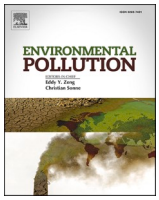
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Climate change, mercury pollution, and global ecology☆

Mercury (Hg) pollution continues to be a significant environmental and public health issue and is interconnected with climate change and global environmental change factors. Hg pollution is addressed by the Minamata Convention on Mercury (MC), a global treaty aimed at protecting human health and the environment from the adverse effects of Hg and its compounds (Minamata Convention on Mercury, 2024). The MC was adopted in 2013 and entered into force in 2017, and the main goals of the MC include: (1) reducing Hg emissions and releases, (2) control, reduction, and phasing out the use of Hg, (3) management of Hg waste, (4) protection of vulnerable populations including, but not limited to, artisanal and small-scale gold mining miners, subsistence fishers, and other individuals who consume high amounts of seafood and freshwater fish, (5) promoting the development of safe alternatives to Hg, and (6) support of international cooperation to provide technical and financial assistance to developing countries and regions with high Hg exposure and pollution issues. (Minamata Convention on Mercury, 2024). The goals set forth by the MC reflect a global commitment to reducing Hg's harmful effects on human health and the environment, acknowledging its persistence, toxicity, and potential for bioaccumulation in fish, wildlife, and humans.

The poorly understood atmospheric chemistry dynamics of Hg, its long-term residence times, transformation processes, and complex biogeochemical cycle make this ubiquitous pollutant difficult to model without high degrees of uncertainty, especially when considering that Hg can be repeatedly recycled and re-emitted across the land-ocean-atmosphere interface. Emissions of Hg, particularly Hg(II) compounds, are challenging to characterize and measure, and their impact on different ecosystem types and species may occur at broad spatiotemporal scales (Gustin et al., 2020). Thus, the fine-scale and complex chemistry of Hg remains poorly understood. Integrating global environmental change and climate factors into the development of evidence-based models and Hg research has been an important focus of the Hg scientific community and has been undertaken for over a decade (Bank, 2020). However, despite the importance and increased attention, the role of climate change on Hg cycling, toxicological impacts and its fate and transport dynamics remains poorly understood. This knowledge gap is primarily attributed to the complex reemission dynamics and the highly reactive nature of Hg.

Mercury and its organic form methylmercury (MeHg) can bioaccumulate and biomagnifies within food webs. MeHg is the more toxic form of Hg and can be transferred more efficiently than the inorganic fractions of Hg. Biota occurring at higher trophic positions, often indicated by nitrogen stable isotope signatures, have higher concentrations of Hg and MeHg and recent advances in use of compound-specific nitrogen isotope analysis of amino acids have helped refine our understanding of these relationships (Ishikawa, 2018).

Impacts of climate change on Hg cycling and bioaccumulation is a research area of considerable interest to both scientists and policymakers (Bank, 2020; Bank et al., 2023). However, most modeling studies still report significant degrees of uncertainty, especially atmospheric models which can often have $\geq$ 40 % uncertainty terms (Braaten et al., 2022, Pang et al., 2022), and which can limit their use and application in legally binding regulatory frameworks (Bank, 2020; Bank et al., 2023). Yang et al. (2016) reported that soil warming from −2 to 8 °C led to a 10-fold increase in net MeHg production in the Arctic, and Schuster et al., 2018 reported that permafrost can store significant amounts of (Hg), yet their models also report significant uncertainty at 57 %, thus highlighting the difficulty of upscaling and developing precise estimates of Hg abundances, mass balances, ecosystem flux rates, and accurate export models. Staniszewska et al. (2023) reported that summer glacial erosion and meltwater transport, as opposed to permafrost melt, was the greatest source of Hg export in the Yukon River basin, challenging how Hg export in this basin may respond to climate change as reported by Schaefer et al. (2020). The findings by Staniszewska et al., (2023) also highlight that within the Yukon River basin, Hg methylation, export, and uptake by Arctic Ocean marine biota from Hg produced upstream were all quite low. Lastly, for marine fish, Bank et al. (2023) reported a slight temporal decline in length-normalized, fillet Hg (≥71 % as MeHg) concentrations during 1994–2021 in the Barents Sea using a large data set (n = 1999), across a wide array of size classes of Northeast Arctic cod (*Gadus morhua*) from the Barents Sea ecosystem. This temporal decline in cod fillet Hg concentrations occurred despite significant increases in sea temperature and decreases in sea ice extent during the study period. These findings were in sharp contrast to the findings of a theoretical modeling study reported by Schartup et al. (2019) that modeled large-bodied, 15 Kg cod which only represents an extremely small fraction of the population in the Gulf of Maine. Bank et al. (2023) further postulated that the current degree of climate change may not be substantial enough to result in increasing or decreasing Hg concentrations in cod from the Barents Sea, and that different trends for warm water, tropical marine ecosystems, different species, and in the far future may be observed.

Collectively, these findings highlight the complexity and context-specific nature of this topic and demonstrate a great need to further understand how climate change and global environmental change factors affect Hg dynamics across a wide array of ecosystem types and

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species. Scientists likely need to be more mindful and fairer in their modeling assessments and will need to consider all potential outcomes when considering how Hg is modulated by climate change including the potential for increases, decreases, and stable (e.g., no change) results in abiotic and biotic sampling matrices, as well as for process-based results influenced by post-deposition dynamics and complex changes in food webs which may be inherently difficult to model and interpret (Bank, 2020).

This special issue (SI) has delivered 23 novel research articles highlighting the intricate and complex interactions between climate change and the global Hg cycle, emphasizing how geographic, ecological, and biogeochemical factors influence Hg bioaccumulation and its broader environmental impacts. Key findings illustrate how Hg dynamics vary with ecosystem type, Hg loading, methylation and demethylation regimes, temperature, land-sea exchanges dynamics, trophic complexity, and food web composition, underscoring the context-specific, and nuanced nature of Hg cycling in a rapidly changing world.

Some highlights are summarized below. For example, recent advancements in Hg research have provided significant insights into its environmental dynamics, biological impacts, and mitigation strategies. Knowledge on Hg methylation and bioavailability has also advanced, with findings on distinct aquatic sediments revealing differences in these complex processes (Qin and Xu, 2023). Notably, organic matter derived from sulfur-rich rape straw has been shown to suppress soil Hg methylation and reduce methyl Hg accumulation in rice, offering potential mitigation strategies (Zheng et al., 2024).

In terms of Hg dynamics in aquatic and marine systems, bioaccumulation regimes in top predators, like lake trout in Alaska (Bartz et al., 2023), and Arctic char (*Salvelinus alpinus*) in the high Arctic (Hudelson et al., 2023), underscore the global scale of Hg pollution. Further research evaluates long-term Hg bioaccumulation trends, ocean warming, and climate change dynamics in Northeast Arctic cod (Bank et al., 2023), and the broader Barents Sea ecosystem (Gundersen et al., 2023). Penguins have emerged as effective bioindicators for assessing Hg contamination in Southern Hemisphere marine ecosystems (Gimeno et al., 2024), while studies on Pacific saury (*Cololabis saira*) evaluate food webs and trophic transfer dynamics in the North Pacific Ocean (Lee et al., 2024). Studies have also explored Hg evasion from contaminated soils and the role of vegetation in such processes, particularly in the Isonzo River region of Italy (Floreani et al., 2023a) and coastal environments of the northern Adriatic Sea (Floreani et al., 2023b). Additionally, research highlights ecosystem-wide Hg contamination spanning a century, with seabirds from the South Atlantic serving as long-term indicators of global environmental change (Cusset et al., 2023). Genetic studies on oceanic bacteria revealed detoxification mechanisms for methyl Hg (Pereira-Garcia et al., 2024), while investigations into methanotrophs (Zhang et al., 2023) and methylating bacteria (Wang et al., 2024a) enhance understanding of Hg adsorption and uptake (Dong et al., 2024).

Human and ecological impacts of Hg are also under scrutiny. Research in marine protected areas assessed their influence on Hg exposure in shark communities (Le Croizier et al., 2023), while studies in Croatian nature parks examined how eagle nestling diets affect Hg dynamics (Bjedov et al., 2023). Microcosm studies also suggest that wastewater containing Hg, and other metals, for microalgae cultivation may pose risks to consumers (Lown et al., 2023). Novel analytical and biological studies provide deeper insights into Hg dynamics. Seasonal variation in Hg isotope composition in lichens highlight atmospheric and environmental changes (Božič and Horvat, 2024).

Technological innovations have emerged, such as green materials derived from wood for Hg detection and removal in water (Liu et al., 2023) and graphene oxide-based aerogels that improve plant resilience under Hg stress (Alp-Turgut et al., 2024). Lastly, global and regional surveys shed light on legacy mining impacts, with studies from Germany examining Hg concentrations in conifers and mushrooms (Franzaring et al., 2024), and worldwide analyses of Hg methylation genes in aquatic sediments providing a comprehensive view of their global processes (Wang et al., 2024b).

The papers presented in this SI not only expand our understanding of Hg's role in ecological and biogeochemical systems but also pose questions and novel research areas for students, researchers, and policymakers. This collection aims to guide future research efforts, foster policy relevant, science-based synthesis, and support actions to mitigate Hg's detrimental effects on the environment, its inhabitants, and human health.

CRediT authorship contribution statement

Michael S. Bank: Writing – review & editing, Writing – original draft, Conceptualization. **Zoyne Pedrero Zayas:** Writing – review & editing. **Vernon Somerset:** Writing – review & editing. **Lynwill G. Martin:** Writing – review & editing. **Milena Horvat:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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