distribution. In a

1 second step, we considered the low fidelity group only and used the longitude and latitude of

2 seabird winter median positions during the different winters to determine the direction from the

3 previous to the newly used wintering ground (North-West, North-East, South-West or South-

4 East). As we were interested in the direction of migration and the variation of Δ [Hg] (i.e.,

5 decreasing or increasing depending on the direction), we worked on Δ [Hg] raw values.

6 Therefore, we used Linear Mixed Models (LMMs) to test if Δ [Hg] changed depending on

7 overwintering area (i.e., direction), distances (in km) and species. The individual identity was

8 added as a random effect to take into account the non-independence in our data (i.e., repeated

9 Δ [Hg] measures). The full model was (Table 2 – LMM2): Δ [Hg] ~ direction (North-West,

10 North-East, South-West or South-East) + distance (in km) + species + direction * species +

11 distance * species + (1| Bird ID). Residuals from this model were normally distributed and

12 homoscedastic, thus no transformation of Δ [Hg] was needed. The common eiders were not

13 added to this analysis as all individuals showed high fidelity to their wintering grounds. Finally,

14 we tested [Hg] differences between species using mixed models, with the full model being [Hg]

15 ~ species + (1| Bird ID). We used the Akaike's information criteria (AIC) to select the best

16 model (Burnham & Anderson 2002). If the difference in AIC between two models is <2, the

17 models are considered to have equal statistical support and in case of nested models, the

18 simplest (i.e., most parsimonious) was preferred. All statistical analyses were performed with

19 R (version 4.0.3) and RStudio version 1.3.1093 (R Core Team 2017).

20

3. Results

Our results showed a variation in Hg concentrations between species with the highest mean concentration for the Brünnich's guillemots followed by the black-legged kittiwakes, common guillemots, little auks and northern fulmars. The common eiders presented the lowest mean Hg concentrations (Table 1, Fig. S3).

Our results indicate that Δ [Hg] varied among species and fidelity (i.e., low or high) for their wintering ground. Indeed, our model selection indicates that the best model included these two variables, without interaction (Table 2) with the variation of Δ [Hg] impacted by the species ($F_{5,193.96}$ = 3.70; p = 0.003) and their fidelity to a wintering ground ($F_{1,252.92}$ = 6.10; p = 0.014). More specifically, the Δ [Hg] decrease from low (intercept = 1.11 $\pm$ 0.12 µg g^{-1} dw) to high fidelity (estimate = 0.97 $\pm$ 0.06 µg g^{-1} dw). The lack of interaction between the fidelity and the species suggested that the difference between low and high fidelity is the same for all species, except common eiders which only present individuals with high fidelity to a wintering ground (Table 1, Figs. 3 & S4). Indeed, seabirds with low fidelity presented higher variation of Δ [Hg] compared to seabirds with high fidelity to a wintering ground. The results were similar when considering other thresholds (Table S4). Black-legged kittiwakes, common guillemots and little auks (species for which only two years of tracking information were available) presented an equal number of individuals with either a low or a high fidelity to a wintering ground. Most of the Brünnich's guillemots were faithful to a wintering ground, while most of the northern fulmars showed low fidelity (Table 1).

1   Within the low fidelity group, our results indicate that Δ [Hg] varied among direction,

2   distances and species. Indeed, our model selection indicates that the model with the lowest

3   AICc includes the direction, distance and interaction between distance and species. This

4   interaction decreased the model AICc by less than 2 units and seems mostly driven by a

5   difference between the common guillemot and little auk and all the other species (Fig. 4, Fig.

6   S5). More specifically, the Δ [Hg] significantly decreased with the distance for the common

7   guillemot, little auk and northern fulmar, compared to the other species (Fig. S6). This result is

8   supported by a lower AIC (AIC = 357.68) for a model where species is under two modalities

9   (Species 1 = common guillemots + little auks + northern fulmars *versus* Species 2 = black-

10   legged kittiwakes + Brünnich's guillemots). The model also indicates that the Δ Hg variation

11   was the highest when individuals changed their winter distribution to the northwest direction

12   and the lowest when individuals changed to the southeast direction, and these effects were

13   similar among species (i.e., the interaction between direction and species was not selected;

14   Table 2).

15   **4. Discussion**

16   Seabirds can adopt different non-breeding strategies and show contrasting fidelity to their

17   wintering sites, at species, population and individual scales (Hanssen et al. 2016, Merkel et al.

18   *In press*, Hatch et al. 2010, McFarlane Tranquilla et al. 2014, Orben et al. 2015). Hence, while

19   some seabirds use the same wintering ground every year, others change and occupy different

20   places from one year to the other. Such different strategies can have large effects on their

exposure to environmental stressors, particularly pollutants, which could in turn impact their contamination level, body condition, reproduction and ultimately their population dynamics. By combining for the first time the use of tracking devices on multiple species with Hg analyses, we demonstrated that inter-annual fidelity of individuals to wintering areas affect their contamination level, with a major effect of the location of these areas in the North Atlantic and sub-Arctic.

Interannual changes in Hg contamination might be driven by several non-exclusive factors, including different diets, changing migratory strategies between years (i.e., resident *vs* migrating, fidelity to wintering sites) or different regions used during winter in the North-Atlantic Arctic. Hg concentrations in Arctic seabirds, like in other predators, are closely related to their diet. For example, previous studies found that Hg concentrations increased in sub-Antarctic seabirds, from those feeding at low trophic levels (i.e. on crustaceans) to those feeding at higher trophic levels (i.e. on fish, squid and carrion consumers) (Carravieri et al. 2014). During winter, common guillemots and northern fulmars generally feed on relatively high trophic levels (mainly fish; Erikstad 1990, Gaston & Jones 1998) compared to Brünnich's guillemots, black-legged kittiwakes, little auks, (mainly zooplankton; Karnovsky et al. 2008, Fort et al. 2010, Frederiksen et al. 2012, Reiertsen et al. 2014, Gaston & Jones 1998) or common eiders (bivalves; Goudie et al. 2020). Therefore, higher Hg concentrations, if explained by diet differences only, should be expected in common guillemots and northern fulmars, followed by Brünnich's guillemots, black-legged kittiwakes, little auks and then common eiders. However,

our results showed a different contamination pattern, with values consistent with the existing

knowledge (Albert et al., 2019). Indeed, we found that the Brünnich's guillemots had the

highest mean Hg concentrations, followed by black-legged kittiwakes, little auks, common

guillemots and northern fulmars being more contaminated than the common eiders (Table 1).

Additionally, our results showed that Hg concentrations above 5 µg g $^{-1}$ dw in feathers, the

threshold above which the first deleterious effects are observed in birds (Eisler, 1987), were

observed in variable proportions according to the species with 2% in northern fulmars, 4% in

common guillemots, 15% in black-legged kittiwakes and 37% in Brünnich's guillemots.

Altogether, these results suggest an interspecies variation in Hg toxicity and that interannual

variations in winter Hg contamination cannot be explained by the diet alone, but potentially by

seabird movements and distribution.

Our study focused on six species breeding at 17 different colonies, showing contrasting

fidelity to their wintering grounds. The common eider was the only species for which all

individuals showed a high fidelity to their wintering grounds, overwintering year after year in

the same areas. This is the case for both eiders breeding in the Low Arctic and resident year-

round, and populations from the High Arctic migrating to southernly, but constant, locations

during winter (Bustnes & Erikstad 1993, Hanssen et al. 2016). As a consequence, all individual

common eiders in this study showed similar constant and low Hg concentrations from one year

to the other. The five other study species encompassed individuals with low or high fidelity to

their wintering grounds (Table 1). Accordingly, seabirds with low inter-annual fidelity had a

1 higher Δ [Hg] mean than individuals with high inter-annual fidelity (Figs. 2 & A1), confirming

2 an effect of adopted migratory movements on seabird winter Hg contamination, and suggesting

3 spatial variations over the North-Atlantic Arctic.

4   In addition, in individuals experiencing low fidelity to a wintering ground, we found

5 that while the effect of the direction was similar between species, the effect of the distance was

6 not. More specifically, regardless of the species, our results indicated that Hg concentrations

7 tended to be higher when individuals migrated northwest of their previous wintering ground.

8 In comparison, Hg concentrations tended to be lower when migrating in the three other

9 directions (Figs. 3, Fig. S2). We found that when the distance to their previous wintering ground

10 increased, Hg concentrations decreased for common guillemots, little auks and northern

11 fulmars, and increased for black-legged kittiwakes and Brünnich's guillemots. Overall, this

12 supports the hypothesis of a heterogeneous distribution of Hg in the marine environment at

13 large spatial scale. In the present study, wintering Brünnich's guillemots and northern fulmars

14 covered a large part of the North-Atlantic, while common guillemots, black-legged kittiwakes

15 and little auks were distributed over a part of it only (Fig. 1, Fig. S1). With such a large-scale

16 study, seabirds found on the eastern (or western) areas for the first year of our assessment had

17 more chance to migrate in the western (or eastern) areas the following years and such a point

18 was not possible to incorporate into the statistical analysis. But despite these spatial differences,

19 our results showed that their Hg concentrations varied the same way between years according

20 to changes in their distribution and directions, strengthening our interpretation. We therefore

believe that our results confirm the role of seabird winter movements and distribution on their

contamination to Hg and highlight spatial differences in Hg concentrations through the North-

Atlantic Arctic, with an increasing east-west gradient. Previous studies on the Arctic wildlife

also suggested a positive east-west Hg gradient during spring and summer (breeding period),

with species distributed in the Canadian Arctic being more contaminated than those in the

European Arctic (Provencher et al. 2014, AMAP 2018, Albert et al. 2019). The present data set

covers a large but fragmented part of the North-Atlantic Arctic. But a more precise dataset

could allow us to confirm and extend such a trend in the North-Atlantic Arctic.

Seabirds are exposed to various environmental threats during the winter period (e.g. oil

spills, storms, contaminants; Frederiksen et al. 2012, Petersen et al. 2012, Fort et al. 2014,

Guéry et al. 2017) which might impact their condition, survival or subsequent reproduction

(Votier et al. 2005, Mesquita et al. 2015, Anker-Nilssen et al. 2016). The large-scale distribution

of Hg in the marine environment is assumed to be relatively stable over years (Mason et al.

1998). Hence, high fidelity to their wintering ground likely expose seabirds to repeated threats

and constant pollution issues associated to this specific area (e.g. human industries), possibly

impacting their short-term survival and reproduction with long-term impacts on their

population dynamics (Guéry et al. 2017, 2019). On the other hand, seabirds wintering

constantly in an area with low level of such threats might only be exposed to limited acute

pollution events, which could have severe effects on their survival and subsequent reproduction

but limited long-term impacts on their populations. Conversely, seabirds with low fidelity to

wintering grounds and winter distribution will exploit contrasting wintering environments with

different Hg concentrations years after years (Quillfeldt et al., 2010) which might lower long-

term risks associated with Hg contamination. Therefore, the inter-individual variability in Hg

concentrations depending on their winter ground fidelity should be taken into account while

studying population dynamic of migratory species as it could have large effects on the survival,

reproduction and subsequently on population dynamics.

Our study demonstrates that individual migratory strategy and the consistency of

occupied wintering grounds affect their exposure to Hg and likely of other contaminants. Given

the high diversity of areas used by single individuals over two to three winters only, we urge to

extend ecotoxicological studies investigating seabird winter contamination and its impacts in

order to consider these interannual variations and fully apprehend the risks that Hg and other

pollutants represent for seabirds and other marine organisms.

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Table 1. Difference in Hg concentrations (mean ± *SD* Δ[Hg] in µg/g dw, absolute value) within low and high fidelity group (consistency in wintering grounds used, see methods for details), in addition to the mean [Hg] ± *SD* per species (pool of winter $_{t,t+1}$ and $_{t+2}$; details are summarized in Table S1). The sample size represents the number of individuals presenting a high or a low fidelity to a wintering ground between winter. 17 individuals (i.e., 7 Brünnich's guillemots, 6 common guillemots and 4 northern fulmars) with low fidelities have been found to have either low fidelity for all the interannual observations of the present study, either low fidelity for two inter-years and high fidelity for two other inter-years. Therefore, those birds have been added to both groups. ND: no data available.

Species	|Δ[Hg]| in High fidelity group (n)	Range	|Δ[Hg]| in Low fidelity group (n)	Range	Mean [Hg] ± SD (n)	Nb of individual with high fidelity	Nb of individual with low fidelity	Nb of individual with both fidelities	Total sample size (i.e., number of individuals)
Black-legged kittiwakes	1.03 ± 0.98 (5)	0.39 - 2.71	1.48 ± 0.91 (8)	0.02 - 2.82	3.10 ± 1.67	5	8	0	13
Brünnich's guillemots	1.00 ± 0.89 (47)	0.00 - 3.79	1.31 ± 1.22 (25)	0.07 - 4.64	4.09 ± 2.24	40	18	7	65
Common eiders	0.27 ± 0.28 (22)	0.03 - 1.23	ND	ND	0.81 ± 0.29	22	0	0	22
Common guillemots	0.68 ± 0.76 (24)	0.07 - 3.73	1.23 ± 0.86 (21)	0.04 - 2.95	2.73 ± 1.18	18	15	6	39
Little auks	1.26 ± 0.93 (3)	0.37 - 2.22	1.17 ± 1.21 (3)	0.15 - 2.50	2.93 ± 1.23	3	3	0	6
Northern fulmars	0.81 ± 0.74 (17)	0.14 - 2.78	0.97 ± 0.81 (25)	0.01 - 3.37	2.34 ± 1.16	13	21	4	38

Table 2. AIC model ranking for winter [Hg] within species and individuals with low fidelity to their wintering ground from one year to the other. The LMM results are presented in a decreasing order, from the best model (lowest AIC and Δ AIC) explaining variations in Δ [Hg]. The table includes the AICc, the Δ AICc and the AIC weight. Individuals (Bird ID) were added as a random effect.

Variable	Model	Number of parameters	AICc	Δ AICc	AIC Weight
LMM 1					
|Δ [Hg]|	~ fidelity + species + (1|Bird ID)	10	287.20	0.00	0.82
	~ species + (1|Bird ID)	9	290.97	3.77	0.13
	~ fidelity * species + (1| Bird ID)	14	294.02	6.83	0.03
	~ fidelity + (1| Bird ID)	5	294.39	7.19	0.02
	~ 1	4	302.58	15.38	0.00
LMM 2					
Δ [Hg]	~ direction + distance * species + (1|Bird ID)	16	362.88	0.00	0.52
	~ direction + distance + species + (1|Bird ID)	12	364.22	1.34	0.27
	~ direction * species+ (1|Bird ID)	20	366.42	3.54	0.09
	~ direction * species + distance + (1|Bird ID)	21	367.70	4.82	0.05
	~ direction * species + distance * species + (1|Bird ID)	24	368.01	5.13	0.04
	~ direction + species + (1|Bird ID)	11	368.65	5.76	0.03
	~ direction + distance + (1|Bird ID)	8	372.90	10.02	0.00
	~ direction + (1|Bird ID)	7	378.83	15.95	0.00
	~ distance + species + (1|Bird ID)	8	380.36	17.48	0.00
	~ distance * species + (1|Bird ID)	13	380.47	17.59	0.00
	~ species + (1|Bird ID)	8	380.73	17.85	0.00
	~ distance + (1|Bird ID)	5	385.98	23.10	0.00
	~1	4	387.74	24.86	0.00

Captions of Figures:

Fig. 1. Winter distribution of black-legged kittiwakes, Brünnich's guillemots, common eiders, common guillemots, little auks (median position from November to January) and northern fulmars (median position from November to December). Sampling sites (Table S1) are identified by (▲). Details per species are presented in Fig. S1.

Fig. 2. Schematic representation of i) [Hg] into internal organs along the time and during periods of the annual cycle ($_t$ and $_{t+1}$), ii) distribution (from geolocators) for winter $_t$ and $_{t+1}$ and iii) [Hg] measured in feathers representing the non-breeding period for winter $_t$ and $_{t+1}$. This schematic representation is based on the samples of 2015 and 2016.

Fig. 3. Δ [Hg] (absolute – see methods) between one year and the other for seabirds with low (> 372 km) or high fidelity (< 372 km) for their wintering grounds. Each species is represented by a specific color (see legend). The mean Δ [Hg] is represented by a red dotted line (detailed boxplot per species is provided in Fig. S1). Boxplots show the median (horizontal black line within the boxes), 1st and 3rd quartiles, the minimum (1st-1.5x interquartile range) and maximum (3dt-1.5x interquartile range) concentrations (lower and upper whiskers) and outliers.

Fig. 4. Δ [Hg] in the fourth different directions (NE=North-East, NW=North-West, SE=South-East, SW=South-West) in species and individuals with low fidelity to their wintering grounds. The mean Δ [Hg] is represented by a red dotted line. The zero axis is represented by a black dotted line (detailed boxplot per species is in Fig. S4). Boxplots show the median (horizontal black line within the boxes), 1st and 3rd quartiles, the minimum (1st-1.5x interquartile range) and maximum (3dt-1.5x interquartile range) concentrations (lower and upper whiskers) and outliers.
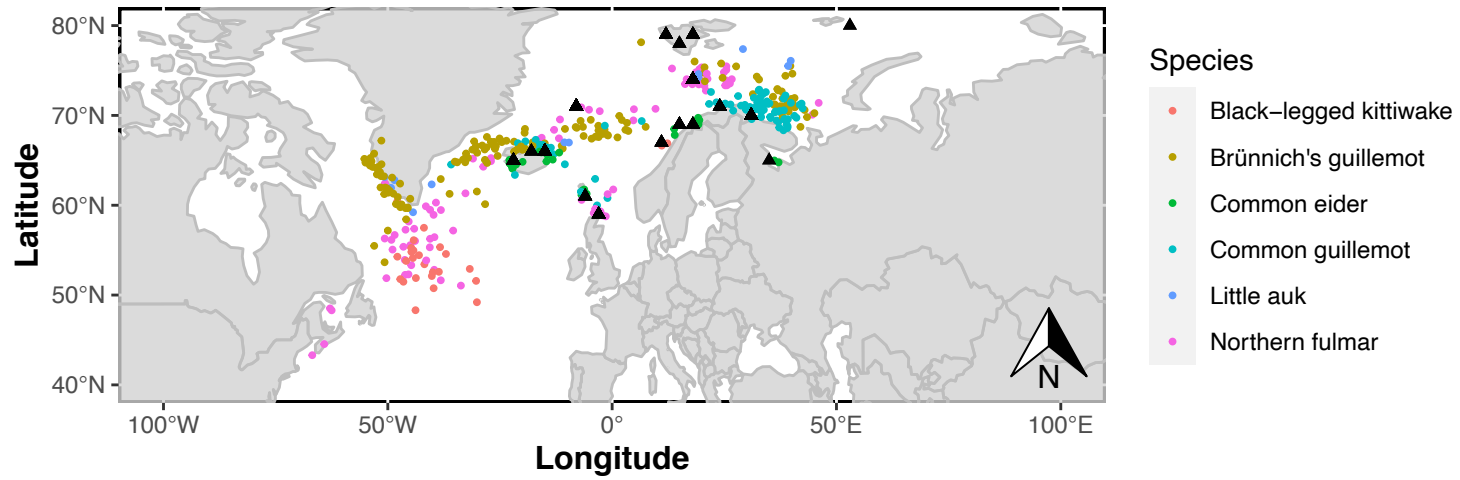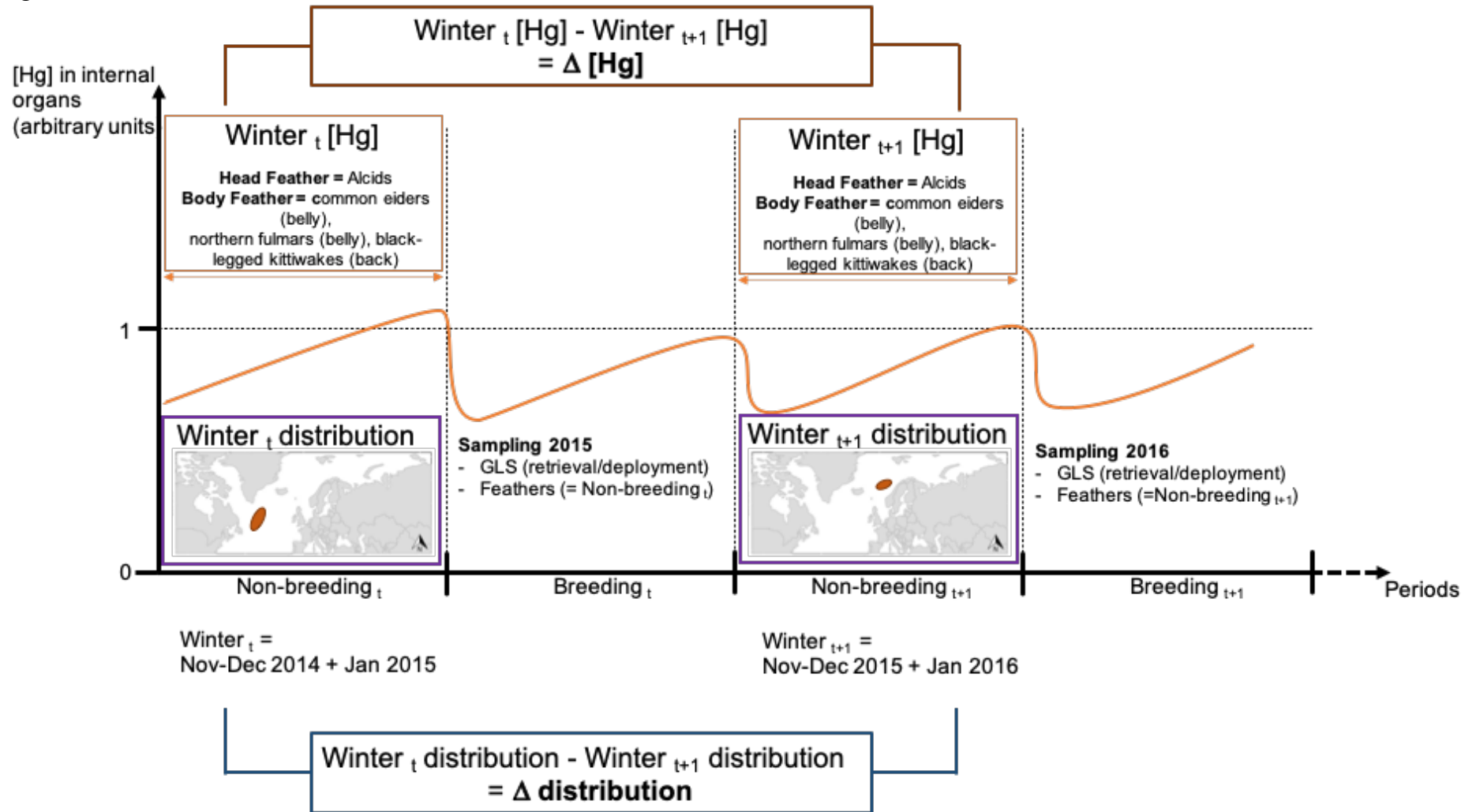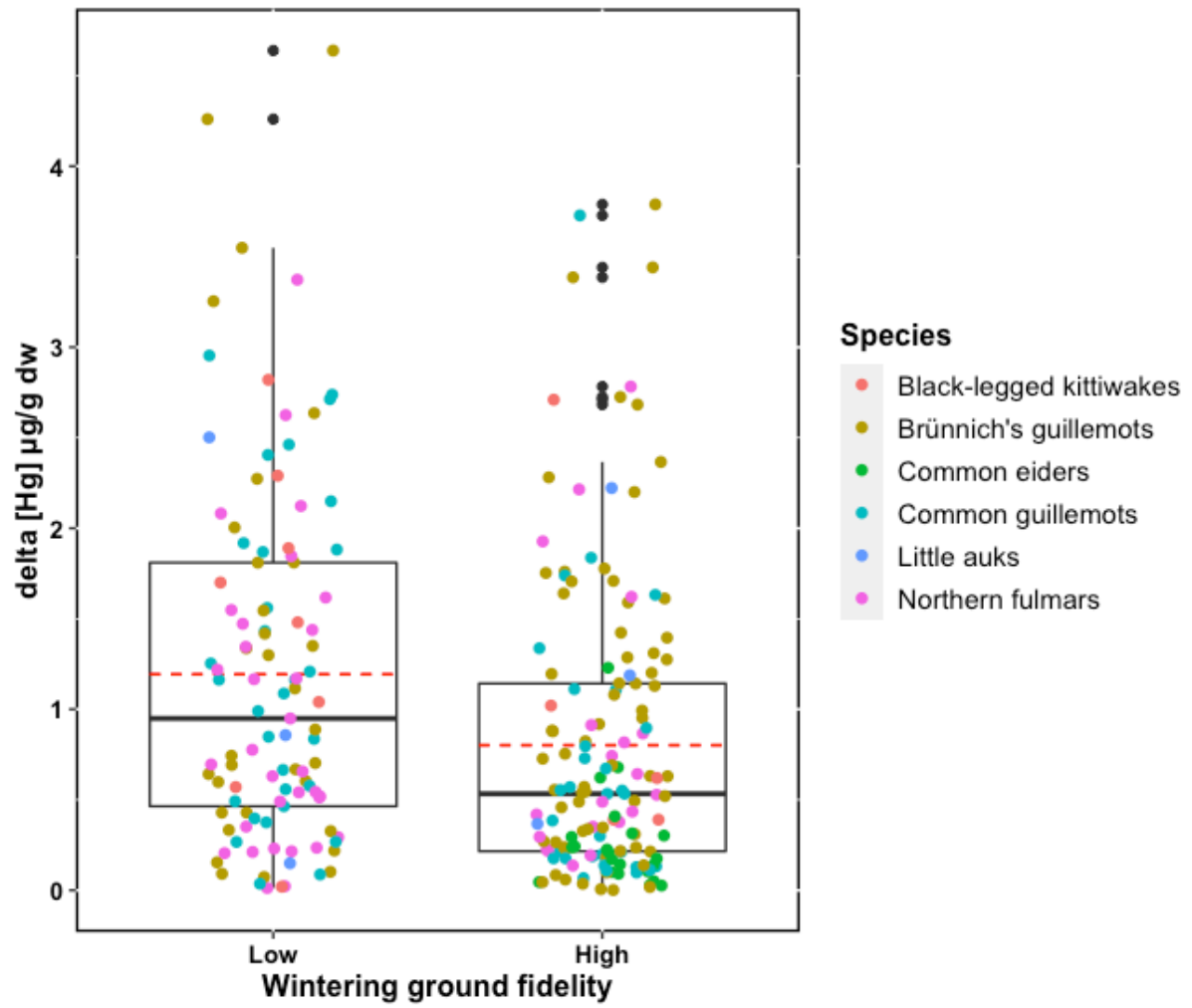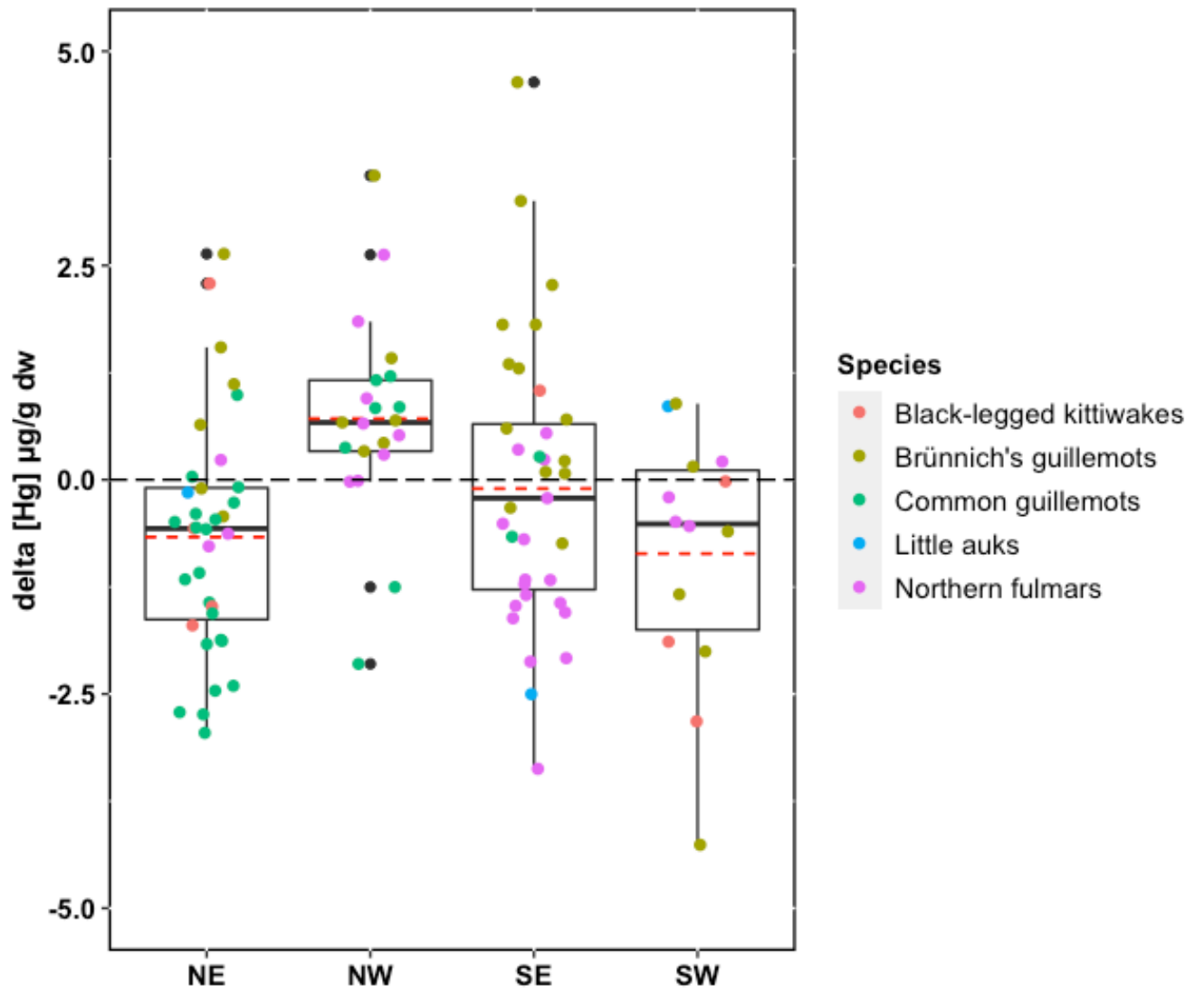
Fig. 1

Fig. 2

Fig. 3

Fig. 4

Supplementary material

Table S1. Sampling effort (n) and mean Hg concentrations (mean ± *SD* µg g^{-1} dw) per species and sampling sites for the three winters studied in the present study: winter$_t$ (November and December 2014, January 2015), winter$_{t+1}$ (November and December 2015, January 2016), winter$_{t+2}$ (November and December 2016, January 2017)

Species	Sampling site	GPS coordinates of sampling site	Winter$_t$	Winter$_{t+1}$	Winter$_{t+2}$
Black legged kittiwake	Anda	69.07°N, 15.17°E	3.29 ± 0.54 (2)	3.29 ± 2.84 (3)	2.88 ± 1.19 (3)
	Hornøya	70.39°N, 31.16°E	-	0.85 ± 0.04 (2)	1.36 ± 0.71 (2)
	Langanes	66.18°N, 15.99°W	4.36 ± 1.23 (4)	4.16 ± 0.79 (4)	
	Rost	67.45°N, 11.91°E	-	3.55 ± 2.20 (3)	2.11 ± 1.23 (3)
Brünnich's guillemot	Alkefjellet	79.58°N, 18.51°E	-	1.85 ± 0.49 (5)	1.57 ± 0.82 (5)
	Bjørnøya	74.50°N, 18.96°E	2.45 ± 1.42 (13)	3.50 ± 2.26 (9)	2.52 ± 1.15 (6)
	Grimsey	66.54°N, 18.00°W	-	5.89 ± 1.24 (5)	5.87 ± 1.04 (5)
	Hornøya	70.39°N, 31.16°E	2.73 ± 1.38 (17)	2.31 ± 1.32 (12)	2.59 ± 1.14 (16)
	Isfjorden	78.25°N, 15.51°E	6.36 ± 1.43 (2)	5.97 ± 1.21 (2)	-
	Jan Mayen	71.03°N, 8.29°W	5.58 ± 1.12 (11)	6.77 ± 2.36 (22)	5.19 ± 0.97 (17)
	Langanes	66.18°N, 15.99°W	4.33 ± 0.98 (4)	5.67 ± 0.64 (3)	4.69 ± 0.41 (3)
Common eider	Breidafjordur	65.08°N, 22.74°W	-	0.82 ± 0.23 (8)	1.03 ± 0.37 (8)
	Faroes	61.98°N, 6.65°W	-	0.65 ± 0.13 (4)	0.49 ± 0.16 (4)
	Kongsfjorden	79.00°N, 11.67°E	0.72 ± 0.13 (4)	0.98 ± 0.21 (4)	-
	Solovetsky archipelago	65.05°N, 35.79°E	0.82 (1)	-	1.44 (1)
	Tromsø	69.64°N, 18.85°E	0.80 ± 0.24 (2)	0.74 ± 0.13 (3)	0.46 ± 0.00 (2)
Common guillemot	Bjørnøya	74.50°N, 18.96°E	2.72 ± 0.95 (13)	1.85 ± 0.31 (17)	1.91 ± 0.56 (16)
	Hjelmsøya	71.11°N, 24.73°E	4.29 ± 1.18 (4)	2.35 ± 0.39 (5)	2.94 ± 0.90 (4)
	Jan Mayen	71.03°N, 8.29°W	3.23 ± 1.46 (3)	3.71 ± 1.86 (5)	2.25 ± 1.17 (4)
	Langanes	66.18°N, 15.99°W	3.84 ± 0.55 (8)	4.31 ± 0.98 (6)	2.79 ± 1.14 (4)
Little auk	Bjørnøya	74.50°N, 18.96°E	4.12 ± 0.33 (2)	2.35 ± 0.41 (3)	3.34 ± 1.41 (5)
	Hooker Island	80.23°N, 53.02°E	-	1.67 (1)	1.52 (1)
Northern fulmar	Bjørnøya	74.50°N, 18.96°E	1.57 ± 0.84 (11)	1.93 ± 1.34 (6)	1.09 ± 0.60 (8)
	Eynhallow	59.14°N, 3.12°W	-	3.49 ± 0.42 (5)	3.06 ± 1.14 (5)
	Jan Mayen	71.03°N, 8.29°W	3.35 ± 0.78 (3)	2.95 ± 1.15 (3)	1.79 ± 0.84 (6)
	Langanes	66.18°N, 15.99°W	2.87 ± 1.42 (11)	2.79 ± 0.86 (12)	2.28 ± 0.88 (13)

Table S2. Number geolocators deployed, retrieved and downloaded per species, sampling site and year. The number of individuals used in the present study, per year and in total is also mentioned. The data available for downloading represents the three studied winters: winter $_t$ (November and December 2014, January 2015), winter $_{t+1}$ (November and December 2015, January 2016), winter $_{t+2}$ (November and December 2016, January 2017). "<2015" includes geolocators deployed before 2015 and retrieved from 2015 to 2016. ND: no data available.

Species	Sampling site	Year of geolocators deployment			Year of geolocators retrieval			Data available for downloading			Studied indidviduals			
		<2015	2015	2016	2015	2016	2017	winter $_t$	winter $_{t+1}$	winter $_{t+2}$	2015	2016	2017	Total
Black-legged kittiwake	Anda	48	30	42	25	14	36	17	13	32	2	3	3	4
	Hornøya	37	30	30	30	19	21	25	18	19	ND	2	2	2
	Langanes	20	30	30	8	15	15	8	14	12	4	4	ND	4
	Røst	51	30	31	26	25	23	26	22	23	ND	3	3	3
Brünnich's guillemot	Alkefjellet	ND	20	29	ND	14	15	ND	14	14	ND	5	5	5
	Bjørnøya	32	29	30	19	24	9	18	16	9	13	9	6	13
	Grimsey	2	10	16	1	8	14	0	8	11	ND	5	5	5
	Hornøya	53	40	39	35	34	31	27	26	29	17	12	16	18
	Isfjorden	34	16	13	8	8	6	7	5	6	2	2	ND	2
	Jan Mayen	58	20	41	14	32	31	14	23	28	11	22	17	22
	Langanes	38	21	11	14	4	8	14	4	4	4	8	3	5
Common eider	Breidafjordur	37	39	46	20	0	27	17	ND	21	ND	8	8	8
	Faroes	8	32	40	ND	12	17	ND	10	16	ND	4	4	4
	Kongsfjorden	47	31	ND	19	14	ND	12	13	ND	4	4	ND	4
	Solovetsky archipelago	40	30	30	4	6	18	2	5	11	1	ND	1	1
	Tromsø	37	36	40	12	14	15	10	9	11	2	3	2	3
Common guillemot	Bjørnøya	31	30	30	20	32	18	19	28	17	13	17	16	20
	Hjelmsøya	34	35	26	20	12	22	17	7	11	4	5	4	6
	Jan Mayen	49	23	30	15	11	21	13	7	16	3	5	4	5
	Langanes	36	30	33	21	18	19	17	9	10	8	6	4	8
Little auk	Bjørnøya	31	16	30	8	13	21	8	12	17	2	3	5	5
	Hooker Island	35	30	29	22	8	11	17	7	10	ND	1	1	1
Northern fulmar	Bjørnøya	48	35	19	17	13	14	17	11	13	11	6	8	11
	Eynhallow	42	28	55	ND	20	13	ND	13	11	ND	5	5	5
	Jan Mayen	30	18	27	11	17	22	11	14	22	3	3	6	6
	Langanes	30	27	30	14	18	27	13	18	26	11	12	13	16

Table S3. Mean days with no positions per per winter median position from November to January

	November	December	January
Black-legged kittiwake	0.0	0.1	1.3
Brünnich's guillemots	2.7	4.7	3.5
Common eiders	1.1	2.7	0.9
Common guillemots	0.6	8.8	4.0
Little auks	10.5	12.9	10.9
Northern fulmar	6.5	10.1	NA

Table S4. Mean Hg concentrations ± *SD*, with or without common eiders, for low or high fidelity for seabirds wintering grounds, depending on different distance limits

With common eiders	Distance limit (km)	Fidelity	mean ± SD µg g^{-1} dw
	200	Low	1.10 ± 0.96
		High	0.72 ± 0.73
	300	Low	1.11 ± 0.95
		High	0.80 ± 0.83
	350	Low	1.15 ± 0.96
		High	0.81 ± 0.83
	372	Low	1.19 ± 0.98
		High	0.80 ± 0.81
	450	Low	1.24 ± 1.00
		High	0.81 ± 0.81
	500	Low	1.30 ± 1.01
		High	0.80 ± 0.80
Without common eiders	**Distance limit (km)**	**Fidelity**	**mean ± SD µg g^{-1} dw**
	200	Low	1.11 ± 0.96
		High	0.85 ± 0.77
	300	Low	1.11 ± 0.95
		High	0.92 ± 0.86
	350	Low	1.15 ± 0.96
		High	0.92 ± 0.86
	372	Low	1.19 ± 0.98
		High	0.89 ± 0.84
	450	Low	1.24 ± 1.00
		High	0.90 ± 0.84
	500	Low	1.30 ± 1.01
		High	0.88 ± 0.83

Figure S1. Winter distribution (i.e. median latitude and longitude position) from November to January (for black-legged kittiwakes, Brünnich's guillemots, common eiders, common guillemots, little auks) and from November to December (northern fulmars)
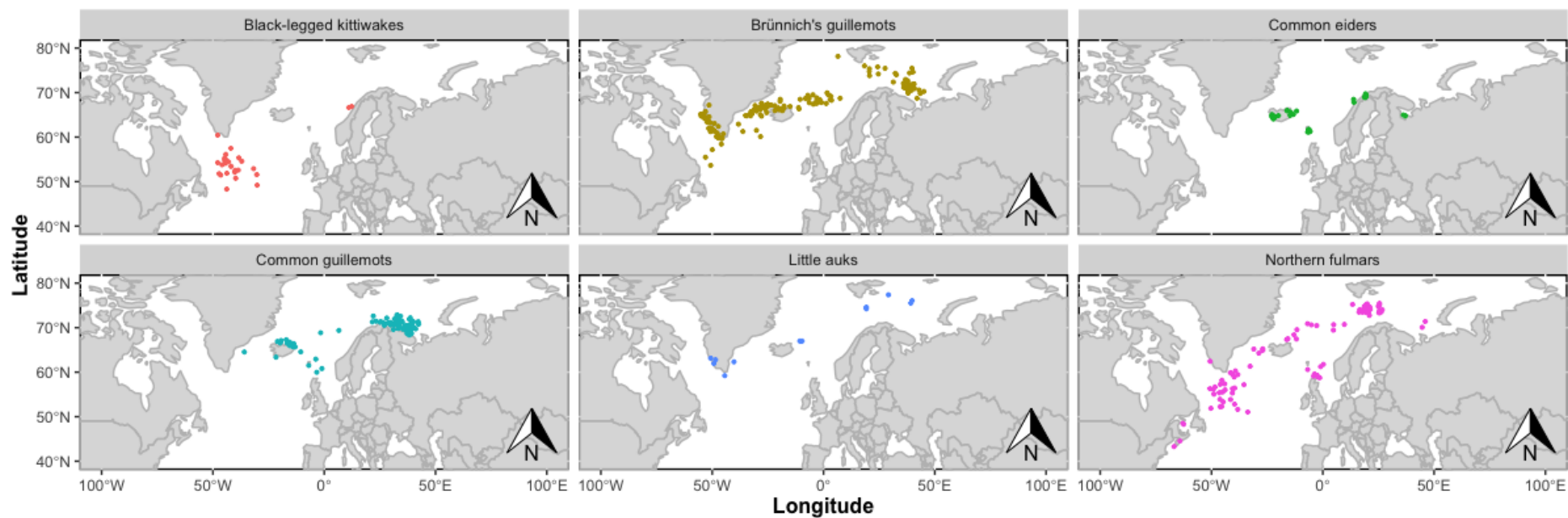
Figure S2. Median latitudes from November to January, and November to December for the northern fulmar specifically, plotted as a function of the deviance from the maximum number of positions that in theory can be calculated from light-level data using the threshold method. The maximum expected number is 2 positions each day, e.g. 122 positions for the Northern fulmar and 184 for the remaining species. As expected, the deviance increases drastically as the median latitude reaches 70°N because the absence of daylight under the polar night. From the plot, especially northern wintering common guillemots, little auks, northern fulmars and Brünnich's guillemots lack positions during the darkest part of the year – with ~43 days without data for the northernmost Brünnich's guillemot, and ~27 days for the northernmost northern fulmar. However, the deviance can also be a result of the removal of unrealistic positions because of disturbance in the recorded light-level data which is likely for some northern fulmars and common eiders that were well below 70°N. Common eiders spend their non-breeding season at the coast and can therefor experience shading from the terrain. Northern fulmars are known to seek out fishing boats with artificial sources of light, in addition to some being coastal for much of the non-breeding season.
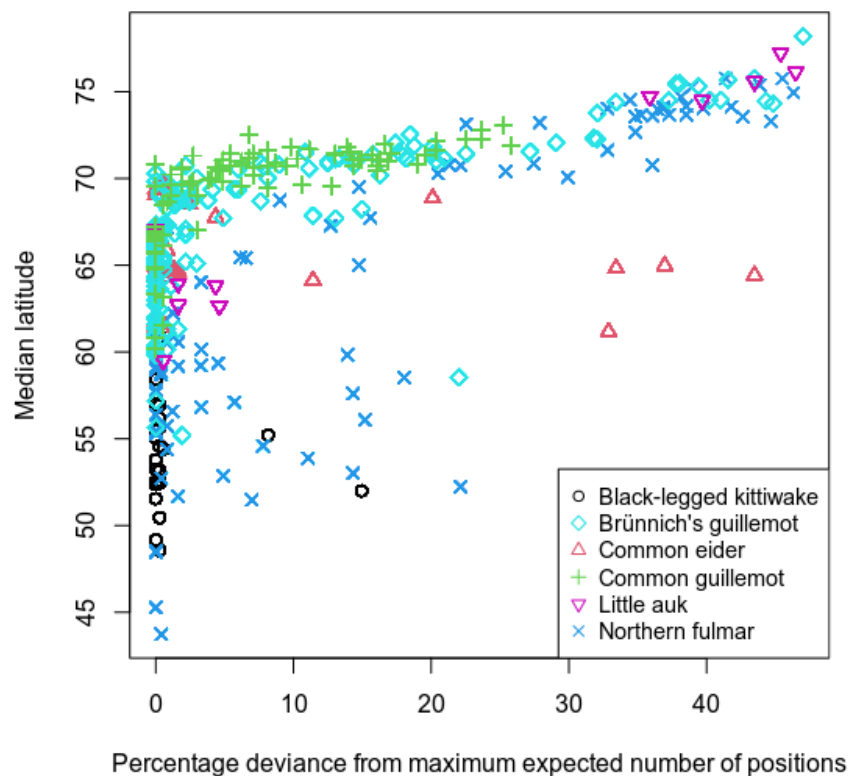
Figure S3. [Hg] in feathers for each species. Mean [Hg] are represented by dashed red lines. The toxicity threshold in feathers of 5 µg g^{-1} (Eisler, 1987) is represented by a dashed grey line. Boxplots show the median (horizontal black line within the boxes), 1st and 3rd quartiles, the minimum (1st-1.5x interquartile range) and maximum (3dt-1.5x interquartile range) concentrations (lower and upper whiskers) and outliers.
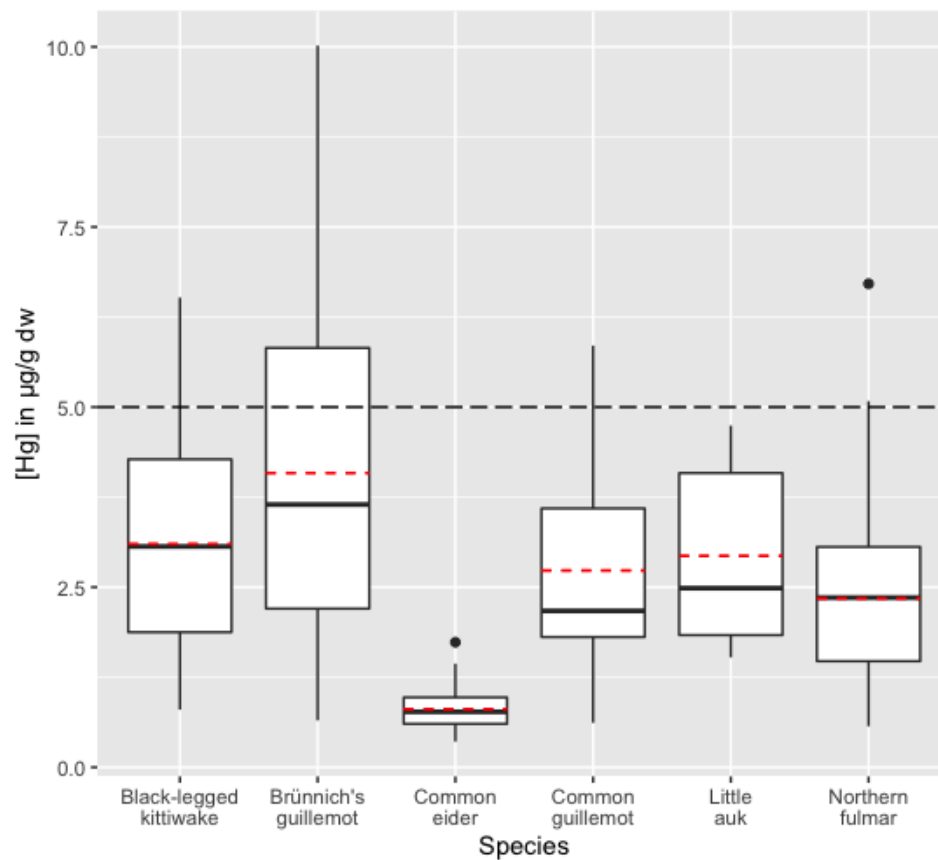
Figure S4. Δ [Hg] (absolute) from one year to the other for birds with low (< 372 km) or high fidelity (> 372 km) for wintering ground, per species. The mean Δ [Hg] is represented by a red dotted line. Boxplots show the median (horizontal black line within the boxes), 1st and 3rd quartiles, the minimum (1st-1.5x interquartile range) and maximum (3dt-1.5x interquartile range) concentrations (lower and upper whiskers) and outliers.
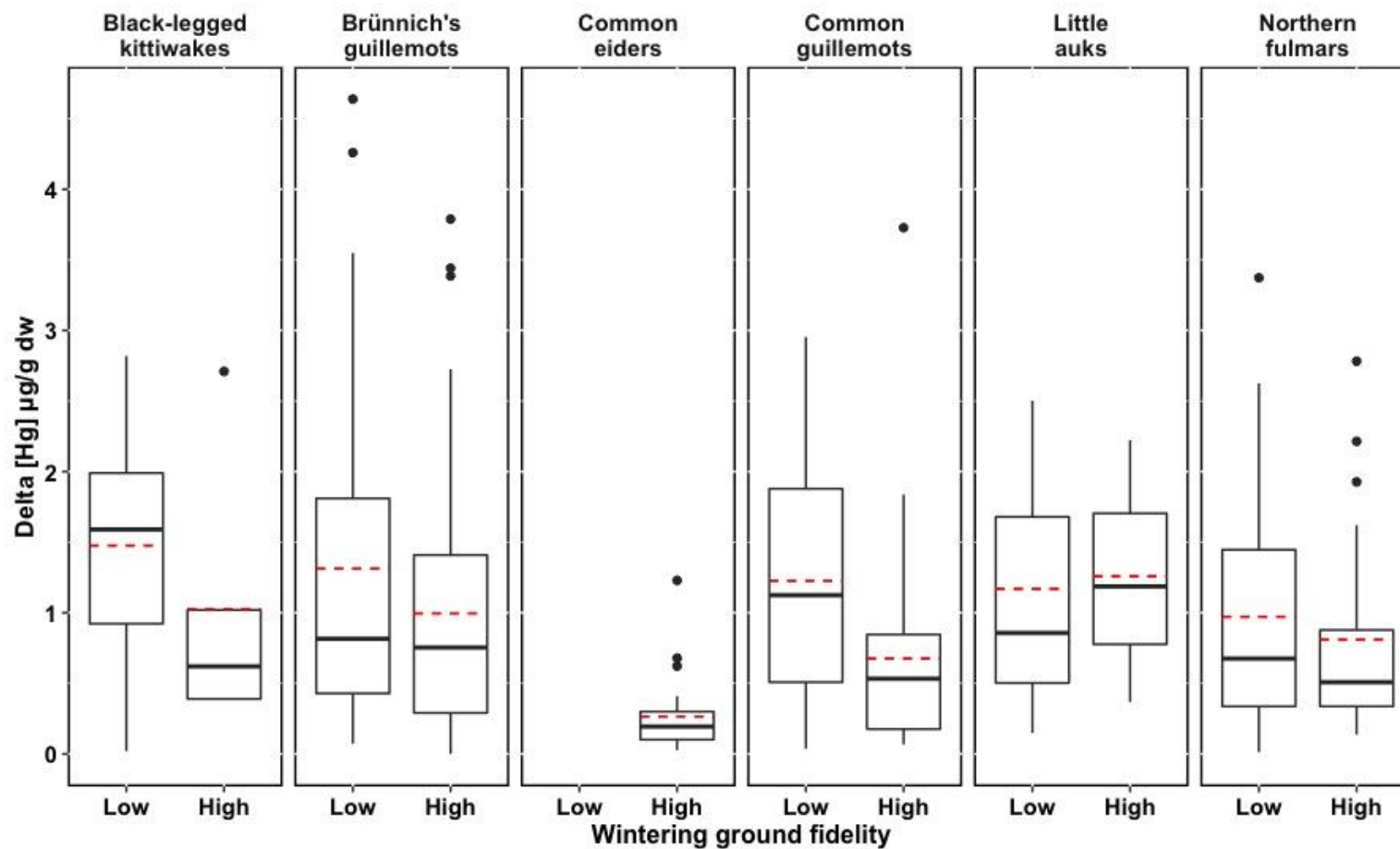
Figure S5. Δ [Hg] (raw) in the fourth different directions (NE=North-East, NW=North-West, SE=South-West, SW=South-West) per species for individuals with low fidelity for wintering ground. The mean Δ [Hg] is represented by a red dotted line. The zero axe is represented by a black dotted line. Boxplots show the median (horizontal black line within the boxes), 1st and 3rd quartiles, the minimum (1st-1.5x interquartile range) and maximum (3dt-1.5x interquartile range) concentrations (lower and upper whiskers) and outliers.
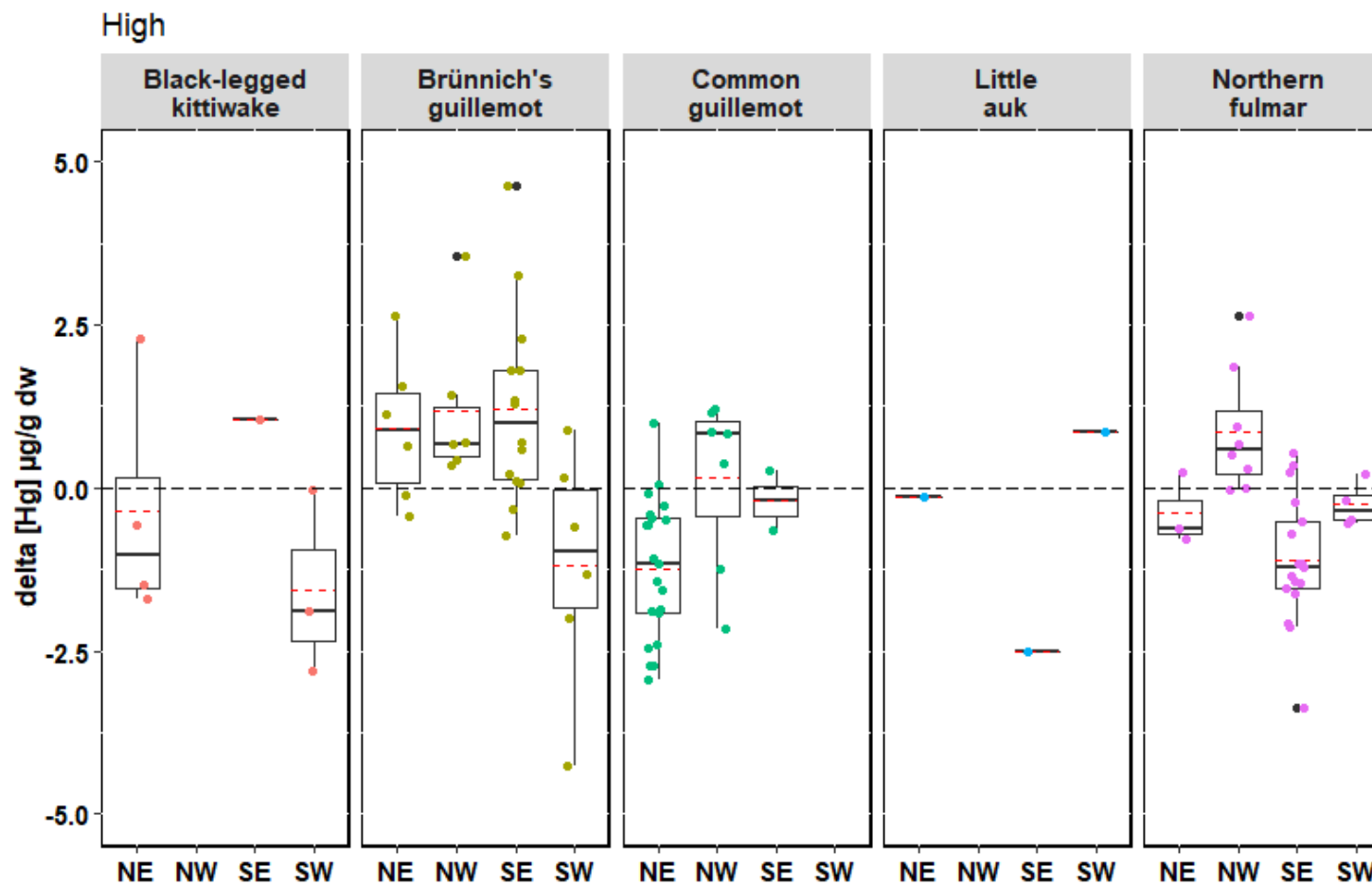
Figure S6. Δ [Hg] in relation to the distance (in km) for the five studied species and individuals with low fidelity for wintering ground