

Supplementary Information

Mercury isotopes uncover climate-driven exposure pathways in Arctic food webs

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Supplementary Tables

Sampling

Table S1. Summary of samples collected and the sampling locations. Number of individuals (N), age and sampling year for ringed seals (*Pusa hispida*) analysed in the present study. Site number assigned by the highest THg group median, 1, to the lowest, 8.

Location	Region	Site no.	N	Sampling year	Age range	Total
GREENLAND						114
Qaanaaq	NW. Greenland	1	36	2014–2023	0–4	36
Ittoqqortoormiit	E. Greenland	2	42	2014–2023	0–4	42
Qeqertarsuaq	W. Greenland	6	36	2014–2024	0–2	36
CANADA						74
Sachs Harbour	NW. Canada/ East edge of the Beaufort Sea	4	34	2018–2022	0–4	34
Arviat	W. Hudson Bay	5	27	2018–2023	0–4	27
Resolute Bay	N. Canada	3	13	2018–2023	0–5	13
NORWAY						16
Isfjorden	W. Svalbard	8	16	2018–2024	0–7	16
ALASKA						30
Gambell	Alaska/ Bering-Chukchi group	7	6	2015–2022	1–4	6
Point Hope			3	2015–2022	2–3	3
Shishmaref			19	2015–2023	1–4	19
Hooper Bay			2	2018	1–4	2
TOTAL			234			234

Results

Table S2. Source data for Figure 1d.

Total mercury (THg) in ppm ww, and isotopes ($\delta^{202}\text{Hg}$, $\Delta^{199}\text{Hg}$ and $\Delta^{200}\text{Hg}$) results presented as median and interquartile ranges

Study	Site No.	Location	n	THg (IQR) ppm ww	$\delta^{202}\text{Hg}$ (IQR)	$\Delta^{199}\text{Hg}$ (IQR)	$\Delta^{200}\text{Hg}$ (IQR)
This study	1	North-West Greenland	36	0.322 (0.251–0.461)	0.343 (0.153–0.525)	0.767 (0.733–0.823)	-0.01 (-0.024–0.004)
This study	2	East Greenland	42	0.298 (0.237–0.427)	0.269 (0.19–0.441)	0.894 (0.833–0.939)	-0.016 (-0.044–0.001)
This study	3	North Canada	12	0.235 (0.182–0.394)	0.082 (-0.013–0.212)	0.574 (0.476–0.788)	-0.021 (-0.032–0.01)
This study	4	North-West Canada	34	0.207 (0.141–0.383)	0.29 (0.163–0.471)	0.676 (0.642–0.755)	-0.007 (-0.019–0.006)
This study	5	Huson Bay, CAD	26	0.151 (0.11–0.172)	0.806 (0.647–0.975)	1.338 (1.258–1.527)	0.037 (0.014–0.053)
This study	6	West Greenland	36	0.108 (0.05–0.175)	1.095 (0.73–1.347)	0.899 (0.814–0.927)	0.013 (-0.008–0.039)
This study	7	Bering/Chukchi	30	0.106 (0.069–0.134)	0.965 (0.854–1.176)	0.79 (0.634–0.867)	0.018 (0.007–0.03)
This study	8	West Svalbard	16	0.098 (0.074–0.108)	1.551 (1.264–1.711)	1.579 (1.481–1.656)	0.018 (0–0.024)
Jiskra et al., (2021)¹	-	North Atlantic Ocean	4	0.57 (0.51–0.67)	-0.45 (-0.66 to -0.36)	0.09 (0.04–0.16)	0.06 (0.02–0.09)
Štok et al., (2015)	-	Nares strait, Arctic Ocean	8		-1.345 (-2.355– -1.125)	0.195 (0.178–0.243)	0.12 (0.108–0.275)

Table S3. Source data for Figure 2.

Data from 3 previous studies measuring Hg isotopes in Atmospheric Hg(o), total gaseous mercury (TGM), vegetation, soil, sediment, zooplankton, seawater, and fish (Arctic Char, *Salvelinus Alpinus*). Data presented as median and interquartile ranges are adapted from supplementary information of corresponding studies and is used for plotting in the conceptual Figure 2, showing fractionation relationships between different matrices in a similar environment.

Matrix	Location	N	$\delta^{202}\text{Hg}$ (IQR)	$\Delta^{199}\text{Hg}$ (IQR)	$\Delta^{200}\text{Hg}$ (IQR)	reference
Atmospheric Hg(o)	Alaska (Toolik)	6	0.695 (0.607–0.708)	-0.245 (-0.275– - 0.230)	-0.060 (-0.077– - 0.043)	Obrist et al., 2017
Vegetation	Alaska (Toolik)	6	-1.470 (-1.588– - 1.308)	-0.190 (-0.207– - 0.180)	-0.035 (-0.040– - 0.015)	Obrist et al., 2017
Soil	Alaska (Toolik)	18	-1.250 (-1.382– - 0.975)	-0.110 (-0.210– - 0.053)	-0.015 (-0.040– 0.000)	Obrist et al., 2017
Sediment	Beaufort Sea	11	-0.900 (-0.980– - 0.815)	-0.120 (-0.180– - 0.010)	0.010 (-0.010– 0.025)	Lim et al, 2024
TGM	Beaufort Sea	3	0.540 (0.470–0.630)	-0.510 (-0.565– - 0.400)	-0.040 (-0.045– - 0.040)	Lim et al., 2024
Zooplankton	Beaufort Sea	13	-0.240 (-0.470– - 0.160)	0.130 (-0.100– 0.290)	0.010 (-0.010– 0.030)	Lim et al., 2024
Zooplankton	Chukchi Sea	22	-0.075 (-0.190–0.103)	-0.100 (-0.325– 0.010)	-0.020 (-0.030– 0.037)	Lim et al., 2024
Fish, Arctic char	Chukchi Sea	3	-0.480 (-0.580– - 0.315)	0.400 (0.325–0.490)	0.000 (-0.025– 0.000)	Lim et al., 2024
Seawater	Beaufort Sea	13	-0.680 (-0.800– - 0.360)	0.090 (-0.030– 0.220)	0.100 (0.050–0.130)	Lim et al., 2024
Seawater	Nares Strait	8	-1.345 (-2.355– - 1.125)	0.195 (0.177–0.243)	0.120 (0.107–0.275)	Strok et al., 2015

Supplementary Figures

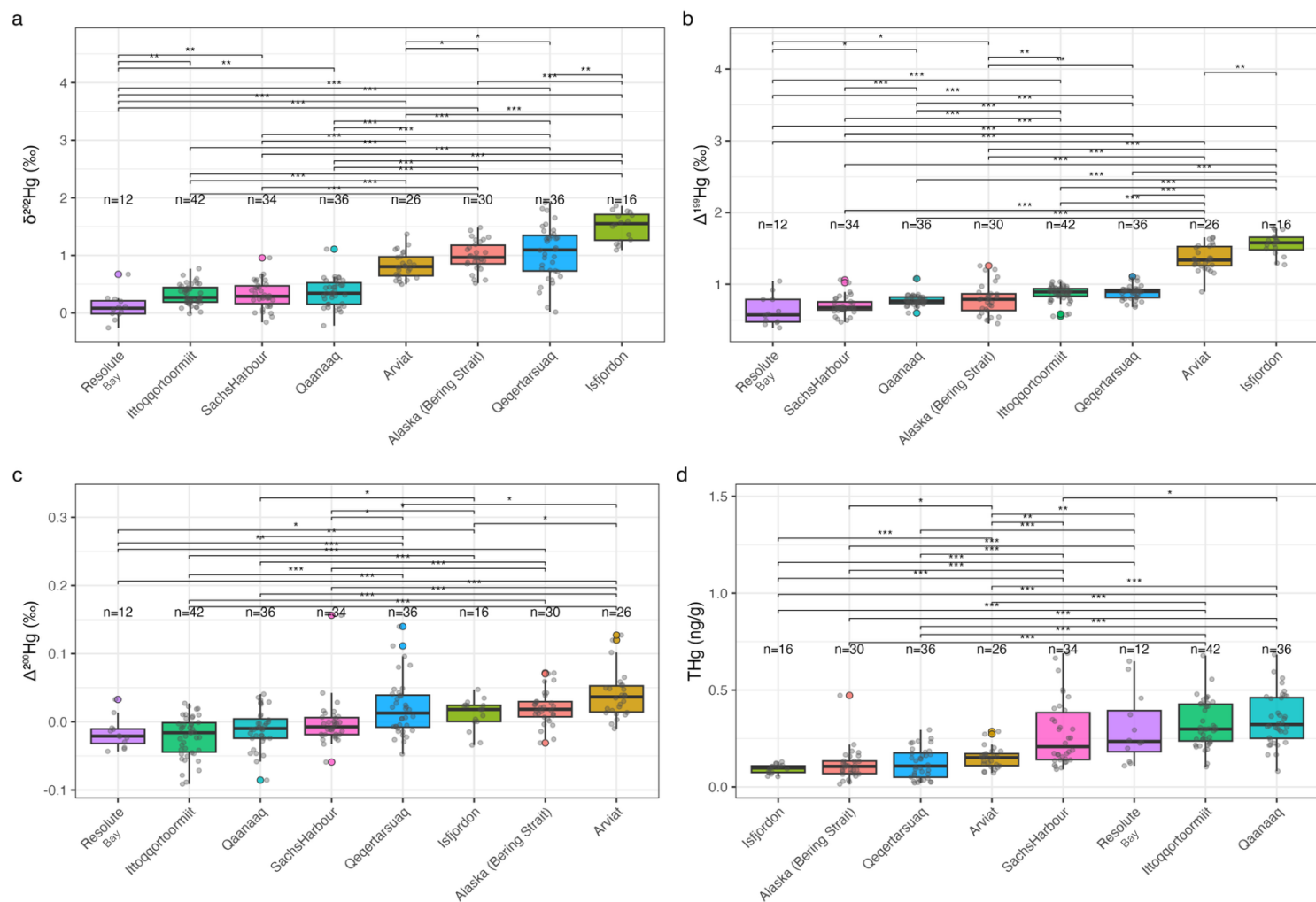


Figure S1. Statistical analysis 1. Distribution of (a) $\delta^{202}\text{Hg}$, (b) $\Delta^{199}\text{Hg}$, (c) $\Delta^{200}\text{Hg}$ and (d) THg, grouped by sampling location. Boxes show the median and interquartile range (IQR); whiskers extend to $1.5 \times \text{IQR}$; points beyond whiskers are shown individually. Sample size (n) for each location is given below each box. Normality was assessed with the Shapiro-Wilk test; as data did not meet normality assumptions, differences among locations were tested with the Kruskal-Wallis test, followed by pairwise Wilcoxon rank-sum tests as post-hoc comparisons. Horizontal brackets indicate statistically significant pairwise comparisons: *p < 0.05, **p < 0.01, ***p < 0.001. Non-significant comparisons are not shown.

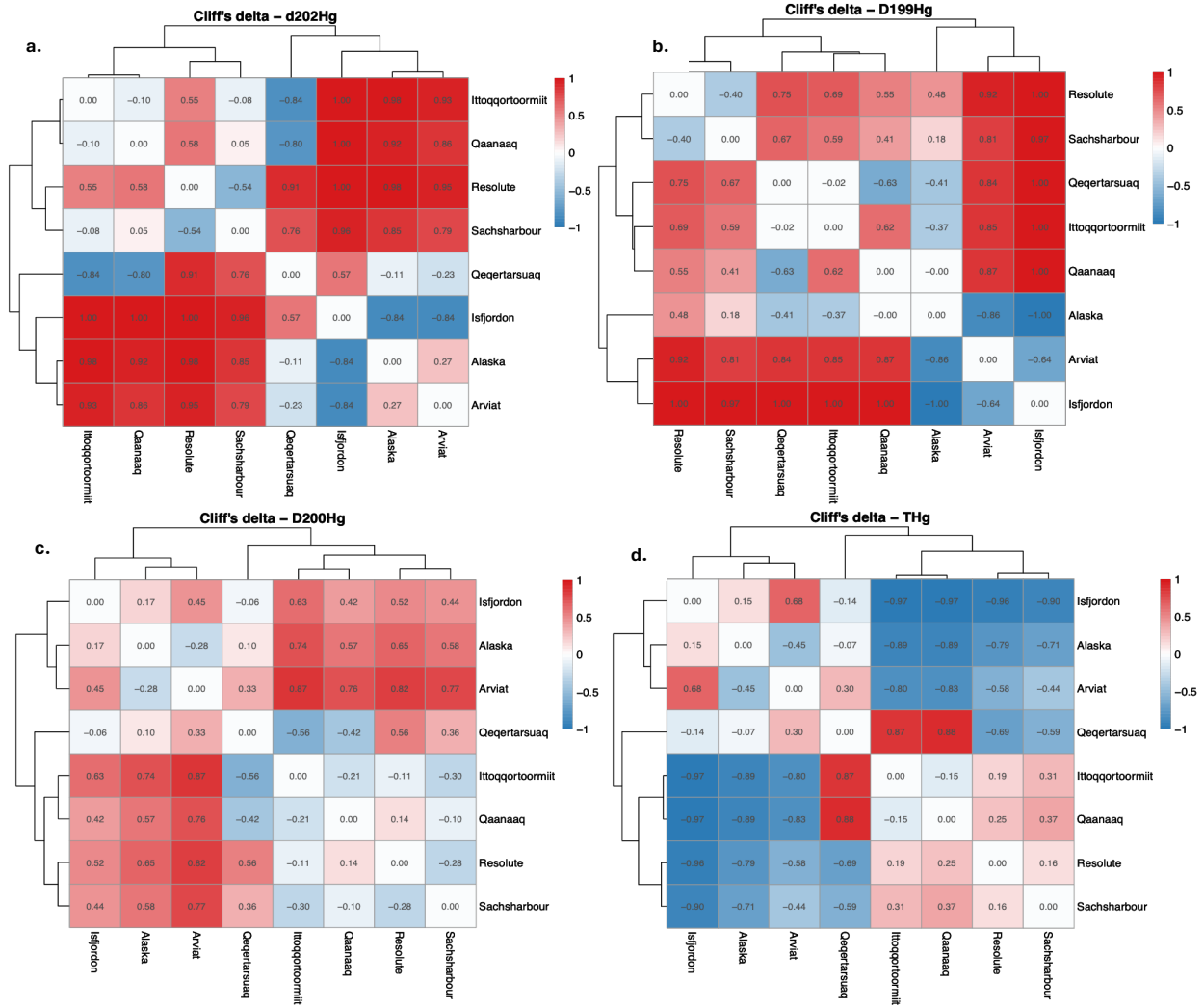


Figure S2. Statistical analysis 2. Cliff's delta (δ) effect-size heatmaps for pairwise comparisons among sampling locations, calculated for (a) $\delta^{202}\text{Hg}$, (b) $\Delta^{199}\text{Hg}$, (c) $\Delta^{200}\text{Hg}$ and (d) THg. Each cell shows the Cliff's delta statistic for the row location relative to the column location; values range from -1 to $+1$, where positive values (red) indicate the row location has higher values than the column location, negative values (blue) indicate the reverse, and values near 0 (white) indicate little to no separation between the two distributions. Effect sizes can be interpreted using negligible ($|\delta| < 0.15$), small ($0.15-0.33$), medium ($0.33-0.47$), and large (≥ 0.47) (Romano et al., 2006). Dendrograms to the left show hierarchical clustering of locations based on similarity of their Cliff's delta scores. n per location as reported in Table S1.

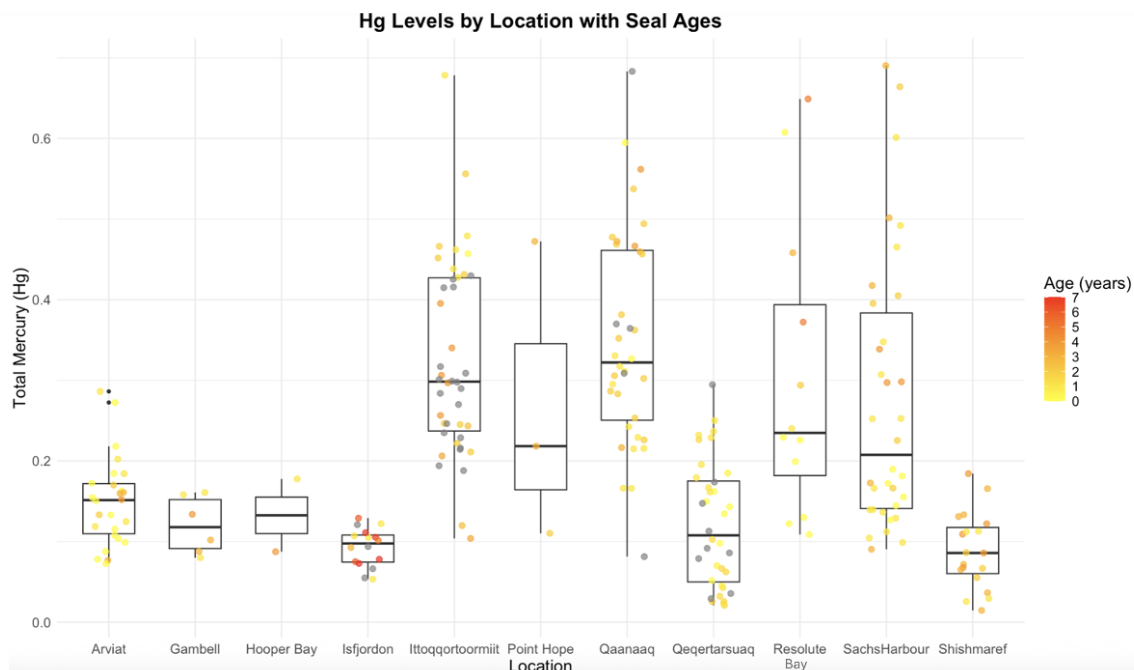


Figure S3. Total mercury (THg) concentrations by age and sampling location. Boxes show the median and interquartile range (IQR); whiskers extend to $1.5 \times$ IQR. Individual points are jittered ringed seal samples, colored by age (years) as indicated in the legend. Isfjorden, Svalbard, included several individuals up to 7 years of age, all other sampled seals were known sub-adults. Despite this age difference, increased age did not control which locations had the highest THg concentrations.

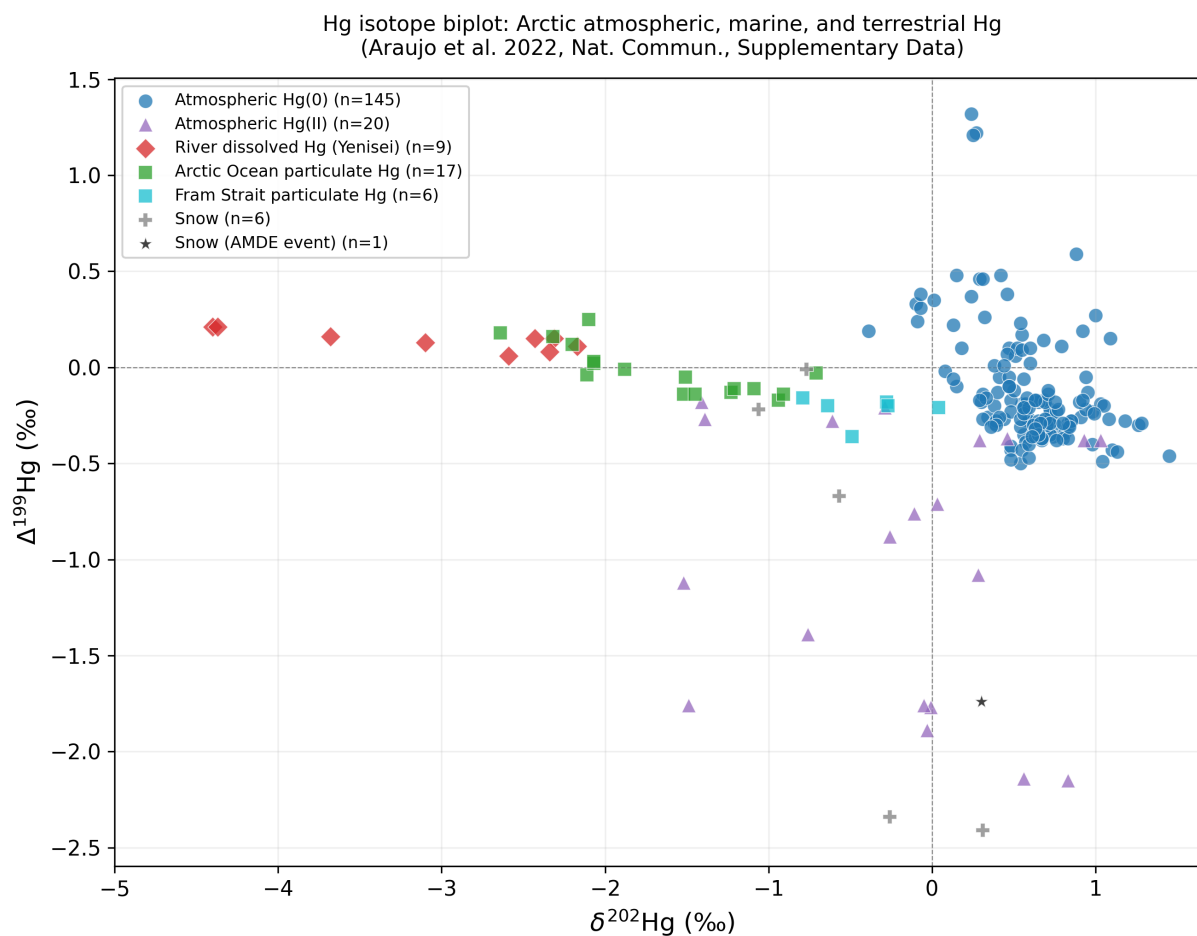


Figure S4. Extended source data biplot for mercury isotopes $\Delta^{199}\text{Hg}$ vs. $\delta^{202}\text{Hg}$.

Arctic Hg matrices, replotted from the supplementary data of ². Data not included in the main text Figure 2, as most samples originate from the Siberian Arctic, geographically distant from this study's European/North American sampling locations. River dissolved Hg from the Yenisei River on the Siberian side shows the most strongly negative $\delta^{202}\text{Hg}$ (below -4‰). Particulate Hg (pHg) from the Arctic Ocean and Fram Strait are also negative in $\delta^{202}\text{Hg}$.

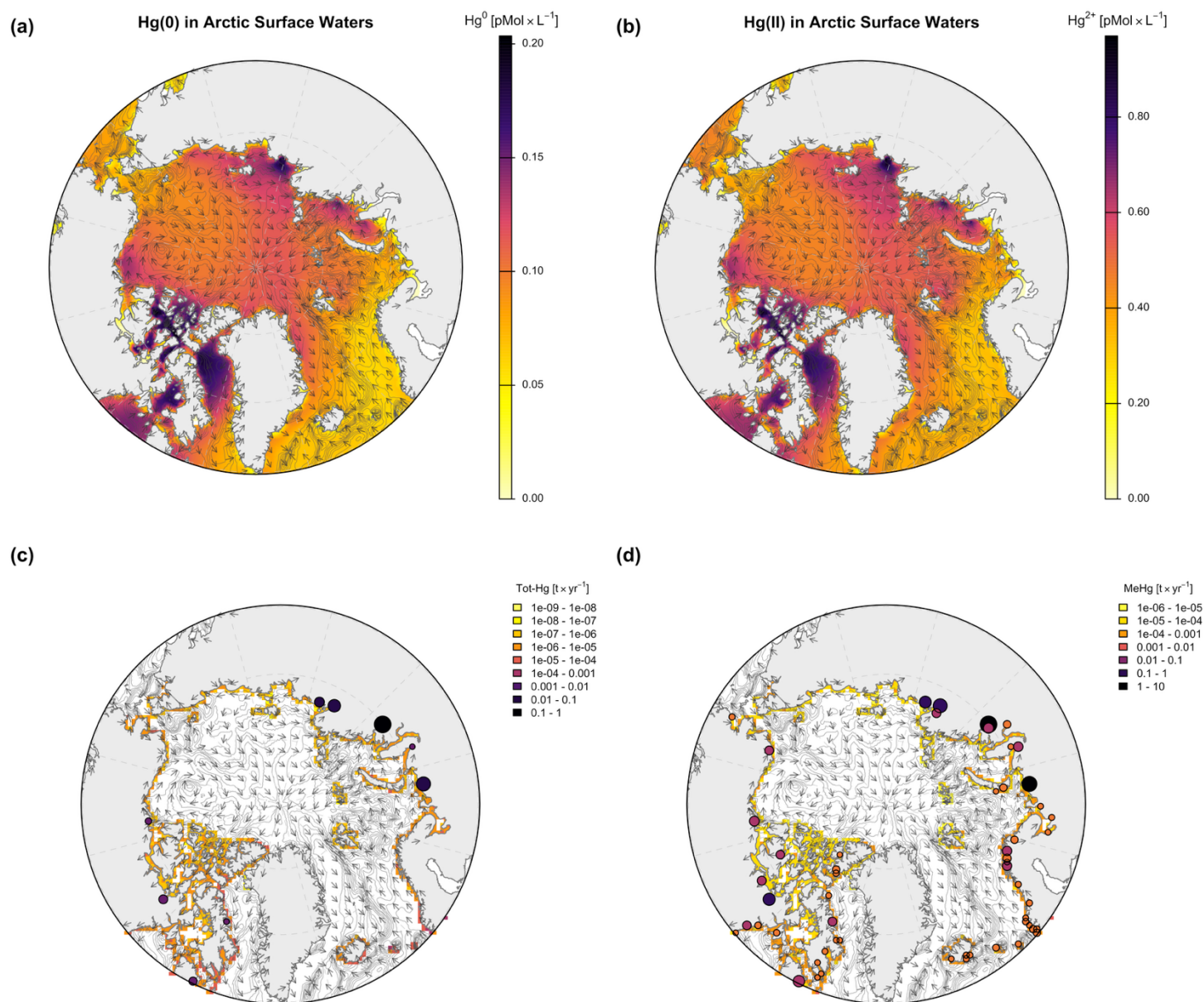
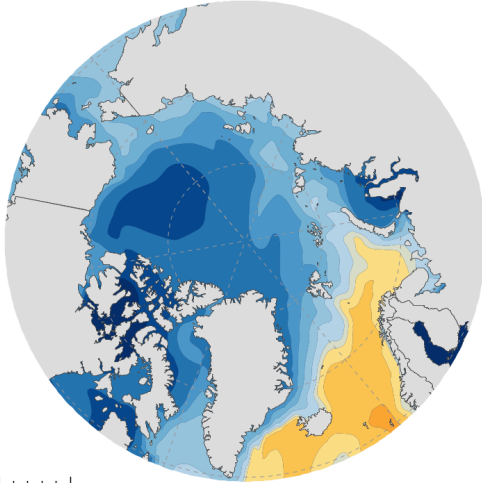


Figure S5. Hg distributions in the Arctic Ocean and its river inputs.

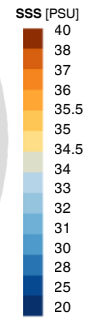
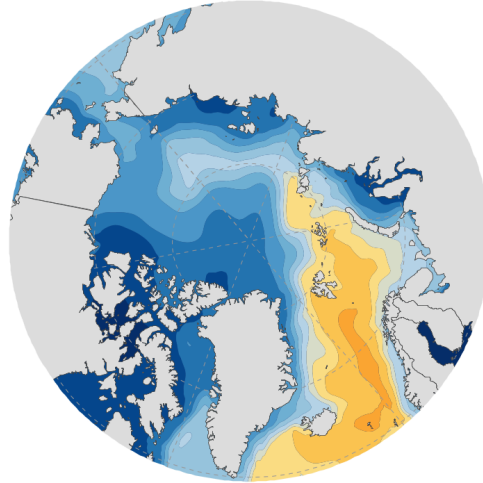
- (a) Annual mean surface ocean elemental mercury (Hg(0)) concentration (pmol L⁻¹), 2006–2015 mean, from the coupled MITgcm ocean–sea-ice mercury model ³. Panels a and b are overlaid with surface ocean current velocity vectors from ECCOV4 (2006–2015 mean), with arrow direction and length indicating current direction and relative speed.
- (b) Annual mean surface ocean methylmercury (MeHg) concentration (pmol L⁻¹), 2006–2015 mean, from the same model (Huang et al., 2025).

- (c) Modelled annual total mercury (THg) export from Arctic rivers to the coastal ocean (t yr^{-1})⁴.
In panels c–d, river mouth exports are shown as gridded raster cells, with high-concentration outflows additionally marked by points scaled to export magnitude
- (d) Modelled annual MeHg export from Arctic rivers to the coastal ocean (t yr^{-1}) (Liu et al., 2021).

A. SSS 2026 (SSP585)

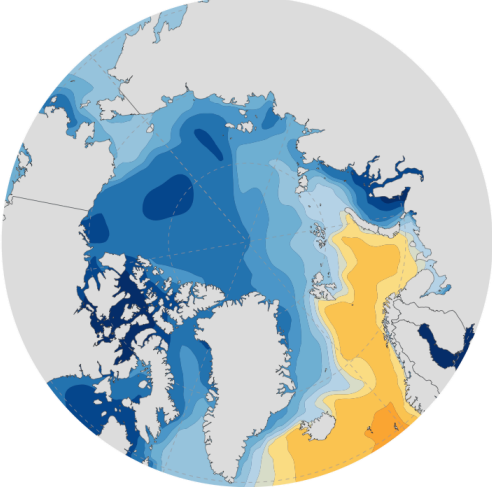


B. SSS 2100 (SSP585)

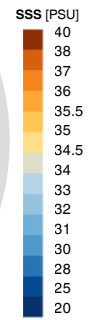
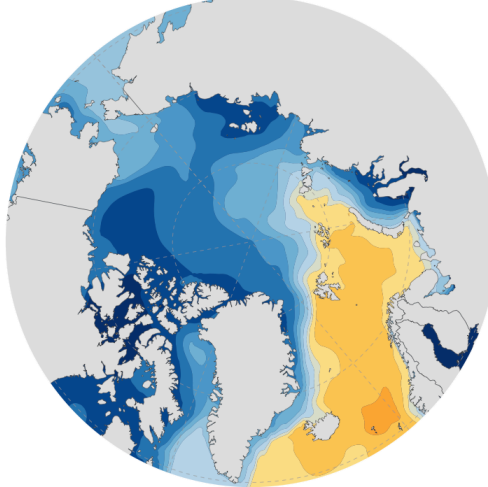


1000 km

C. SSS 2026 (SSP245)



D. SSS 2100 (SSP245)



E. SSS pre-collapse (control)



F. SSS during AMOC hosing

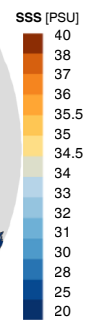
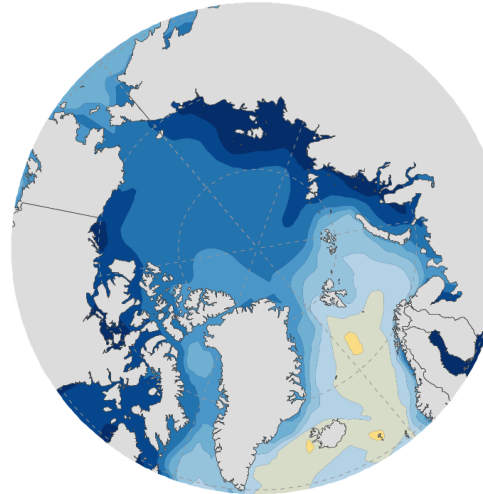


Figure S6. Projected shifts in Arctic sea-surface salinity (SSS) under future climate scenarios.

a-b) Water masses for 2026 and 2100, distinguished by SSS (PSU), from the EC-Earth3-CC model (CMIP6 SSP5-8.5 scenario; Copernicus Climate Change Service, 2021) shown on a north polar stereographic projection.

c-d) Water masses for 2026 and 2100, distinguished by SSS (PSU), from the EC-Earth3-CC model (CMIP6 SSP4-4.5 scenario; Copernicus Climate Change Service, 2021) shown on a north polar stereographic projection.

e-f) Mean SSS before and after collapse. SSS averaged over simulation years 1–30, represent the pre-collapse reference state as a visual control. Projected SSS for AMOC collapse is at years 70–100 of the simulation. Data for e and f were downloaded from the NAHosMIP u03-hos experiment⁵.

Supplementary Methods

1. Sample collection

Aarhus University (AU) in Denmark provided the Greenland samples collected through the AMAP Core biota program. The Alaska Department of Fish and Game (ADF&G) contributed muscle tissues collected under its long-term ice seal biomonitoring program. Environment and Climate Change Canada provided samples collected through the Northern Contaminants Program from three Canadian sites. The Norwegian Polar Institute collected the Svalbard seals from local sport hunters. Sex data is provided by the hunter and may be confirmed during necropsy and with DNA markers⁶. Sex has not been found to significantly influence the accumulation of THg in sub-adults in earlier studies, and therefore no preference was made during sample selection^{6–8}. Age, however, has been reported to be positively associated with increased THg^{8,9}. Sub-adults (i.e. individuals aged ≤ 4 years) were prioritised to minimise age-related variability in the collections for this study. Age determination was performed using cementum annuli analysis from stained thin-sectioned canine tooth slides and, in a few cases for Svalbard seals, immaturity was inferred from body length, weight, and reproductive organ development¹⁰.

2. Chemical analysis

Samples were prepared and analysed for THg and Hg isotopic composition following methods previously described¹¹. In short, the frozen muscle tissues were thawed, and surface material in contact with the sampling media was removed using a ceramic knife. Samples were weighed, freeze-dried, then weighed again to determine water content. Approximately 0.4 g of homogenised sample was digested in 4 mL HNO₃ and 4 mL Milli-Q water using an Anton Paar Multiwave 7000

microwave system at 220 °C for 30 min. Digestions were conducted in 18-vial batches, including at least one procedural blank, one duplicate, and one Certified Reference Material (CRM; DORM-5 fish protein, DOLT-5 dog fish liver, or TORT-3 lobster hepatopancreas) per batch for quality control. Following digestion, 1 mL HCl was added, and the solutions were diluted to a final mass of ~50 g with Milli-Q water. THg concentrations were measured by an Agilent 7900 ICP-MS, with mean CRM recoveries ranging between 94-106% across all CRMs. Based on the THg results from ICP-MS, aliquots were further diluted to 1 ppb for Hg isotopic analyses using an acid solution with a similar acid composition to the digestions. Hg isotopes were measured by a Thermo Scientific Neptune XT MC-ICP-MS equipped with a Cetac HGX-200 cold vapour introduction system. Sample digestions were reduced in 3% SnCl₂ in 10% HCl (v/v) at a flow rate of 0.5 mL min⁻¹. Faraday cups fitted with 10¹³ Ω amplifiers were used for masses of Hg isotopes 198 and 199, while 10¹¹ Ω amplifiers measured masses of isotopes 200, 201, 202, and 204. Instrument sensitivity was approximately 0.5 V on mass 202 for a 1 ppb Hg solution. Analyses were performed using a standard-sample-standard bracketing approach with NIST 3133 as standard¹², matched in concentration and acid composition to the samples, and with a measurement time of 10 min. Matrix effects were considered negligible as indicated by near-equal signal intensities (within ±10%) between diluted sample digestions (diluted based on the ICP-MS results) and the NIST 3133 standard. Hg isotope signatures ($\delta^{202}\text{Hg}$, $\Delta^{199}\text{Hg}$, $\Delta^{200}\text{Hg}$, $\Delta^{201}\text{Hg}$, and $\Delta^{204}\text{Hg}$) were calculated relative to NIST 3133 following standardised procedures¹¹. Quality control included one procedural blank and one NIST 8610 UM-Almaden CRM for every six samples. In addition, the biological CRMs DORM-5, DOLT-5, and TORT-3 were measured along with the samples. Blank signals were consistently <1% of sample intensities. Measurements on CRMs agreed well with certified values for NIST 8610 and previously reported results for DOLT-5¹³ and TORT-3¹⁴ (we have not found previously reported values for DORM-5). The following values (mean ± 2 SD in ‰) were measured in NIST 8610 ($n=79$) ($\delta^{202}\text{Hg}$: -0.55±0.11; $\Delta^{199}\text{Hg}$: -0.02±0.05; $\Delta^{200}\text{Hg}$: 0.01±0.06; $\Delta^{201}\text{Hg}$: -0.04±0.06; and $\Delta^{204}\text{Hg}$: 0.01±0.12), DORM-5 ($n=12$) ($\delta^{202}\text{Hg}$: 0.50±0.11; $\Delta^{199}\text{Hg}$: 0.90±0.06; $\Delta^{200}\text{Hg}$: 0.04±0.06; $\Delta^{201}\text{Hg}$: 0.74±0.08; and $\Delta^{204}\text{Hg}$: -0.05±0.08), DOLT-5 ($n=8$) ($\delta^{202}\text{Hg}$: -0.06±0.05; $\Delta^{199}\text{Hg}$: 0.70±0.04; $\Delta^{200}\text{Hg}$: 0.06±0.03; $\Delta^{201}\text{Hg}$: 0.57±0.03; and $\Delta^{204}\text{Hg}$: -0.11±0.13), and TORT-3 ($n=4$) ($\delta^{202}\text{Hg}$: 0.01±0.15; $\Delta^{199}\text{Hg}$: 0.70±0.04; $\Delta^{200}\text{Hg}$: 0.07±0.07; $\Delta^{201}\text{Hg}$: 0.57±0.08; and $\Delta^{204}\text{Hg}$: -0.04±0.07).

3. Statistical analysis

All statistical analyses were conducted in R (RStudio version 2024.12.1+563). Due to small sample sizes at some Alaskan sites, Hooper Bay, Gambell, Shishmaref, and Point Hope were pooled into a single Bering-Chukchi, Alaska region (Supplementary Table S1). We assessed normality of $\delta^{202}\text{Hg}$, $\Delta^{199}\text{Hg}$, $\Delta^{200}\text{Hg}$, and THg within regions using the Shapiro-Wilk test (Supplementary Table 3). Because several regional subsets deviated from normality, we applied non-parametric Kruskal-Wallis

and pairwise Wilcoxon rank-sum tests with Benjamini-Hochberg correction across all variables (Supplementary Fig. 1). We set significance at $p < 0.05$. Effect sizes were quantified using Cliff's δ heatmaps (Supplementary Fig. 2).

4. Arctic Ocean Hg at the surface, ocean currents and riverine export models

Arctic spatial visualisations of surface Hg(0), ocean circulation, and riverine THg export were generated in R (version 2024.12.1+563) using packages *terra* and *sf*. All maps were displayed in a North Polar Stereographic projection (EPSG:3413), and the Arctic extent was constrained with a circular mask north of $\sim 60^\circ\text{N}$. R's Natural Earth datasets were used for the land boundaries. Surface Hg(0) and Hg(II) fields were obtained from the authors of the coupled ocean-atmosphere Hg model simulation described by Huang et al. (2025)³. The authors provided a 2006-2015 annual average in the NetCDF output. Inverse distance weighting (IDW) with a 100 km search radius and power parameter of 1 was used to generate continuous Arctic surface fields. Ocean surface circulation fields were downloaded from the ECCO Version 4 (ECCOV4)¹⁵, selecting monthly mean eastward (EVEL) and northward (NVEL) surface velocity fields for the same time period of 2006-2015. Surface currents were averaged for the uppermost model layer ($Z = 0$). Current vectors were spatially aggregated using the median values and plotted as directional arrows over the Hg(0) and river Hg export maps. Riverine Hg export data were downloaded from the Arctic_rivers_Hg_export.mat dataset published by Liu et al., (2021)⁴ which provides monthly THg export estimates and river outlet coordinates for Arctic-draining rivers. Mean annual export was calculated for each river by averaging monthly values across the 12-month estimates (Hg.12months). River outlet coordinates were extracted from the same file and projected to the Arctic stereographic map used previously. To improve visualisation of both major and minor river contributions, Hg export values were log10-transformed before raster aggregation. Aggregated fields were then clipped to the Arctic region and displayed with point symbols scaled according to river Hg export magnitude.

5. Future climate projections

Four-panel maps of Arctic sea-surface salinity (SSS) were generated in R version 2024.12.1 using *ggplot2*, *sf*, *akima*, *patchwork*, and *FNN*. For panels (a) and (b) in figure 3, monthly SSS data were obtained from the Copernicus Climate Change Service CMIP6 dataset¹⁶ using the EC-Earth3-CC model under the high-emission SSP5-8.5 scenario. Annual mean SSS fields were calculated for 2026 (near-present baseline) and 2100 (end-of-century). For panel (c), annual mean SSS was obtained from the North Atlantic Hosing Model Intercomparison Project (NAHosMIP)⁵ using EC-Earth3 output from the u03-hos experiment in which 0.3 Sv of freshwater was applied uniformly across the North Atlantic to force AMOC collapse. Panel c shows the sustained collapse (years 70-100). All fields were projected to a North Polar Stereographic projection (70°N true scale, 40°W central

meridian) and interpolated onto a 30 km polar grid using bilinear interpolation. Coastlines were sourced from the R Natural Earth dataset. Sample sites and major ocean current vectors were added corresponding to Figure 1a and the data collected in this study, and were adjusted to the expected outcomes for THg, $\Delta^{200}\text{Hg}$, and $\delta^{202}\text{Hg}$ following the projected changes in temperature and major ocean currents in panels B and C. Arrows for the dominant direction of freshwater release in response to a reduction in Beaufort Gyre Strength were adapted from Athanase et al., 2025¹⁷.

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