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SHORT NOTE

Mercury contamination of seabird and sea duck eggs from high Arctic Greenland

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Abstract
Mercury (Hg) levels in the environment have substantially increased over the past century leading to increased concentrations in many high trophic level predators, including Arctic seabirds. From the Canadian high Arctic, research on seabird eggs has documented some of the greatest concentrations of egg Hg anywhere in the Arctic. Farther east, in high Arctic Greenland, no similar data on Hg concentrations in eggs exist, making spatial comparisons unfeasible. To address this paucity of data, we collected whole eggs from Thick-billed Murre *Uria lomvia* ($n=11$), Black-legged Kittiwake *Rissa tridactyla* ($n=9$), and Common Eider *Somateria mollissima* ($n=12$) in the high Arctic of northwest Greenland in the summer of 2014 and assessed their concentration of total Hg. Thick-billed Murre eggs had the highest mean total Hg concentrations (1.32 ± 0.42 mg g^{-1} dw) followed by kittiwakes (0.64 ± 0.19) and eiders (0.23 ± 0.10). When compared with murre and kittiwake egg samples collected in high Arctic Canada during the same time period, total Hg concentrations from northwest Greenland were higher, but not significantly. Based on what is known about lethal Hg concentrations in murre eggs, these results indicate that some murre eggs may be at risk for increased embryonic mortality and further monitoring is suggested to determine long-term trends in egg Hg concentrations.

Keywords Mercury · Northwest Greenland · Thick-billed Murre · Common Eider · Black-legged Kittiwake · Egg

Introduction

Over the last century anthropogenic sources of mercury (Hg) have substantially increased resulting in much higher levels of Hg in the environment (Dietz et al. 2009; AMAP 2011, 2019; Amos et al. 2015). Through atmospheric deposition and ocean currents Hg can be transferred long distances, to remote areas, such as the Arctic, where long-term increases in Hg concentrations have been documented (Schroeder and Munthe 1998; Dietz et al. 2006; AMAP 2011, 2019 Bond et al. 2015). In mercury's most toxic and bioavailable form, methylmercury (MeHg), its concentration biomagnifies in tissues through the food chain, making species at higher trophic levels particularly susceptible to increased MeHg exposure via their diet (Atwell et al. 1998; Dietz et al. 2000; Campbell et al. 2005; Jaeger et al. 2009; Sonne 2010; Albert 2019). As a result, these upper trophic level organisms are at an amplified risk for a multitude of MeHg related health issues (for review see Dietz et al. 2013, 2019; Scheuhammer et al. 2015; Whitney and Cristol 2017; Evers 2018).

In the Arctic, seabirds have frequently been used for long-term monitoring of Hg due to their high abundance, generally widespread distribution, and relatively high trophic position (e.g., Thick-billed Murre *Uria lomvia*, Black-legged Kittiwake *Rissa tridactyla*) (Becker 2003; Braune 2007; Braune et al. 2015). Tissue types analyzed most commonly include liver, kidney, muscle, feathers, or whole eggs, all of which provide varying measures of Hg exposure (AMAP 2011; Mallory and Braune 2018; Dietz et al. 2019; Albert

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et al. 2020) and have generally shown a pattern of increasing Hg concentrations with latitude (Dietz et al. 1996; Braune et al. 2002, 2014; Akearok et al. 2010; Milijeteig and Babriesen 2010). Eggs in particular are useful monitoring tools due to their relatively non-intrusive collection, the nearly complete maternal transfer of Hg to eggs as MeHg, and their representation of current or recent bioaccumulation (Wiener et al. 2003; Ackermann et al. 2013; Chételat et al. 2020). In the eastern Canadian high Arctic, Hg concentrations in seabird eggs have been monitored since 1975 (Mallory and Braune 2012; Braune et al. 2016). Results have shown increasing Hg egg concentrations from 1975 to the mid-1990s, followed by plateauing (e.g., Thick-billed Murre, Northern Fulmar *Fulmarus glacialis*) or decreasing (e.g., Black-legged Kittiwake, Black Guillemots *Cepphus grylle*) concentrations from the mid-1990s to early-2010s (Braune et al. 2016).

East of these long-term study sites, across Baffin Bay, is the high Arctic of northwest Greenland (Fig. 1). Elevated Hg concentrations in multiple tissue types have been documented for marine species studied in this region (e.g., Nielsen and Dietz 1989; Hansen et al. 1990; Dietz et al. 1996; Rigét and Dietz 2000; Campbell et al. 2005; Rigét et al. 2007). Multi-decadal analyses of polar bear *Ursus maritimus* hair and ringed seal *Pusa hispida* liver, for example, have shown long-term increases in Hg concentrations in both species (Dietz et al. 2011; Rigét et al. 2012), thus highlighting the need to examine long-term Hg trends in other marine species. The coastal region of northwest Greenland is home to the largest remaining seabird and waterfowl colonies in Greenland (Boertmann et al. 1996; Burnham et al. 2012). Recently, Burnham et al. (2018) sampled 24 avian species in the region and found that 11 species had mean blood Hg concentrations suggestive of low risk to Hg toxicity, and a few individuals from three of the 11 species had concentration suggestive of medium risk. Hg concentration in seabird liver and muscle tissue have been analyzed in northwest Greenland (e.g., Nielsen and Dietz 1989; Rigét and Dietz 2000; Dietz et al. 2000). However, Hg concentration in whole eggs has not been reported from this region, which prevents direct comparisons with colonies of nesting seabirds in the eastern Canadian high Arctic.

Here we provide the results of the analysis of Hg concentrations in eggs from Thick-billed Murre, Black-legged Kittiwake, and Common Eider *Somateria mollissima* from high Arctic Greenland. Based on the results of similar studies conducted in Canada (e.g., Akearok et al. 2010; Braune et al. 2016; Mallory and Braune 2018), we hypothesize that murres will have the highest Hg egg concentration followed by kittiwake and eider. These findings are compared with previously published data from the eastern Canadian High Arctic for the same time period. We used

Fig. 1 Distribution of high Arctic study sites and place names as used in this paper. The high Arctic boundary (from CAFF 2010) was used as the southern limit of comparative studies to include. The location indicated with a black circle is the focal site in northwest Greenland for this study

the high Arctic boundary from CAFF (2010) as the southern limit of comparative studies.

Methods

Eggs of Thick-billed Murre ($n = 11$) and Black-legged Kittiwake ($n = 9$) were collected from Saunders Island (76.57° N, 70.04° W) on 8 July 2014 and of Common Eider ($n = 12$) from the Manson Islands (76.65° N, 69.10° W) on 9 July 2014. Thick-billed Murres lay only a single egg, Black-legged Kittiwakes up to three eggs, and Common Eiders up to five eggs (Gaston and Hipfner 2020; Goudie et al. 2020; Hatch et al. 2020). Eggs were randomly sampled and only a single egg was collected per nest.

Eggs were kept cool in the field and within six hours of collection were transferred to a refrigerator where they were stored at 3 °C to stop further embryo development. Eggs were then washed with deionized water, air dried, and weighed. Egg contents were removed and placed in sterilized glass jars and dried at 60 °C.

Egg contents were analyzed for total Hg (THg) using a Milestone Direct Hg analyzer (DMA-80, Milestone Inc., USA) using atomic absorption spectroscopy. THg was used as a proxy for MeHg since nearly 100% of Hg in eggs is in the form of MeHg (Wiener et al. 2003; Ackermann et al. 2013). Dried egg contents were individually homogenized with a clean Proctor Silex grinder then Cuisinart Smart Stick blender, then analyzed individually rather than pooled. Reference samples from the National Research Council of Canada Institute for National Measurements were analyzed approximately every 10 samples and the average (± standard deviation) percent recovery was 101.3 ± 3.79% ($n = 2$) and 97.7 ± 0.47% ($n = 3$) for DORM-3 and PACS, respectively. Duplicate samples were analyzed every 20 samples and the mean relative percent difference was 4.5 ± 1.51% ($n = 2$). All samples were above the limit of detection for THg (0.54 ng or ~ 0.01 μg g^{-1} dw based on the typical sample weight of 0.05 g).

A one-way ANOVA (Welch's F) was used to test for differences in mean THg concentration (ng/g dry weight) of eggs between the three species. Two-tailed t-tests (unequal variances) were used to test for differences in mean THg between species in both our study and between kittiwake and murre samples from our study area and previously published data from Prince Leopold Island (PLI; Fig. 1), Canada (summarized data, Braune et al. 2016, Table 1). Minitab (Minitab LLC, State College, Pennsylvania) was used to conduct statistical analysis and tests with a p value below 0.05 were considered significant.

Results

Thick-billed Murre had the greatest mean egg THg concentration (1.32 ± 0.42 μg g^{-1} dw, range = 0.75–2.32, $n = 11$) followed by Black-legged Kittiwake (0.64 ± 0.19 μg g^{-1} dw, range = 0.44–1.02, $n = 9$) and Common Eider (0.23 ± 0.10 μg g^{-1} dw, range = 0.02–0.35, $n = 12$) (Table 1; Fig. 2). Significant differences were found between mean THg concentrations of eggs for all three species (Welch's $F_{2,\ 14.5} = 48.07$, $p < 0.001$). Mean murre egg THg concentration was significantly greater than that of kittiwake ($T_{14} = -4.19$, $p < 0.001$) and eider ($T_{10} = -8.52$, $p < 0.001$) and kittiwake egg THg concentration was greater than that of eider ($T_{11} = -6.02$, $p < 0.001$).

Black-legged Kittiwake eggs sampled at PLI (~ 635 km west of our study area) in 2013 had a mean THg concentration of 0.57 ± 0.04 μg g^{-1} dw (Braune et al. 2016), slightly but not significantly less than for our study area ($T_9 = 1.06$, $p = 0.315$). Similarly, Thick-billed Murre eggs sampled at PLI in 2014 had a mean THg concentration of 1.09 ± 0.08 μg g^{-1} dw (Braune et al. 2016, Table 1), again, less than for our study area, but not significantly ($T_{13} = 1.53$, $p = 0.149$). No data were available from the Canadian high Arctic for Common Eider during this time period to make comparisons.

Discussion

As hypothesized, murre eggs from northwest Greenland had the highest mean THg concentration and were approximately three times higher than kittiwakes and six times higher than eiders. Burnham et al. (2018) found comparable results for our study area using blood, and mean THg concentrations of murres were approximately double that of kittiwakes and six times higher than that of eiders. These similarities should not be surprising though as Hg concentration in bird eggs has been shown to be highly and positively correlated with the mother's blood Hg concentration (Ackerman et al. 2016b, 2020; note that Burnham et al. (2018) murre and kittiwake samples included both males and females).

While murres lay only a single egg, kittiwakes and eiders lay multiple eggs, and the amount of mercury deposited in individual eggs decreases based on laying order with the greatest difference between the first and second eggs (Ackerman et al. 2016b). For example, Akearok et al. (2010) found that in high Arctic Canada mean THg concentrations in early laid eider eggs were 28% higher than that in late laid eggs. What effect the egg laying sequence had on kittiwake and eider THg concentration

Table 1 Mean total mercury concentrations (μg g^{-1} dw) and standard deviation in eggs from Black-legged Kittiwakes *Rissa tridactyla*, Thick-billed Murres *Uria lomvia*, and Common Eiders *Somateria mollissima* from this study (northwest Greenland) and other locations in high Arctic Canada and Svalbard

Species	Year	Colony location	THg	References
Black-legged Kittiwake	2014	Northwest Greenland	0.64 ± 0.19, *n* = 9	*This study*
	1993	Coburg Is., CAN	0.9 ± 0.22, *n* = 5	Braune et al. (2002)
	2013	Prince Leopold Is., CAN	0.57 ± 0.04, *n* = 15[a]	Braune et al. (2016)
	2008	Prince Leopold Is., CAN	0.80 ± 0.04, *n* = 15[a]	
	2003	Prince Leopold Is., CAN	0.82 ± 0.10, *n* = 12[a]	
	1998	Prince Leopold Is., CAN	0.64 ± 0.16, *n* = 15[a]	
	2008	Svalbard, NOR[b]	0.71 ± 0.17, *n* = 30[b]	Miljeteig and Gabrielsen (2009)
	1993	Svalbard, NOR[b]	0.39 ± 0.12[c], *n* = 5	Barrett et al. (1996)
Thick-billed Murre	2014	Northwest Greenland	1.32 ± 0.42, *n* = 11	*This study*
	2007	Bjørnøya, NOR	0.16 ± 0.07, *n* = 5	Miljeteig and Gabrielsen (2010)
	2003	Bjørnøya, NOR	0.13 ± 0.01, *n* = 5	
	1993	Coburg Is., CAN	1.4 ± 0.04, *n* = 15[a]	Braune et al. (2002)
	2014	Prince Leopold Is., CAN	1.09 ± 0.18, *n* = 15[a]	Braune et al. (2016)
	2012	Prince Leopold Is., CAN	1.18 ± 0.16, *n* = 15[a]	
	2010	Prince Leopold Is., CAN	1.15 ± 0.16, *n* = 15[a]	
	2008	Prince Leopold Is., CAN	1.43 ± 0.25, *n* = 15[a]	
	2006	Prince Leopold Is., CAN	1.33 ± 0.16, *n* = 15[a]	
	2003	Prince Leopold Is., CAN	1.33 ± 0.29, *n* = 15[a]	
	2007	Svalbard, NOR	0.36 ± 0.15, *n* = 5	Miljeteig and Gabrielsen (2010)
	2002	Svalbard, NOR	0.68 ± 0.19, *n* = 5	
	1993	Svalbard, NOR	0.75 ± 0.15[c], *n* = 5	Barrett et al. (1996)
Common Eider	2014	Northwest Greenland	0.23 ± 0.10, *n* = 12	*This study*
	2008	East Bay, CAN	0.43 ± 0.12, *n* = 32[d]	Akearok et al. (2010)
	2004/05	St. Helena Is., CAN	0.89 ± 0.22, *n* = 5	Peck et al. (2016)
	2008	Tern Is., CAN	0.74 ± 0.38, *n* = 32[d]	Akearok et al. (2010)
	2017	Svalbard, NOR	0.28 ± 0.11[c], *n* = 28	Hill (2018)
	2012	Svalbard, NOR	0.25 ± 0.11[c], *n* = 19	Hill (2018)

Similar methodology was used between all studies to process eggs for total mercury

[a]Braune et al. (2002,2016) calculated means in groups of three, then averaged those means to produce Hg concentrations presented here

[b]Combined means and standard deviations from three sample locations in Svalbard, 10 samples per location

[c]Dry weight values have been estimated using mean egg moisture content from this study: kittiwake = 77.0%, murre = 73.2%, eider = 64.3%

[d]Combined means of early and late eggs from same clutch, 16 samples from each category

reported here is unknown, but both are undoubtably lower than if we had been able to collect only the first laid egg in each clutch.

Total Hg levels in eggs from Black-legged Kittiwake and Thick-billed Murre from high Arctic Greenland were greater than those from PLI in the eastern Canadian high Arctic for the same time period, albeit not significantly. When compared with historical data from PLI the mean THg concentration found in kittiwake eggs from high Arctic Greenland is most similar to that found in 1998 (Table 1). For murres the pattern is similar, and the mean murre egg THg concentration from this study is most similar to concentrations reported for PLI in the mid-2000s (Table 1). Aside from PLI the only other available kittiwake and murre data from the Canadian high Arctic are from eggs collected in 1993 at Coburg Island (~ 240 km east of our study area; Fig. 1). Mean egg THg concentrations from our study were slightly lower for murres and almost a third lower for kittiwakes than at Coburg Island (Table 1). Without samples from additional years it is unknown what trends are present in high Arctic Greenland.

Data for THg in Common Eider eggs from the Canadian high Arctic are rare. Peck et al. (2016) reported a mean THg concentration of 0.89 ± 0.22 μg g^{-1} dw for Common Eider eggs sampled at St. Helena Island, Canada (76° N), in 2004/05, almost four times greater than found in our study in 2014 (Table 1; Fig. 1). Akearok et al. (2010) similarly reported a mean THg concentration three times

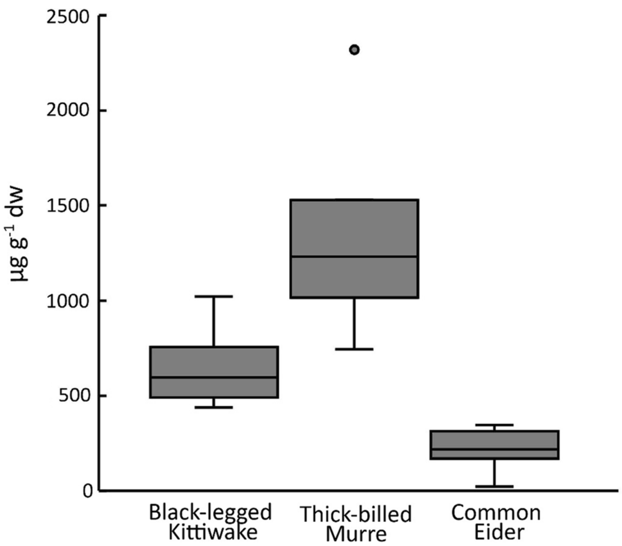

Fig. 2 Boxplots for total Hg concentration (μg g^{-1} dw) in Black-legged Kittiwakes *Rissa tridactyla* ($n=9$), Thick-billed Murres *Uria lomvia* ($n=11$), and Common Eider *Somateria mollissima* ($n=12$) from high Arctic Greenland

greater than our study for eggs sampled at Tern Island, Canada (75° N) in 2008, but found eggs sampled farther south at East Bay (64° N) had approximately half as much mean THg (Fig. 1; Table 1). While this is suggestive of an increasing latitudinal gradient for THg in eiders in the Canadian Arctic, as found in Arctic seabirds, both Mallory et al. (2004, 2017) and Braune et al. (2005) found no such relationship in hepatic Hg analysis of Common Eiders. This difference in latitudinal patterns of Hg in seabirds and sea ducks may result from the benthic feeding behavior of sea ducks compared to the pelagic feeding of seabirds (Chen et al. 2014; Braune et al. 2015) which can correspond to lower trace contaminant levels in mollusk-based diets (Nielsen and Dietz 1989).

Outside of high Arctic Canada data on THg in eggs of Black-legged Kittiwakes, Thick-billed Murres, and Common Eiders breeding in the high Arctic are limited. In Svalbard, Norway, Miljeteig and Gabrielsen (2010) reported mean murre egg THg concentrations in 2003 and 2007 well under half of the concentration reported in our study (Table 1). Farther south, in Bjørnøya, Norway, THg concentrations in murre eggs in 2003 and 2007 were approximately one-tenth of what was found in this study (Table 1). This aligns well with other studies that also found higher Hg concentrations in the Canadian versus European Arctic (AMAP 2018; Albert 2019). In contrast, mean kittiwake egg THg from Svalbard in 2008 was slightly more than reported in our study (Miljeteig and Gabrielsen 2009) (Table 1). Mean THg concentrations in eider eggs sampled in Svalbard in 2012 and 2017 were nearly identical to results from our study (Hill 2018).

Avian risk to Hg toxicity is variable by species and some taxonomic orders transfer more THg to their eggs than others (Ackerman et al. 2016a, 2020; Whitney and Cristol 2017). In a laboratory setting Braune et al. (2012) found that Thick-billed Murre eggs had a medium sensitivity to MeHg exposure. The median lethal concentration (LC_{50}) based on a dose–response curve was 0.48 μg g^{-1} ww, and when maternally deposited Hg was included, the LC_{50} increased to 0.56 μg g^{-1} ww. Converted to dry weight (using mean egg moisture of 73.2% from our study) this suggests an estimated LC_{50} range of 1.79 to 2.09 μg g^{-1} dw, well above the mean for our study. However, a single murre egg from our study had a THg concentration of 2.32 μg g^{-1} dw (Table 1), suggesting some individual murres in our study area may be at elevated risk to reproductive failure. Similarly, Burnham et al. (2018) found 13% of individual murres in our study area had THg concentrations in their blood that put them at medium risk of Hg toxicity, although murres as a whole were at low risk. Although no laboratory studies have been carried out to determine the toxicological effects of Hg on kittiwake or eider eggs, Hg has been shown to negatively affect reproduction in both species (e.g., Tartu et al. 2013, 2016; Goutte et al. 2015; Provencher et al. 2016).

Seabird and sea duck eggs have proven to be important proxies for monitoring Hg in the Arctic. Long-term studies in the Canadian high Arctic have documented increasing then decreasing Hg egg concentrations over a 30-year period. No similar dataset exists yet for seabird and sea duck eggs in northwest Greenland; thus, short- or long-term changes in avian Hg there are less well understood. Based upon results from this study continued monitoring of seabirds and sea ducks in our study area is warranted, particularly for Thick-billed Murre, which have been shown to be at elevated risk to Hg toxicity.

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Author contributions KB, JB, and FM designed the research. KB, JB, FM, and JJ collected and prepped samples in the field, and MC conducted the mercury analysis. All the authors contributed to the writing of the manuscript.

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Data availability All data are available from the corresponding author and are archived by the High Arctic Institute.

Declarations

Conflict of interest The authors report no conflicts of interest.

Ethical approval All standard procedures and protocols were followed, and appropriate permits were received from the Greenland Home Rule Government and other permitting agencies, as required.

Consent to participate All the authors provide their consent to participate.

Consent for publication All the authors provide their consent for this manuscript to be submitted to Polar Biology.

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