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Seabirds reveal mercury distribution across the North Atlantic

Céline Albert[a,1], Børge Moe[b], Hallvard Strøm[c], David Grémillet[d,e], Maud Brault-Favrou[a], Arnaud Tarroux[f], Sébastien Descamps[c], Vegard Sandøy Bråthen[b], Benjamin Merkel[c,g,2], Jens Åström[b], Françoise Amélineau[d,3], Frédéric Angelier[h], Tycho Anker-Nilssen[b], Olivier Chastel[h], Signe Christensen-Dalsgaard[b], Johannis Danielsen[i], Kyle Elliott[j], Kjell Einar Erikstad[f], Alexey Ezhov[k], Per Fauchald[f], Geir W. Gabrielsen[c], Maria Gavrilo[l,m], Sveinn Are Hanssen[f], Hálfdán H. Helgason[c,4], Malin Kjellstadli Johansen[c], Yann Kolbeinsson[n], Yuri Krasnov[k], Magdalene Langset[b], Jérémy Lemaire[a], Svein-Håkon Lorentsen[b], Bergur Olsen[i], Allison Patterson[j], Christine Plumejeaud-Perreau[a], Tone K. Reiertsen[f], Geir Helge Systad[o], Paul M. Thompson[p], Thorkell Lindberg Thórarinsson[n], Paco Bustamante[a,q], and Jérôme Fort[a,1]

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Mercury (Hg) is a heterogeneously distributed toxicant affecting wildlife and human health. Yet, the spatial distribution of Hg remains poorly documented, especially in food webs, even though this knowledge is essential to assess large-scale risk of toxicity for the biota and human populations. Here, we used seabirds to assess, at an unprecedented population and geographic magnitude and high resolution, the spatial distribution of Hg in North Atlantic marine food webs. To this end, we combined tracking data of 837 seabirds from seven different species and 27 breeding colonies located across the North Atlantic and Atlantic Arctic together with Hg analyses in feathers representing individual seabird contamination based on their winter distribution. Our results highlight an east-west gradient in Hg concentrations with hot spots around southern Greenland and the east coast of Canada and a cold spot in the Barents and Kara Seas. We hypothesize that those gradients are influenced by eastern (Norwegian Atlantic Current and West Spitsbergen Current) and western (East Greenland Current) oceanic currents and melting of the Greenland Ice Sheet. By tracking spatial Hg contamination in marine ecosystems and through the identification of areas at risk of Hg toxicity, this study provides essential knowledge for international decisions about where the regulation of pollutants should be prioritized.

mercury | ecotoxicology | spatial distribution

Significance

Mercury (Hg) causes deleterious effects on wildlife and human health. Even though we know that Hg is heterogeneously distributed, its spatial distribution at a very large scale in the marine biota remains poorly documented. Seabirds are commonly used to study the health of marine environments. In this study, we used seabirds as bioindicators of Hg presence through the North-Atlantic Arctic. Our maps highlight a gradient in Hg concentrations, with concentrations increasing from the Barents Sea to the East coast of Canada. This work is of tremendous importance for Arctic communities who rely on the marine environment but also for international initiatives such as the Minamata Convention that actively work for decreasing Hg emissions worldwide.

Mercury (Hg), under its most toxic form (methyl-mercury, MeHg), is a toxicant that bioaccumulates and biomagnifies (1), affects wildlife and human health, and is globally distributed in both marine and terrestrial environments (2). The spatial distribution of Hg in marine systems is largely heterogeneous due to a wide range of abiotic transportation processes and contrasting local environmental conditions and biogeochemistry (3–5). Recent investigations provided new insights on the oceanic and atmospheric distribution of Hg (6–9). Coastal areas' Hg concentrations are mostly influenced by rivers (10), whereas offshore, they are mostly affected by oceanic and atmospheric depositions (11). However, our knowledge about Hg spatial distribution in food webs remains limited (but see refs. 12–14), often with a coarse resolution or restricted to coastal regions (2, 12, 15–17). Such knowledge and the subsequent identification of Hg hot and cold spots (i.e., areas with the highest and lowest concentrations, respectively) is nonetheless essential to assess large-scale exposure of species and support their management and to protect communities, like the Arctic Indigenous peoples, who rely on top predators for subsistence. The mapping of the spatial distribution of Hg will also improve the understanding of Hg cycling and its transfer into food webs, as well as provide essential knowledge for international efforts aiming to reduce Hg in the environment. For instance, the Minamata Convention on Mercury aims to "protect human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds" (18). But to assess the effectiveness of the Minamata Convention and potential changes in Hg release, we first need to track spatial variation of Hg in biota and identify where the hot and cold spots are to identify risks and manage major sources of Hg emissions. In this context, top predators like seabirds are powerful biomonitors of spatial variation of Hg levels (19–21). Seabirds have a wide distribution, occupying all marine regions of the globe (22). They use a variety of marine habitats (e.g., coastal and oceanic, pelagic and benthic) and can be tracked in space and time using miniaturized electronic devices (23–27). The geolocation technology allows us to relate Hg concentrations in specific individuals to their at-sea distribution and thus provide detailed information about environmental Hg for areas that are otherwise difficult to access (15, 23). In this study, we simultaneously tracked the spatial winter distribution of 837 seabirds belonging to seven species breeding at 27 colonies across the North Atlantic

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[1]To whom correspondence may be addressed. Email: celine_albert567@hotmail.com or jerome.fort@univ-lr.fr.

[2]Present address: Akvaplan-niva, Fram Centre, Tromsø NO-9007, Norway.

[3]Present address: Ecosystèmes, biodiversité, évolution, UMR 6553 CNRS–Université de Rennes 1, Rennes 35000, France.

[4]Present address: East Iceland Nature Research Centre, Egilsstaðir 700, Iceland.

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Arctic (i.e., Eastern Canada, Greenland, Iceland, Scotland, Faroe Islands, Norway, Western Russian Arctic) and their individual winter contamination with Hg measured in feathers. Our aim was to provide new insights into Hg spatial distribution and hot and cold spots within marine food webs at the North Atlantic scale. As coastal and offshore areas do not have the same sources of Hg, we used a multispecies approach which includes a wide range of life history traits (foraging ecology and trophic position) known to affect seabird Hg uptake, thus providing the most comprehensive spatial distribution of Hg.

Seabirds as Indicators of Mercury Distribution in North Atlantic Food Webs

Mercury concentrations varied along both longitudes and latitudes (Fig. 1*B* and *SI Appendix*, Table S1 and Fig. S1*B*), with a general positive east-west gradient across the North Atlantic. Results from our ocean-scale data extend previous investigations for the North Atlantic and sub-Arctic which suggested higher coastal Hg concentrations off eastern Canada compared to European coasts (19, 20, 28). Beyond this general pattern, our approach provides in situ evidence that Hg distribution in biota was largely heterogeneous at fine scale and across the entire oceanic North Atlantic (Fig. 1*B*). Previous work mapped MeHg in phytoplankton worldwide, but this was a modeling work based on abiotic observations and transfer of MeHg at the base of the food chain only (29). In the present study, the highest concentrations occurred in Hg hot spots located along the eastern Canadian coasts as well as off the southern and southeastern coasts of Greenland. Mercury concentrations, in feathers representing contamination at these hot spots, were found to be up to three times as high as in the Barents and Kara Seas (minimum–maximum estimated values 1.55 to 4.05 μg g^{-1} dry weight). Additionally, cold spots where Hg concentrations measured in feathers were the lowest were found in waters west of Iceland, around Jan Mayen, on the north Norwegian coast, and in the White Sea.

Identifying the large-scale distribution of Hg in marine ecosystems is possible through large at-sea sampling campaigns. Such programs (e.g., GEOTRACES) exist and have proven their importance for the understanding of contaminant ecodynamics (5, 30, 31). Nonetheless, they are particularly costly and logistically difficult to implement and maintain over time. Therefore, complementary approaches such as the use of bioindicators that provide information about the contamination status of an environment are essential. To efficiently inform about Hg contamination in the marine environment, the chosen bioindicator species are usually top predators (i.e., highest concentration of Hg due to biomagnification process), long-lived (i.e., highest concentration of Hg due to bioaccumulation process), and widely distributed (i.e., cover different and large environments) (22, 26, 27). With this study, we demonstrate how the use of Hg measurements in seabird feathers combined with biologging (tracking data) can be used to identify Hg hot spots and cold spots at a large spatial scale (see refs. 15 and 16 for previous species- and population-specific investigations). Over the last two decades, the improvement of tracking technologies (e.g., smaller and lighter devices, battery autonomy) has allowed scientists to follow seabird movements and distribution outside the breeding period [e.g., the SEATRACK database, https://seapop.no/en/seatrack/, and associated publications (23, 24, 26), BirdLife Seabird Tracking Database https://www.seabirdtracking.org, and associated publication (27, 32) http://www.seabirdtracking.org]. The collection of feather samples from bioindicators, like seabirds that integrate Hg contamination over a period (e.g., seasonal or yearly contamination (28)), allows for concurrent measurements of Hg concentrations (see network ARCTOX https://arctox.cnrs.fr/en/home/, refs. 4 and 23) at a very large scale and high resolutions that cannot easily be done by research vessels that can only make ad hoc measurements. With their global distribution, seabirds are thus excellent candidates for a global investigation of Hg distribution in marine ecosystems. In addition, these in situ approaches and their outputs are essential to complement and feed modeling approaches (29). We nonetheless stress that almost all seabird species are feeding within the epipelagic zone (<200 m depth) and thus can only be used to quantify the spatial distribution of Hg in this water layer. Previous investigations showed the heterogeneous distribution of Hg along the water column and dependence on its stratification (33, 34). Other bioindicators, such as marine mammals or predatory fishes, that can also be tracked to follow environmental conditions in space and time (33) could be considered as good bioindicators for deeper stratification layers. For instance, large-scale variations in Hg concentrations were shown in the Tropical Pacific using skipjack tuna (*Katsuwonus pelamis*) (12). Similarly, seabirds have previously been used to highlight differences in Hg exposure between different regions at the species and population level and thus suggested spatial differences in environmental contamination (e.g., refs. 16 and 35 in the North Pacific, ref. 15 in the North Atlantic). However, those studies were species specific and therefore covered only a limited compartment of the environment (e.g., specific habitat and diet). Multispecies analysis, in contrast, allows us to cover different ecologies, spanning multiple habitats and diets.

Spatial Origin of Mercury in the Marine Environment and Seabird Conservation

The underlying drivers of the spatial variability seen in the present study are not well understood, but two hypotheses can be made. First, the presence of Hg in oceanic currents could explain the east–west difference. In the North Atlantic, ascendant oceanic currents circulating along the Norwegian and Spitsbergen coasts transport 43 ± 9 Mg y^{-1} (i.e., gross flux) of Hg to the Arctic, where it accumulates with a residence time of 50 to 100 y (36). Similarly, 54 ± 13 Mg y^{-1} of Hg is exported south by descendant oceanic currents from the Arctic to southern Greenland passing along the East coast of Greenland before flowing up its west coast (37). This high export of Hg from the Arctic could explain the increased concentrations of Hg measured in the eastern and southern parts of Greenland. Second, the melting of the Greenland Ice Sheet could release Hg from geological sources, resulting in high concentrations of Hg along the south coasts of Greenland (38, 39). Mercury is also deposited on ice sheets and snow through the Arctic because of atmospheric deposition (40) and then released into the marine environment during periods of melting (36, 41). These multiple sources of Hg in North Atlantic and Arctic marine systems strengthen the need to use multiple seabird species that rely on oceanic and/or coastal, pelagic and/or benthic environments to derive a more comprehensive understanding about Hg distribution in biota. Finally, because Hg contamination mostly originates from diet and consumed prey, bird species, which have different trophic ecology, were included as a random factor in the statistical and spatial analyses so that it would not bias Hg spatial distribution (*Methods*). Doing so, seabirds were specifically used as bioindicators of Hg contamination. Characterizing hot spots of Hg in marine ecosystems is essential to highlight areas where the marine biota may be at risk of toxicity. By combining existing tracking data from multiple seabird species in the North Atlantic, major hot spots of biodiversity have been identified in the middle

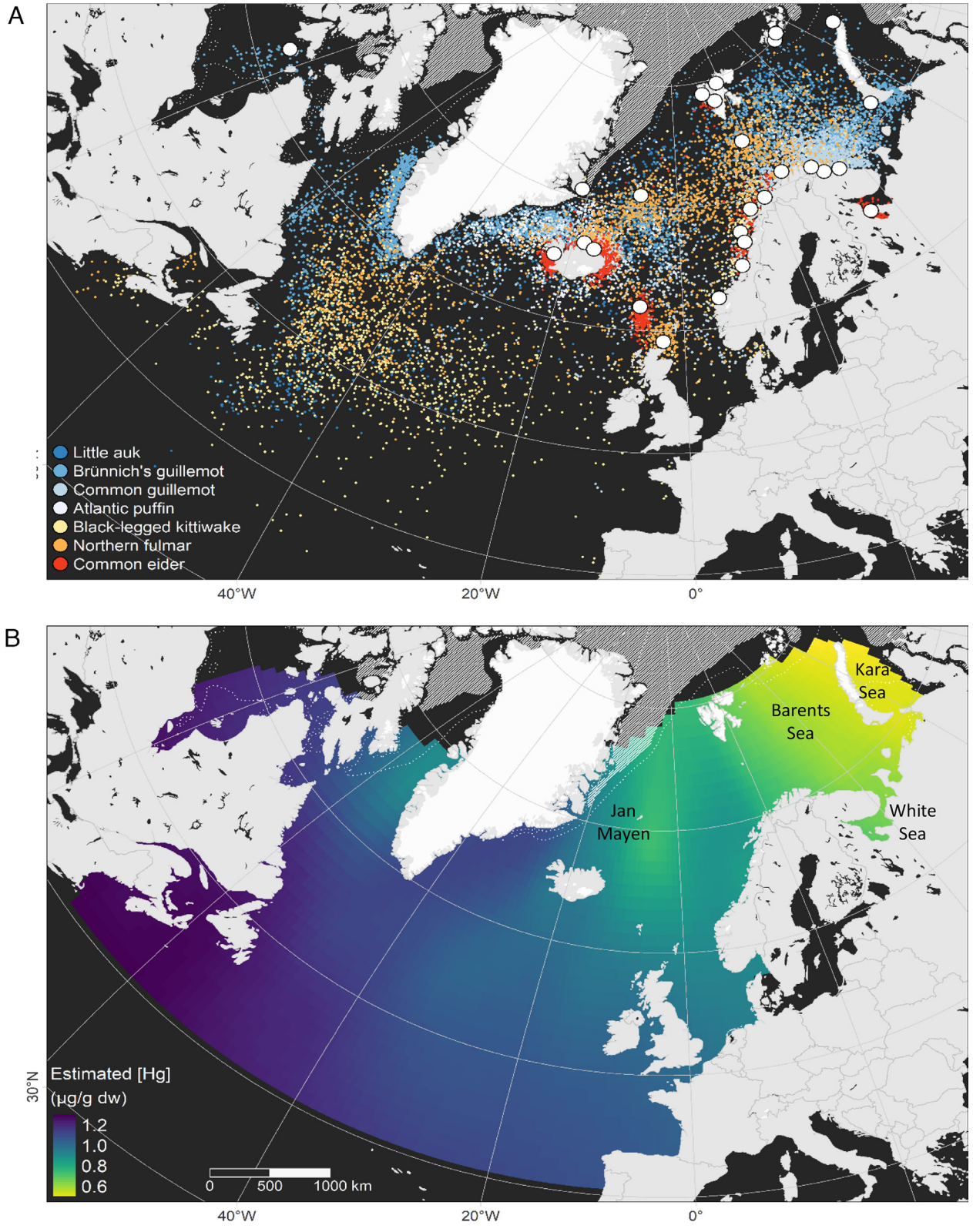

Fig. 1. (*A*) Winter distribution (weekly medoid locations from November to January for Atlantic puffins, black-legged kittiwakes, Brünnich's guillemots, common eiders, common guillemots, and little auks and from November to December for Northern fulmars) colored by species (colored points) and breeding colonies (black points). (*B*) Predictions of the estimated Hg concentrations (in log) for 1,000 iterations (*Methods*) with highest values in dark blue and lowest predictions in yellow.

of the North Atlantic and by the Great Bank and northward into the Labrador Sea (27, 42). In our present study, model outputs show that these western areas had some of the highest predictions for Hg contamination which implies a higher toxicity risk compared to the biota wintering in the eastern part of the North Atlantic. Acknowledging the existence of high risk of Hg contamination within these hot spots strengthens the need for protecting these areas. Based on these hot spots of biodiversity, the OSPAR commission has recently established a marine protected area in the middle of the North Atlantic (27). However, because of the

high transportability of Hg at a large spatial scale, it is international regulations like the Minamata Convention, that entered into force in 2017 and have been ratified by over 145 parties to date, that can act to strengthen the decrease of Hg emissions. The evaluation of the efficiency of associated mitigation measures requires monitoring of Hg both in the environment and in food webs. By providing information at large spatial and temporal scales, and with a high resolution (15, 16), our data thus fill an important knowledge gap and complement existing studies regarding Hg distribution in water masses (29, 37), in biota (11), and international programs such as the Global Mercury Assessment led by UN Environment (2).

Societal and Stakeholder Implications

Arctic human communities mostly rely on traditional food resources, usually top predators, exposing them to high Hg concentrations. Consequently, the Arctic Indigenous Peoples possess some of the highest human concentrations of Hg worldwide (36, 43). Various deleterious effects have been found with for instance neurological deficits in children or cardiovascular disease in adults (44). The Hg concentrations measured in the Greenlandic and Canadian Inuit populations are among the highest measured in the Arctic and are in accordance with our results (44). Therefore, as our study gives new insight about the spatial distribution of Hg through the North Atlantic, we urge 1) the international community to take new actions to protect both the environment and human health from Hg toxicity as presented within the Minamata Convention and 2) international programs to coordinate a global action toward an improved knowledge of Hg monitoring in marine ecosystems. The assessment of the biota in the open sea is a complicated endeavor, as species migrate and are not easily accessible. However, this study and our technical approach of tracking and sampling feathers of seabirds have proved its efficiency to assess Hg contamination where seabirds are at sea. Our work demonstrates how wildlife can be used as cost-efficient bioindicators to gather important information about Hg distribution at a large scale. Such information is essential for the international community to take new and rapid action regarding the contamination by Hg of the environment and the subsequent risk for wildlife, human health, and the environment.

Methods

Species, Study Sites, and Sample Collection. From June–July 2014 to June–July 2017, chick-rearing Atlantic puffins (*Fratercula arctica*, n = 42), black-legged kittiwakes (*Rissa tridactyla*, n = 119), Brünnich's guillemots (thick-billed murres; *Uria lomvia,* n = 239), common guillemots (common murres; *Uria aalge*, n = 131), little auks (dovekies; *Alle alle*, n = 64), northern fulmars (*Fulmarus glacialis*, n = 124), and incubating common eiders (*Somateria mollissima*, n = 118) were outfitted with light-level geolocators (GLS–Global Location Sensor) at 27 breeding colonies, for 1 to 4 y during the breeding season. These colonies were distributed across the northern part of the North Atlantic (*SI Appendix*, Table S1), encompassing Eastern Canada, Greenland, Iceland, Scotland, Faroe Islands, Norway, and Western Russian Arctic (Fig. 1*A*). The outfitted seabirds were of undetermined sex for all species but common eiders, for which only females were studied. GLSs were retrieved in each subsequent breeding season (one to four retrievals per individual in the period 2015 to 2018) (*SI Appendix*, Table S2). At each GLS retrieval, three feathers per individual (from head, back, or belly) were collected for subsequent Hg analyses (15, 23, 28, 45). Collected feathers were selected to represent Hg contamination during the nonbreeding period (i.e., from approx. October to February, see "*Hg analyses*" below), a period comparable to that actually spent at the wintering grounds (i.e., from approx. November to January, see "*Spatial analyses*" below) and successfully used in previous research (15, 23). Nonbreeding periods include migration. We assumed that Hg accumulated at stopovers and acquired along migration routes (a few days within the October–February period, ref. 24) could be neglected in comparison to Hg accumulated over the about 5 mo spent at wintering grounds. Feather collection and GLS deployments/retrieval were mostly done as part of the ARCTOX network (https://arctox.cnrs.fr/en/home/) and SEATRACK (https://seapop.no/en/seatrack/) project which aim to track Hg contamination across Arctic marine food webs and model the nonbreeding distribution of seabirds breeding throughout the North Atlantic, respectively. Mercury concentrations in coastal areas are mostly influenced by river (10), whereas offshore areas are mostly affected by oceanic and atmospheric depositions (11). Therefore, we used species that use either coastal (i.e., common eiders) or offshore environment (i.e., Atlantic puffins, black-legged kittiwakes, Brünnich's guillemots, common guillemots, little auks, northern fulmars). Additionally, we used species that feed at the surface (black-legged kittiwakes, northern fulmars) or on benthic preys (common eiders), or feed on epipelagic prey down to 50 to 150 m depth, depending on the birds' body size (in increasing order: little auks, Atlantic puffins, Brünnich's guillemots, and common guillemots).

Spatial Analyses. GLS light-level data were converted into a positional dataset by identifying the timing of twilights, using a threshold method (45), from which two daily latitudes and longitudes were estimated from apparent day and night lengths and from time of midnight and noon, respectively (see ref. 46 for details). The accuracy of locations estimated from light-level data is usually considered low, and it is recommended to use such data to study movements >200 km (46, 47). Low accuracy is mainly due to errors in latitude and less so in longitudes, when light conditions are affected by factors such as weather, habitat, topography, behavior, and artificial light. Further, constant daylight and polar night prevent estimation of location. When using a light threshold corresponding to sun elevation angles around −3° to −4°, this occurs above 63°N and 70°N at summer and winter solstice, respectively. In addition, latitudes are increasingly unreliable closer to spring or autumn equinox, when the day length is similar at all latitudes on the planet. We therefore discarded latitude during a three week period on each side of the apparent equinox (8 September to 20 October and 20 February to 3 April) for all species.

To mitigate these multiple issues, we first applied several filters to improve the timing of twilights, to remove the most erroneous locations, as described in ref. 48. Then, we applied an informed random movement algorithm [IRMA (49)] to fill the data gaps (including during the equinoxes) by modeling a maximum of two random locations per day. This method follows an approach originally proposed by Technitis et al. (50) and takes into account complementary information on light levels, land masks to replace the missing locations with the most plausible estimates, thereby reducing the sampling bias in our dataset to the minimum possible (49). More specifically, in winter, the model uses information about land and sea-ice masks (constraining random positions to areas with <80% sea-ice concentration), whether the logger recorded a continuous night (constraining the seabird to north of the limit of the polar night area), and species-specific movement rates (constrain each additional location to remain within a certain distance to adjacent locations). IRMA is parametrized for offshore, pelagic species only and is not suitable for common eiders that are benthic species relying on coastal environments. Hence, IRMA could not be used for this particular species, for which the positional gaps were not corrected.

To link Hg contamination to areas with the most extensive feeding through the winter season, we excluded the post- and prebreeding periods. Thus, we considered the winter period to be the same within species as the timing of seabirds' nonbreeding period is small (24, 51–53) and should not affect Hg spatial distribution. Therefore, we defined the winter period as the period November to January for Atlantic puffins (see ref. 24), black-legged kittiwakes (54), Brünnich's and common guillemots (52, 55, 56), common eiders (57) and little auks (53). As northern fulmars have been returning to their colonies as early as January in the literature (58), which was also observed in our dataset (*SI Appendix*, Fig. S1), the nonbreeding period was defined from November to December for this species (SEATRACK, *Unpublished*). Although individual seabirds show a rather restricted distribution during winter at the scale of the North Atlantic, they can

show small-scale changes in their spatial distribution (24). To take this small-scale winter spatial distribution into account, a medoid winter location (i.e., the location with the shortest and – nearest neighbor distance–to all the other locations of a given track) was calculated per week, for each individual and for their entire winter period (mean values of positions per species and sampling sites are presented in *SI Appendix*, Table S1).

Mercury Analyses. Feathers were used as indicators of individual Hg contamination during winter, when seabirds are at sea (28). Briefly, during their molt, seabirds excrete ~70 to 90% of accumulated Hg into their feathers (59–61). Hence, Hg in feathers inform about the Hg accumulated by an individual between two molting sequences. Alcids and Larids undergo a total molt after the breeding season (i.e., right before, during or right after the postbreeding migration, September to October) resulting in the winter plumage, and a partial molt (i.e., cheek, neck, throat for Alcids, back and head for Larids) at the end of the nonbreeding period (i.e., right before or during the prenuptial migration, March to April) resulting in the nuptial plumage (62, 63). Female common eiders undergo a partial molt (i.e., body contour feathers) after the breeding season, and a complete molt at the end of the nonbreeding period (64, 65). Hence, head, back, and belly feathers provide information about Hg contamination specifically during the nonbreeding period in alcids, black-legged kittiwakes, and common eiders, respectively. Northern fulmars undergo one total molt per year after the breeding season (body feathers molted between September and March, ref. 66). Recent studies indicated that Hg concentrations in body feathers of northern fulmars reflect interindividual variations in Hg contamination during the winter period (66). Consequently, and in order to investigate Hg contamination during the nonbreeding period, we collected in the following breeding season head feathers from Atlantic puffins, Brünnich's guillemots, common guillemots and little auks, back feathers from black-legged kittiwakes, and belly feathers from common eiders and northern fulmars. Feathers were stored in plastic bags at ambient temperature until Hg analyses.

Prior to Hg analyses, feathers were cleaned to remove external contamination. To do so, they were plunged into a 2:1 chloroform:methanol solution for 3 min in an ultrasonic bath, rinsed twice in a methanol solution, and dried at 45 °C for 48 h. Mercury analyses were performed on a ~0.20 to 1.00 mg subsample of a pool of three homogenized feathers (i.e., to avoid heterogeneity between feathers), using an Advanced Mercury Analyzer spectrophotometer (Altec AMA 254–detection limit of 0.05 ng). The analysis of each sample was repeated (two to three times) until the relative SD for two subsamples was <10%. The mean concentration for these two subsamples was then used for statistical analyses. Prior to Hg analyses, blanks were run, and to ensure the accuracy of measurements, certified reference materials were used every fifteen samples (lobster hepatopancreas TORT-3; NRC, Canada; reference values were of 0.29 ± 0.02 μg g^{-1} dry weight (dw) SD, mean measured ± SD = 0.30 ± 0.002 μg g^{-1} dw, recovery = 102.0 ± 1.5%; and lobster hepatopancreas TORT-2; 0.27 ± 0.06 μg g^{-1} dw SD, mean measured = 0.26 ± 0.01 μg g^{-1} dw SD, recovery = 97.3 ± 1.0%). Mercury concentrations are expressed in μg g^{-1} dry weight (dw). Total Hg concentrations are used as proxies of MeHg as more than 80% of the Hg excreted into feathers is under its organic and toxic MeHg form (67, 68).

Statistical Analyses. Mercury spatial distribution in the North Atlantic was predicted by regression-kriging (RK) (using package "*gstat*" ref. 69). Within the different regression-kriging methods, we used the ordinary-kriging (hereafter OK) (70). This technique is based on a spatial interpolation on a surface that uses the closest cell to calculate its prediction in each cell and allows to use regression models. More specifically, as we want to use seabirds as bioindicators (i.e., homogenize the different ecologies), this method allowed us to use mixed models to add species as random effects. The regression-kriging technique consists of two steps. The first step uses linear regression to model the spatial trends in the dataset and the second step interpolate the residuals from the linear regression using kriging. The final spatial predictions on the surface are the sum of the predictions from the two steps.

Step 1. Applying a regression (linear mixed model–LMM) and predict Hg concentrations at the medoid winter locations. Our full model was Hg ~1 + fixed effects (longitude + latitude) + random effects (species:sampling sites). All seabird species were included in the model, and "species" was included as a random effect. This allows us to take into account their different ecologies in the model (e.g., habitat, prey) and therefore use seabirds as bioindicators only. Indeed, during the nonbreeding period, seabirds rely on different habitats where Hg concentrations are under different influences (10, 40) and prey. Food is the main pathway for Hg accumulation in seabirds (71). Therefore, and due to biomagnification processes (72), contrasting diet, trophic status, and habitats (both between populations and species) might affect measured Hg concentrations and need to be taken into account in the model. However, the use of seabirds with different ecologies as bioindicators could have some limitations. Our models captured the dataset heterogeneity as shown for instance by the ICC (see below). A common method in ecology to take into account different ecologies consists of using carbon and nitrogen stable isotopes. However, this method could not be applied here as stable isotopes do not cover the same period as Hg contamination in feathers (73). Indeed, while Hg concentrations in feathers represent an intermolt period, the stable isotope values only represent the period of the feather growth. Additionally, as our study is based on a multicolony analysis, colonies ("sampling sites") were included as a random effect to take into account the different breeding distributions and the different nonbreeding strategies (e.g., length of migration–*SI Appendix*, Fig. S2). As several species can breed at a sampling site, we have nested the variable species into the variable sampling site. The intraclass correlation coefficient (ICC) indicates that 64 to 69% of the variances in Hg concentrations comes from the variables species and sampling site. For each winter, individuals had one Hg concentrations for one to 14 winter location (*Spatial Analyses*) and 212 individuals (15 Atlantic puffins, eight black-legged kittiwakes, 72 Brünnich's guillemots, 25 common eiders, 39 common guillemots, seven little auks, and 46 northern fulmars) have been sampled for 2 to 4 y (*SI Appendix*, Table S1). To take into account the individual variability and nonindependence of this variable, we used a bootstrap approach (i.e., random extraction–see details below in step 2), which allowed us to exclude "individual" from the LMM. This random extraction of the data was necessary as individuals were attributed to several (weekly) nonbreeding medoid points (*Spatial Analyses*) making this variable nonindependent.

Step 2. We summed the predictions from the LMM and OK. More specifically, we used the residuals of the LMMs to run the interpolation with the OK on a 1° × 1° grid covering the entire North Atlantic (Fig. 1*B* and *SI Appendix*, Fig. S3) (74). The use of the residuals of the LMM to run the kriging analyses is the most common method of regression kriging, and allows us to include the spatial variability of our dataset that is not captured by the LMM (70). The use of regression kriging requires that one or more covariates (here longitude and latitude of the medoid winter locations) are significantly correlated with the dependent variable (i.e., Hg concentrations) to ensure the strength between the response and predictive variables, which was the case [correlation coefficient (2.5 to 97.5 quantiles): −0.47 to −0.43, *P*-value (2.5 to 97.5 quantiles): 4.9e-48 to 1.3e-39; correlation coefficient (2.5 to 97.5 quantiles): −0.38 to −0.35, *P*-value (2.5 to 97.5 quantiles): 4.9e-31 to 3.2e-21; respectively].

In order to take the lack of independence in our data into account (i.e., repeated individual positions), we used a bootstrap approach (i.e., random extraction) (Fig. 2). To do so, we randomly extracted one medoid position per individual to create a subset of independent data. We repeated this procedure 1,000 times to create a total of 1,000 subsets. On each subset, we ran the two steps of the regression kriging method and calculated the predicted values from both the LMM and the OK. After that, we were able to sum both predictions from the LMM and OK to get improved predictions (75).

The final output is a map of the mean predictions from each subset (Fig. 1*B* and *SI Appendix*, Fig. S3). A map of the variance calculated for all the predictions is also provided in appendix (*SI Appendix*, Fig. S3). It presents the variance between our 1,000 subsamples. To determine the minimally sufficient number of subsets to account for the heterogeneity of our dataset, and this validate our approach using 1,000 subsets, we calculated the variance between each final map each time we added an iteration until we reached a stable variance (Fig. 2 and *SI Appendix*, Fig. S4).

Mercury concentrations (the LMM response variable) were log transformed to meet the parametric assumptions of normality and homoscedasticity of the residual distributions. Statistical analyses were performed with R version 3.4.3

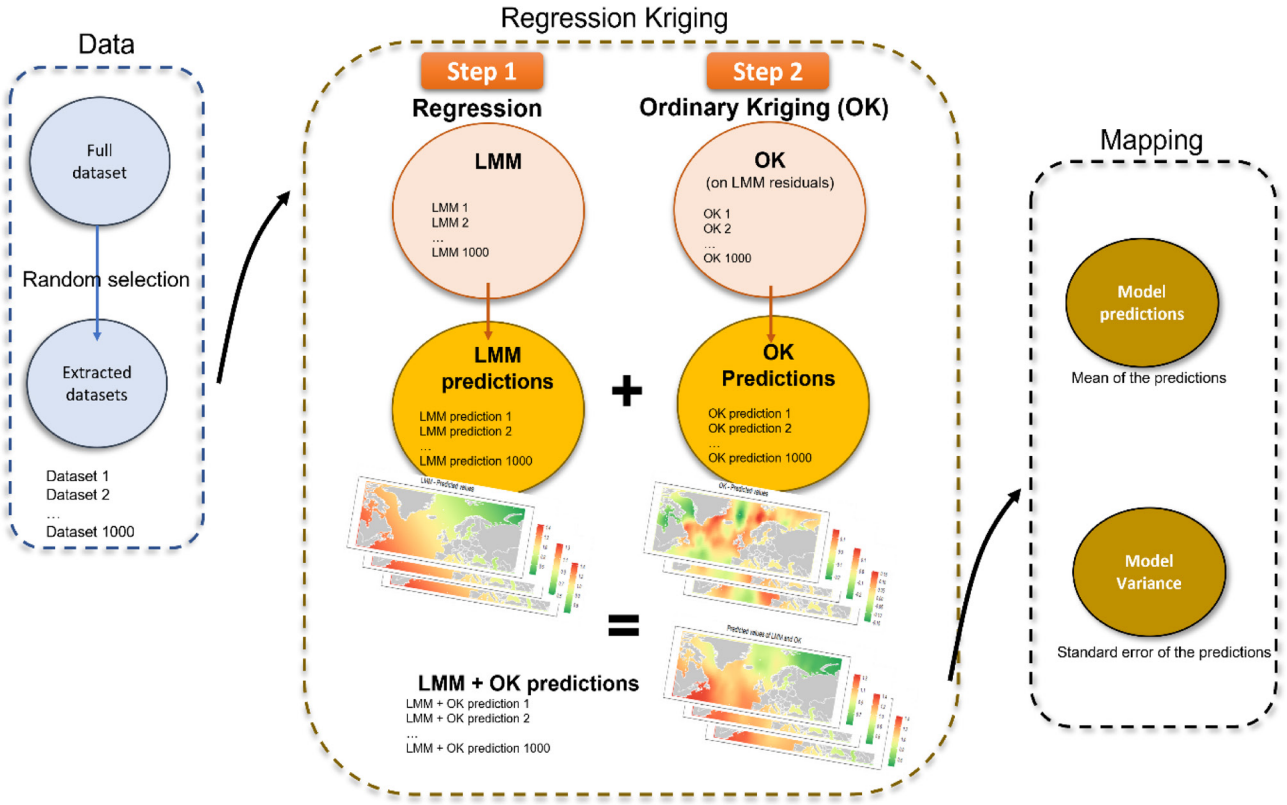

Fig. 2. Schematic description of the statistical analyses with 1) data preparation, 2) regression kriging with step 1 (regression) and step 2 (ordinary kriging), and 3) mapping of model predictions (estimated Hg concentrations).

and RStudio version 1.3.1093 (76). Means are reported with SD (mean ± SD) unless reported otherwise.

Data, Materials, and Software Availability. Scripts data have been deposited in Zenodo (https://zenodo.org/records/10651209) (77). Some study data available. [Data collected within ARCTOX and SEATRACK can be shared upon request to both networks. The reason being that those data belong to each data owners (e.g. co authors); not to ARCTOX and SEATRACK directly.]

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Author affiliations: [a]Littoral, Environnement et Sociétés, UMR 7266 CNRS-La Rochelle Université, La Rochelle 17000, France; [b]Norwegian Institute for Nature Research, Trondheim 7034, Norway; [c]Norwegian Polar Institute, Fram Centre, Tromsø 9296, Norway; [d]Centre d'Ecologie Fonctionnelle et Evolutive, UMR5175, Univ Montpellier, CNRS, Ecole Pratique des Hautes Etudes, Institut de Recherche pour le Développement, Montpellier 34293, France; [e]FitzPatrick Institute of African Ornithology, University of Cape Town, Rondebosch 7701, South Africa; [f]Norwegian Institute for Nature Research, Fram Centre, Tromsø 9296, Norway; [g]Akvaplan-niva, Fram Centre, Tromsø NO-9007, Norway; [h]Centre d'Etudes Biologiques de Chizé, UMR 7372 CNRS La Rochelle Université, Villiers-en-Bois 79360, France; [i]Seabird Ecology Department, Faroe Marine Research Institute, Tórshavn FO-100, Faroe Islands; [j]Department of Natural Resource Sciences, McGill University, Ste Anne-de-Bellevue, QC H9X 3V9, Canada; [k]Murmansk Marine Biological Institute, Murmansk 183010, Russia; [l]Association Maritime Heritage, Icebreaker "Krassin", Saint-Petersburg RU–199106, Russia; [m]National Park Russian Arctic, Archangelsk RU-168000, Russia; [n]Northeast Iceland Nature Research Centre, Húsavík 640, Iceland; [o]Norwegian Institute for Nature Research, Bergen N0-5006, Norway; [p]University of Aberdeen, School of Biological Sciences, Lighthouse Field Station, Ross-shire, Cromarty IV11 8YJ, Scotland; and [q]Institut Universitaire de France, Paris 75005, France

Author contributions: C.A. and J.F. designed research; C.A., B. Moe, A.T., S.D., V.S.B., B. Merkel, J.Å., and J.F. performed research; C.A., B. Moe, M.B.-F., A.T., S.D., V.S.B., B. Merkel, J.Å., J.L., C.P.-P., and J.F. analyzed data; C.A., B.M., V.S.B., and J.F. sample and data collection, data coordination and management, statistical methodology; H.S. sample and data contribution and Data coordination and management; D.G., M.B.-F., F. Amélineau, F. Angelier, T.A.-N., O.C., S.C.-D., J.D., K.E., K.E.E., A.E., G.W.G., M.G., S.A.H., H.H.H., M.K.J., Y. Kolbeinsson, Y. Krasnov, M.L., J.L., S.-H.L., B.O., A.P., C.P.-P., T.K.R., G.H.S., P.M.T., T.L.T., and P.B. sample and data contribution; A.T., P.F. and S.D. sample and data contribution and statistical methodology; J.Å. statistical methodology; J.F. supervision; and C.A., B. Moe, H.S., D.G., A.T., S.D., V.S.B., B. Merkel, J.Å., F. Amélineau, F. Angelier, T.A.-N., O.C., S.C.-D., J.D., K.E., K.E.E., A.E., P.F., G.W.G., M.G., S.A.H., H.H.H., Y. Kolbeinsson, Y. Krasnov, S.-H.L., B.O., A.P., T.K.R., G.H.S., P.M.T., T.L.L., P.B., and J.F. wrote the paper.

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