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

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Abstract

Mercury (Hg) concentrations in Arctic top predators continue to rise in many regions despite declining global anthropogenic Hg emissions, a discrepancy that remains unresolved by current Hg cycling models. Using Hg stable isotope ratios ($\delta^{202}\text{Hg}$, $\Delta^{199}\text{Hg}$, and $\Delta^{200}\text{Hg}$) in ringed seals (*Pusa hispida*) sampled across the Arctic, this study identifies key drivers for the regionally diverging Hg trends seen in Arctic marine mammals. Elevated Hg burdens and low isotope signatures in the Canadian High Arctic and northern Greenland are consistent with substantial contributions from terrestrially processed Hg originally deposited as atmospheric Hg(o), while Hg transported by ocean currents from lower latitudes influences lower Hg exposures in West Svalbard and Central West Greenland. Continued warming and accelerated fluvial runoff will further intensify terrestrial Hg inputs to the Arctic Ocean, while important changes in ocean circulation may extend the spatial range of high Hg concentrations, increasing overall Hg exposure to top predators and Indigenous communities. Despite globally declining anthropogenic Hg emissions, we foresee growing threats to wildlife and human health from climate change-driven increases in Hg exposure.

Introduction

The Arctic environment is changing faster than anywhere else on Earth, with record-breaking sea ice declines, warming ocean temperatures, wildfires, and ocean acidification^{1,2}. These changes are tightly coupled to planetary systems, affecting global weather patterns, ocean circulation, and sea-level rise³. Scientific debate on the collapse of the Atlantic Meridional Overturning Circulation (AMOC) has brought the global significance of Arctic instability to public attention^{4,5}. Less discussed are the consequences for long-range transport, transformation, and biomagnification of persistent toxic contaminants like mercury (Hg), despite increasing concerns for Arctic ecosystems and northern people, with some of the highest Hg exposures observed in human populations globally^{6–8}. Long-range atmospheric transport is thought to be the dominant pathway by which Hg reaches such remote places, explaining sustained increases in Arctic human populations and biota since the

Industrial Revolution^{7,9}. Efforts reinforced through the Minamata Convention have curbed the Northern Hemisphere's share of anthropogenic Hg emissions, resulting in measurable declines in atmospheric Hg at High Arctic monitoring stations^{10,11}. Despite this progress, Hg levels in Arctic top predators, including marine mammals and seabirds, continue to increase in some regions^{12–14}.

Advances in Hg isotope geochemistry have improved our ability to identify and quantify sources and pathways through which Hg enters Arctic food webs^{15–17}. Briefly, the $\delta^{202}\text{Hg}$ isotope signature (a proxy for Mass Dependent Fractionation, MDF) records the processing history, including Hg transformations in the environment and internal metabolism, the $\Delta^{199}\text{Hg}$ and $\Delta^{201}\text{Hg}$ (proxies for odd-mass Mass Independent Fractionation, MIF) signals exposure of Hg to photochemical activity under the sun's UV, before entering food webs, and the $\Delta^{200}\text{Hg}$ signature (a proxy for even-mass Mass Independent Fractionation) reflects Hg speciation (as $\text{Hg}(\text{O})$ or $\text{Hg}(\text{2+})$) associated with deposition from the atmosphere^{18,19}. Recent studies have documented the growing importance of terrestrial Hg sources^{18–20} and ocean-current inputs^{16,21} to the marine environment, as Arctic warming continues to remobilise and redistribute legacy Hg among environmental reservoirs^{22–24}. Yet, Hg isotope data for Arctic marine biota remain sparse, and no geographical comparison of Hg isotopes within a single marine species across the Arctic is available.

This is the first study to investigate Hg isotopes in a single marine species across the Arctic region, using ringed seals (*Pusa hispida*) as a key species. The ringed seal is an ideal sentinel species for Arctic ecosystems, as an abundant, circumpolar, ice-associated, and relatively stationary, predatory species. Effect assessments for Hg across the Arctic show that most ringed seal populations fall within the "no risk" and "low risk" categories, although a small proportion of individuals, mainly adults from the Canadian Arctic, are at severe risk¹². Ringed seals are also an important prey species for top predators such as polar bears, and they are a key component of the subsistence diet of Arctic Indigenous peoples, making them central to long-term biomonitoring programmes^{6,14,25}. Here, we present total Hg concentration data and isotope signatures ($\delta^{202}\text{Hg}$, $\Delta^{199}\text{Hg}$, $\Delta^{200}\text{Hg}$ and $\Delta^{201}\text{Hg}$) in muscle tissue in ringed seals from eight locations across Alaska, Canada, Greenland, and Svalbard (Norway), and link these to ocean-coupled Hg models at the surface with ocean current velocities, and fluvial Hg export models to further explore transport of Hg to Arctic food webs^{20,26,27}. Our study provides evidence of distinct Hg sources and processing histories before Hg enters the Arctic marine food web, helping explain drivers of diverging Hg time trends across Arctic regions. We use these spatial relationships to explore how future changes in freshwater inputs and ocean circulation could alter Hg distribution and exposure pathways.

Main:

Regional patterns in total Hg (THg) and Hg isotope signatures ($\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$)

Total Hg (THg) concentrations and Hg isotope signatures ($\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$) in ringed seal muscle vary significantly across sites, showing strong regional patterns (Figs. 1a and b). The highest THg levels are found in Northwest and Central East Greenland (Sites 1-2) and in the Canadian High Arctic (Sites 3-4), where seals cluster with low $\delta^{202}\text{Hg}$ (-0.26 to 1.1‰) and low $\Delta^{199}\text{Hg}$ (0.39 to

1.0‰; Fig. 1d). Svalbard (Site 8) show significantly lower THg than all other locations, consistent with previous Hg assessments reported for marine mammals across the Arctic^{12,14}. Svalbard's low Hg is paired with the highest isotope fractionation values for $\delta^{202}\text{Hg}$ (1.1 to 1.9‰) and $\Delta^{199}\text{Hg}$ (1.3 to 1.8‰) across all sites. Results from Hudson Bay and the Bering-Chukchi region (Sites 5 and 7) show intermediate $\delta^{202}\text{Hg}$ values (0.6 to 1.4‰), although Hudson Bay is elevated in $\Delta^{199}\text{Hg}$. Seals from Central West Greenland (Site 6) show the widest range in $\delta^{202}\text{Hg}$ values (2‰) (Supplementary Tables S1-2, Figs. S1-3). The seal muscle $\delta^{202}\text{Hg}$ values measured in this study are consistently higher than previously reported seawater $\delta^{202}\text{Hg}$ levels from the ocean basin supplying the food web, and surface seawater $\delta^{202}\text{Hg}$ is systematically higher in Atlantic-influenced waters (median -0.45‰ , IQR -0.66 to -0.36)²⁸ than in Arctic-influenced waters in Baffin Bay (median -1.35‰ , IQR -2.36 to -1.13 ; Supplementary Table 2)²⁹. The range in $\delta^{202}\text{Hg}$ across ringed seal sampling sites therefore parallels basin-scale seawater gradients (Fig. 1a).

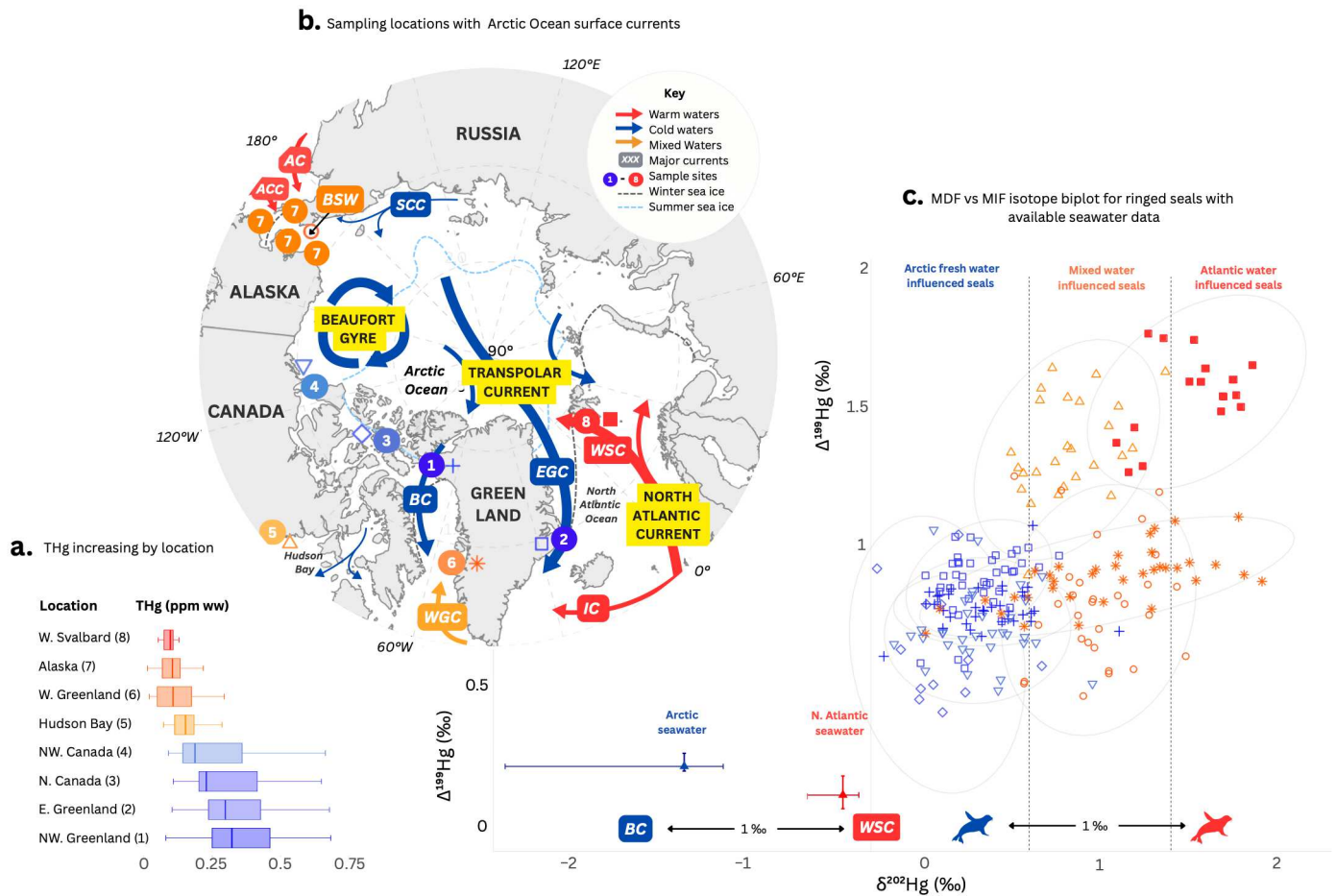


Figure 1 | THg, $\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$ in Arctic ringed seal muscle reflect ocean basin influences.

- (a) **Sampling locations ranked by median THg concentration**, lowest (Site 8) to highest (Site 1), overall range: 0.014–0.690 $\mu\text{g/g ww}$. Shape symbols denote sampling location, and colours correspond to the degree of Hg isotope fractionation (MDF, $\delta^{202}\text{Hg}$; MIF, $\Delta^{199}\text{Hg}$), as in Fig. 1c, with red indicating higher and blue lower fractionation. Site shape symbols, numbering, and colours are used consistently across panels.
- (b) **Sampling locations for the 232 ringed seals (*Pusa hispida*) included in this study**, collected between 2014 and 2024, are shown on a polar stereographic projection. Sites 1-4 show the locations of the highest median total mercury (THg) concentrations, and the colours correspond to isotope data, as in Fig. 1c. Warm (red), cold (blue), and mixed (orange) Arctic Ocean surface currents are shown as directional arrows^{30–32}. Currents/water mass abbreviations are listed

alphabetically: ACC, Alaskan Coastal Current; AC, Anadyr Current; BC, Baffin Current; BSW, Bering Strait Water; EGC, East Greenland Current; IC, Irminger Current; SCC, Siberian Coastal Current; WGC, West Greenland Current; WSC, West Spitsbergen Current. The Transpolar Drift, Beaufort Gyre, and North Atlantic Current are highlighted in yellow as major oceanographic features influencing Arctic circulation. Average sea ice extent boundaries are shown for winter (March 2017, dashed grey) and summer (September 2017, dashed blue)³³.

- (c) **MIF ($\Delta^{199}\text{Hg}$) plotted against MDF ($\delta^{202}\text{Hg}$) isotope results** for ringed seal muscle tissue analysed in this study. Dotted lines separate distinct groups, with the total variation in $\delta^{202}\text{Hg}$ for ringed seal samples (blue coloured seals to red coloured seals) reflecting potential influences from distinct ocean-basin Hg sources (seawater measured in Arctic water at Nares Strait (BC)²⁹ to seawater measured in North Atlantic water (WSC))²⁸. Hg isotope data in the biplot are found in Supplementary Table 2.

While diet is a common driver of isotopic variation in marine predators, dietary differences alone are unlikely to explain the full magnitude of the observed variation. The latitudinal $\delta^{15}\text{N}$ gradient previously detected in Canadian ringed seals³⁴ could, in principle, elevate THg and MDF of Hg in the north through trophic enrichment, however, this gradient was attributed to spatial variation in isotopic baselines rather than true trophic differences³⁴. In line with this, our northernmost Canadian and Greenlandic populations are depleted, rather than enriched, in $\delta^{202}\text{Hg}$ values, contrary to what would be expected under a system governed solely by trophic control of $\delta^{202}\text{Hg}$. Recent observations show $\delta^{202}\text{Hg}$ values are consistently lower (by 0.5–0.6‰) in Northwest and Central East Greenland than in Central West Greenland, across multiple environmental matrices, including peat and shorthorn sculpin (*Myoxocephalus scorpius*)³⁵. Together, suggesting that regional differences in feeding behaviour are of limited importance here.

We find that the large spatial shifts in THg and Hg isotope signatures across the eight study sites (Figs. 1a and c) are likely reflecting distinct regional Hg sources at the base of Arctic marine food webs. Despite limited seawater Hg isotope data across the Arctic, available measurements reveal substantial regional variability for MDF ($\delta^{202}\text{Hg}$). High Arctic waters show the most negative $\delta^{202}\text{Hg}$ values, with a median of -1.35‰ (IQR: -2.36 to -1.13‰) measured at Nares Strait, Baffin Bay²⁹ (near Site 1); -0.68‰ (IQR: -0.80 to -0.36‰) in the Beaufort Sea³⁶; and -0.45‰ (IQR: -0.66 to -0.36‰)²⁸ measured in North Atlantic surface waters passing west of Svalbard (Site 8), with values closer to Mediterranean signatures than to those of High Arctic waters²⁸. A similar spatial gradient in THg and Hg isotopes is evident between ringed seal groups that are influenced by these oceanographic regions (Fig. 1a and c), suggesting that ocean-transported Hg contributes to the Hg isotopic variability observed across sample sites^{28,29}. Regional differences in sunlight exposure, driven by sea ice cover, offer one mechanism for isotopic variability across Arctic Ocean basins³⁵. Unlike MDF ($\delta^{202}\text{Hg}$), the odd-mass MIF ($\Delta^{199}\text{Hg}$) value is set at the base of the food web and indicates photochemical demethylation of MeHg prior to biological uptake¹⁷. Aqueous photochemical demethylation imparts a coupled positive shift in both $\Delta^{199}\text{Hg}$ and $\delta^{202}\text{Hg}$ in the residue MeHg at a characteristic slope of $\sim 2.43 \pm 0.10$ ^{37,38}. Hudson Bay, Canada and the more northern Canadian sampling sites broadly follow this trajectory. Because sea ice limits sunlight penetration and thus photodemethylation, ice-associated biota typically show lower $\Delta^{199}\text{Hg}$ and $\delta^{202}\text{Hg}$ ^{35,37}, as observed in the lower Hg signature values in ringed seals in Northern Canada, Northwest and East Greenland.

This is in line with $\Delta^{199}\text{Hg}$ values as low as $\sim 0.5\text{‰}$ previously reported for beluga whales and seabirds from other ice-covered regions^{35,39,37}. Ringed seals from Svalbard (Site 8) show significantly higher odd-mass MIF and MDF, consistent with the inflow of warmer, sunlit surface waters carried from the Atlantic by the North Atlantic and West Spitsbergen Currents²¹ (Fig. 1b).

Environmental sources and Hg export models provide a framework for interpreting Hg isotope variation

Figure 2 shows $\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$ fractionation patterns across the North American Arctic, linking atmospheric, terrestrial, and marine Hg pools to the high Arctic ringed seals. Atmospheric Hg(O) previously measured at Toolik Field Station, Alaska, shows a positive median $\delta^{202}\text{Hg}$ of 0.695‰ (IQR: $0.607\text{--}0.708\text{‰}$), contrasting sharply with the negative signatures assimilated into tundra vegetation (median -1.470‰ ; IQR: $-1.588\text{ to }-1.308\text{‰}$) and underlying soils from the same study area (median -1.250‰ ; IQR: $-1.382\text{ to }-0.975\text{‰}$)⁴⁰. This atmosphere-to-terrestrial isotope shift is mirrored on the Siberian side of the Arctic (Fig. S4), where $\delta^{202}\text{Hg}$ of dissolved Hg in the Yenisei River reaches values below -4.0‰ , and is reflected further downstream in marine surface waters, with $\delta^{202}\text{Hg}$ of particulate Hg in the transpolar drift current of the central Arctic Ocean measured at $-1.7 \pm 0.4\text{‰}$ ⁴¹. This consistency across terrestrial and fluvial compartments highlights that the terrestrial influence on isotope signatures is retained during fluvial transport to the coastal ocean^{42,41}.

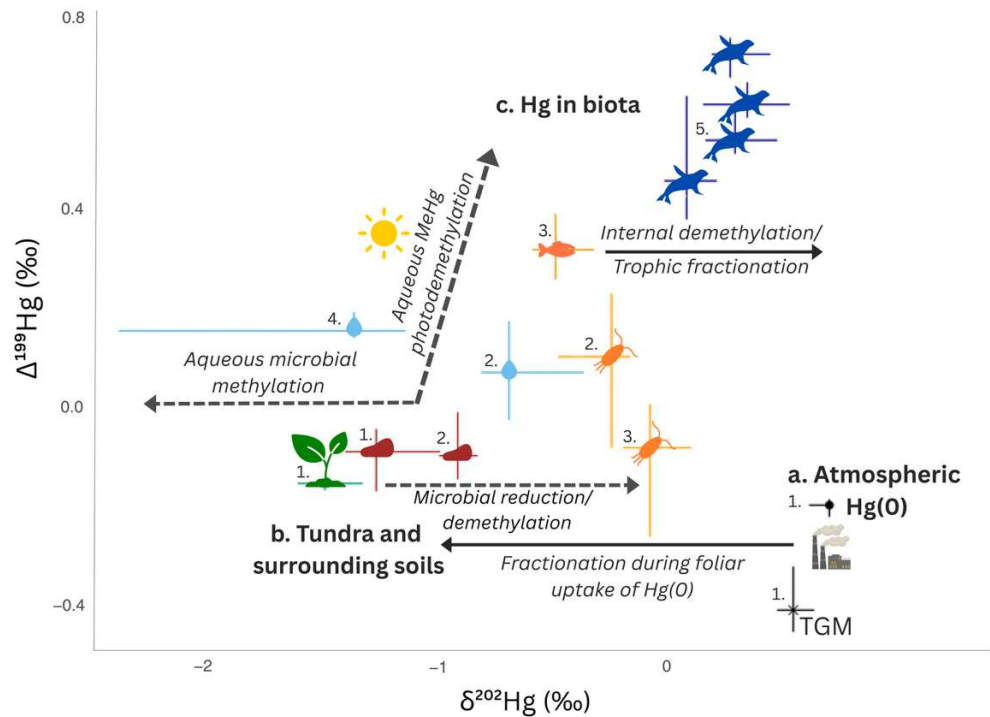


Figure 2 | Conceptual pathway linking atmospheric deposition, terrestrial processing and Hg exposure in Arctic top predators explained with $\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$ isotope fractionation pathways in the North American Arctic.

- (a) Atmospheric Hg(O), delivered to the Arctic via long-range atmospheric transport and evasion from oceanic transport.
- (b) Vegetation preferentially assimilates Hg(O) in terrestrial environments, causing a large shift toward negative $\delta^{202}\text{Hg}$ values.

(c) Hg is transported from terrestrial stores to Arctic marine food webs through erosion and fluvial exports. Source data; 1) atmospheric Hg(o), TGM (total gaseous mercury), vegetation and soil from Toolik Field station in Alaska⁴⁰, 2) seawater, sediment and zooplankton from Beaufort Sea³⁶, 3) zooplankton and fish from Chukchi Sea³⁶, 4) seawater from Nares Strait²⁹, and 5) ringed seals from sampling sites 1-4 in the current study. Source data for Figure 2 are found in Supplementary Table S3. Fractionation slopes are based on experimentally derived values^{15,17,38}.

The low $\delta^{202}\text{Hg}$ signatures concomitant with high THg levels detected in North Canada, Northwest and Central East Greenland ringed seal samples (Sites 1-4) suggests that terrestrial cycling is likely to have an important influence for the Arctic Ocean hotspot areas for Hg assimilation, as Arctic tundra vegetation preferentially assimilates isotopically light Hg(o) from the atmosphere, resulting in strongly negative $\delta^{202}\text{Hg}$ signatures in surrounding soils and permafrost^{40,43} (Fig. 2). Long-range atmospheric transport is a well-established primary source of Hg to the Arctic, where centuries of deposition have resulted in substantial amounts of Hg accumulating in the upper 0-3 m of permafrost soils, 597,000 Mg, compared to just 2,415 Mg stored in glaciers and 330 Mg in the atmosphere⁴⁴. This disproportionate accumulation reflects the efficiency of Arctic tundra vegetation as a sink for gaseous Hg(o), combined with slow decomposition rates, resulting in an unusually strong retention of Hg in Arctic soils and permafrost, relative to temperate systems⁴⁰. Permafrost thaw, erosion and river discharge enhance the mobilisation and transport of historically accumulated terrestrial Hg to the coastal ocean^{18,19,45}. This mechanism may explain the increase in THg in most biota time series across the Arctic in recent decades¹⁴, including the unexpected temporal rise in Hg concentrations documented in narwhal (*Monodon monoceros*) tusks in Northwest Greenland since approximately 2000, which dietary shifts alone could not fully account for¹³.

The elevated $\delta^{202}\text{Hg}$ values observed in the muscle tissue of ringed seals in this study relative to previously reported values for Arctic River Hg and coastal water Hg (Fig. 2), can be explained by trophic-level enrichment in bioaccumulating MeHg. Of all Hg types entering marine food webs, only MeHg is easily transported across the intestinal wall, allowing it to biomagnify in Arctic marine food chains and reach toxic concentrations in some top predators⁴⁶⁻⁴⁸. MeHg sources in coastal marine food webs are not always well constrained and include contributions from in situ microbial methylation in the water column and sediments. River discharge delivers both terrestrially derived MeHg and inorganic Hg substrates, along with dissolved organic carbon, which promotes microbial methylation in coastal water^{44,49}. In the Canadian Arctic, this methylation occurs unusually close to the surface (~100–300 m), overlapping the euphotic zone and coupling Hg methylation directly to peak biological productivity and trophic uptake⁵⁰. Once assimilated into the food web, MeHg is progressively enriched in heavier $\delta^{202}\text{Hg}$ at higher trophic levels, a well-constrained process driven by internal demethylation in marine mammals, which preferentially breaks down lighter isotopes of MeHg, subsequently excreted as inorganic Hg, leaving the remaining internal MeHg isotopically heavier^{16,51,52}. As MeHg accounts for nearly 100% of THg in muscle of Alaskan ringed seals⁵³, muscle tissue clearly captures trophic fractionation of $\delta^{202}\text{Hg}$, with documented shifts of approximately 0.5-1.75‰ between prey and consumer muscle^{16,51,52}.

Figure 3a shows modelled elemental Hg (Hg(o)) hotspots in Arctic surface waters, concentrated in the Canadian Arctic and near the outflow points of major Arctic rivers²⁶. These hotspots coincide with regions of elevated Hg concentrations measured in surface seawater by GEOTRACES and are consistent with the distribution of modelled river-exported Hg shown in Figure 3b²⁰. Ocean current vectors overlaid on the Hg model outputs indicate the dominant surface-water circulation pathways, including the Transpolar Drift Current, Beaufort Gyre, southward export via the East Greenland Current, and northward advection toward western Svalbard via the North Atlantic and West Spitsbergen Current⁵⁴ (Fig. 1b).

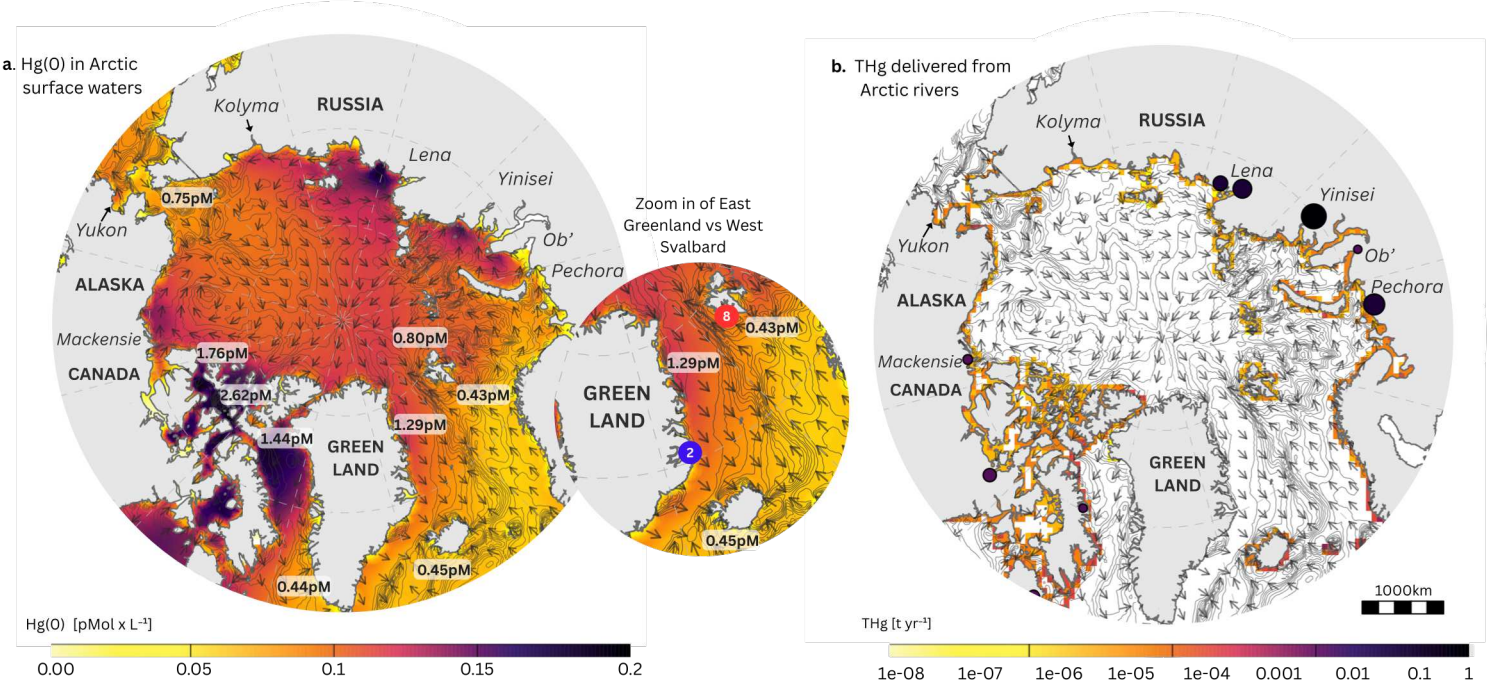


Figure 3 | Hg(o) hotspots in the Arctic Ocean align with river-exported Hg and surface water dynamics.

- (a) **Modelled annual surface ocean elemental Hg (Hg(o)) concentrations** (pMol L⁻¹) from the coupled MITgcm ocean-sea-ice mercury model²⁷ (2006- 2015 mean values). Surface water THg(pM) concentrations sourced from GEOTRACES cruises^{21,59,55}, are plotted where data are available. Grey contour lines show ocean current speed (10th–90th percentile), while arrows indicate current direction, sourced from the ECCOV4 reanalysis (2006- 2015 mean)²⁶. The zoom-in of West Svalbard and East Greenland (Sites 2 and 8) highlights opposing directions for surface advection and Hg(o) differences in the diverging surface currents.
- (b) **Modelled annual total mercury (THg) export from Arctic rivers** to the coastal ocean (t yr⁻¹)²⁰. River mouth exports are displayed as gridded raster cells, with high-concentration outflows shown as scaled points proportional to export magnitude. Outflow points of major Arctic rivers are labelled in italics¹⁹.

Concentrated Hg(o) at the outflow points of several of the major Arctic rivers, and the dense network of smaller rivers draining the Canadian Arctic coast, support a strong influence of river-derived Hg for the elevated Hg concentrations and low $\delta^{202}\text{Hg}$ values observed in Canadian Arctic ringed seals (Figs. 1 and 3). Arctic rivers, streams and groundwater export a significant quantity of Hg to the Arctic Ocean (approximately 37,000 kg y⁻¹), reflecting the Arctic Ocean's disproportionate share of global freshwater input and substantial permafrost Hg reservoir, where only the top 30 cm of soil is estimated to hold over 12 times the global atmospheric Hg burden (surface soils, 49,000 Mg;

atmosphere, 4,000 Mg)^{19,56,57}. The Arctic Ocean's strong halocline stratification limits vertical mixing of fresh riverine inputs, promoting the retention and lateral transport of river-derived freshwater and associated terrestrial constituents within the surface layer^{58,59}. Within the Canada Basin, anticyclonic circulation and Ekman convergence drive freshwater toward the centre of the Beaufort Gyre. Similarly, the Transpolar Drift transports Siberian river-influenced freshwater and terrestrial material toward Fram Strait and East Greenland, although the fraction of terrestrially derived Hg retained in this pathway requires further verification^{58,59}. In contrast, waters around Svalbard are influenced by warmer, saline surface waters carried North via the West Spitsbergen Current, resulting in a distinct hydrographic regime between West Svalbard and East Greenland (Fig. 3)⁵⁹.

Latitudinal trends in Mass Independent Fractionation (MIF) patterns support ocean transport of Hg

Even-mass MIF ($\Delta^{200}\text{Hg}$) signatures in ringed seal muscle tissues are near zero (Fig. 4a) and broadly follow a latitudinal trend (Fig. 4b)²⁸. Three sites deviate from the expected trend: Western Svalbard shows significantly higher $\Delta^{200}\text{Hg}$ than expected for its latitude, while East Greenland displays a dip from the latitudinal $\Delta^{200}\text{Hg}$ trend. Central West Greenland shows high variability in $\Delta^{200}\text{Hg}$ values, with a mean value slightly more positive than expected (Fig. 4a and b). For the $\Delta^{199}\text{Hg}$, Svalbard seals deviate significantly from seals at similarly high latitudes (Fig. 4c), and the odd-mass MIF relationship ($\Delta^{199}\text{Hg}$ vs $\Delta^{201}\text{Hg}$, Fig. 4d), generally follows the slope for uptake of residual MeHg after photoreduction of MeHg³⁸.

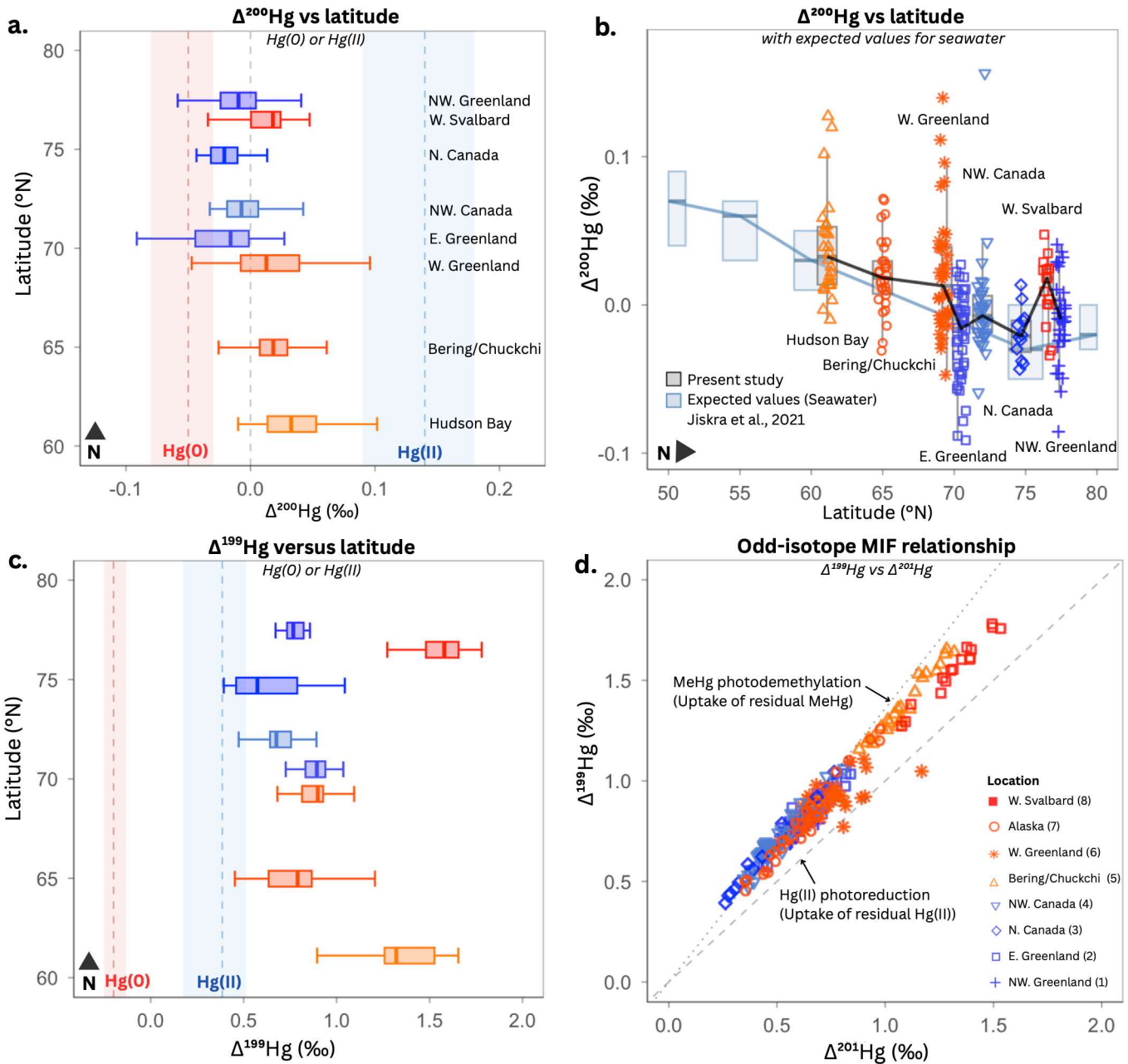


Figure 4 | $\Delta^{200}\text{Hg}$, $\Delta^{199}\text{Hg}$, and $\Delta^{201}\text{Hg}$ in ringed seals at different Arctic latitudes show atmospheric deposition pathways and indicate long-distance oceanic transport across a latitudinal gradient, as well as uptake mechanisms.

- (a) $\Delta^{200}\text{Hg}$ values measured in ringed seal muscle tissues sampled between 2014 and 2024 ($n=232$), grouped by sampling sites with increasing latitude on the y-axis. Boxes in Figures 4a- c show the interquartile range; the centre line represents the median, and the whiskers extend to the data range. The dashed reference lines on the x-axis show reported $\Delta^{200}\text{Hg}$ values associated with atmospheric deposition as Hg(0) (red, median = -0.05‰ , IQR -0.08 to -0.03‰) and Hg(II) (blue, median = 0.14‰ , IQR 0.09 to 0.18‰)²⁸.
- (b) $\Delta^{200}\text{Hg}$ versus latitude. Observed values from ringed seal sampling locations in this study are shown with a median trend line (black), overlaid with expected latitudinal seawater $\Delta^{200}\text{Hg}$ data for $\Delta^{200}\text{Hg}$ values in seawater (blue boxes and trend line)²⁸.
- (c) $\Delta^{199}\text{Hg}$ versus latitude. The red dashed line and band correspond to the source atmospheric deposition of Hg(0) (median, -0.20‰ ; IQR -0.25 to -0.13‰), and the blue dashed line and band correspond to pooled rainfall and reactive Hg(II) values (median around 0.37‰ ; IQR, 0.175 to 0.515‰)²⁸.
- (d) $\Delta^{199}\text{Hg}$ versus $\Delta^{201}\text{Hg}$. Dashed lines indicate slopes of ~ 1.0 and ~ 1.3 corresponding to uptake of residual MeHg and Hg(II) , respectively³⁸.

The near-zero $\Delta^{200}\text{Hg}$ values in high Arctic ringed seal muscle (Fig. 4a), are consistent with previous measurements suggesting an average of 70% of Hg in Arctic biota originates from atmospheric deposition of $\text{Hg}(\text{O})$ ³⁶. The even-mass isotope signature ($\Delta^{200}\text{Hg}$) is altered only by photochemical reactions occurring in the upper atmosphere and is not influenced by biological or marine processes, making it a useful tracer of how Hg reaches the ocean surface^{60,61}. At mid-latitude temperate zones, $\text{Hg}(\text{II})$ wet deposition is more important and carries a positive $\Delta^{200}\text{Hg}$ of +0.17‰ (blue line, Fig. 4a)²⁸, whereas Arctic Hg inputs are dominated by $\text{Hg}(\text{O})$ dry deposition and riverine export of Hg that was originally deposited as $\text{Hg}(\text{O})$ and accumulated in soils and permafrost, carrying a negative $\Delta^{200}\text{Hg}$ of -0.05‰ (red dashed line in Fig. 4a)^{42,61,36}. Across study sites, muscle $\Delta^{200}\text{Hg}$ values are largely consistent with $\text{Hg}(\text{O})$ -dominated inputs at high latitudes, though, they are slightly more positive compared to expected seawater values, reflecting preferential uptake of freshly produced MeHg, methylated by near-surface oxidation of $\text{Hg}(\text{II})$, which carries a slightly more positive $\Delta^{200}\text{Hg}$ than the bulk seawater average^{28,36}. West Svalbard is an exception to the general patterns observed, with significantly higher $\Delta^{200}\text{Hg}$ than expected for its northern latitude (Fig. 4b), consistent with Hg transport from lower latitudes, where $\text{Hg}(\text{II})$ wet deposition is more dominant^{30,31}. The Atlantic influence at Svalbard is also evident in the latitudinal $\Delta^{199}\text{Hg}$ pattern (Fig. 4c). As MeHg undergoes photolytic breakdown, the residual pool becomes progressively enriched in the heavy odd isotopes (^{199}Hg and ^{201}Hg), with higher odd-isotope MIF values reflecting greater photodegradation before food web uptake, independent of the original $\text{Hg}(\text{O})/\text{Hg}(\text{II})$ deposition pathway^{28,38}. $\Delta^{199}\text{Hg}$ in biota is therefore better interpreted as a measure of photodegradation extent than of deposition source²⁸. The relationship between the two odd MIF $\Delta^{199}\text{Hg}/\Delta^{201}\text{Hg}$ slope (Fig. 4d) shows ringed seal Hg derives primarily from residual MeHg following water-column photodemethylation, consistent with elevated $\Delta^{199}\text{Hg}$ at Svalbard, where solar penetration and more extensive photodemethylation are expected in Svalbard's ice-free, North Atlantic-influenced surface waters.

Ringed seals from Central West Greenland show the widest range in $\Delta^{200}\text{Hg}$ of all sampled locations (Figs. 4a and b; Tables S1-S2), likely reflecting the convergence of mixed Atlantic and Arctic waters in the West Greenland (Irminger) Current, consistent with Søndergaard et al. (2025)¹⁶, who found only ~64% of recent Hg deposition in Central West Greenland peat being derived from $\text{Hg}(\text{O})$, compared to ~97% in Northeast Greenland. Finally, seals at Central East Greenland, situated at a similar latitude, have the most negative $\Delta^{200}\text{Hg}$ values of all sampled sites, consistent with a Hg pool dominated by high-latitude $\text{Hg}(\text{O})$ deposition (Figs. 4a and b). The strong contrast in THg concentrations and Hg isotope signatures between East Greenland and West Svalbard supports the role of major ocean currents as an important means of Hg (re)distribution across Arctic marine food webs¹⁶, with important implications for regional Hg exposure pathways in future climate scenarios.

Climate-driven shifts in regional Hg exposure

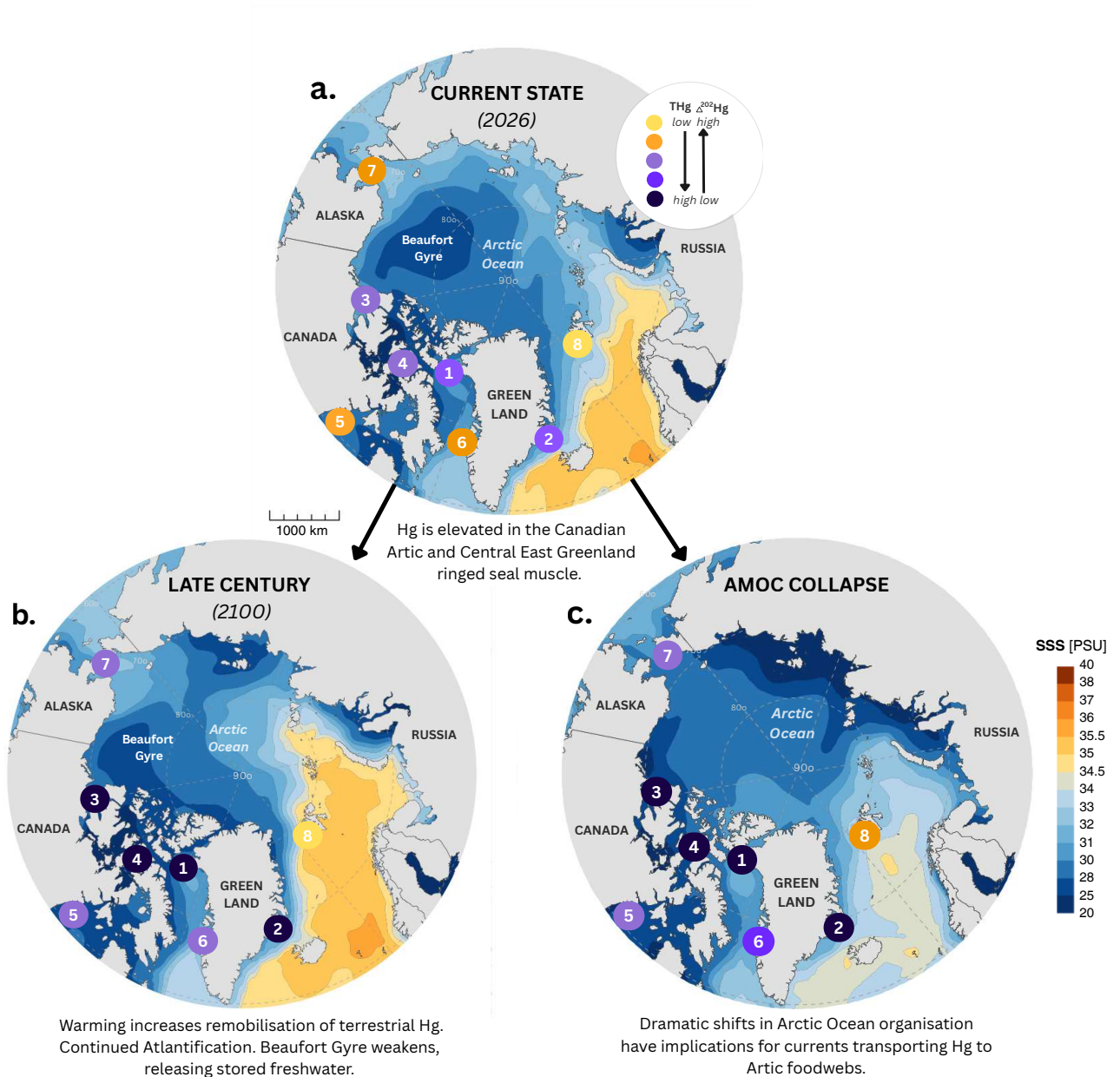


Figure 5 | Projected Arctic Ocean water mass reorganisation under medium-emissions and AMOC collapse scenarios inferred from changes in sea-surface salinity, with implications for future Hg exposures in Arctic marine biota.

- 2026 water masses separated by sea-surface salinity (SSS, PSU)** from the EC-Earth3-CC model (CMIP6 SSP5-8.5 scenario), displayed on a north polar stereographic projection and overlaid with ringed seal sampling sites from this study (1-8). Site colours are used across panels to reflect median site THg levels from this study, ranging from low THg with high $\delta^{202}\text{Hg}$ values (in yellow) to high THg with low $\delta^{202}\text{Hg}$ (in magenta).
- Projected SSS for 2100** under the intermediate-emissions SSP2-4.5 scenario CMIP6 SSP2-4.5 (EC-Earth3-CC model, 2021). Sample site colour shifts indicate assumed increases in ringed seal THg and Hg isotope signatures. A weakened Beaufort Gyre has been previously estimated to increase freshwater release through the Canadian Arctic and East Greenland^{62,63}.
- Projected mean SSS with AMOC collapse** (NAHosMIP u03-hos experiment, EC-Earth3, simulation years 70-100)⁶⁴.

Based on the spatial relationships observed in the ringed seal isotope dataset and projected changes in Arctic climate and ocean circulation, we expect increasing contributions of terrestrially

remobilised Hg to Arctic marine food webs by 2100, despite mitigation under the Minamata Convention. These projections assume that present day linkages between Hg isotope signatures and environmental Hg sources remain broadly consistent, although associated biogeochemical processes and ecological changes will also influence Hg transport and exposure pathways^{58,59}. Following IPCC AR6 guidance, we use CMIP6 SSP2-4.5 We use SSP2-4.5 to examine changes under an intermediate-emissions scenario^{65,66}. The late-century hydrological shifts inferred from sea surface salinity are subject to continued warming and cryosphere loss, freshening the coastal Arctic Ocean^{1,58,67}(Fig. 5b). Combined with permafrost thaw and erosion of Hg-rich tundra soils, increased freshwater inputs are expected to intensify delivery of terrestrial Hg to aquatic ecosystems^{19,45,67}. An earlier spring freshet raises additional concern by increasing the overlap between peak biological productivity and the period of highest Hg delivery^{68,19,45}. We predict that ringed seals in areas increasingly influenced by fresh terrestrial inputs will show higher THg concentrations with strong negative $\delta^{202}\text{Hg}$ signatures (1-4).

The reorganisation of Arctic surface waters is also subject to major changes in ocean circulation patterns^{62,63,69}. 1) Beaufort Gyre instability has received growing attention in Arctic climate projections because of its importance for basin-wide freshwater distribution^{62,63}. The gyre has accumulated around 40% more freshwater since the 1970s, and many models project significant weakening or disappearance of the BG by 2100^{62,63,70}, evident here by the redistribution of the freshwater blob at the gyre's centre (Figs. 5a and b). Passive tracer experiments indicate that BG-stored freshwater is released primarily through the Canadian Arctic Archipelago via the Baffin Current and western Fram Strait via the East Greenland Current⁶², potentially transporting Hg-elevated surface waters from the Canada Basin (1.76 ± 1.15 pM) and Baffin Bay (2.62 ± 1.97 pM) towards lower latitudes^{21,71}. 2) Changes in Atlantic circulation provide an additional control on the distribution of Arctic surface waters. Although the CMIP6 model predictions do not foresee a complete collapse of the Atlantic Meridional Overturning Circulation (AMOC) within the century, they indicate a weakening of 34-45% of present-day strength by 2100⁶⁹. The AMOC currently drives the influx of warm, northward-flowing Atlantic waters into the Fram Strait, which carries significantly lower THg (West Spitsbergen Current = 0.80 ± 0.26 pM, and Labrador Sea inflows = 0.65 ± 0.18 pM)²¹ than waters exported southward via the East Greenland Current and Baffin Current (1.29 ± 0.43 pM and 1.58 ± 0.53 pM, respectively)²¹. Consistent with this, the CMIP6 SSP2-4.5 model shows continued Atlantification of Arctic waters in 2100, with northward Atlantic advection remaining active^{72,73}. The stability and potential tipping points of the AMOC remain a hot topic for scientific debate, as CMIP models have known biases in Arctic Ocean projections, and physics-based and statistical early warning approaches have suggested a complete shutdown as early as the mid-21st century^{74,5,69}. The forced AMOC-collapse experiment (Fig. 5c) illustrates how an extreme circulation reorganisation could increase the influence of Arctic-origin surface waters at Sites 6 and 8. The climate simulations describe changes in water masses rather than directly modelling Hg transport, methylation or food-web uptake. The future scenarios should therefore be interpreted as hypotheses for continued monitoring rather than quantitative exposure predictions.

As $\delta^{202}\text{Hg}$ decreases with depth in Greenland peat profiles¹⁶, decreasing $\delta^{202}\text{Hg}$ in biota may serve as a tracer for the growing contributions of legacy terrestrial Hg across Arctic sites. Consequently, this ringed seal dataset can serve as a baseline for continued monitoring of Arctic conditions and the effectiveness of the Minamata Convention, which is why the ringed seal has been selected as a Key Monitoring species within the AMAP (Arctic Monitoring and Assessment Programme) framework. Future climate projections highlight the need to study the Arctic broadly in terms of climate change, biodiversity, pollution, human health, and governance. Northern Indigenous communities are most directly affected and their subsistence diets, central to cultural identity and food security, expose them to some of the highest mercury levels globally^{6,7,25}. A 'One Health' approach, recognising that human, animal, and ecosystem health are inseparable, is increasingly adopted by governing bodies, including the Arctic Council and World Health Organisation²⁴, which call for a better understanding of evolving contaminant exposure pathways, essential to environmental monitoring, public health policy, and the long-term effectiveness of the Minamata Convention.

In conclusion, we show that Hg stable isotope compositions in Arctic ringed seals are geographically distinct, reflecting differences in the dominant Hg sources supplying regional ocean basins that feed their respective food webs. Sites receiving coastal Arctic Ocean waters have consistently elevated THg levels, low in $\delta^{202}\text{Hg}$, $\Delta^{199}\text{Hg}$, and $\Delta^{200}\text{Hg}$ isotope values. These values are characteristic of Hg(o) dry deposition, terrestrial processing, riverine Hg loading, limited photochemical processing, and transport via strong southward currents. Sites influenced by Atlantic Water inflows show opposite trends, lower in THg and high in $\delta^{202}\text{Hg}$, $\Delta^{199}\text{Hg}$, and $\Delta^{200}\text{Hg}$ despite being located at equivalent or higher latitudes. These patterns cannot be explained by trophic or dietary differences and are supported across multiple environmental matrices¹⁶, modelled fluvial exports, surface currents, and surface water Hg(o) distributions. As warming temperatures, sea-ice dynamics, river discharge patterns, and ocean circulation continue to shift under climate change, the contributions of various Hg sources to Arctic food webs are expected to change. Continued isotopic monitoring of Hg in sentinel Arctic biota could help track these changes and provide a new measure of how the Arctic environment is responding to ongoing climate change.

Methods

The 232 frozen ringed seal muscle samples collected between 2014 and 2024 were obtained through collaborative agreements with established Arctic biomonitoring programs and local subsistence hunters, in accordance with relevant guidelines and regulations (See Supplementary Methods 1). Samples were shipped to the AU, Department of Ecoscience, Roskilde, Denmark for analysis. All samples were prepared and analysed for THg and Hg isotopic composition following methods previously described¹⁶. Details for chemical analysis are found in Supplementary Methods (2) together with the statistical analysis (3).

To visualise large-scale controls on Arctic Hg distribution in surface waters, we mapped mean surface water Hg(O) and Hg(II), ocean circulation and riverine Hg export (THg and MeHg) using model data made available for 2006–2015. Surface Hg(O) and Hg(II) fields were obtained from the authors of coupled ocean-atmosphere model simulations^{26,27} and gave similar results (See Supplementary Fig. 5). Riverine Hg export for the Arctic region was sourced from published global models²⁰. These datasets were harmonised in a common polar stereographic framework to visualise spatial patterns in Hg occurrence, transport and terrestrial inputs (See Supplementary Methods 4). To assess changes in Hg exposure pathways linked to potential climate-driven reorganisation of Arctic surface waters, we compared annual mean sea-surface salinity from EC-Earth3-CC for 2026 and 2100 under SSP5-8.5 and SSP2-4.5 with EC-Earth3 output from the NAHosMIP uo3-hos forced AMOC experiment (years 70–100), (Supplementary Figure S6)^{64,75}. We used projected changes in salinity, ocean circulation, and freshwater release to infer spatial shifts in THg, and $\delta^{202}\text{Hg}$ at the study sites. Full model-processing and mapping procedures are described in Supplementary Methods 5.

Data availability

All data presented in this paper are provided in the Supplementary Information.

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Contributions

Conceptualisation of the study was done by T.P., J.S., B.E., C.S. and R.D. Samples were provided by K.K., H.R., C.L., D.M., M.H., S.F., L.Q., A.B., J.S., C.S. and R.D. Methodology was developed by J.S. Investigations were carried out by J.S., C.S., M.A., B.E., R.D., and led by T.P. Hg-ocean model outputs were led by T.P., with support from oceanographer and spatial modeller M.J. and A.H.. Funding acquisition was led by R.D. (Carlsberg, GREENPATH), and J.S. (MINAMATA, AMAP Core). Data analysis was led by T.P., who also led the paper writing. All authors contributed to data interpretation and writing of the manuscript.

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Competing interests

The authors declare no competing interests.

References

1. Arctic Monitoring and Assessment Programme (AMAP). Arctic Climate Change Update 2024: Key Trends and Impacts: Summary for Policy Makers. Tromsø, Norway. 16 (2025).
2. Zhang, X. *et al.* Weather and climate extremes in a changing Arctic. *Nat. Rev. Earth Environ.* **6**, 691–711 (2025).
3. Amaka, C. *et al.* The impacts of climate feedback loops on global climate stability: A comprehensive analysis of tipping points, threshold, and cascading effects. *Int. J. Innov. Environ. Stud. Res.* **3**, 117–129 (2025).
4. Boot, A. A. *et al.* Global marine ecosystem response to a strong AMOC weakening under low and high future emission scenarios. *Earths Future.* **13**, e2024EF004741 (2025).
5. Ditlevsen, P. & Ditlevsen, S. Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. *Nat. Commun.* **14**, 4245 (2023).
6. Basu, N. *et al.* The impact of mercury contamination on human health in the Arctic: A state of the science review. *Sci. Total Environ.* **831**, 154793 (2022).
7. Dietz, R. *et al.* Special issue on the AMAP 2021 assessment of mercury in the Arctic. *Sci. Total Environ.* **843**, 157020 (2022).
8. Dietz, R. *et al.* Mercury exposure of six Greenland societies from toothed whale harvest over three decades spanning 1993–2020. *Environ. Res.* **285**, 122555 (2025).
9. Outridge, P. M. *et al.* Updated global and oceanic mercury budgets for the United Nations Global Mercury Assessment 2018. *Environ. Sci. Technol.* **52**, 11466–11477 (2018).

- 501 10. Zhang, Y. *et al.* Observed decrease in atmospheric mercury explained by global decline in anthropogenic
502 emissions. *Proc. Natl Acad. Sci. USA*. **113**, 526–531 (2016).
- 503 11. MacSween, K. *et al.* Updated trends for atmospheric mercury in the Arctic: 1995–2018. *Sci. Total Environ.* **837**,
504 155802 (2022).
- 505 12. Dietz, R. *et al.* A risk assessment review of mercury exposure in Arctic marine and terrestrial mammals. *Sci. Total*
506 *Environ.* **829**, 154445 (2022).
- 507 13. Dietz, R. *et al.* Analysis of narwhal tusks reveals lifelong feeding ecology and mercury exposure. *Curr. Biol.* **31**,
508 2012–2019.e2 (2021).
- 509 14. Morris, A. *et al.* Temporal trends of mercury in Arctic biota: 10 more years of progress in Arctic monitoring. *Sci.*
510 *Total Environ.* **839**, 155803 (2022).
- 511 15. Blum, J. *et al.* Mercury isotopes in Earth and environmental sciences. *Annu. Rev. Earth Planet. Sci.* **42**, 249–269
512 (2014).
- 513 16. Søndergaard, J. *et al.* Stable isotopes unveil ocean transport of legacy mercury into Arctic food webs. *Nat.*
514 *Commun.* **16**, 5135 (2025).
- 515 17. Masbou, J. *et al.* Hg-stable isotope variations in marine top predators of the Western Arctic Ocean. *ACS Earth*
516 *Space Chem.* **2**, 479–490 (2018).
- 517 18. Sonke, J. E. *et al.* Eurasian river spring flood observations support net Arctic Ocean mercury export to the
518 atmosphere and Atlantic Ocean. *Proc. Natl Acad. Sci. USA*. **115**, E11586–E11594 (2018).
- 519 19. Zolkos, S. *et al.* Mercury export from Arctic great rivers. *Environ. Sci. Technol.* **54**, 4140–4148 (2020).
- 520 20. Liu, M. *et al.* Rivers as the largest source of mercury to coastal oceans worldwide. *Nat. Geosci.* **14**, 672–677
521 (2021).
- 522 21. Petrova, M. V. *et al.* Mercury species export from the Arctic to the Atlantic Ocean. *Mar. Chem* **225**, 103855
523 (2020).
- 524 22. Wang, F. *et al.* When noise becomes the signal: Chemical contamination of aquatic ecosystems under a changing
525 climate. *Mar. Pollut. Bull.* **60**, 1633–1635 (2010).
- 526 23. St. Pierre, K. A. St. *et al.* Unprecedented increases in total and methyl mercury concentrations downstream of
527 retrogressive thaw slumps in the Western Canadian Arctic. *Environ. Sci. Technol.* **52**, 14099–14109 (2018).
- 528 24. Arctic Monitoring and Assessment Programme (AMAP). Assessment 2021: Mercury in the Arctic. Tromsø,
529 Norway. 324 pp (2021).
- 530 25. Dietz, R. *et al.* Interactions of climate, socio-economics, and global mercury pollution in the North Water. *Ambio*
531 **47**, 281–295 (2018).
- 532 26. Zhu, S. *et al.* A high-resolution marine mercury model MITgcm-ECCO2-Hg with online biogeochemistry. *Geosci.*
533 *Model Dev.* **16**, 5915–5929 (2023).
- 534 27. Huang, S. *et al.* Oceanic evasion fuels Arctic summertime rebound of atmospheric mercury and drives transport
535 to Arctic terrestrial ecosystems. *Nat. Commun.* **16**, 903 (2025).
- 536 28. Jiskra, M. *et al.* Mercury stable isotopes constrain atmospheric sources to the ocean. *Nature*. **597**, 678–682
537 (2021).
- 538 29. Štrok, M., Baya, P. A. & Hintelmann, H. The mercury isotope composition of Arctic coastal seawater. *C. R. Geosci.*
539 **347**, 368–376 (2015).

- 540 30. Boertmann, D. & Mosbech, A. Eastern Baffin Bay - A strategic environmental impact assessment of hydrocarbon
541 activities. Scientific Report no. 9. *Aarhus University, DCE – Danish Centre for Environment and Energy*, 270
542 pp. - Scientific Report from DCE – Danish Centre for Environment and Energy (2011).
- 543 31. Constantin, A. & Johnson, R. S. On the dynamics of the near-surface currents in the Arctic Ocean. *Nonlinear*
544 *Anal. Real World Appl.* **73**, 103894 (2023).
- 545 32. Pisareva, M. N. et al. Chukchi Sea circulation and Bering Strait flow reversals from reprocessed satellite
546 altimetry. *Ocean Dyn.* **75**, 26 (2025).
- 547 33. Perovich, D. et al. Sea ice. *Arct. Rep. Card 2017 NOAA 2017* [https://arctic.noaa.gov/report-card/report-card-](https://arctic.noaa.gov/report-card/report-card-2017/sea-ice-6/)
548 [2017/sea-ice-6/](https://arctic.noaa.gov/report-card/report-card-2017/sea-ice-6/) (2017).
- 549 34. Facciola, N. et al. Feeding and contaminant patterns of sub-arctic and arctic ringed seals: Potential insight into
550 climate change-contaminant interactions. *Environ. Pollut.* **313**, 120108 (2022).
- 551 35. Point, D. et al. Methylmercury photodegradation influenced by sea-ice cover in Arctic marine ecosystems. *Nat.*
552 *Geosci.* **4**, 188–194 (2011).
- 553 36. Lim, S. H. et al. Near surface oxidation of elemental mercury leads to mercury exposure in the Arctic Ocean biota.
554 *Nat. Commun.* **15**, 7598 (2024).
- 555 37. Bergquist, B. A. & Blum, J. D. Mass-dependent and -independent fractionation of Hg isotopes by photoreduction
556 in aquatic systems. *Science* **318**, 417–420 (2007).
- 557 38. Masbou, J. et al. Hg stable isotope time trend in ringed seals registers decreasing sea ice cover in the Alaskan
558 Arctic. *Environ. Sci. Technol.* **49**, 8977–8985 (2015).
- 559 39. Day, R. D. et al. Mercury stable isotopes in seabird eggs reflect a gradient from terrestrial geogenic to oceanic
560 mercury reservoirs. *Environ. Sci. Technol.* **46**, 5327–5335 (2012).
- 561 40. Obrist, D. et al. Tundra uptake of atmospheric elemental mercury drives Arctic mercury pollution. *Nature* **547**,
562 201–204 (2017).
- 563 41. Araújo, B. F. et al. Mercury isotope evidence for Arctic summertime re-emission of mercury from the cryosphere.
564 *Nat. Commun.* **13**, 4956 (2022).
- 565 42. Campeau, A. et al. Sources of riverine mercury across the Mackenzie River Basin; inferences from a combined
566 HgC isotopes and optical properties approach. *Sci. Total Environ.* **806**, 150808 (2022).
- 567 43. Jiskra, M. et al. Insights from mercury stable isotopes on terrestrial–atmosphere exchange of Hg(o) in the Arctic
568 tundra. *Biogeosciences* **16**, 4051–4064 (2019).
- 569 44. Dastoor, A. et al. Arctic mercury cycling. *Nat. Rev. Earth Environ.* **3**, 270–286 (2022).
- 570 45. Feng, D. et al. Recent changes to Arctic river discharge. *Nat. Commun.* **12**, 6917 (2021).
- 571 46. Berlin, M. Mercury. in *Handbook on the Toxicology of Metals* 2nd edn (eds Friberg, L., Nordberg, G. F. & Vouk,
572 V. B.) **2**, 387–445 (Elsevier, 1986).
- 573 47. Bloom, N. S. On the chemical form of mercury in edible fish and marine invertebrate tissue. *Can. J. Fish. Aquat.*
574 *Sci.* **49**, 1010–1017 (1992).
- 575 48. Dietz, R. et al. What are the toxicological effects of mercury in Arctic biota. *Sci. Total Environ.* **443**, 775–790
576 (2013).
- 577 49. Jonsson, S. et al. Arctic methylmercury cycling. *Sci. Total Environ.* **850**, 157445 (2022).
- 578 50. Wang, K. et al. Subsurface seawater methylmercury maximum explains biotic mercury concentrations in the
579 Canadian Arctic. *Sci. Rep.* **8**, 14465 (2018).
- 580 51. Li, M. et al. Assessing sources of human methylmercury exposure using stable mercury isotopes. *Environ. Sci.*
581 *Technol.* **48**, 8800–8806 (2014).

- 582 52. Li, M. *et al.* Internal dynamics and metabolism of mercury in biota: A review of insights from mercury stable
583 isotopes. *Environ. Sci. Technol.* **56**, 9182–9195 (2022).
- 584 53. Olnes, J. *et al.* Trace elements in Alaska's ice seals in the 2000s and 2010s. *Sci. Total Environ.* **958**, 178126
585 (2025).
- 586 54. Fukumori, I. *et al.* ECCO Consortium. ECCO Central Estimate (Version 4 Release 4). Retrieved
587 from: <https://podaac.jpl.nasa.gov/announcements/2021-04-27-ECCO-Version-4-Datasets-Release>, Date
588 accessed: 01, 21, 2026.
- 589 55. Agather, A. M. *et al.* Distribution of mercury species in the Western Arctic Ocean (U.S. GEOTRACES GNo1). *Mar.*
590 *Chem.* **216**, 103686 (2019).
- 591 56. Hugelius, G. *et al.* Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and
592 identified data gaps. *Biogeosciences*. **11**, 6573–6593 (2014).
- 593 57. Sonke, J. E. *et al.* Global change effects on biogeochemical mercury cycling. *Ambio*. **52**, 853–876 (2023)
- 594 58. Carmack, E. C. *et al.* Freshwater and its role in the Arctic marine system: Sources, disposition, storage, export,
595 and physical and biogeochemical consequences in the Arctic and global oceans. *J. Geophys. Res. Biogeosciences*
596 **121**, 675–717 (2016).
- 597 59. Timmermans, M. L. & Marshall, J. Understanding Arctic Ocean circulation: A review of ocean dynamics in a
598 changing climate. *J. Geophys. Res. Oceans* **125**, e2018JC014378 (2020).
- 599 60. Blum, J. D. & Johnson, M. W. Recent developments in mercury stable isotope analysis. *Rev. Mineral. Geochem.*
600 **82**, 733–757 (2017).
- 601 61. Song, Z., Sun, R. & Zhang, Y. Modeling mercury isotopic fractionation in the atmosphere. *Environ. Pollut.* **307**,
602 119588 (2022).
- 603 62. Zhang, J. *et al.* Labrador Sea freshening linked to Beaufort Gyre freshwater release. *Nat. Commun.* **12**,
604 1229 (2021).
- 605 63. Athanase, M. *et al.* The Arctic Beaufort Gyre in CMIP6 models: Present and future. *J. Geophys. Res. Oceans* **130**,
606 e2024JC021873 (2025).
- 607 64. Jackson, L. *et al.* NAHosMIP data. *Zenodo*. [10.5281/zenodo.7324394](https://zenodo.org/record/7324394) (2023).
- 608 65. Hausfather, Z. & Peters, G. P. Emissions – the ‘business as usual’ story is misleading. *Nature*. **577**, (2020).
- 609 66. Riahi, K. *et al.* in *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the*
610 *Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Shukla, P. R. *et al.*) 295–408
611 (Cambridge Univ. Press, 2022).
- 612 67. Rantanen, M. *et al.* The Arctic has warmed nearly four times faster than the globe since 1979. *Commun. Earth*
613 *Environ.* **3**, 168 (2022).
- 614 68. Leitch, D. R. *et al.* The delivery of mercury to the Beaufort Sea of the Arctic Ocean by the Mackenzie River. *Sci.*
615 *Total Environ.* **373**, 178–195 (2007).
- 616 69. Dijkstra, H. A. & van Westen, R. M. The probability of an AMOC collapse onset in the twenty-first century. *Annu.*
617 *Rev. Mar. Sci.* **18**, 23–46 (2026).
- 618 70. Lin, P. *et al.* Recent state transition of the Arctic Ocean's Beaufort Gyre. *Nat. Geosci.* **16**, 485–491 (2023).
- 619 71. Soerensen, A. L. *et al.* A mass budget for mercury and methylmercury in the Arctic Ocean. *Global Biogeochem.*
620 *Cycles*. **30**, 560–575 (2016).
- 621 72. Ingvaldsen, R. B. *et al.* Physical manifestations and ecological implications of Arctic Atlantification. *Nat. Rev.*
622 *Earth Environ.* **2**, 874–889 (2021).

623 73. De Rovere, F. *et al.* Future Atlantification of the European Arctic limited under sustained global warming. *Sci.*
624 *Rep.* **15**, 30802 (2025).

625 74. Ben-Yami, M. *et al.* Uncertainties too large to predict tipping times of major Earth system components from
626 historical data. *Sci. Adv.* **10**, eadl4841 (2024).

627 75. Copernicus Climate Change Service. CMIP6 predictions underpinning the C3S decadal prediction prototypes.
628 *ECMWF*. [10.24381/cds.c82deddb](https://doi.org/10.24381/cds.c82deddb) (2021).

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