

AMAP Technical Report: Using mercury stable isotopes to advance mercury research and monitoring in the Arctic

AMAP

Arctic Monitoring and Assessment Programme (AMAP)

Educational use: This report (in part or in its entirety) and other AMAP products available from www.amap.no can be used freely as teaching materials and for other educational purposes.

The only condition of such use is acknowledgement of AMAP as the source of the material according to the recommended citation.

In case of questions regarding educational use, please contact the AMAP Secretariat (amap@amap.no).

Note: This report may contain material (e.g. photographs) for which permission for use will need to be obtained from original copyright holders.

Disclaimer: The views expressed in this report are the responsibility of the authors of the report and do not necessarily reflect the views of the Arctic Council, its members or its observers.

AMAP Technical Report: Using mercury stable isotopes to advance mercury research and monitoring in the Arctic

AMAP

Arctic Monitoring and Assessment Programme (AMAP)
Tromsø, 2026

AMAP Technical Report: Using mercury stable isotopes to advance mercury research and monitoring in the Arctic

Citing whole report

AMAP, 2026. AMAP Technical Report: Using mercury stable isotopes to advance mercury research and monitoring in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. AMAP Technical Report 2026:1 iv+44pp.

ISBN – 978-82-8440-000-6

© Arctic Monitoring and Assessment Programme, 2026

Published by

Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway (www.amap.no)

Ordering

This report is published as an electronic document, available from the AMAP website at www.amap.no

Authors and contributors

Coordinating authors: John Chételat (Environment and Climate Change Canada, Canada), Simon Wilson (Arctic Monitoring and Assessment Programme, Norway), Rune Dietz (Aarhus University, Denmark)

Contributing authors (in alphabetical order): Marina Arregui (Aarhus University, Denmark), Niladri Basu (McGill University, Canada), Bridget Bergquist (University of Toronto, Canada), João Canário (Instituto Superior Técnico, Portugal), John Chételat (Environment and Climate Change Canada, Canada), Rune Dietz (Aarhus University, Denmark), Sofi Jonsson (Stockholm University, Sweden), Mi-Ling Li (University of Delaware, USA), John Munthe (IVL Swedish Environmental Research Institute, Sweden), Michelle Nerentorp (IVL Swedish Environmental Research Institute, Sweden), Tove Petersson (Aarhus University, Denmark), Marianna Pinzone (Norwegian Polar Institute, Norway), Henrik Skov (Aarhus University, Denmark), Jens Søndergaard (Aarhus University, Denmark), Simon Wilson (Arctic Monitoring and Assessment Programme, Norway)

Editing: Melissa McKinney (McGill University, Canada), Christian Sonne (Aarhus University, Denmark), Eva Kruemmel (Inuit Circumpolar Council, Canada), Tomasz Maciej Ciesielski (The University Centre in Svalbard, Norway), Eva Cecilie Bonefeld-Jørgensen (Aarhus University, Denmark)

Production

Layout, design and production

Burnthebook, United Kingdom (www.burnthebook.co.uk)

Cover photograph

Bo Elberling, icefreegreenland.com

Contents

Executive Summary	iv	6.2 Tracing of anthropogenic mercury sources	25
1. Introduction	5	6.3 Laboratory and analytical considerations	25
1.1 Why is mercury in the Arctic important to study and monitor?	5	7. What are opportunities for incorporating mercury isotopes in AMAP monitoring? ...	27
1.2 What are mercury stable isotopes?	5	7.1 Laboratory quality assurance and quality control	27
1.3 Why is AMAP conducting a scoping initiative on mercury stable isotopes?	5	7.2 Identify key transport processes of mercury to and within the Arctic	27
2. What do mercury isotopes tell us about mercury in the environment, and how are they measured?	7	7.3 Identify key exposure pathways of mercury to wildlife and humans	28
2.1 Fractionation in sources and pathways	7	7.4 Monitor change in environmental mercury isotopes	28
2.2 Analytical methods	7	7.5 Provide Arctic science relevant to the Minamata Convention on Mercury	28
3. What are mercury isotope values in Arctic environmental matrices, and can they be used to evaluate mercury transport and transformation processes?	10	7.6 Overarching recommendations	29
3.1 Summary of available mercury isotope data for abiotic matrices	10	7.7 Closing	29
3.2 Mercury isotopes in the Arctic atmosphere	10	8. References	30
3.3 Mercury isotopes in the cryosphere	13	Appendices	35
3.4 Mercury isotopes in soil, bedrock and vegetation ..	14	Acronyms and Abbreviations	44
3.5 Mercury isotopes for permafrost research	15		
3.6 Mercury isotopes in water and sediments	16		
3.7 Mercury isotopes for tracing sources	17		
4. What are mercury isotope values in Arctic biota, and can they be used to evaluate sources and pathways of mercury into Arctic food webs?	18		
4.1 Biological fractionation	18		
4.2 Summary of available published mercury isotope data for biota	18		
4.3 Sources and pathways	18		
4.4 Metabolic influences on the internal distribution of Hg isotopes in biota	21		
4.5 The importance of tissue selection	21		
4.6 Temporal trends in biota	22		
5. How can mercury isotopes be used for human biomonitoring of mercury exposure?	23		
5.1 Human biomonitoring	23		
5.2 Mercury stable isotopes in key sources and human biomarkers of exposure	23		
5.3 Arctic-relevant examples of human biomonitoring for mercury exposure	24		
6. What knowledge gaps and other challenges need to be considered for mercury isotope applications in AMAP monitoring?	25		
6.1 Available mercury isotope data for Arctic environmental matrices and biota	25		

Executive Summary

The Arctic Monitoring and Assessment Programme (AMAP) has been reporting on mercury contamination of the Arctic environment and human exposure to mercury since the 1990s. Findings have shown elevated risk to some wildlife and human populations. More recently, a new measurement tool, mercury stable isotopes, has become available to better understand the mercury cycle. Mercury has seven stable isotopes and their ratios provide “fingerprint” information to trace transport and exposure pathways, and in some cases, to evaluate mercury sources. This technical report examines the potential for mercury stable isotopes to be incorporated into AMAP activities and to contribute new policy-relevant science on mercury contamination in the Arctic.

Mercury isotope applications are examined through existing studies for the Arctic and, in some cases, exemplary studies in other regions. These studies show that mercury isotopes hold promise for generating new information on key transport processes and exposure pathways of mercury in the Arctic. Climate change effects on the Arctic mercury cycle can be traced with mercury isotopes. Mercury isotopes can also provide critical evidence for understanding mercury transport pathways and response times following reductions in anthropogenic emissions of mercury to air, given the longer residence times of mercury in the oceans compared to the atmosphere. These advances help explain how human emissions of mercury reach the Arctic environment and how the mercury cycle will respond to regulatory actions under the United Nations Minamata Convention on Mercury and under future environmental changes.

In contrast with process-focused applications, the use of mercury isotopes for identifying sources, particularly human sources of mercury emissions, is not currently feasible for mercury that reaches the Arctic through long-range transport. Obstacles include overlap of source isotopic composition, complex isotopic fractionation during biogeochemical cycling and transport, mixing of multiple sources in the mercury pool with increasing distance from emission sources, and exchange processes between matrices. Mercury isotopes can be useful for source attribution in the case of local point-source pollution where a clear isotopic signal can be measured. However, as most mercury contamination within the Arctic originates from emission sources outside the Arctic, the relevance of tracing local point-sources using mercury isotopes is limited.

Through this scoping initiative, published literature is compiled on mercury isotopes in Arctic abiotic matrices and biota to identify strengths and knowledge gaps, and to provide supporting data for future studies. Currently, few mercury isotope measurements are available for 1) abiotic matrices, including air, seawater, sediment and permafrost soils, and 2) fish and wildlife, with available data largely for marine species. Most environmental measurements of mercury isotopes have limited geographic coverage within the Arctic, and only one Arctic human biomonitoring study has been published using mercury isotopes to identify dietary exposure pathways.

Six key recommendations were developed through this scoping initiative to support future incorporation of mercury stable isotopes in AMAP activities:

- Establish AMAP guidelines for consistent laboratory quality assurance and quality control across Arctic studies and matrices to ensure comparability of mercury isotope measurements;
- Prioritize ecosystem level studies that evaluate 1) transport pathways delivering mercury to the Arctic, particularly the Arctic Ocean, 2) the role of climate change on the mercury cycle, and 3) exposure pathways for wildlife;
- Apply isotope-based models to estimate the relative contribution of diet items to mercury exposure in humans, as a valuable complement to traditional dietary exposure assessment;
- Prioritize mercury isotope measurements of abiotic matrices that support interpretation of transport and fate studies, including evolving techniques using compound specific isotope analysis of methylmercury;
- Track change in mercury burdens and pathways using specimen bank archives of Arctic fish and wildlife tissues as well as environmental archives to measure multi-decadal time series of mercury isotopes in key bioindicator species and abiotic matrices; and
- Integrate AMAP mercury isotope measurements with other regional and global monitoring efforts to support the Minamata Convention effectiveness evaluation.

These recommendations aim to strengthen policy-relevant science on mercury contamination in the Arctic and to align AMAP activities with global monitoring and the effectiveness evaluation under the United Nations Minamata Convention on Mercury.

1. Introduction

1.1 Why is mercury in the Arctic important to study and monitor?

Mercury (Hg) is among the most toxic of the heavy metals and its concentrations in the Arctic environment have increased since pre-industrial times (AMAP 2011; AMAP 2018; AMAP 2021a). Mercury is released from both natural and anthropogenic sources, and it is transported via the atmosphere, rivers and ocean currents into and within the Arctic (AMAP 2011; AMAP 2021a). Since the dawn of industrialization, Hg has been released by human activities, with current human sources originating mainly from artisanal and small-scale gold mining, burning of fossil fuels, in particular coal, industries including cement and non-ferrous metal production, and disposal of waste (AMAP 2011; AMAP 2021a). These anthropogenic emissions along with bioaccumulation and biomagnification have resulted in significant increases of Hg burdens in Arctic biota, which today are up to 10-30-fold higher compared with the pre-industrial period (Dietz et al. 2009; Dietz et al. 2011; Dietz et al. 2021; Desforges et al. 2022). Bioaccumulation and biomagnification are the processes by which Hg accumulates in biological tissues and concentrates in organisms as it is transferred up the food chain (Mason et al. 1996). In the Arctic, Hg biomagnifies to high concentrations in top predators, such as toothed whales, seals and polar bears (*Ursus maritimus*), threatening the health of these species. Risks to human health are also a concern in the Arctic, especially for some Indigenous populations that consume affected country foods, such as seal and whale meat, as part of their traditional diets (AMAP 1998; AMAP 2003; AMAP 2021a; AMAP 2021b).

The Arctic Monitoring and Assessment Programme (AMAP), a working group of the Arctic Council, has been conducting scientific assessments and reporting on the state of mercury pollution in the circumpolar Arctic for more than three decades (AMAP 2021a; Reiersen et al. 2024). These assessments address policy-relevant questions on mercury pollution and support decision making by Arctic Council member states and Arctic Indigenous Peoples. These findings also support activities under international treaties, including the United Nations (UN) Minamata Convention on Mercury and the Convention on Long-Range Transboundary Air Pollution of the UN Economic Commission for Europe (AMAP 2021c).

Stable isotopes of Hg have emerged since the early 2000s as a method for tracing Hg transport pathways, biogeochemical processes and even sources of Hg in the environment (Blum et al. 2014; Tsui et al. 2020; Zhou et al. 2023). Applications of Hg isotopes are now well demonstrated, and there is wide interest in using this tool for policy-relevant science, including to support the UN Minamata Convention on Mercury, which aims to reduce Hg emissions globally (Kwon et al. 2020).

1.2 What are mercury stable isotopes?

Mercury has seven naturally occurring stable isotopes, that is, atoms of the same element that contain different

numbers of neutrons and therefore differ slightly in atomic mass. Differences in isotopic abundance among Hg sources and subsequent fractionation processes (i.e. separation and recombination of isotopes due to chemical, physical and biological processes) in the environment lead to Hg isotope compositions varying among natural samples (Blum et al. 2014; Sun et al. 2019). Consequently, Hg isotopes can potentially be used as a tracer to distinguish between Hg sources and to study transport pathways and biogeochemical transformations of Hg in the environment (Bergquist 2018; Kwon et al. 2020). The development of analytical methods for measurement of natural Hg isotopes in the environment is relatively recent (Hintelmann and Lu 2003; Bergquist and Blum 2007; Blum and Johnson 2017), and scientific momentum over the last two decades has demonstrated its source tracing potential, making it a powerful tool.

Limited information is currently available for Hg isotopes in the Arctic environment, and it is currently difficult to predict what new information this approach can provide regarding mercury sources that impact the Arctic. Yet, Hg isotopes may have a number of potentially important applications in Arctic monitoring and assessment work, such as: 1) differentiating between old Holocene and recently deposited Hg in permafrost soils and thus tracing secondary releases and processes due to climate change in the Arctic, 2) differentiating the importance of atmospheric and oceanic transport pathways to the Arctic, which can clarify how long it takes for Hg to be transported from lower-latitude sources to the Arctic Ocean, 3) evaluating whether increases in biomagnified Hg in Arctic top predators since pre-industrial times are associated with changes in Hg isotope composition, reflecting changes in sources, pathways and bioavailability due to climate change, changes in diet and/or increases in anthropogenic inputs, 4) identifying exposure sources for humans, and 5) identifying foraging habitats of fishes and marine mammals, such as feeding depth in the water column of the Arctic Ocean.

1.3 Why is AMAP conducting a scoping initiative on mercury stable isotopes?

The objective of this scoping initiative is to evaluate the potential utility of Hg isotopes to be adopted by AMAP as a monitoring tool within its mercury monitoring and assessment activities. While challenges still exist, advances in analytical techniques have made the measurement of Hg isotopes more broadly accessible to scientists, and several datasets are now published on mercury isotopes in the Arctic. Within this document, Arctic context is provided for the relatively young discipline of Hg isotopes, which has already generated groundbreaking knowledge essential for understanding bioaccumulation, temporal trends and the origins of Hg and could potentially produce future evidence on the effectiveness of action by policy makers within and affiliated to the Arctic Council as well as the UN Minamata Convention.



Photo: Rune Dietz, Savissivik, northwest Greenland

This scoping document begins with an overview of Hg isotopes as a tool followed by separate examination of applications to the Arctic abiotic environment, Arctic biota, and human health. Across sections, compiled information is used to address the following three overarching questions:

- i. How are mercury isotopes useful to monitor mercury and generate policy relevant science for the Arctic under AMAP?
- ii. What mercury isotope information is currently available for the Arctic?
- iii. What opportunities, knowledge gaps and challenges should be considered in developing mercury isotope applications for AMAP monitoring?

Finally, recommendations are put forth for consideration by AMAP Heads of Delegation on the utility of Hg isotopes to provide information on Arctic sources and pathways of Hg and their potential inclusion within AMAP monitoring activities.

2. What do mercury isotopes tell us about mercury in the environment, and how are they measured?

Understanding how Hg moves, transforms, and accumulates in the environment is critical for developing strategies, and evaluating their effectiveness, towards mitigating Hg exposures and effects. Traditional analyses measure concentrations and chemical forms, but it can be challenging to trace, identify and quantify sources and transformation pathways, leaving important knowledge gaps in the complex biogeochemical cycle of Hg. The development of Hg isotope geochemistry has fundamentally changed this, providing a powerful tool to better trace and understand the transport and fate of Hg in the environment.

2.1 Fractionation in sources and pathways

Mercury has seven stable isotopes: ^{196}Hg , ^{198}Hg , ^{199}Hg , ^{200}Hg , ^{201}Hg , ^{202}Hg and ^{204}Hg . Their natural abundances, determined in the National Institute of Standards and Technology (NIST) Standard Reference Material (SRM) 3133, are approximately as follows: $^{196}\text{Hg} = 0.16\%$, $^{198}\text{Hg} = 10.04\%$, $^{199}\text{Hg} = 16.94\%$, $^{200}\text{Hg} = 23.14\%$, $^{201}\text{Hg} = 13.17\%$, $^{202}\text{Hg} = 29.73\%$, and $^{204}\text{Hg} = 6.83\%$, as referenced to the certified thallium (Tl) ratio ($^{205}\text{Tl}/^{203}\text{Tl}$) of 2.38714 (Blum and Bergquist 2007).

In many chemical and physical processes, mercury isotopes will react and behave slightly differently mainly because the small isotopic mass differences affect the vibrational energies of atomic bonds and molecular motions. For example, in kinetic reactions lighter isotopes tend to react or diffuse more rapidly than heavier ones, leading to preferential accumulation of lighter isotopes in reaction products. In both kinetic and equilibrium reactions, fractionation driven by the slight differences in mass results in mass-dependent fractionation (MDF), which follows well known and predictable fractionation patterns.

A major advance in understanding mercury isotopic behavior came from the work of Bergquist and Blum (2007), who measured Hg isotope fractionation occurring during photochemical reactions. In a series of controlled laboratory experiments using simulated sunlight, they reduced dissolved Hg species, Hg(II) and MeHg , in the presence of dissolved organic matter. These experiments displayed classical MDF, where the remaining aqueous Hg species became progressively enriched in heavier isotopes and the volatilized elemental Hg, Hg(0) , was isotopically lighter. However, in addition to MDF, aqueous photochemical reduction and demethylation also resulted in large mass-independent fractionation (MIF) in the odd-mass isotopes (^{199}Hg and ^{201}Hg). The authors attributed this behavior to the magnetic isotope effect (MIE), which arises from differences in nuclear spin between even- and odd-mass isotopes and the effects these differences have on spin-dependent radical-pair processes. Because these reactions are driven by sunlight and do not change after entering the food web, the presence of odd-MIF in environmental samples provides diagnostic evidence of photochemical processing prior to biological uptake (Bergquist and Blum 2007; Blum et al.

2014). Studies reporting MDF ($\delta^{202}\text{Hg}$) and odd-isotope MIF ($\Delta^{199}\text{Hg}$ and $\Delta^{201}\text{Hg}$) for key transformation pathways of Hg in both abiotic and biotic matrices are summarized in Table 2.1.

In addition to odd-MIF, Hg can also exhibit even-mass MIF ($\Delta^{200}\text{Hg}$, $\Delta^{204}\text{Hg}$) that is commonly attributed to photochemical processes in the atmosphere (Blum and Johnson 2017; Kwon et al. 2020). More detail on this atmosphere fractionation of even-MIF is presented in Section 3.2.

$$\delta^{xxx}\text{Hg} = \left[\left(\frac{^{xxx}\text{Hg}/^{198}\text{Hg}_{\text{sample}}}{^{xxx}\text{Hg}/^{198}\text{Hg}_{\text{SRM3133}}} \right) - 1 \right] \times 1000$$

Mercury isotopic compositions are reported using delta (δ) notation for mass-dependent fractionation (MDF), and capital delta (Δ) notation for mass-independent fractionation (MIF), relative to the commonly used NIST SRM-3133 standard. Mass-dependent fractionation is commonly reported as $\delta^{202}\text{Hg}$, describing the per mil (‰) deviation in isotope ratio from the standard according to:

where xxx refers to a given isotope (e.g., 202, 201, 199). Mass-independent fractionation (as $\Delta^{199}\text{Hg}$ or $\Delta^{201}\text{Hg}$) is reported as the deviation of the measured $\delta^{xxx}\text{Hg}$ from the theoretical MDF predicted from $\delta^{202}\text{Hg}$. Specifically, $\Delta^{xxx}\text{Hg}$ is the difference between the observed δ value of a sample and the δ value estimated from the measured $\delta^{202}\text{Hg}$ using theoretical scaling factors usually based on kinetic MDF laws (0.2520 for ^{199}Hg and 0.7520 for ^{201}Hg). The use of ^{198}Hg as the denominator is agreed upon by most research groups and is highly recommended (Blum and Bergquist 2007; Blum et al. 2014).

By analyzing both $\delta^{202}\text{Hg}$ (MDF) and $\Delta^{199}\text{Hg}-\Delta^{201}\text{Hg}$ (MIF) patterns, scientists can reconstruct environmental transformations across the atmosphere, hydrosphere, and biosphere. Mercury from industrial or geogenic emissions typically shows MDF but no MIF. However, limitations of this interpretation need to be considered when analyzing environmental samples.

2.2 Analytical methods

2.2.1 Overview of mercury isotope analysis

Mercury isotope values are measured using multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS), usually with cold vapor generation for sample introduction. In this approach, dissolved Hg(II) is chemically reduced to Hg(0) vapor, which enhances analytical sensitivity and can minimize matrix effects compared to conventional nebulization (Hintelmann 2012; Blum and Johnson 2017). One of the major caveats with MC-ICP-MS measurements is that the instrument itself induces large MDF, typically referred to as instrumental mass bias, which must be corrected. Many groups use a combination of sample standard bracketing and

Table 2.1. Examples of reactions and expected mercury isotope fractionation. Adapted from Bergquist and Blum (2007) and from Blum et al. (2014).

Reaction / Process	Characteristic Isotopic Fractionation	Typical Environmental Setting / Source	Key References
Photochemical reduction of Hg(II)	Residual Hg(II): positive $\Delta^{199}\text{Hg}$, $\Delta^{201}\text{Hg}$; volatilized Hg(0): negative $\delta^{202}\text{Hg}$. MIF magnitude increases with light intensity and dissolved organic matter	Surface waters and photic zones; reduction of dissolved Hg(II) to gaseous Hg(0)	[1], [2]
Photochemical oxidation of Hg(0)	Formed Hg(II): positive $\Delta^{199}\text{Hg}$, small MDF shift; residual Hg(0) slightly lighter $\delta^{202}\text{Hg}$	Atmospheric oxidation of Hg(0) by halogen radicals (bromine, chlorine) or hydroxide; leads to wet and dry deposition	[2-4]
Photodemethylation of MeHg	Residual MeHg: negative $\Delta^{199}\text{Hg}$, $\Delta^{201}\text{Hg}$; released inorganic Hg: complementary positive MIF; minor MDF	Sunlit surface waters; photodegradation of MeHg in plankton or dissolved organic matter	[2], [5], [6]
Microbial methylation of Hg(II)	MeHg: negative $\delta^{202}\text{Hg}$; negligible MIF; reflects kinetic isotope effects during methyl transfer	Anoxic sediments, wetlands, microbial biofilms dominated by sulfate- or iron-reducing bacteria	[2], [7], [8]
Microbial demethylation of MeHg	Residual MeHg: positive $\delta^{202}\text{Hg}$; minimal MIF; opposite direction to methylation	Anaerobic sediments and microbial communities degrading MeHg	[9], [10]
Atmospheric oxidation–reduction cycling	Oxidized Hg(II): positive $\Delta^{199}\text{Hg}$; reduced Hg(0): negative $\Delta^{199}\text{Hg}$; balance depends on sunlight and radical chemistry	Tropospheric and stratospheric cycling; long-range transport and deposition	[2-4]
High-temperature industrial and geogenic processes	MDF only; $\delta^{202}\text{Hg}$ reflects kinetic isotope effects; negligible MIF	Coal combustion, metal smelting, volcanic emissions, hydrothermal vents	[2], [11], [12]
Sorption and volatilization	MDF: heavier residual Hg (positive $\delta^{202}\text{Hg}$), lighter volatilized Hg(0); MIF absent	Soils, sediments, and organic interfaces; exchange between bound and gaseous Hg	[13-15]

References: [1] Bergquist and Blum (2007), [2] Blum et al. (2014), [3] Sherman et al. (2010), [4] Gratz et al. (2010), [5] Ghosh et al. (2008), [6] Zheng and Hintelmann (2009), [7] Kritee et al. (2007), [8] Tsui et al. (2020), [9] Kritee et al. (2009), [10] Poulin et al. (2021), [11] Estrade et al. (2009), [12] Smith et al. (2005), [13] Jiskra et al. (2019), [14] Hintelmann and Lu (2003), [15] Grégoire et al. (2021)

internal normalization based on addition of a Tl standard for instrumental mass bias correction. Strict control of reduction efficiency, matrix removal, and analytical blanks is essential to avoid artificial mass-dependent fractionation during analysis, particularly for low-Hg environmental samples (Shi et al. 2023).

The internationally accepted reference material for Hg isotope analysis is NIST SRM 3133, an acidified aqueous Hg solution that serves as the zero-point standard for all δ and Δ values ($\delta^{202}\text{Hg} = 0\text{‰}$; $\Delta^{199}\text{Hg}$, $\Delta^{200}\text{Hg}$, $\Delta^{201}\text{Hg}$, $\Delta^{204}\text{Hg} = 0\text{‰}$). All Hg isotope data are reported relative to this standard to ensure interlaboratory comparability (Bergquist and Blum 2007; Blum et al. 2014). Secondary reference materials such as NIST RM 8610 (UM-Almadén) and selected environmental standards are routinely analyzed as quality control checks. To our knowledge, no formal programs for laboratory performance intercalibration (such as the international organization Quality Assurance of Information for Marine Environmental Monitoring in Europe, QUASIMEME) have been established for mercury isotopes.

2.2.2 Sample preparation

The growing interest in applying Hg stable isotopes to Arctic and subarctic matrices has led to some standardization of sample preparation and isotopic analysis protocols across laboratories, enabling increasingly inter-comparable datasets, inter-laboratory comparison exercises, and coordinated assessments of Hg sources and transformation pathways in northern environments. There are a variety of sample collection techniques available, but purification and concentration are mostly done either by digestion followed by bubbling into an oxidizing trap or by combustion and then trapping into an oxidizing trap. While specific details of the methods can vary, these are the two major concentration approaches that have been adopted.

Atmospheric Hg is collected in a variety of ways, which affects the pools of atmospheric Hg sampled as well as the time needed for obtaining enough Hg for isotopic measurements. Traditionally, gaseous Hg species were collected through traps (gold or iodated or sulfur-impregnated activated carbon cartridges) by actively pumping air through the traps. Generally, these measurements were thought to collect total gaseous Hg (TGM), which is a mix of gaseous elemental Hg (GEM) and gaseous oxidized Hg. More recent active methods now can separate these two groups by using different trap materials. Another common way to collect GEM for isotopic analysis is passive samplers with sulfur impregnated activated-carbon (Szponar et al. 2020). This technique only collects GEM and usually is left out for 1-3 months for isotopic analysis. Particle bound Hg is also collected and captured on pre-combusted quartz or teflon filters fitted to high-volume air samplers (Jiskra et al. 2019; Zheng et al. 2021). Mercury from TGM and GEM trap materials is typically thermally desorbed from the trap material and trapped in an oxidizing trap. This both purifies and concentrates the Hg from these samples. Mercury from particulate filters typically is combusted similar to other solid samples to purify and concentrate the Hg.

Mercury isotopes have also been measured in snow. Snow samples are collected using acid-cleaned polyethylene tools and containers and oxidized with 1% bromine monochloride (BrCl) while thawing to convert all Hg species to Hg(II) (Sherman et al. 2010; Douglas and Blum 2019; Jiskra et al. 2019; Zheng et al. 2021). Once in solution, Hg from these samples can be purified using reduction by stannous chloride (SnCl_2) in a bubbler set up with subsequent collection of released Hg(0) in an oxidizing trap.

Seawater and meltwater samples generally follow the same oxidation–reduction–purge procedure as snow (Jiskra et al.

2021) but with larger volumes due to the lower amounts of Hg. Samples are typically oxidized with BrCl to ensure complete conversion of all Hg species and to minimize loss of volatile aqueous species.

Most sediments, suspended particulates, soils and other solid samples including organic-rich samples (e.g., moss, lichen, peat) are freeze-dried, and the Hg is subsequently purified and concentrated using combustion and trapping into an oxidized trap (Biswas et al. 2008). Combustion is the preferred method for complex, aged, recalcitrant organic-rich matrices, such as coal (Biswas et al. 2008; Blum and Johnson 2017). It is almost impossible to quantitatively obtain all the Hg from these types of digestion solutions through reduction and bubbling (Biswas et al. 2008; Blum and Johnson 2017). For some organic-rich samples, microwave digestion has worked.

For fresher organic-rich samples, such as biotic tissues, oxidative digestion followed by reduction and bubbling of Hg into an oxidizing trap is effective (Blum et al. 2014). Biological samples are commonly freeze-dried and then digested in HNO₃:HCl (3:1) with some amount of heat or microwave digestion system. Following digestion, hydrogen peroxide (H₂O₂) is sometimes added for further digestion of organic matter. This step is especially important for keratinous matrices, including hair and feathers (Point et al. 2011; Rua-Ibarz et al. 2019; Renedo et al. 2020; Charrier et al. 2024; Pinzone et al. 2024; Søndergaard et al. 2025).

2.2.3 Isotopic Analysis

Mercury isotope ratios are determined using MC-ICP-MS; usually a Thermo Scientific Neptune, Neptune Plus, Neptune XT, and Nu Instruments Plasma II systems, and usually coupled with cold-vapor generators (CVG; usually Cetac HGX-200 or equivalent CVG units). This configuration is preferred because Hg(0) is highly volatile and this configuration allows easy introduction to the instrument as a gas with high efficiency. It also has the benefit of another layer of purification from the liquid matrix. A CVG converts dissolved Hg(II) to gaseous Hg(0) and introduces it directly into the plasma. Most CVG set ups convert Hg quantitatively, which helps reduce matrix problems and minimize variable instrument mass bias correction. The multi-collector array allows simultaneous measurement of six of the stable Hg isotopes (¹⁹⁸-²⁰⁴Hg; ¹⁹⁶Hg is usually too low for high precision measurements).

The stability and predictability of instrumental mass bias is usually the largest source of error for the Hg isotope measurements, especially MDF. Thus, many groups opt to correct instrument mass bias using both sample-standard bracketing and internal normalization using a Tl standard (Blum and Bergquist 2007). During typical analysis, Hg(II) in solution is continuously reduced to Hg(0) within the CVG reactor using SnCl₂. The resulting Hg(0) is then combined with another gas flow carrying Tl aerosol (usually generated using a desolvating nebulizer) and the combined Hg and Tl are carried to the plasma. The instrument mass bias is first estimated and corrected for using the Tl internal standard. Then differences in Hg and Tl instrument mass bias are captured by strict sample-standard bracketing and normalization of sample measurements to the bracketing standards.

2.2.4 Quality assurance and quality control

It is recommended that each analytical batch includes reagent blanks, duplicate digestions, and process standards with published Hg isotopic compositions that are similar in matrix and concentration to the sample types being processed. A list of CRMs with Hg isotope values reported from studies is provided in Hintelmann (2012) and Blum and Johnson (2017), and there are several labs that frequently do intercomparisons with internal standards and process standards as well. Since instrumental mass bias varies with signal size, matrix and methods, it is recommended that sample and bracketing standard concentrations and signals are matched to within 10-15% of each other and that sample purification results in >90% recovery. Uncertainties are typically ± 0.08–0.15‰ for MDF (δ²⁰²Hg) and better than ± 0.05‰ for MIF (Δ¹⁹⁹Hg, Δ²⁰¹Hg). Mass independent fractionation has better precision (and usually accuracy) than MDF because it is not sensitive to changes in instrumental mass bias. However, it can still be affected by matrix and blank issues.

3. What are mercury isotope values in Arctic environmental matrices, and can they be used to evaluate mercury transport and transformation processes?

3.1 Summary of available mercury isotope data for abiotic matrices

The isotopic composition of abiotic compartments can provide insights into transformation and transportation processes within the Arctic environment, and sometimes there are characteristic end-member isotopic compositions of the Hg bioaccumulating in food webs that are maintained and traceable. Several studies published on Hg isotope composition of various abiotic components in Arctic environments including sediment, soil, bedrock, seawater, fresh water, air, snow, and ice (Fig. 3.1, see also Appendix tables). Yet, the geographic coverage remains sparse, and both data availability and coverage vary across matrices. Although vegetation is not an abiotic compartment, it is included here because it is an important parent material for soil and an indicator of atmospheric exchange of Hg with the terrestrial environment.

Published data on Hg isotopes in Arctic vegetation largely originate from the Eurasian continent, whereas data for other matrices are largely missing from this region, particularly from Siberian sites. Most studies focused on one or two matrices, and only a few locations have many major compartments characterized. For some sites, such as Barrow in Alaska, data from multiple compartments are available.

The geographic coverage of data for compartments such as soils and sediments will likely improve significantly in the coming decade as those matrices are easier to measure for Hg isotopes than air or water, and soil/sediment samples from across the Arctic are available in long-term archives. Better coverage of these compartments will provide isotopic compositions of terrestrial endmembers that can be used to quantify Hg

transported to aquatic ecosystems. Important matrices for which Hg isotope data are currently lacking or very scarce include bedrock, coastal erosion sites, permafrost soils, melting glaciers, and rivers. For riverine inputs of Hg to the marine environment, capturing annual dynamics is important for both the dissolved and particulate fractions to assess the influence of freshwater inputs (Campeau et al. 2022). Due to the low concentrations of Hg in ice and water compared to soils and sediments, and potential contamination issues during sampling and storage, the geographic coverage of these matrices will likely remain sparse. Environmental archives, including sediment, ice, and peat cores, show promise to characterize long-term temporal variation in environmental Hg isotopes, covering both pre-industrial and modern compositions. To date, few studies have reported Hg isotopes in environmental archives from Arctic regions (Zdanowicz et al. 2016; Søndergaard et al. 2025).

3.2 Mercury isotopes in the Arctic atmosphere

3.2.1 Overview of atmospheric mercury transport

About 2500 tonnes of Hg are emitted to the atmosphere per year from human activities compared to 340 tonnes per year from natural sources (Outridge et al. 2018). Most of the Hg in the atmosphere is found as Hg(0). The residence time of Hg(0) in the atmosphere is about 6 months (Goodsite et al. 2004; Holmes et al. 2006) but it is much shorter in the Arctic during spring, where Hg(0) is oxidized to Hg(II) initiated by Br atoms

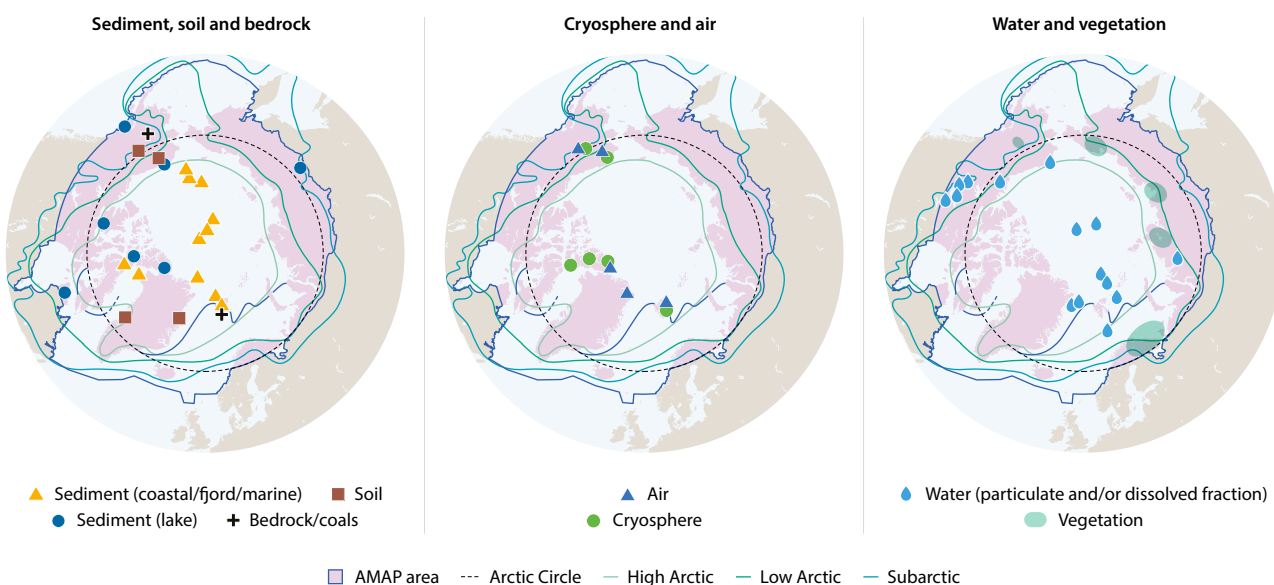


Figure 3.1. Geographic coverage of available data on Hg isotope measurements in abiotic compartments. Left map: sediment, soil and bedrock; middle map: cryosphere (snow and ice) and air; right map: water and vegetation.

(Skov et al. 2004; Wang et al. 2019). Mercury can be transported over long distances and is found throughout the troposphere, including in the Arctic. An important question to assess is the relationship between anthropogenic Hg emissions and final deposition, in particular, how much Hg is transported to the Arctic and deposited in terrestrial and marine environments (AMAP 2021a). To provide data and knowledge that address this question, a series of studies have been conducted in recent years measuring Hg stable isotope distribution in the atmosphere to constrain the budget of atmospheric burden of Hg to the Arctic environment. The principle fractionation processes and their importance are illustrated in Figure 3.2.

It is important to note that Hg isotope measurements show how processes are affecting the isotope composition in the atmosphere, but do not describe kinetic or mass-transfer aspects of those processes, such as reaction rates, emission rates or deposition velocities, which provide information on how fast and how much Hg is being transported.

3.2.2 Isotope methodology for air

Mercury isotopes are measured in the atmosphere by sampling on quartz filters for pHg and different cartridges for gas phase Hg as Hg(0) and Hg(II). Zheng et al. (2021) applied passive air samplers at Arctic sites using a diffusive barrier

and sulfur-impregnated activated carbon sorbent for Hg(0) over one month. Araujo et al. (2022) actively pumped air through activated carbon traps to sample Hg(0) isotopes and polyethersulfone membranes to collect gaseous and aerosol Hg(II) across Arctic stations. Also in the Arctic, Jiskra et al. (2019) collected pHg on a filter and Hg(0) on an iodated activated carbon cartridge at time resolutions of 6–8 weeks and during visits of 2–4 days during one year. For each sample technique listed above, attempts were made to minimize sample artefacts, and to document and control them. This is especially true for the passive air sampler technique where there is a MDF offset that needs to be corrected as Hg is fractionated during sorption. For the active techniques, Hg isotopic compositions are maintained during sampling.

3.2.3 Available measurements of mercury isotopes in the Arctic atmosphere and at sites influenced by Arctic air masses

There are very few studies of Hg isotopes in the atmosphere and even fewer from the Arctic (Sherman et al. 2010; Obrist et al. 2017; Douglas and Blum 2019; Jiskra et al. 2019; Zheng et al. 2021; Araujo et al. 2022). Two published studies measured Hg isotopes in precipitation or dry deposition influenced by Arctic air masses (Chen et al. 2012; Yuan et al. 2022) and a

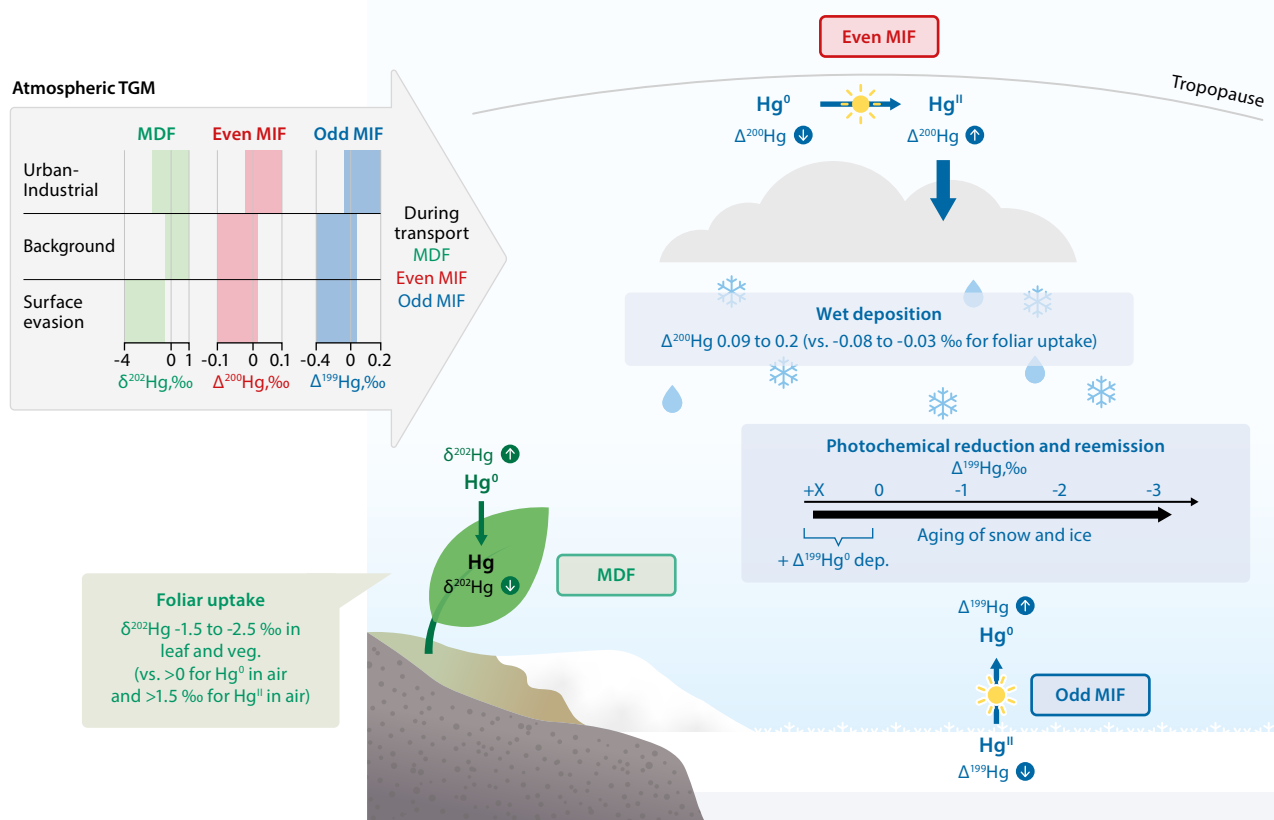


Figure 3.2. Conceptual illustration of Hg isotopes in Arctic air and the interface between air and surfaces. Typical isotopic compositions of TGM from urban-industrial sources, background (remote from anthropogenic point sources) and surface evasion from land and waters are shown in the upper left part of the illustration (ranges from Know et al 2020). Mass dependent fractionation of $\delta^{202}\text{Hg}$ occurs in all biological and chemical reactions. Natural and anthropogenic emission sources mostly have small negative values of $\delta^{202}\text{Hg}$, whereas positive $\delta^{202}\text{Hg}$ values are associated with the atmospheric Hg pool. There is large MDF observed for the process of atmospheric Hg(0) uptake in foliage (Demers et al. 2013; Obrist et al. 2017). Mercury also undergoes even isotope MIF in the tropopause, and $\Delta^{200}\text{Hg}$ is commonly used as a conservative tracer for Hg(II) wet and dry deposition. Large odd isotope MIF ($\Delta^{199}\text{Hg}$ and $\Delta^{201}\text{Hg}$) arises mostly from aqueous photochemical reduction of Hg(II) species in surface waters, cloud waters and snow. This process leads to negative odd-MIF associated with atmospheric Hg(0) and positive odd-MIF associated with atmospheric oxidized Hg species. Odd-MIF values of around zero are associated with primary Hg sources (Zhang and Sun 2026).

single paper measured Hg isotopes in firn snow from glaciers (Zdanowicz et al. 2016).

A recent review compared ambient air TGM and GEM isotopes measured at different locations (Gačnik et al. 2025). Polar and remote sites showed similar and more positive median $\delta^{202}\text{Hg}$ values (+0.64 and +0.55 ‰) than high altitudes (+0.31‰), the marine boundary (-0.23‰) and urban/industrial sites (-0.26‰). The more positive values in polar and remote regions was hypothesized to be due to lower anthropogenic influences as more industrial Hg tends to shift atmospheric TGM and GEM to more negative values. More positive and variable $\delta^{202}\text{Hg}$ values in the Arctic also show evidence of Hg exchange processes between the surface and atmosphere (Araujo et al. 2022). For $\Delta^{199}\text{Hg}$, polar sites varied from -0.62 to 1.32 ‰, indicating a high degree of photochemical transformation either due to photochemical reduction and reemission from snow or photochemical processes in surface waters (Araujo et al. 2022). Observed ratios of $\Delta^{199}\text{Hg}/\Delta^{201}\text{Hg}$ suggest evidence of general photoreduction of Hg(II) in the atmosphere and at polar sites, the additional Br initiated oxidation of Hg(0) by Br radicals. These findings confirm previous observations by Wang et al. (2019) and references therein.

Douglas and Blum (2019) found the Hg isotopic composition of GEM in the Arctic (Utqiaġvik and Toolik Lake) was similar to locations at lower latitudes. During atmospheric Hg depletion events (AMDEs), they found a characteristic Hg isotope composition for deposited Hg to snow, with high $\delta^{202}\text{Hg}$ and values of $\Delta^{199}\text{Hg}$ depending on the degree of photoreduction of snowpack Hg(II) and re-emission of Hg(0) to air. By using Hg isotopic composition, it was concluded that 24% of Hg released during the melt season originates from atmospheric GEM deposited during AMDEs. Most of the Hg in snowmelt came from GEM within the snowpack that had been oxidized by reactive halogens.

Zheng et al. (2021) measured stable isotopes in atmospheric PHg and GEM in the high Arctic (Alert, Canada) during polar spring from March to July in the years 2011, 2013 and 2014. In addition, snow samples were taken from March to June in 2013 to 2015. They concluded that PHg measured at Alert was due to in situ and almost complete oxidation of GEM to RGM followed by uptake on particles. Further, they concluded in situ oxidation of background GEM was the dominant source of PHg at Alert, rather than primary anthropogenic PHg transported to Alert. This interpretation was based on PHg samples collected during periods of the strongest GEM depletion (e.g., in 2013) showing the most GEM-like isotope values, while PHg collected during periods of least GEM depletion departed from the GEM isotope values the most. This finding agrees with an earlier study (Jiskra et al. 2012). At Alert, Hg reemission between 0%–~60% was found for all snow samples, with an average of $20 \pm 31\%$ observed in early spring (March and April). In contrast, late spring showed generally <20% loss of Hg, confirming earlier results measuring directly the fluxes of Hg fractions (GEM, RGM and PHg) (Brooks et al. 2006).

In 2018 and 2019, Araujo et al. (2022) sampled air for isotopic analysis of Hg(0) and Hg(II) in gas and aerosol phases at Alert in Canada and at Villum Research Station in Greenland. The study confirms earlier findings that almost all Hg(0) is oxidized to Hg(II) followed by deposition but without formation of PHg

intermediates (Zheng et al. 2021). Based on back-trajectory calculations, it was concluded that re-emission of Hg(0) during summertime in North Greenland and Ellesmere Island accounted for ~60% of the total, due to sea ice sources and snow-covered coastal land. Boundary layer trajectories never reached ice-free Siberian shelf waters, where most terrestrial Hg is discharged into the Arctic Ocean where it might, in turn, escape to the atmosphere. It was thus concluded that it was not a major source for the summer GEM peak, and it was suggested that terrestrial Hg from rivers and coastal erosion likely impacts Arctic Ocean marine ecosystems, but not the atmosphere. Based on air mass origins and Hg isotope values, it was concluded that the summertime atmospheric Hg(0) peak is most likely sustained by re-emission of Hg deposited during the previous spring season to the cryosphere. This re-emission takes place directly from the cryosphere but also from regional open marine waters that receive meltwater Hg inputs.

Chen et al. (2012) found that measuring Hg isotope fractionation in precipitation coupled with meteorological data provided useful information about Hg transport. They sampled snow and precipitation at 44 degrees North (Peterborough) in Canada where winter samples with higher $\Delta^{200}\text{Hg}$ provenance originated from Arctic stratospheric air masses (based on HYSPLIT back trajectory modeling). The $\Delta^{200}\text{Hg}$ anomalies observed in these samples were concluded to relate to photo-initiated oxidation on aerosols in the troposphere. Yuan et al. (2022) performed a similar study at the same site in winter about 10 years later and found generally lower Hg concentrations in precipitation. In addition, the isotope fractionation showed more positive $\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$, which may have been due to a change in source contribution because of seasonally increased combustion of coal. Most samples with higher Hg concentrations showed lower $\Delta^{199}\text{Hg}$, indicating a decline in anthropogenic emissions compared to the measurements made earlier by Chen et al. (2012). During events when the stratospheric polar vortex reached the sampling site, results showed the largest variations in $\Delta^{199}\text{Hg}$ and $\Delta^{200}\text{Hg}$ when air masses mostly originated from the Arctic. This shows that in Arctic air, Hg(II) originates both from the stratosphere and troposphere. At the same time, $\Delta^{202}\text{Hg}$ showed positive values, further indicating background atmospheric Hg.

A core from the Agassiz ice cap located on Ellesmere Island, Canada (80.7°N) showed a ~ +1‰ shift in $\delta^{202}\text{Hg}$ over the nineteenth to twentieth centuries that could reflect changes in the isotopic composition of the atmospheric Hg pool in the high Arctic in response to growing industrial emissions of Hg at lower latitudes (Zdanowicz et al. 2016). This study is the first ever to report on the historical variations of Hg stable isotope ratios in Arctic ice cores. Results could help constrain future modeling efforts of the global Hg biogeochemical cycle and the atmospheric response to changing Hg emissions, past and future (Zdanowicz et al. 2016).

Isotopic Hg fractionation reveals that the Arctic Ocean receives Hg like other oceans of the world, mainly via atmospheric deposition and riverine input of Hg(II) (Lim et al. 2024). Observed spatial differences include pathways and locations where atmospheric Hg(0) is oxidized. In the Arctic, a substantial part of this oxidation is via Br initiated oxidation followed by deposition in precipitation at mid-latitudes (Lim et al. 2024),

where Br most likely is produced from emission of Br₂ from snowpack on sea ice as the main source with minor contribution from Br release from sea salt aerosols (Gong et al. 2025).

A recent comprehensive review of methods and theoretical knowledge on atmospheric Hg processes, including the use of Hg isotopes, concluded that Hg species in air (GEM, GOM, PHg) are isotopically separated and, thus, measurement data can be used for a better understanding of atmospheric processes (Sommar et al. 2025). Furthermore, the observed variations in isotopic fractionation of atmospheric Hg cannot be fully explained, partly due to the large number of processes that give rise to fractionation (including chemical transformations, air-surface exchange etc.) and partly due to limitations in available data. Nevertheless, inclusion of Hg isotope fractionation in key chemical transformations in atmospheric transport models has been used to constrain the net flux of Hg to the ocean (Song et al. 2025).

3.2.4 Mercury deposition on terrestrial vegetation

Moving from the high Arctic to lower Arctic latitudes, Obrist et al. (2017) studied tundra vegetation (and soil and snow) in northern Alaska and applied Hg isotope values ($\delta^{202}\text{Hg}$, $\Delta^{199}\text{Hg}$, $\Delta^{200}\text{Hg}$) and three-isotope mixing models to conclude that atmospheric gaseous Hg(0) is the dominant source (70%) of Hg in vegetation. A large negative shift in $\delta^{202}\text{Hg}$ of $\sim 2\text{‰}$ was found in vegetation due to foliar uptake relative to atmospheric Hg(0). Jiskra et al. (2019) similarly found that Hg(0) in soil pore air at Toolik Field Station, located 180 km inland from the coast of Alaska, originates primarily from the deposition of Hg(0) and that AMDEs did not play a major role in atmospheric Hg deposition. This finding was further supported by vegetation examined across a broader geographic area (Sonke et al. 2023).

Olson et al. (2019) examined tundra vegetation in northern Alaska covering a range of species, including feather moss (*Hylocomium splendens*), peat moss (*Sphagnum* sp.), brown lichen (*Masonhalea richardsonii*), white lichen (*Cetraria islandica*), tussock grass (*Carex aquatic*), and dwarf birch (*Betula nana*), at nine sites from the Toolik Field station to the Arctic Ocean. The authors concluded that atmospheric Hg(0) is the dominant source of Hg to the tundra in this area. Negative shifts in $\delta^{202}\text{Hg}$ of $\sim 1\text{--}2\text{‰}$ were found in different vegetation relative to atmospherically deposited Hg(0). Significantly higher $\Delta^{199}\text{Hg}$ values were observed in most species compared to atmospheric Hg(0) ($-0.25 \pm 0.07\text{‰}$), being most pronounced in the brown ($0.23 \pm 0.02\text{‰}$) and white lichens ($0.17 \pm 0.11\text{‰}$), indicating significant photo-reduction and re-emission of foliar Hg(II) or contributions of inorganic Hg(II) from atmospheric deposition and/or dust. Dwarf birch showed no difference in $\Delta^{199}\text{Hg}$, indicating little to no foliar photoreduction/reemission in vascular species in this high Arctic environment.

Sonke et al. (2023) examined terricolous and epiphytic tree lichens and mosses collected primarily across Siberia, with a small number of samples from southwest Greenland. Total Hg was substantially higher in both terricolous lichens and epiphytic tree lichens near the Arctic Ocean shore compared to sites greater than 300 km inland. The combined $\delta^{202}\text{Hg}$, $\Delta^{199}\text{Hg}$, and $\Delta^{200}\text{Hg}$ values suggested that the elevated coastal

Hg levels were delivered by marine air masses rich in gaseous and particulate-oxidized Hg(II) forms, such as HgBr₂. The $\Delta^{200}\text{Hg}$ in inland terricolous lichen and moss were near zero, indicating a dominant contribution (63%) of atmospheric Hg(0). In contrast, the inland epiphytic tree lichens had more positive $\Delta^{200}\text{Hg}$ of 0.15‰, similar to the atmospheric Hg(II) end-member, suggesting that they preferentially accumulate Hg(II) from wet and dry deposition compared to terricolous lichens.

3.3 Mercury isotopes in the cryosphere

The cryosphere includes glaciers, ice sheets, snow, sea ice, lake ice, and river ice, as well as permafrost, though the latter compartment is addressed separately in Section 3.5. In addition to storing most of the Earth's fresh water, the cryosphere serves as an important interface between the atmosphere and surfaces in the Arctic environment. It should thus be considered both as an important source and sink of atmospheric Hg (discussed above), as well as a potential source of Hg to downstream systems. The Greenland ice sheet holds the largest amount of frozen water in the Arctic and has been suggested to contain as much as 7.4 meters of sea level rise (Morlighem et al. 2017). Over the last three decades, the Greenland ice sheet has lost ice at a rate of 169 ± 9 giga tonnes per year (Otosaka et al. 2023). Other parts of the Arctic cryosphere, including snow, sea ice, and permafrost, are also being lost due to the accelerated warming of the Arctic environment. These changes will affect the biogeochemical cycling of Hg in the Arctic environment, including Hg isotopes.

In terms of the isotopic compositions, the few existing studies have focused mostly on snow and ice, particularly processes related to the MIF occurring due to photoreduction of Hg(II) in snow and ice and re-emission of Hg(0) back to the atmosphere (Sherman et al. 2010; Sherman et al. 2012; Araujo et al. 2022). Sherman et al. (2010) was the first to demonstrate the very negative $\Delta^{199}\text{Hg}$ left behind in snow after sunlight-induced reduction using chamber measurements. The study also observed large negative odd-MIF in snowfall ($\Delta^{199}\text{Hg}$ of -0.95 to -1.20‰), surface snow ($\Delta^{199}\text{Hg}$ of -2.41 to -2.63‰), and snow drifts ($\Delta^{199}\text{Hg}$ of -3.84 to -5.08‰) after an AMDE. A shift in $\delta^{202}\text{Hg}$ was also observed. Based on the observed values of $\Delta^{199}\text{Hg}$ and fractionation factors from chamber experiments, they estimated $\sim 5\text{--}30$, $\sim 35\text{--}50$, and $\sim 65\text{--}75\%$ of the Hg originally in the snowfall, surface snow, and drifting snow, respectively, was re-emitted to the atmosphere due to photoreduction. In another study, also conducted near Barrow, Alaska, Sherman et al. (2012) observed positive $\Delta^{199}\text{Hg}$ in newly formed frost flowers (mean $\Delta^{199}\text{Hg}$ of $0.77 \pm 0.13\text{‰}$) after an AMDE and suggested these positive $\Delta^{199}\text{Hg}$ values were because of deposition of Hg(0) recently emitted from nearby snowpack. As for the snow, the $\Delta^{199}\text{Hg}$ shifted to more negative values (mean $\Delta^{199}\text{Hg}$ of $0.10 \pm 0.05\text{‰}$) as the frost flowers aged. As discussed above, Araujo et al. (2022) suggested, based on air mass origins and Hg isotope values, that the summertime atmospheric Hg(0) peak most likely is sustained by re-emission of Hg from the cryosphere. The close interaction between the atmosphere and cryosphere based on Araujo et al. (2022) is shown in Fig. 3.3.

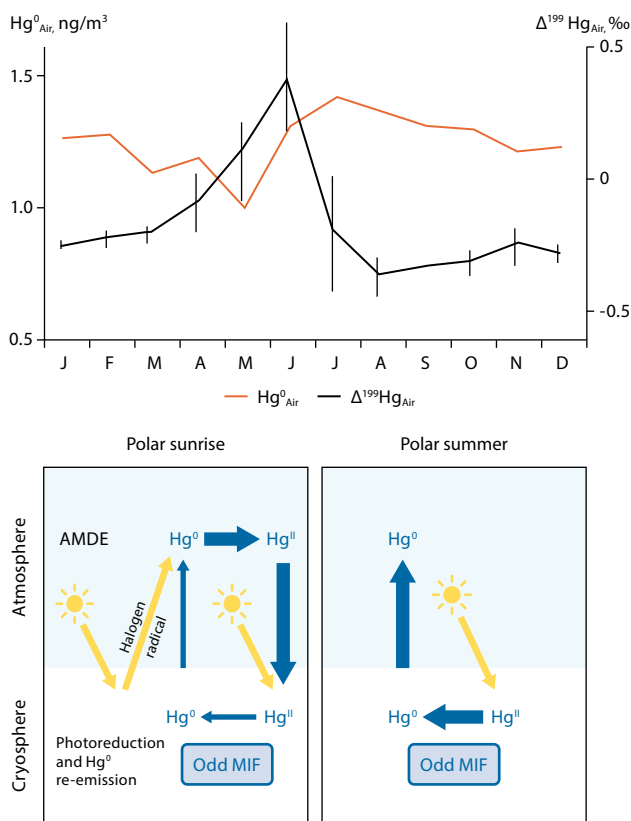


Figure 3.3. Examples of interactions between the atmosphere and cryosphere based on data from Araujo et al. (2022). The top panel shows measured concentrations of Hg in the atmosphere and $\Delta^{199}\text{Hg}$ values of atmospheric Hg. The lower panel illustrates the underlying biogeochemical processes. In spring, halogen radicals released from snow and ice trigger AMDEs, resulting in deposition of $\text{Hg}(\text{II})$ to surface snow. Because sunlight also induces odd-mass-independent fractionation (odd-MIF), the $\Delta^{199}\text{Hg}$ value of atmospheric Hg becomes more positive. After polar sunrise and the AMDEs, photoreduction of Hg in snow and ice leads to a renewed buildup of Hg in the atmosphere and a continued increase in $\Delta^{199}\text{Hg}$. As $\Delta^{199}\text{Hg}$ in the cryosphere decreases, this eventually causes a decline in atmospheric $\Delta^{199}\text{Hg}$ as the atmospheric Hg pool is replenished by Hg re-emitted from the cryosphere.

The impact of glacial meltwaters as a source of Hg into Arctic marine waters remains uncertain, and further studies are needed to elucidate the risk glaciers may pose. Only one study has so far reported Hg isotopic values from an Arctic glacier (Zdanowicz et al. 2016). They found $\Delta^{199}\text{Hg}$ (and $\Delta^{201}\text{Hg}$) signals (-1 to 3 ‰) exceeding the typical range reported for Arctic snow impacted by AMDEs and argued that such events did not act as a major source of Hg to the ice. Positive $\Delta^{199}\text{Hg}$ values are also reported from glaciers elsewhere (up to 4 ‰, Tibetan plateau (He et al. 2025). Reported $\delta^{202}\text{Hg}$, $\Delta^{199}\text{Hg}$, and $\Delta^{201}\text{Hg}$ values in the ice were similar to Arctic $\text{Hg}(\text{0})$ signals, as well as to mid-latitude precipitation and the Hg composition of industrial sources. The influence of industrial sources of Hg to the ice was also supported by the observed increase in Hg concentrations (from ≤ 0.2 ng/L for the preindustrial era to ~ 0.8 – 1.2 ng/L for the last ~ 200 years).

3.4 Mercury isotopes in soil, bedrock and vegetation

The terrestrial environment, and the processes occurring within it, influence Hg biogeochemical cycling in Arctic

freshwater ecosystems and the marine environment. While freshwater ecosystems that receive most of their Hg directly from atmospheric deposition may show a relatively rapid recovery, land surfaces can delay the response in other systems due to the postponed export of deposited Hg to downstream systems. Thus, understanding the atmosphere–land–ocean interplay is important for evaluating the effectiveness of the Minamata Convention and the timeframe over which reduced anthropogenic Hg emissions will lead to reduced Hg burdens in Arctic biota.

In addition to modern, anthropogenically derived Hg being deposited to Arctic terrain, the terrestrial compartment of the Arctic stores large amounts of Hg from pre-industrial emission sources, such as volcanoes and wildfires (Schuster et al. 2018). This Hg was sequestered together with soil carbon over hundreds to thousands of years due to the cold climate and slow remineralization rates.

Findings on Hg isotopes in Arctic bedrock and vegetation are included here as these matrices represent the parent material for soils and are important both for constraining the source composition of terrestrial Hg to downstream systems and for quantifying net fluxes and transformations of Hg through various biogeochemical processes. Isotopic data from soils and bedrock (including coal) have so far been reported from only a few locations including Svalbard, Alaska, and Greenland, and they are characterized by negative $\Delta^{199}\text{Hg}$ and $\delta^{202}\text{Hg}$ values (Fig. 3.1). In contrast, vegetation is better represented, with coverage spanning large geographical areas of Eurasia (Sonke et al. 2023), as well as more regional studies from, for example, Alaska (Obrist et al. 2017).

Mercury isotope measurements played a key role in constraining sources of Hg to Arctic soils near the Toolik Field Station in Alaska (Fig. 3.4). Obrist et al. (2017) conducted an extensive two-year field campaign, where they investigated multiple pathways of Hg input to Arctic tundra ecosystems. Based on measured Hg fluxes, they concluded that Hg deposition via wet deposition and AMDEs was less significant than previously

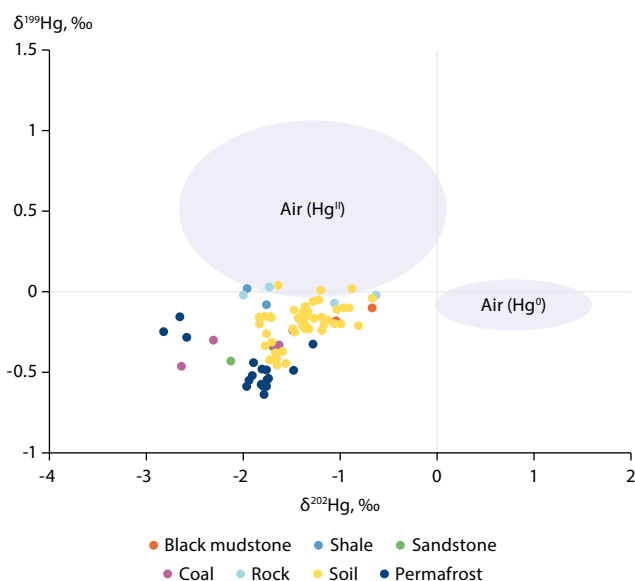


Figure 3.4. Available data on Hg isotopes in Arctic bedrock, coals, and soils. See Appendix 2 for sampling locations and years.

thought. The isotopic values of Hg in soils and other local matrices provided independent support for these conclusions. By exploiting the distinct isotopic values ($\delta^{202}\text{Hg}$, $\Delta^{199}\text{Hg}$, and $\Delta^{200}\text{Hg}$) of atmospheric Hg^0 and Hg^{2+} , geogenic Hg^{2+} in bedrock, and Hg^{2+} deposited during AMDEs, they attributed approximately 90%, 73%, and 55% of the Hg in vegetation, organic soil, and mineral soil, respectively, to atmospheric deposition of $\text{Hg}(0)$. Inputs of Hg from snowmelt following AMDEs contributed less than 5% of the Hg. Geogenic Hg contributed 0% and 40% of the Hg in the organic and mineral soil horizons, respectively.

In addition to examining Hg deposition pathways, Hg isotopes are also useful for tracing reduction processes in soils. Jiskra et al. (2017) investigated Hg isotopic compositions in a boreal soil profile and found that most Hg originated from atmospheric $\text{Hg}(0)$ uptake, with approximately 10% derived from precipitation. In the podzol O_e horizon, $\Delta^{199}\text{Hg}$ and $\delta^{202}\text{Hg}$ values were similar to those of the litter layer; however, the underlying O_a/H_a horizons were enriched in heavy isotopes, exhibiting a MIF enrichment of approximately 0.11‰. The isotopic values observed in the Histosols could not be explained by a simple litter–precipitation mixing model, suggesting the influence of post-depositional processes. Comparison of $\Delta^{199}\text{Hg}/\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}/\Delta^{201}\text{Hg}$ relationships indicated re-emission of legacy Hg mediated by natural organic matter. Thus, Hg isotopes may be a powerful tool for investigating pathways of Hg remobilization from permafrost soils during thaw (Jiskra et al. 2017).

3.5 Mercury isotopes for permafrost research

Permafrost is defined as ground that remains at or below 0 °C for at least two consecutive years (Osterkamp and Burn 2003) and, in the Arctic, it is a major long-term geochemical reservoir of Hg (Martins, Hintelmann, Pilote, Vieira, et al. 2025). Over millennial timescales, continuous atmospheric deposition, coupled with low temperatures, limited microbial activity, and restricted hydrological export, has facilitated the efficient sequestration of Hg in frozen soils (Vonk et al. 2015). Recently, a pan-Arctic assessment estimated permafrost soils store approximately $1,600 \pm 800$ Gg of Hg, corresponding to nearly twice the Hg inventory of the atmosphere, oceans, and non-permafrost terrestrial reservoirs combined (Schuster et al. 2018). This large stock was strongly associated with soil organic carbon pools, reflecting the affinity of Hg for organic matter and its co-accumulation during soil formation and cryoturbation processes (Schuster et al. 2018). However, Lim et al. (2020) and Olson et al. (2018) suggested that this amount of Hg stored in permafrost was overestimated. These authors asserted that the type of soil and depth range of permafrost have a profound effect on ratio of Hg to organic carbon, which Schuster and co-authors used to generate their estimate of the Hg pool. Thus, Lim, Olson and co-authors suggested the Hg pool in permafrost soils could be three to four times lower than what was estimated by Schuster et al. (2018).

Field observations across Alaska, Canada, and Siberia indicate that total Hg concentrations in permafrost soils typically range between 30 and 70 ng/g, with elevated concentrations

(up to 150 ng/g) in organic-rich horizons such as peat layers and yedoma deposits (Schuster et al. 2018). The stability of these reservoirs is, however, increasingly threatened by rapid Arctic warming. Climate projections indicate that 30–99% of near-surface permafrost may thaw by 2100, depending on emission scenarios, leading to enhanced mobilization of previously sequestered Hg into active biogeochemical cycles (Peng et al. 2023; Martins, Hintelmann, Pilote, Vieira, et al. 2025). Importantly, permafrost thaw not only increases Hg release but also alters hydrological pathways, redox conditions, and microbial activity, all of which influence Hg speciation and transport (Vonk et al. 2015).

Upon thaw, Hg previously bound to frozen organic matter becomes susceptible to leaching, erosion, and fluvial transport. Empirical data from major Arctic river systems, including the Yukon and Mackenzie rivers, show that Hg export can increase by 20–50% during periods of active layer deepening and high discharge, highlighting the sensitivity of Hg fluxes to thaw dynamics (Schuster et al. 2011; Mu et al. 2019). Additionally, thermokarst processes and coastal erosion can directly release Hg-rich permafrost material into aquatic systems, further enhancing regional Hg inputs (Martins, Hintelmann, Pilote, Vieira, et al. 2025).

Mercury stable isotope analysis has emerged as a potential tool to trace these processes and to differentiate between Hg sources and transformation pathways in permafrost-dominated environments (Fig. 3.5). Permafrost-derived Hg is typically characterized by negative MDF ($\delta^{202}\text{Hg} \approx -0.5$ to -2.5 ‰) and near-zero MIF ($\Delta^{199}\text{Hg} \approx 0$ ‰), consistent with long-term accumulation in the absence of photochemical processing (Blum et al. 2014). In contrast, Hg in surface waters and snowpack often exhibits positive $\Delta^{199}\text{Hg}$ values (up to $+2.0$ ‰), indicative of photoreduction and photooxidation reactions (Bergquist and Blum 2007). These isotopic distinctions enable the quantification of permafrost contributions to downstream Hg pools and provide constraints on Hg cycling under changing environmental conditions. On-going and future isotopic studies will likely improve constraints on the fate of Hg in thawing permafrost systems.

Despite the clear potential of Hg stable isotopes, it is important to emphasize that their application in permafrost environments remains relatively limited. To date, only a small number of studies have directly investigated Hg isotopic fractionation in permafrost soils, thaw gradients, and associated aquatic systems. Published Hg isotope data are available for only two Greenland permafrost cores (Søndergaard et al. 2025). In fact, Hg isotope techniques have been used mainly to quantify Hg methylation and MeHg demethylation rates (Gambardella et al. 2025; Martins, Hintelmann, Pilote, Cesário, et al. 2025). Thus, most existing knowledge is derived from temperate or marine environments, with comparatively sparse datasets from Arctic permafrost regions. This scarcity is largely due to logistical challenges associated with remote Arctic fieldwork, the complexity of permafrost systems, and the analytical demands of high-precision isotope measurements. Consequently, significant uncertainties remain regarding the variability of isotopic composition across different permafrost types (e.g., yedoma versus peat), the effects of thaw processes on isotope fractionation, and the coupling between Hg cycling and carbon mobilization.

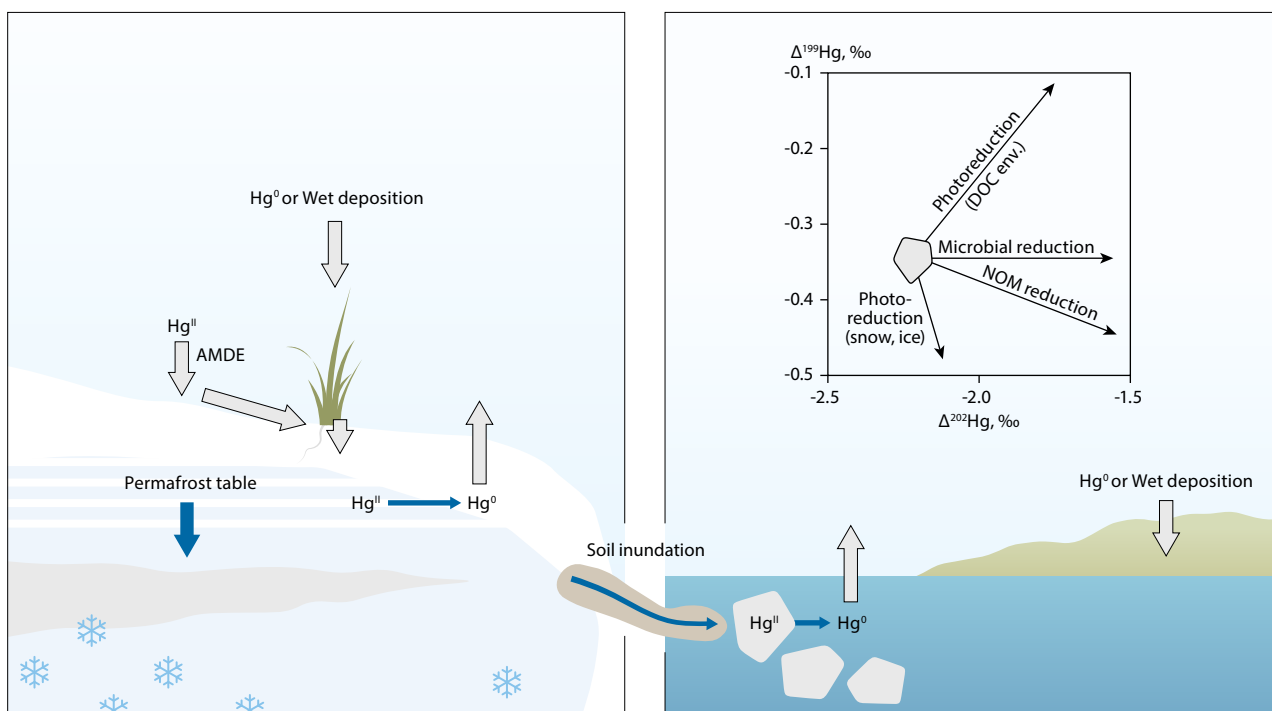


Figure 3.5. Conceptual illustration of how Hg isotopes can be used to trace Hg transformation and transport pathways in a thawing permafrost landscape. On the left, a peat plateau underlain by permafrost is shown. As permafrost thaws, increasing amounts of Hg-containing peat become available for microbial remineralization. In addition, permafrost thaw may result in ground subsidence and collapse of peat into the surrounding fen. As the peat becomes inundated, conditions favorable for both downstream Hg export and Hg reduction may develop. These reduction processes can be traced using Hg isotopes as illustrated in upper right box (DOC = dissolved organic carbon, NOM = natural organic matter). Adapted from Jiskra et al. (2017).

Permafrost thaw also enhances the potential for *in situ* methylation of inorganic Hg, driven by increased microbial activity in newly thawed, water-saturated soils and sediments. Microbial methylation induces characteristic isotopic fractionation, typically resulting in shifts of -0.5 to -1.5‰ in $\delta^{202}\text{Hg}$, which can be used to trace the production and accumulation of MeHg (Rodríguez-González et al. 2009; Janssen et al. 2016).

In addition to local production, permafrost thaw significantly influences Hg transport pathways at the land–ocean interface (Vonk et al. 2015). Enhanced hydrological connectivity promotes the transfer of Hg from terrestrial systems to rivers and ultimately to the Arctic Ocean (Mu et al. 2019). Current estimates suggest that Arctic rivers export approximately 50–80 tonnes of Hg annually, with potential up to two-fold increases under intensified thaw scenarios (Zolkos et al. 2020). Isotopic compositions may provide a means to distinguish between riverine Hg derived from permafrost (low $\Delta^{199}\text{Hg}$) and Hg originating from atmospheric deposition (more variable and often positive $\Delta^{199}\text{Hg}$) (Blum et al. 2014; Campeau et al. 2022). Such information is critical for constraining Hg budgets and predicting future exposure risks in Arctic marine ecosystems.

Although Hg stable isotopes provide an opportunity to investigate Hg processes in permafrost settings, this application remains underdeveloped and is a key research gap. Using Hg isotopes in these complex and highly heterogeneous landscapes can provide important insights into Hg mobilization to various compartments over time, as well as net post-depositional fluxes. Expanding isotopic studies in Arctic permafrost environments will improve predictive models of Hg cycling and assessment of the environmental and human health implications of accelerated Arctic change.

3.6 Mercury isotopes in water and sediments

Arctic rivers transport vast amounts of Hg to the Arctic Ocean, and biological uptake of Hg from water at the base of the food web represents the strongest enrichment step. Due to the low concentrations of Hg in natural waters, measurements of Hg isotopes in aquatic systems are challenging, and only a limited number of datasets have been reported to date. The most extensive study of Hg isotopes in natural waters, including both dissolved and particulate fractions, examined Hg isotope values across the Mackenzie River Basin (Campeau et al. 2022). The isotopic compositions of dissolved Hg (DHg) and PHg suggest that these two pools originate from different sources—atmospheric sources for the dissolved fraction and terrestrial sources for the particulate fraction—and that they are not readily exchanged. However, isotopic values among different catchments were not statistically different. The $\Delta^{201}\text{Hg}/\Delta^{199}\text{Hg}$ slopes were 1.39 for DHg and 1.08 for PHg. The relatively high $\Delta^{201}\text{Hg}/\Delta^{199}\text{Hg}$ ratios were suggested to result from multiple fractionation processes that cannot be individually distinguished. Štrok et al. (2015) investigated Hg isotopes in coastal seawater of the Canadian Arctic Archipelago. They suggested that approximately 50% of the Hg originated from terrestrial runoff at sites with $\Delta^{200}\text{Hg}$ values of 0.3 – 0.5‰ , and around 80% at sites with $\Delta^{200}\text{Hg}$ values of 0.1 – 0.2‰ . Furthermore, the data indicated a limited influence of AMDEs, as reflected by positive $\Delta^{199}\text{Hg}$ values. No differences in Hg isotope values were observed with water depth.

While few studies have measured Hg isotopes in Arctic waters, several studies report Hg isotope values in Arctic sediments. Lepak et al. (2020), for example, compared Hg isotopic

compositions of sediments in Arctic lakes with those from lakes in Minnesota, USA. They found a positive correlation between $\Delta^{200}\text{Hg}$, $\Delta^{199}\text{Hg}$, and $\delta^{202}\text{Hg}$, suggesting that isotopic variability among these systems is primarily driven by source compositions, since $\Delta^{200}\text{Hg}$ is considered a conservative tracer that does not change during near-surface processes. Hughes-Allen et al. (2024) examined a lake sediment core from Siberia and used $\Delta^{200}\text{Hg}$ to estimate the contribution of Hg^{2+} wet deposition over time. More negative $\Delta^{200}\text{Hg}$ values were not accompanied by a decrease in $\delta^{202}\text{Hg}$, suggesting that the observed shift in $\Delta^{200}\text{Hg}$ resulted from direct uptake of atmospheric $\text{Hg}(0)$ in the lake, potentially linked to enhanced algal primary production. Gleason et al. (2017) examined deep Arctic Ocean sediments and concluded that terrestrially derived sources dominated Hg inputs to these sediments. Similar observations are reported from sediment cores collected in fjords on Svalbard (Lee, Kwon, Lee, et al. 2021).

Sediments are environmental archives that can be used to examine Hg loading over longer timescales and under varying climatic conditions. In Arctic Ocean sediment cores, Gleason et al. (2017) observed temporal variability in $\delta^{202}\text{Hg}$, whereas $\Delta^{199}\text{Hg}$ remained relatively stable through time. In another study focusing on lake sediments dominated by atmospheric Hg inputs, Lepak et al. (2020) concluded that over “broad timescales” there is evidence for isotopic shifts—characterized by increases in $\Delta^{200}\text{Hg}$, $\Delta^{199}\text{Hg}$, and $\delta^{202}\text{Hg}$ —following global industrialization around 1800. However, no isotopic signals were observed from short-lived Hg release events, such as the California gold and silver rush, and there was little evidence for isotopic shifts associated with the more recent decline in global Hg emissions. Furthermore, no correlation was found between water concentrations of dissolved organic carbon and the $\Delta^{199}\text{Hg}/\delta^{202}\text{Hg}$ ratio, suggesting that changes in $\delta^{202}\text{Hg}$ were not driven by differences in photochemical reduction rates occurring in the atmosphere prior to deposition. Hughes-Allen et al. (2024) examined a sediment core from a Siberian lake to trace temporal shifts in Hg isotope values. The values of $\Delta^{199}\text{Hg}$ peaked in the deepest layer (approximately 13,000 years before present) and decreased to -0.15‰ near the surface. This trend did not mirror changes in $\Delta^{200}\text{Hg}$, suggesting that variations in $\Delta^{199}\text{Hg}$ were driven by post-depositional processes linked to in-lake conditions, such as changes between clear-water and turbid-water states.

3.7 Mercury isotopes for tracing sources

Coal combustion is a major source of atmospheric Hg emissions. The isotopic composition of Hg in coal is variable, reflecting fractionation during natural geological processes that influence coal deposits. For example, tectonic activity can mix coal reservoirs containing Hg with distinct isotopic compositions (Cao et al. 2024). Processes affecting the chemical form of Hg in the deposit also influence the isotope composition. Li et al. (2021) explored differences in Hg isotopic values in emissions from domestic coal combustion and emissions from modern coal fired power plants, taking into account the isotopic shift occurring in the flue gas cleaning steps. Sun (2019) presented a model for predicting isotope fractionation in emissions from coal fire power plants with different control technology

configurations directly explaining observed fractionation in measured GEM in ambient air. Sun et al. (2014) compiled a comprehensive database on Hg isotopes which together with results from field measurements and modelling were used for emission source identification. The authors conclude that further work is needed on characterizing Hg isotope changes during coal combustion with varying control technologies installed, as well as isotope values from other anthropogenic emission source materials such as minerals (Smith et al. 2008) and Hg used in artisanal gold mining (Garnier et al. 2025).

Gačnik et al. (2025) stated that atmospheric Hg isotopes in principle can be used to discern between natural and anthropogenic emissions but that uncertainties exist due to introduced bias during sample treatment, preconcentration and analytical measurement. Furthermore, interpretation is hampered by lack of data on Hg isotope composition in specific emission sources, which may also vary due to differences in emission control installations.

Zhang and Sun (2026) reviewed available knowledge and data for atmospheric Hg isotopes and discussed the possibilities for source and process identification using isotope measurements of Hg species. They concluded that GEM isotope composition can reflect direct anthropogenic inputs in locations close to sources but the more variable isotope values of PHg and precipitation Hg are more readily influenced by photochemical processing, thus obscuring the source-receptor relationship. In polar regions, shifts in $\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$ values can be observed to identify post-depositional transformations, e.g., for Hg deposited during AMDEs and subsequently reduced and re-emitted. Scenario projections suggest that Hg isotopes can be used to trace shifts in future emission sources from direct anthropogenic to legacy re-emissions. The authors also present a list of recommendations for future research to improve Hg isotope applications to evaluate the effects of regulatory measures under the Minamata Convention.

4. What are mercury isotope values in Arctic biota, and can they be used to evaluate sources and pathways of mercury into Arctic food webs?

4.1 Biological fractionation

Many biological processes cause fractionation of Hg isotopes with most only resulting in MDF. Mercury transformations mediated by microbes, including MeHg formation, MeHg demethylation, and MeHg reduction to Hg(0) all result in MDF (Kritee et al. 2013; Zhang et al. 2022). These microbial transformations, largely occurring in water, soil, and sediment, affect Hg isotopes following deposition and transport to receiving environments. In the terrestrial environment, uptake and adsorption of Hg(0) by plants is the main pathway for Hg entry into soils, and this process results in MDF of -1 to -3‰ compared to atmospheric GEM as well as small MIF that is thought to occur on or within leaves (Demers et al. 2013; Enrico et al. 2016; Zheng et al. 2016; Zhou et al. 2021). Greater MDF of $\sim -4.2 \pm 1.0\text{‰}$ was observed in Arctic tundra (Jiskra et al. 2019). Small MIF of $\Delta^{199}\text{Hg}$ (e.g., ~ -0.1 to -0.3‰) in plants, litter and soil relative to atmospheric GEM is thought to result from photochemical reduction of Hg(II) in foliage and organic matter (Demers et al. 2013; Enrico et al. 2016; Zhou et al. 2021; Liu et al. 2024).

Within vertebrates, large MDF is observed between tissues due to metabolic processing of Hg, including internal redistribution, transformation and elimination (Li et al. 2022). Consequently, Hg isotope values in biota are not only influenced by Hg sources in the environment but also by the tissue examined, and the storage, transformation, or elimination of Hg in that tissue (Tsui et al. 2020; Li et al. 2022). A detailed discussion of metabolic influences on the internal distribution of Hg isotopes in biota is provided in Section 4.4.

Evidence to date indicates that trophic transfer does not result in substantial MDF or MIF of Hg, though there is uncertainty regarding MDF (Tsui et al. 2020; Li et al. 2022). Feeding studies showed no MDF or MIF of Hg isotopes in fish compared with their diet following an equilibration period (Kwon et al. 2012; Kwon et al. 2013; Feng et al. 2015; Lee et al. 2020). However, several factors are important to consider when interpreting $\delta^{202}\text{Hg}$ values of biota in relation to their diet. Tissue type of the consumer may obscure the $\delta^{202}\text{Hg}$ composition of their diet because of internal metabolic processes. For example, a feeding study with hooded seals (*Cystophora cristata*) found $\delta^{202}\text{Hg}$ values were not significantly different between diet and seal muscle, however MDF was observed from diet to seal hair, liver and kidney (Pinzone et al. 2024). No MIF was observed between any seal tissues and the diet. The equilibration period may be relevant, as it may take months for the Hg isotopes of large, long-lived consumers to equilibrate with their diet (Kwon et al. 2016). For large Pacific bluefin tuna (*Thunnus orientalis*), small MDF (~ -0.1 to -0.2‰) was observed relative to the diet during a long-term feeding experiment (Kwon et al. 2016). Experimental studies of trophic transfer have focused on vertebrate animals, and little information is available on Hg isotope fractionation at the base of the food web where biota, such as algae and invertebrates, contain a mix of MeHg and inorganic Hg.

4.2 Summary of available published mercury isotope data for biota

Published studies are shown in Fig. 4.1 that report original, new Hg stable isotope data in biota sampled within or directly relevant to the AMAP geographic scope. In total, 23 studies were found within the high Arctic and subarctic regions across Canada, Greenland, the Faroe Islands, Finland, Iceland, Norway, Russia, Sweden, and the United States. The published papers are summarized below and a more detailed overview of individual studies can be found in Appendix 3.1.

The application of Hg stable isotopes on Arctic biota is relatively new, with yearly publications increasing from zero to five in recent years due to advances in MC-ICP-MS instrument precision and extensive analytical method development. From 2008 to 2018, at most one paper was published on the topic each year. In 2024, the number of publications had increased to five, and studies of Hg isotopes in Arctic biota cover terrestrial, freshwater and marine ecosystems, with a strong emphasis on marine ecosystems, which account for 78% of the publications. A wide range of species and animal groups have been examined from plankton and invertebrates to fish, seabirds, and marine mammals. Fish and invertebrates were the most sampled taxa. Liver, muscle, kidney, and eggs were the most frequently sampled tissues in Arctic biota.

4.3 Sources and pathways

Determining Hg sources and pathways in the environment based on Hg isotope composition in biota is challenging due to the complex nature of the Hg cycle. A range of processes affect the isotope composition from the point of release until it is bioaccumulated (see Section 3).

Mass-dependent fractionation of $\delta^{202}\text{Hg}$ occurs in all investigated biogeochemical transformation processes in the environment, including foliar uptake of gaseous Hg (Obrist et al. 2017) and methylation of inorganic Hg by bacteria (Rodríguez-González et al. 2009), as well as internally in many species, including birds and mammals, associated with metabolic detoxification (Li et al. 2022). Consequently, the $\delta^{202}\text{Hg}$ value in biota is not only influenced by the Hg source input to the environment but also by tissue selection and the degree of metabolic processing of Hg within that tissue (Tsui et al. 2020; Li et al. 2022). However, MDF does not occur appreciably during trophic transfer and the $\delta^{202}\text{Hg}$ signature of diet is retained in the consumer, barring any internal metabolic effects (Kwon et al. 2013; Tsui et al. 2020) (Section 4.1).

In contrast to MDF, MIF ($\Delta^{199}\text{Hg}$, $\Delta^{200}\text{Hg}$, $\Delta^{201}\text{Hg}$, and $\Delta^{204}\text{Hg}$) is only associated with processes involving photochemical reactions (Bergquist and Blum 2007; Cai and Chen 2016). Mass independent fractionation is therefore considered to be conserved

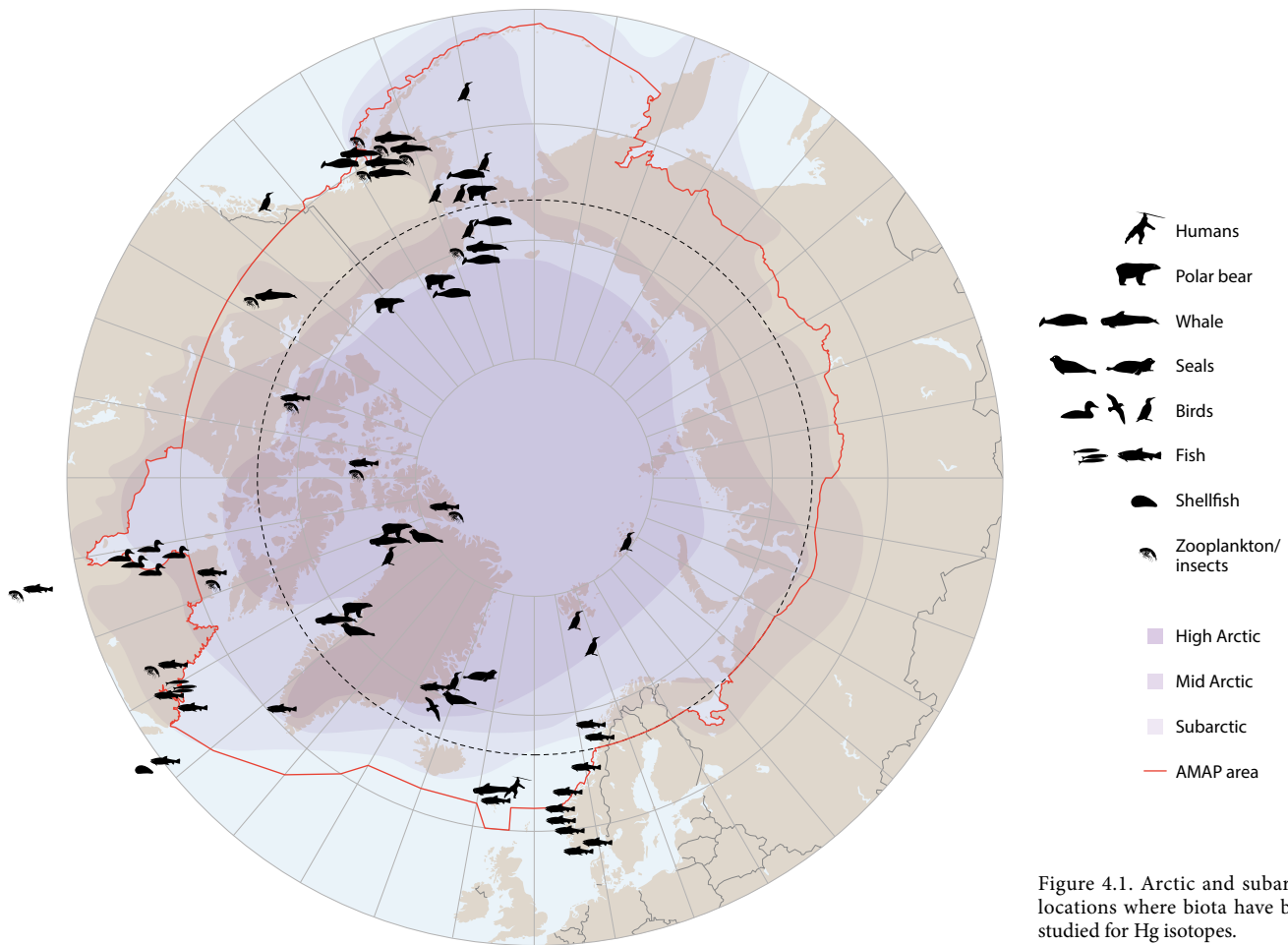


Figure 4.1. Arctic and subarctic locations where biota have been studied for Hg isotopes.

once Hg accumulates in the food web and is no longer exposed to sunlight (Tsui et al. 2020). Nonetheless, different species of Hg can have different MIF, and the proportion of different Hg species (e.g., inorganic Hg(II) versus MeHg) can lead to variation in MIF, especially in lower trophic levels. Of the MIF values, odd-isotope $\Delta^{199}\text{Hg}$ (or the related $\Delta^{201}\text{Hg}$) is commonly used as a tracer of Hg source after biological uptake within the aquatic environment, e.g., for tracing species-specific habitats and foraging depths in the water column (Le Croizier et al. 2020) and/or as an indicator of changes in light conditions, e.g., due to changes in sea ice cover (Masbou et al. 2015). The even-isotope $\Delta^{200}\text{Hg}$ is linked to photo-oxidation of gaseous Hg(0) in the tropopause (Cai and Chen 2016) and has been used as a conservative tracer of atmospheric deposition pathways as Hg(0) or Hg(II) wet or dry deposition, respectively (Obrist et al. 2017; Jiskra et al. 2019). Jiskra et al. (2021) proposed a two-source mixing model for the northern hemisphere with a $\Delta^{200}\text{Hg}$ value of -0.05 as the Hg(0) dry deposition end-member and a $\Delta^{200}\text{Hg}$ value of 0.14 as the end-member for Hg(II) of combined wet and dry deposition. This isotopic differentiation can be used in biotic measurements as a tracer for the dominant deposition forms of Hg.

Several studies have used Hg isotopes in biota to study Hg sources and pathways in the Arctic, with an increasing number of publications in recent years (Fig. 4.2). Gantner et al. (2009) studied crustaceans and fishes in subarctic and Arctic lakes in Canada. Marked differences in both $\delta^{202}\text{Hg}$ and odd-isotope MIF values (i.e., $\Delta^{199}\text{Hg}$ and $\Delta^{201}\text{Hg}$) were found between locations and species, and variations in $\Delta^{199}\text{Hg}$ in predatory fish species were attributed to source uptake from benthic versus planktonic sources.

Geographic patterns of Hg isotopes were found in eggs of common murre (*Uria aalge*) and thick-billed murre (*Uria lomvia*) from Alaska, the North Pacific Ocean, the Bering Sea, and the western Arctic Ocean (Point et al. 2011). The $\delta^{202}\text{Hg}$ and odd-isotope MIF of eggs were geographically different, with $\Delta^{199}\text{Hg}$ and $\Delta^{201}\text{Hg}$ values decreasing at higher latitudes. The authors concluded that differences in odd-isotope MIF values could not be explained by differences in Hg sources, solar radiation fluxes, or foraging behaviour between locations. Instead, they proposed that they were related to variations in sea ice cover.

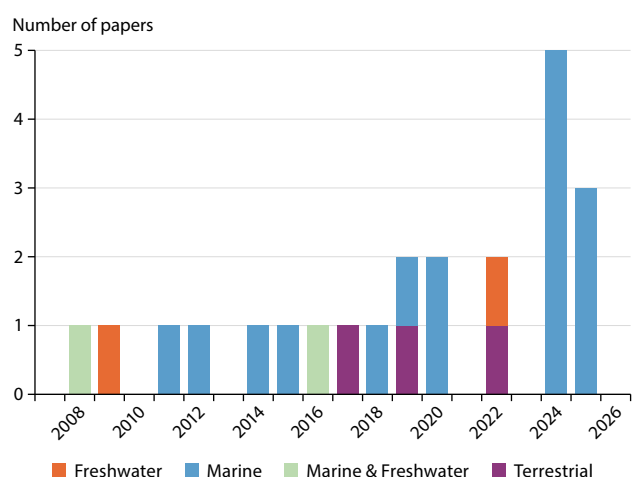


Figure 4.2. Numbers of published papers by year providing new Hg isotope data for Arctic biota from different ecosystem types since 2008, including terrestrial studies on tundra, moss and lichens.

Day et al. (2012) applied Hg isotopes in eggs of Alaskan murre (*Uria sp.*) from breeding colonies in the Gulf of Alaska, the southern and northern Bering Sea, and the Norton Sound in Alaska to evaluate Hg uptake from terrestrial geogenic sources versus marine sources. An increasing inshore Hg gradient was found, with eggs from the coastal embayment of Norton Sound having higher total Hg concentrations and lower $\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$ values typical of geological sources, compared to the ocean sites. The Yukon River and smaller Seward Peninsula watersheds were likely dominant Hg sources to the Norton Sound food web. This conclusion was supported by significantly lower $\delta^{13}\text{C}$ values in Norton Sound eggs compared with those from more ocean-influenced colonies, indicating a significant terrestrial carbon source.

Li et al. (2016) examined 16 fish species (including freshwater, marine, and anadromous species) and blue mussels (*Mytilus edulis*) from the main freshwater tributary to Lake Melville (lower Churchill River), the estuary (Lake Melville), and the Labrador Sea in Canada. A shift in $\delta^{202}\text{Hg}$ was found in juvenile and adult rainbow smelt (*Osmerus mordax*) when they transitioned between freshwater and marine environments as their dominant foraging territory. The Hg isotopic composition of Atlantic salmon (*Salmo salar*) indicated that fish received most of their MeHg from the marine environment despite a similar or longer duration spent in freshwater habitats. This study showed that Hg isotopes can be applied to effectively track sources of MeHg exposure in fish across different growth stages.

Rua-Ibarz et al. (2019) studied the marine fish tusk (*Brosme brosme*) at eight locations along the coastline of mainland Norway, including two sites in Arctic Norway. Lower $\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$ values were found in individuals at polluted southern sites (influenced by Hg pollution from a Zn-smelter and a sunken submarine) compared to Arctic sites (Lofoten and Landegode). Thus, in some cases, $\Delta^{199}\text{Hg}$ may be used to trace Hg sources entering food webs.

Renedo et al. (2020) investigated the feathers of little auks (*Alle alle*) from five breeding colonies across the Arctic Ocean in Greenland, Norway and Russia. Higher $\Delta^{199}\text{Hg}$ values in bird feathers from northern colonies indicated greater photochemically impacted MeHg, supporting shallow-water MeHg production and bioaccumulation in high Arctic waters. Body feathers had higher $\Delta^{199}\text{Hg}$ compared to head feathers of little auks, which indicated seasonal variation in Hg exposure because of different molt times for body and head feathers. Renedo et al. (2020) attributed this pattern to different diet/Hg sources, ranging from mainly copepods in summer to krill, amphipods, and fish larvae in winter.

Lepak et al. (2022) studied lake trout (*Salvelinus namaycush*) and sockeye salmon (*Oncorhynchus nerka*) from 13 remote lakes in Lake Clark and Katmai National Parks in southwestern Alaska. Mercury isotopes were used to assess the importance of atmospheric deposition from volcanic activity and the influence of migrating oceanic sockeye salmon, which spawn and subsequently die in the lakes, on the lake trout Hg burden. Fish $\Delta^{199}\text{Hg}$ values varied significantly between the lakes, reflecting differences in site-specific photochemical demethylation. Since photochemical demethylation also results in MDF, the authors applied a method to correct for its effects on $\delta^{202}\text{Hg}$ and then used the corrected $\delta^{202}\text{Hg}$ to differentiate between two possible

Hg sources (volcanic versus migratory salmon) in the lake trout. Consistently lower corrected $\delta^{202}\text{Hg}$ values were observed in lake trout from lakes near volcanoes, known to produce Hg emission with low $\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$, showing that volcanic Hg is likely an important additional source to lake trout in the proximate lakes. The isotope values of the migratory sockeye salmon did not overlap with those in the lake trout, indicating that the salmon were not an important dietary Hg source to the lake trout. However, indirect inputs via decay and subsequent ecosystem uptake of Hg were not ruled out.

Lim et al. (2024) studied zooplankton and Arctic cod (*Boreogadus saida*), and several abiotic matrices in the Bering Strait, Chukchi Sea and the Beaufort Sea, including the Mackenzie River Estuary. The study found near-zero $\Delta^{200}\text{Hg}$ in zooplankton and Arctic cod, consistent with mostly atmospheric Hg(0) deposition but positive $\Delta^{200}\text{Hg}$ in seawater, reflecting atmospheric Hg(II) deposition. As no known environmental process affect $\Delta^{200}\text{Hg}$ values after atmospheric deposition (Cai and Chen 2016), the bioavailable Hg pools in seawater may have originated from near-surface Hg(0) oxidation supplied from terrestrial vegetation, coastally evaded halogens, and sea salt aerosols.

Chételat et al. (2024) studied common eider (*Somateria mollissima*) in eastern Hudson Bay and eastern James Bay, Canada. Eiders from Chisasibi in James Bay had significantly higher total Hg and $\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$ values than eiders from four other communities, indicating different Hg sources or exposure pathways. The Hg isotopes in eiders from Chisasibi showed higher photodegradation of MeHg, indicating Hg of freshwater origin and suggesting that elevated Hg in the coastal food web of eastern James Bay was likely due to Hg loading from hydro development on the La Grande River.

Charrier et al. (2024) studied different egg compartments (albumen, yolk, membrane, and shell) from the common eider, black-legged kittiwake (*Rissa tridactyla*), and the little auk in East Greenland. Total Hg and $\delta^{202}\text{Hg}$ were higher in the most protein-rich egg compartments, albumen and membrane, suggesting possible fractionation within the eggs during formation. Similar $\Delta^{199}\text{Hg}$ values were observed in eggs from all three species, indicating a similar MeHg source and no fractionation of this Hg isotope.

Søndergaard et al. (2025) compared muscle tissue from shorthorn sculpin (*Myoxocephalus scorpius*) and ringed seal (*Pusa hispida*) across three regions in Greenland to evaluate Hg sources. In addition, peat profiles from the same regions were included. There was consistently higher $\delta^{202}\text{Hg}$ (by ~0.5‰) in Central West Greenland compared to northern-eastern Greenland for both peat (mainly influenced by atmospheric Hg(0) uptake) and marine species (mainly influenced by marine MeHg uptake), suggesting an overall difference in Hg source inputs between the regions. The regional differences in Greenland could not be explained by the modelling results for atmospheric Hg deposition, but they correlated well with the influence of ocean currents from the Arctic and Atlantic Oceans, respectively. Consequently, the authors proposed that ocean currents carrying large inventories of legacy Hg may be the main driver of Hg uptake in marine and coastal environments in Greenland. This work is currently being followed up with more species and matrices in Greenland and other Arctic regions.

4.4 Metabolic influences on the internal distribution of Hg isotopes in biota

In vivo Hg stable isotope analysis is increasingly carried out in marine organisms to study the dynamics of Hg transfer within food webs. The MDF of $\delta^{202}\text{Hg}$ has been widely observed in both abiotic and biotic processes, including methylation, demethylation, and species-specific metabolic transformations. As a result, $\delta^{202}\text{Hg}$ values vary widely across aquatic ecosystems (ranging from -3 to 2‰), making their interpretation difficult. Few studies have focused on understanding *in vivo* Hg fractionation dynamics, linking these processes mostly to factors such as tissue biochemical composition and metabolic rates, species-specific trophic ecology, and organism age (Li et al. 2022). Mass independent fractionation of Hg isotopes is not influenced by organism metabolism and does not change during trophic transfer within a food web.

Liver is a tissue where *in vivo* demethylation occurs and isotopically lighter MeHg is preferentially demethylated, resulting in newly formed inorganic Hg characterized by lower $\delta^{202}\text{Hg}$ values, which then bind with selenium (Se) and precipitate as inert inorganic Hg-selenide crystals (tiemannite). As a result, tissues dominated by MeHg consistently display higher $\delta^{202}\text{Hg}$ values, whereas tissues rich in inorganic Hg, such as the liver and kidney, exhibit lower $\delta^{202}\text{Hg}$ (Bolea-Fernandez et al. 2019).

Perrot et al. (2016) conducted a compound-specific analysis of Hg stable isotopes in beluga (*Delphinapterus leucas*) liver and multiple tissues of Baikal seals (*Pusa sibirica*) and showed that MeHg was enriched in heavy isotopes ($\delta^{202}\text{Hg}$ up to +2.5‰) relative to inorganic Hg ($\delta^{202}\text{Hg}$ down to -1.2‰), pointing to kinetic fractionation during demethylation. Similarly, Masbou et al. (2018) found that in belugas and polar bears from Alaska, liver $\delta^{202}\text{Hg}$ values were lower than muscle values, again supporting *in vivo* MeHg demethylation.

Li et al. (2020) showed that in long-finned pilot whales (*Globicephala melas*), muscle and heart tissues displayed elevated $\delta^{202}\text{Hg}$ values, consistent with the accumulation of residual MeHg that has escaped demethylation. In contrast, liver and kidney tissues, which are central to Hg detoxification and elimination, had lower $\delta^{202}\text{Hg}$ values due to the accumulation of demethylated inorganic Hg. In the same study, $\delta^{202}\text{Hg}$ values measured in the brains of pilot whales reflected mixing between enriched MeHg (+1.4‰) and depleted inorganic Hg (-1.6‰), indicating that MeHg *in vivo* demethylation could also occur in that tissue.

Pinzone et al. (2024) measured MDF and MIF dynamics in hooded seals fed a controlled diet and, therefore, a controlled intake of MeHg and iHg, for two years. They confirmed a positive correlation between $\delta^{202}\text{Hg}$ values and the proportion of MeHg in tissues. Tissues dominated by MeHg, such as hair and muscle, consistently displayed higher $\delta^{202}\text{Hg}$ values, whereas tissues rich in iHg, such as the liver and kidney, exhibited lower $\delta^{202}\text{Hg}$ values. However, in this study, the kidney was found to be significantly lower in $\delta^{202}\text{Hg}$ compared to the liver, again suggesting that *in vivo* MeHg demethylation is not the only process affecting MDF and $\delta^{202}\text{Hg}$ values. This finding was supported by studies on seabirds, where the proportions of different organic pools were shown to strongly affect $\delta^{202}\text{Hg}$ values between tissues (Li et al. 2022).

Li et al. (2020) examined age-specific patterns of internal Hg isotope distribution in pilot whales. They found juvenile pilot whales had higher $\delta^{202}\text{Hg}$ values in brain and liver tissues than adults, reflecting a larger contribution of isotopically enriched dietary MeHg. In juveniles, $\delta^{202}\text{Hg}$ decreased with increasing Hg exposure, consistent with preferential demethylation of lighter isotopes and progressive accumulation of isotopically depleted Hg(II). In contrast, adult whales displayed an opposite trend, with $\delta^{202}\text{Hg}$ values increasing with Hg burden in the liver. The authors attributed this trend to the selective export of isotopically light, labile Hg(II) and retention of heavier HgSe-bound Hg. These results indicate that MeHg demethylation dominates Hg isotope behaviour in juveniles, whereas in adults, Hg redistribution and Se-mediated immobilization increasingly control $\delta^{202}\text{Hg}$ variability.

Overall, isotopic analyses of Hg in organism tissues have revealed that Hg metabolism, previously thought to occur primarily in the liver, may also take place in other tissues, such as the brain. At the same time, large MDF was also linked to other processes beyond MeHg demethylation, such as inorganic Hg precipitation and mineralization, as well as tissue-specific differences in the bioaccumulation of inorganic Hg pools. Understanding the dynamics of Hg *in vivo* is essential for using Hg isotopes to trace food web exposure pathways in the Arctic.

4.5 The importance of tissue selection

Interpreting $\delta^{202}\text{Hg}$ values in Arctic wildlife requires an understanding of how Hg is transformed and retained in different tissues. Each tissue displays unique metabolic turnover rates and varying affinities for MeHg or inorganic Hg, which affect both the half-life of Hg within the tissue and the $\delta^{202}\text{Hg}$ composition retained. The MDF shifts observed between tissues, such as from -0.78‰ in the kidney to +0.80‰ in the hair of hooded seals (Pinzone et al. 2024), correlate with tissue-specific speciation including bioaccumulation of different Hg pools and metabolic transformations. Tissue selection can strongly influence isotopic patterns and inferences. Comparing $\delta^{202}\text{Hg}$ values across studies requires consistent sampling of the same tissue (e.g., fish muscle, marine mammal hair) to ensure that observed differences arise from environmental variation rather than tissue-specific biochemical effects. Additionally, the selection of a particular tissue over another must correspond to the specific scientific question of the study.

These species-specific examples reinforce the importance of matching tissue selection to research objectives. Tissues with slow turnover and minimal demethylation, such as muscle, hair, and feathers, are best suited for tracing environmental Hg sources using $\delta^{202}\text{Hg}$. In contrast, the liver and kidney are informative for studying detoxification and internal cycling but require cautious interpretation due to isotope fractionation during biotransformation. To ensure comparability across studies, standardized tissue selection is essential for robust spatial, temporal, and interspecific assessments of Hg exposure in Arctic biota.

4.6 Temporal trends in biota

Few studies have evaluated temporal trends of Hg isotopes in Arctic biota. Masbou et al. (2015) evaluated temporal trends in ringed seals collected at Point Barrow and Nome, Alaska between 1988-2002. Values of $\Delta^{199}\text{Hg}$ significantly increased by $\sim 0.2\text{‰}$ in ringed seal liver from Point Barrow during the study period, suggested to be related to the progressive disappearance of summer sea ice.

Søndergaard et al. (2025) evaluated temporal trends in Greenland biota using ringed seal and polar bears samples collected between 1983 and 2024. The authors found a significant increase in $\delta^{202}\text{Hg}$ in ringed seals in Northwest Greenland ($\sim 0.5\text{‰}$) and polar bears from Central East Greenland ($\sim 1.7\text{‰}$) over the past 40 years. No significant changes in $\delta^{202}\text{Hg}$ were found in any of the Greenland time series. The increase in $\delta^{202}\text{Hg}$ can be caused by changes in diet and metabolism as well as Hg sources and transformation processes in the environment. The large increase observed in $\delta^{202}\text{Hg}$ for East Greenland polar bears is considered to be mainly influenced by changes in diet, shifting from mostly feeding on ringed seals in the 1980s towards more harp seals and hooded seals in recent years, the latter prey having higher $\delta^{202}\text{Hg}$ in their tissues. However, this may not explain the entire increase in $\delta^{202}\text{Hg}$. The observed trend towards generally higher $\delta^{202}\text{Hg}$ in both ringed seals and polar bears in Greenland during the last four decades is consistent with long-term isotopic trends observed in Hg deposition globally caused by greater contributions of anthropogenic Hg (Sun et al. 2016; Lee, Kwon, Yin, et al. 2021). Søndergaard et al. (2025) found evidence that ocean currents are now possibly the dominant Hg pathway to Greenland marine ecosystems, and the large inventories of legacy Hg in the oceans may thus result in a long response time from anthropogenic release to uptake in the Arctic food web. Alternatively, the trend may reflect changes in environmental transformation processes affecting the $\delta^{202}\text{Hg}$ values of MeHg taken up in the food web (Blum et al. 2014; Tsui et al. 2020).

While the study region was located outside the Arctic, Chételat et al. (2026) demonstrated the utility of temporal trends in biotic Hg isotopes to evaluate the transport pathways and sources of Hg in food webs downstream of large boreal river in northern Canada. Mixing model estimates derived from Hg isotopes indicated that the river was the source of $\sim 50\text{-}90\%$ of the Hg burdens in tern eggs from two lake sites that received river inflow. A time series of Hg isotope measurements between 2009 to 2022 showed that in years where tern eggs had higher Hg concentrations, there was a higher proportion of Hg that originated from the river inflow. Mercury isotope data from potential abiotic sources within the river basin suggested a predominately terrestrial origin of Hg bioaccumulated in the tern eggs.

These studies highlight the potential of temporal datasets of Hg isotopes in Arctic biota to provide new information on the sources, transport and food web exposure of Hg. Many Arctic national monitoring programs have specimen bank archives of Arctic fish and wildlife tissues that could be used to measure multi-decadal time series of Hg isotopes in key bioindicator species.

5. How can mercury isotopes be used for human biomonitoring of mercury exposure?

5.1 Human biomonitoring

Mercury human biomonitoring is well established and practiced by several countries, organizations, and researchers for scientific and regulatory purposes (WHO 2018; UNEP 2019). Such biomonitoring has been conducted in the Arctic for decades by circumpolar nations as well as through AMAP programs (AMAP 2021a). Human exposures to Hg can be gauged by understanding source-exposure routes and by measurement of the chemical in biological samples. The broad conclusion remains that human exposures to Hg (MeHg, in particular) among Arctic Indigenous Peoples (largely Inuit) are amongst the highest in the world (Basu et al. 2018).

In most population groups worldwide, exposure to elemental and inorganic Hg may occur in occupational settings and from contact with certain products (Ha et al. 2017; Basu et al. 2023; ATSDR 2024), though these are not as relevant in the Arctic. In the Arctic, exposures to inorganic Hg may be high amongst individuals who consume whale and seal liver or kidney. However, for most Arctic populations, exposures to Hg are largely in the organic form (MeHg), arising from dietary sources, including meat from fish and marine mammals.

Human exposure to Hg is commonly assessed by measuring its concentration in biological samples, with hair, urine, and blood (including cord blood) being the most widely used (Basu et al. 2018). Urine analysis primarily reflects recent exposure within approximately 1–2 months to inorganic and elemental Hg; however, in individuals with high seafood intake, MeHg can also contribute to Hg levels in urine. Mercury in whole blood provides information about recent exposure (about 1–2 months) to both MeHg and inorganic Hg, and many biomonitoring programs focus on blood measurements. Blood collection is invasive, and its storage and transport can present logistical and financial challenges, particularly in resource-limited settings such as the Arctic. Hair analysis for total Hg is frequently used to evaluate MeHg exposure in humans, which typically accounts for 80–90% of the total Hg present in hair (Basu et al. 2018). Hair sampling offers advantages such as ease of collection, transport, and storage, but cultural objections in some population groups and short hair length may limit its feasibility. Importantly, a careful hair sampling method must be used remembering that the near scalp 0.5–1 cm represents recent exposure 1–3 weeks to a month prior and distance from scalp reflects progressively older exposures.

5.2 Mercury stable isotopes in key sources and human biomarkers of exposure

Dietary intake is the major route of MeHg exposure for human populations, who regularly consume fisheries products, rice, and vegetables grown in Hg contaminated regions (Sunderland 2007; Feng et al. 2008; Du et al. 2018; Sunderland et al. 2018).

People who have dental fillings made from Hg amalgam or who live or work in Hg-contaminated places may also be exposed to significant amounts of inorganic Hg (Li et al. 2008; Laffont et al. 2011; Sherman et al. 2013; Du et al. 2021). Although it is not fully understood how Hg moves through the entire human body, current studies suggest that humans may process Hg in similar ways to marine mammals. For example, HgSe granules, a known demethylation product in marine species, have been identified in the human brain following MeHg poisoning using synchrotron X-ray absorption spectroscopy (Korbas et al. 2010). Likewise, several laboratory studies provide evidence that MeHg can be transformed into inorganic Hg in human brain and liver cells — a metabolic pathway that closely mirrors what has been observed in marine mammals (Nagano et al. 2010; Mailloux et al. 2015).

The application of Hg isotopes to human biomarkers of exposure such as hair and urine has shown strong potential for identifying dietary exposure sources and internal metabolic processes. As in other biological systems, MIF observed in humans originates from MeHg photodegradation in the environment, rather than from human metabolism (Li et al. 2014). The $\Delta^{199}\text{Hg}$ values in both hair and urine consistently differentiate exposure types: individuals with higher $\Delta^{199}\text{Hg}$ values (dark blue symbols in Fig. 5.1) are typically fish consumers, whereas those exposed predominantly to inorganic Hg—from rice ingestion or elemental Hg during gold mining—show near-zero $\Delta^{199}\text{Hg}$ (green and gray symbols in Fig. 5.1) (Li et al.

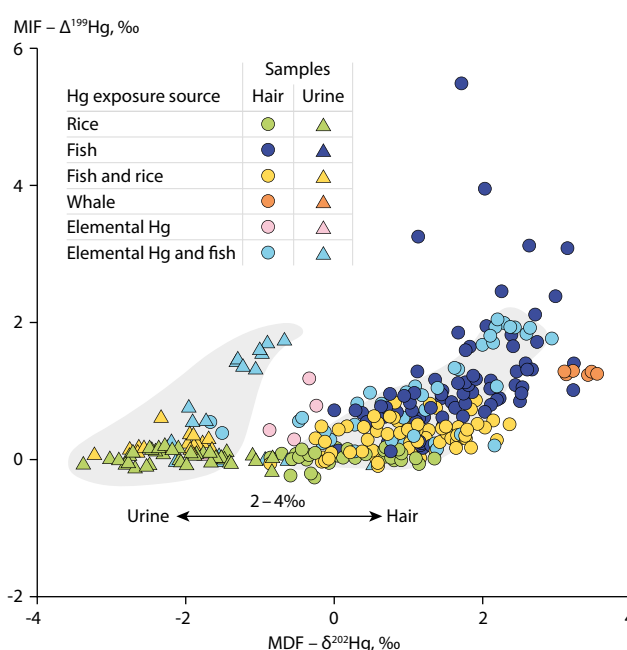


Figure 5.1. Mercury isotope ratios of hair and urine samples from human populations exposed to different Hg sources based on the compiled data of previous studies. The gray shades signify the approximate Hg isotope range of urine and hair samples of individuals who obtain Hg from different sources, specifically rice, fish, fish and rice, elemental Hg or elemental Hg and fish. Note: the Hg exposure source category “rice” includes local rice, vegetables, and soil. Source: Li et al. (2022).

2022). In addition, the $\Delta^{199}\text{Hg}$ value in hair serves as a robust tracer for distinguishing among Hg sources based on ecological characteristics of consumed seafood—such as inshore versus offshore habitats and foraging depths, including surface-feeding versus deeper-water fishes and marine mammals (Senn et al. 2010; Li et al. 2014; Li, von Stackelberg, et al. 2016).

The MDF between human biomarkers and dietary MeHg sources is well documented and is attributed to *in vivo* demethylation. Like marine mammals, the human body preferentially breaks down MeHg containing lighter Hg isotopes, resulting in residual MeHg enriched in heavier isotopes and inorganic Hg with lower $\delta^{202}\text{Hg}$ values than MeHg. Since urine is the main excretion route for inorganic Hg (Clarkson and Magos 2006; Beasley et al. 2014), it typically shows lower $\delta^{202}\text{Hg}$ values (triangles in Fig. 5.1), while the remaining MeHg pool becomes enriched in heavier isotopes, as seen in higher $\delta^{202}\text{Hg}$ values in hair (circles in Fig. 5.1). Human metabolism can increase hair $\delta^{202}\text{Hg}$ by 2–3‰ compared to the $\delta^{202}\text{Hg}$ values found in muscle tissues of consumed seafood (Laffont et al. 2009; Sherman et al. 2013; Li et al. 2014; Bonsignore et al. 2015; Li, von Stackelberg, et al. 2016). Additionally, an average offset of about 1‰ has been observed between inorganic Hg in urine and MeHg from dietary sources, reflecting isotopic changes during demethylation (Sherman et al. 2013).

Human populations exposed to both inorganic Hg and MeHg tend to show a wider range of $\delta^{202}\text{Hg}$ values in hair compared to populations with more limited or single-source exposures. This broader variation is largely explained by differences in the proportion of inorganic Hg exposure, which strongly influences $\delta^{202}\text{Hg}$ values across biomarkers of exposure (Laffont et al. 2011; Rothenberg et al. 2017). As a result, $\delta^{202}\text{Hg}$ values are useful not only for tracking metabolic fractionation, but also for distinguishing between dietary sources of Hg. Several studies have applied isotope-based mixing models to estimate the relative contributions of various sources—such as rice, fish, and elemental Hg from artisanal gold mining. These models provide a valuable complement to traditional dietary exposure assessments, which often rely on self-reported dietary recall—a method known to introduce recall bias and uncertainty (Laffont et al. 2011; Li, von Stackelberg, et al. 2016; Rothenberg et al. 2017).

5.3 Arctic-relevant examples of human biomonitoring for mercury exposure

While examples of Hg stable isotope applications are limited for human biomonitoring studies in the Arctic, initial investigations outlined below indicate that this isotopic tool holds strong potential for identifying human Hg exposure sources in northern environments.

Mercury isotope compositions in fish and marine mammals can effectively reveal their habitat use and dietary sources, which in turn have relevance for human exposure. For instance, in the subarctic estuary of Lake Melville, Hg isotopes distinguish estuarine fish from those in the offshore Atlantic Ocean. Marine species like Atlantic salmon and Atlantic cod show distinct isotope profiles compared to freshwater species, such as northern pike and longnose sucker (Li, Schartup, et al. 2016).

In the Arctic, ongoing research in the northern Bering Sea and Beaufort Sea demonstrates that Hg isotopes can differentiate ecological niches, such as surface versus deep foraging, and even distinguish between biota like fish and beluga whales. These findings highlight the strong potential of Hg isotope tracers to improve source attribution in human biomonitoring, especially in Arctic and subarctic populations for whom seafood is a major source of Hg exposure (AMAP 2021a). Ultimately, such knowledge may help improve the ability to conduct Hg exposure assessments in regions like the Arctic.

This potential is further supported by Li et al. (2014), who characterized Hg isotope fractionation between human hair and diet using samples from Faroese whalers exposed to MeHg mainly from pilot whales. There was an enrichment of ~2‰ in $\delta^{202}\text{Hg}$ values between pilot whale muscle and human hair, while $\Delta^{199}\text{Hg}$ values remained unchanged. Similar offsets have been observed in other populations and are likely applicable to Arctic Indigenous Peoples, as well as strengthening the case for using Hg isotopes as tracers of dietary Hg exposure in Arctic human biomonitoring efforts.

6. What knowledge gaps and other challenges need to be considered for mercury isotope applications in AMAP monitoring?

Through this scoping initiative, published studies were reviewed for Hg isotope measurements in the Arctic. The compilation of Arctic Hg isotope data provided an accounting of available information and data gaps for future research and monitoring. In addition, the state of the science on laboratory analyses of Hg isotopes and on environmental and human health applications was considered to identify opportunities and difficulties for incorporating this tracer into AMAP monitoring. A summary of knowledge gaps and challenges is provided below, while opportunities and recommendations are presented in Section 7.

6.1 Available mercury isotope data for Arctic environmental matrices and biota

Some Hg isotope data are currently available for several environmental matrices in the Arctic, including sediment, soil, bedrock, seawater, fresh water, air, snow, and ice (Section 3, Fig. 3.1). These Arctic studies provide examples demonstrating how Hg isotopes can be used to inform biogeochemical models about net fluxes that would otherwise be difficult to constrain with other scientific methods. While currently limited, the geographical coverage of data for compartments such as soils and sediments will likely improve significantly in the coming decade as these matrices are easier to measure for Hg isotope composition, and samples are available in archives. Better coverage of these compartments will help with interpreting the isotopic compositions of terrestrial endmembers and with quantifying Hg exported to aquatic systems. Important endmembers for which data are currently lacking or very scarce include bedrock, coastal erosion sites, permafrost soils, and melting glaciers. Due to the low concentrations of Hg in ice and water compared to soils and sediments, and challenges related to contamination issues during sampling and storage, as well as challenges with concentrating Hg from these samples with a high degree of recovery, the geographical coverage of those matrices is likely to remain sparse.

Over the last two decades, considerable Hg isotope data were generated in Arctic biota with a particular emphasis on marine fish and wildlife (Section 4, Fig. 4.1), as well as terrestrial vegetation, specifically lichens and mosses (Section 3, Fig. 3.1). Those studies provide important information on the dispersion and central tendencies of Hg isotope values in Arctic food webs. One factor that limits the utility of previous data for comparison with future studies is the wide range of tissue types analyzed in biota. The variety of tissues analyzed for Hg isotopes includes eggs, blood and feathers for seabirds, and liver, muscle, kidney and hair for marine mammals. The exposure time represented by the bioaccumulated Hg varies among tissue types (e.g., blood versus feathers), and the percent composition of inorganic Hg and MeHg also varies (e.g., liver versus muscle) (Chételat et al. 2020). Likewise, biological metabolism and sequestration within vertebrate animals result in Hg isotope fractionation between tissues, which can complicate interpretation (Li et al.

2022). Another limiting factor of currently available Hg isotope data is the modest geographic coverage of biotic measurements across the circumpolar Arctic. The degree of spatial variation in Hg isotopes for a given species remains unclear, and geographic or temporal variation in processes could confound the data interpretation in the absence of site-specific measurements.

6.2 Tracing of anthropogenic mercury sources

The development of Hg isotope applications has generated widespread interest in the use of this tracer for distinguishing industrial from natural sources of Hg in the environment (Kwon et al. 2020; Tsui et al. 2020; Zhang and Sun 2026). In the context of the Arctic, the use of Hg isotopes for identifying sources, particularly human sources of Hg emissions, is not currently feasible for Hg transported over long distances through the atmosphere or ocean currents. Several obstacles include overlap of isotopic compositions of anthropogenic and natural Hg sources, complex isotopic fractionation during biogeochemical cycling, and mixing of multiple sources in the Hg pool with increasing distance from emission sources (Sun et al. 2014; Sherman et al. 2015; Zhang and Sun 2026). Mercury isotopes could be useful for source attribution in the case of local point-source pollution, where a clear isotopic signal can be measured (Wiederhold et al. 2013; Demers et al. 2018). However, since most Hg contamination within the Arctic originates from emission sources outside the Arctic (AMAP 2021a), the opportunity for tracing local point-sources using Hg isotopes is limited.

6.3 Laboratory and analytical considerations

6.3.1 Technical expertise

The measurement of Hg stable isotopes remains a highly specialized analytical technique, and there are few laboratories around the world with the expertise and capacity to conduct this kind of work. A compilation of known laboratories (Appendix 1) suggests there are possibly less than 15 established around the world, though the list is not exhaustive and may increase in the future. Many of the existing laboratories are in academic institutions, where project priorities may differ from those of AMAP monitoring activities and high-throughput of externally submitted samples is limited. There are also matrix-specific methods for extraction and purification of Hg from samples prior to analytical detection (e.g., for air, seawater, coal) that may only be performed in a subset of laboratories. Information on the cost per sample for Hg isotope analysis is not widely available and likely varies, though clearly the costs are hundreds of Euros or US dollars per measurement and hence by far more expensive than total Hg analyses. Together, these

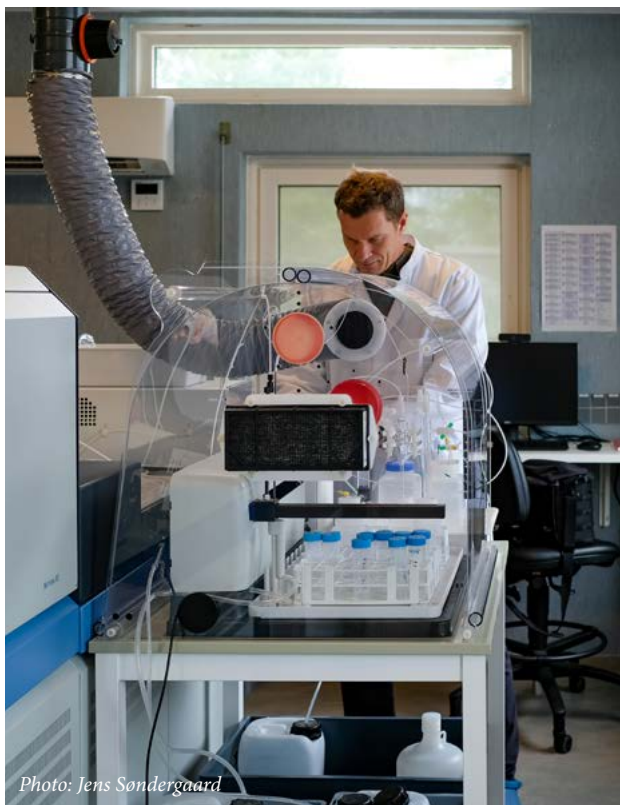


Photo: Jens Søndergaard

factors limit the degree to which Hg isotope measurements could be incorporated into AMAP monitoring activities, and routine measurements within monitoring programs are not recommended. Rather, a focused, prioritized strategy, potentially as collaborative programs between Arctic countries, is needed to harness this powerful tool for generating policy-relevant science on Hg in the Arctic.

6.3.2 Compound-specific isotope analysis of methylmercury

Progress in the application of Hg stable isotopes in the Arctic will, among other things, depend on moving beyond bulk analyses toward compound-specific isotope analysis (CSIA). Bulk $\delta^{202}\text{Hg}$ values integrate processes acting on both inorganic Hg and MeHg, whereas CSIA can distinguish their respective isotope fractionation pathways by measuring the Hg isotope values of only MeHg (Masbou et al. 2025).

Methods for the CSIA measurement of MeHg in abiotic matrices are in an early stage of development with few published data currently available (Rosera et al. 2020; Zhang et al. 2022). More research is needed before CSIA methods for abiotic matrices are available for Arctic studies. Nonetheless, more progress has been made with CSIA methods for biotic matrices (Rosera et al. 2022; Crowther et al. 2023; Masbou et al. 2025). For food webs, the distinction between inorganic Hg and MeHg is critical because bulk isotope values cannot be interpreted uniformly across trophic levels. In lower-trophic organisms, such as zooplankton, a substantial fraction of Hg may remain in inorganic form, meaning that $\delta^{202}\text{Hg}$ values primarily reflect environmental inputs and transformations of iHg. In contrast, in higher trophic-level predators, priority is given to matrices where Hg is almost exclusively present as MeHg like muscle, hair and blood and where isotopic signals largely

trace the pathways and transformations of MeHg along the food chain. Without CSIA, these contrasting controls cannot be disentangled across species and trophic levels.

Another key challenge is the limited understanding of how the molecular composition of tissues drives isotopic fractionation in vertebrate animals. In bird liver, complexation of MeHg with selenocysteine residues induces a measurable kinetic isotope effect (Poulin et al. 2021). Complementary work has shown that $\delta^{202}\text{Hg}$ differences among tissues may also reflect binding to selenoproteins in addition to MeHg demethylation (Li et al. 2022). In marine mammals and fishes, however, the identity and abundance of Hg-binding ligands, such as selenoproteins, metallothioneins, and heme proteins, remain poorly characterized, limiting the interpretation of tissue-specific $\delta^{202}\text{Hg}$ patterns. Addressing these gaps through integrated CSIA and Hg–Se speciation approaches will be crucial to disentangle the relative contributions of demethylation, ligand complexation, and redistribution processes in shaping isotope compositions in Arctic food webs.

6.6.3 Mercury isotope analysis of low-mercury content samples

Abiotic samples with low Hg content remain an analytical challenge for Hg isotope measurements (Sun et al. 2025). Specialized laboratory methods for pre-concentration of low Hg matrices, such as water, ice and snow, require thorough validation and quality control to minimize method effects on accuracy and precision (Blum and Johnson 2017). Likewise, methodological constraints continue to hinder the application of CSIA of MeHg in monitoring Arctic wildlife. Keratin (hair, feathers), teeth, chitin-rich exoskeletons (krill, shrimp), and siliceous organisms (diatoms) are ecologically important matrices that pose significant analytical challenges due to low Hg recoveries, risks of MeHg - inorganic Hg interconversion, and levels of Hg too low for high precision isotopic measurements. Advances in preconcentration strategies and instrumental interfaces such as dry cold-vapor generation and combustion MC-ICP-MS, together with inter-laboratory validation at sub-ng Hg levels, are essential to extend CSIA to these matrices (Masbou et al. 2025).

7. What are opportunities for incorporating mercury isotopes in AMAP monitoring?

Mercury isotopes have the potential to provide important new insights into the Hg cycle. A prioritized strategy is outlined below to harness this powerful tool for generating policy-relevant science on Hg in the Arctic.

7.1 Laboratory quality assurance and quality control

A critical component of AMAP reporting is the quality assurance and quality control of contaminant data used in monitoring agencies of circumpolar Arctic countries and observer countries. Interlaboratory studies are routinely performed (typically on an annual basis) to evaluate the proficiency of AMAP-associated laboratories to conduct quality analytical measurements of contaminants, with the broader goal of ensuring accurate and precise results across monitoring programs. Comparability of high-quality data is a fundamental cornerstone for AMAP science assessment and reporting. Within the context of Hg stable isotopes, efforts will be required to ensure consistent measurements among laboratories analyzing Arctic samples. This will likely include interlaboratory comparisons of Hg isotope measurements on the same samples and reporting of agreed-upon certified reference materials. Other guidelines may be needed for quality control of Hg isotope data used in AMAP activities.

7.2 Identify key transport processes of mercury to and within the Arctic

7.2.1 Atmospheric delivery of mercury to Arctic environments

Measurements of Hg isotopes in air may provide new valuable information on pathways and processes in the transport of Hg from southern emission sources to the Arctic atmosphere and its subsequent deposition. In a recent comprehensive review of methods and theoretical knowledge on atmospheric Hg processes, Sommar et al. (2025) concluded that Hg species in air (GEM, GOM, PHg) are isotopically separated and their measurement can thus be used for a better understanding of processes, including air-water and air-cryosphere exchanges within the Arctic (Araujo et al. 2022). Outside the Arctic, inclusion of Hg isotope fractionation in key chemical transformations in atmospheric transport models has been used to constrain the net flux of Hg to the ocean (Song et al. 2025). Future isotope studies are recommended in conjunction with atmospheric measurements examining Hg(0), Hg(II) and PHg and using atmospheric or multi-media modelling, with the capacity to include isotope fractionation in transformation processes. In this way, observed Hg isotope fractionation in the Arctic within atmospheric processes and deposition monitoring may provide new insights into the fate of atmospheric Hg.

7.2.2 Role of ocean currents, large rivers and atmospheric deposition as dominant transport pathways for mercury supply to the Arctic Ocean

Recent findings using Hg isotopes as a tracer in the European Arctic revealed that ocean currents are carrying large inventories of legacy Hg, which may be the dominant pathway driving present Hg uptake in Arctic marine and coastal areas. Regional differences in Hg isotopes in muscle tissue of shorthorn sculpin, ringed seal and peat bog profiles from Greenland hence correlated well with the influence of ocean currents from the Arctic Ocean and Atlantic Ocean, respectively (Søndergaard et al. 2025). Consequently, the authors proposed that ocean currents carrying large inventories of legacy Hg may be the main driver of Hg uptake in marine and coastal environments in Greenland, either through direct uptake of Hg from ocean waters or through Hg evasion from the ocean surface followed by atmospheric redeposition and uptake. This explains the discrepancy between decreasing atmospheric Hg deposition in the Arctic over recent decades due to reduced global anthropogenic emissions, and the lack of response or increases in Hg-trends in many Arctic species. This delay in many marine species therefore has major implications for the effectiveness evaluation of the Minamata Convention (Søndergaard et al. 2025). These studies are currently being expanded under the GreenPath programme (Aarhus University 2024) with polar bear hair and muscle, ringed seal muscle, Arctic char muscle and human hair samples across a large part of the Arctic being analyzed to verify the Søndergaard et al. (2025) results. In the Beaufort Sea, Hg isotopes suggested terrestrial vegetation, coastally evaded halogens, and sea salt aerosols could be important sources of Hg to biota in this river-influenced region of the Arctic Ocean (Lim et al. 2024). Likewise, in shallow coastal areas, large river inputs of Hg may be important near shore (Chételat et al. 2024). Thus, the relative contributions of Hg transport pathways to the Arctic Ocean should be examined within a regional environmental context.

7.2.3 Role of permafrost thaw on mercury transport to downstream freshwater systems

Recent estimates show that permafrost regions are a dominant reservoir of the Earth's global soil Hg pool (Schuster et al. 2018; Lim et al. 2020), and some studies from Arctic Canada and Alaska describe elevated Hg fluxes in rivers attributed to permafrost and glacier ice thawing (Vermilyea et al. 2017; St. Pierre et al. 2018; Martins, Hintelmann, Pilote, Vieira, et al. 2025). Limited research has been conducted on impacts of permafrost thaw on Hg transport and bioaccumulation in downstream receiving environments and, to date, no studies have included Hg isotopes as a tracer. Future studies are needed to determine if there are broad differences in $\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$ in active layers and upper permafrost in the Arctic, which could be used to trace the transport and fate of Hg released from permafrost thaw.

7.3 Identify key exposure pathways of mercury to wildlife and humans

7.3.1 Foraging habitat and diet pathways leading to mercury exposure in top predator fish and wildlife.

A demonstrated application of Hg isotopes is for identifying dietary pathways and foraging habitats that lead to elevated Hg exposure in top predator fish and wildlife (Madigan et al. 2018; Masbou et al. 2018; Besnard et al. 2021; Besnard et al. 2025). Mercury isotope analysis is complementary to more traditional food web tracers (i.e. stable isotopes of carbon, nitrogen and sulfur) by expanding isotopic separation among biota and by providing additional information on Hg biogeochemical processes, such as photodemethylation and atmospheric deposition. Within the Arctic, alternate foraging strategies and differences in food web structure can strongly influence Hg bioaccumulation in fish and wildlife (McKinney et al. 2017; Treu et al. 2018; Hilgendag et al. 2022; McKinney et al. 2022; Roffler et al. 2025). Thus, Hg isotopes are recommended to identify drivers of regional variation in Hg concentrations of key top predators within the Arctic.

7.3.2 Expand isotopic characterization of traditional foods

A critical next step for advancing Hg isotope applications in Arctic human biomonitoring is the development of isotopic baselines for traditional foods commonly consumed by Indigenous Peoples. Currently, there is a lack of $\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$ data for key marine-based dietary sources, such as marine mammals (e.g., seals, whales), fishes (both marine and freshwater), and seabirds. These species vary widely in geographic locations, foraging depth, and ecological niche factors, all of which can influence their Hg isotope composition. Without isotopic data on these culturally and nutritionally significant foods, it is difficult to link biomarker Hg isotope signals in humans to specific dietary sources. Future research should prioritize building comprehensive isotope libraries of traditional Arctic foods across regions to support accurate exposure source attribution.

7.3.3 Mercury isotope pilot study linking diet and human exposure

To date, no $\delta^{202}\text{Hg}$ or $\Delta^{199}\text{Hg}$ values have been reported for Arctic Indigenous Peoples, limiting the application of Hg isotope tracers in human exposure assessments. Establishing baseline isotopic values in human biomarkers is essential for interpreting biomonitoring data in the context of local diets, country foods, and environmental exposures. Given the long-standing consumption of traditional marine foods and potential genetic variation in Hg metabolism, Arctic populations may exhibit unique isotope fractionation patterns. Developing these baselines is critical for understanding exposure pathways and for applying isotopic tools effectively in Arctic human health research.

To directly link dietary Hg sources to human exposure, a paired food–human biomarker isotope study in an Arctic

Indigenous community would be a critical step forward. This pilot study should focus on a community with an important traditional marine-based diet, where species such as fishes, seals, whales, and seabirds form a major part of food intake and comparisons could be made with store-bought foods. By collecting and analyzing both food samples and matched human biomarkers (e.g., hair, blood, urine) along with detailed food frequency survey information, researchers can assess how dietary $\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$ values are reflected in human tissues and the validity of survey tools. This approach will provide essential calibration for interpreting Hg isotope signals in Arctic humans, validate ecological source attribution models and food frequency questionnaires, and serve as a template for broader community-based monitoring programs.

7.4 Monitor change in environmental mercury isotopes

Temporal trends of Hg isotopes in environmental archives and in biota are priorities for future study to provide new information on changes to Hg sources and exposure pathways in the Arctic. Environmental archives, such as ice, sediment and peat cores, which represent historical accumulation of Hg over time, have the potential to provide new information on trends in anthropogenic contributions to Arctic Hg as interpreted by shifts in MDF of Hg (Zdanowicz et al. 2016; Štok et al. 2019; Søndergaard et al. 2025). While attribution to specific sources is not currently possible, shifts in MDF of Hg towards more positive values have been attributed to anthropogenic Hg sources (Gačnik et al. 2025). Similarly, one of the cornerstones of AMAP activities is the long-term temporal trends monitoring of contaminants in biota through national programs of circumpolar Arctic countries. Specimen bank archiving is typically a component of those programs, and multi-decadal time series of Hg isotopes could be generated through retrospective analysis of archived tissues for key bioindicator species. Methylmercury-rich tissues are required (e.g., muscle, hair) rather than tissues with higher and more variable inorganic Hg content, such as liver. A multi-decadal examination of changing sources could be assessed through trends in MDF of Hg in biota, as demonstrated by muscle trends for Greenland polar bears (Søndergaard et al. 2025). Likewise, inter-year variation in contributions of Hg transport pathways can be identified using a time-series of biotic Hg isotopes (Chételat et al. 2026). In addition to source-related signals, environmental drivers associated with climate change are currently impacting abiotic and biotic components of the Hg cycle (Chételat et al. 2022; McKinney et al. 2022), and Hg stable isotopes hold promise for more clearly identifying contributions of climate change to Hg exposure in the Arctic, such as glacier melt (He et al. 2025) and atmospheric deposition processes (Song et al. 2025).

7.5 Provide Arctic science relevant to the Minamata Convention on Mercury

The United Nations Environmental Programme (UNEP) released a guidance document on monitoring of Hg and Hg compounds to support evaluation of the effectiveness of the

Minamata Convention (UNEP 2021). Under this guidance, Hg stable isotopes are considered an advanced technique that is recommended for “quantifying key environmental processes to improve understanding of cause-effect relationships”. Referred to as a component of Tier 3 programs, which involve more detailed and complex measurements, Hg isotopes are recommended by UNEP for both air and biotic process-focused studies. This technique is not recommended by UNEP for baseline Hg monitoring. Tier 3 study is defined as intensive monitoring (i.e. a co-located suite of measurements including Hg isotopes) for a selected area with a focus on insights to processes that are broadly applicable. In the context of Arctic research and AMAP activities, the Arctic Ocean is a major biome for monitoring (UNEP 2021) due to its vulnerability to ecosystem contamination and connection to Hg exposure in Arctic Indigenous populations (AMAP 2021a). Thus, more detailed Hg isotope study is recommended for the Arctic Ocean to provide critical information on the Hg cycle that is relevant to on-going regulation and effectiveness evaluation under the Minamata Convention. Temporal trends of Hg isotopes in biota will inform on recovery processes in remote ecosystems following reductions in anthropogenic Hg emissions as well as climate change drivers affecting the Hg cycle. These Arctic efforts would contribute to global compilation of Hg stable isotope observations in support of the Minamata Convention such as through the organization Global Observation System for Mercury (GOS⁴M) (Sonke et al. 2026).

1. Published Hg isotope data for abiotic matrices and biota in the Arctic were compiled. These data and the summary of findings provide a foundation for future studies.
2. Knowledge gaps and opportunities for future work were identified to prioritize which measurements and applications would be most useful for generating new policy-relevant science on Hg in the Arctic.
3. Specific recommendations were developed for incorporation of Hg isotope applications in AMAP monitoring, with consideration of global relevance for activities under the UN Minamata Convention on Mercury.

Mercury stable isotope analysis is an evolving field with continuing advances in laboratory techniques and environmental applications. As the field broadens, more opportunities will likely become available to further the understanding of Hg contamination and transport in the Arctic.

7.6 Overarching recommendations

- Establish guidelines for consistent laboratory quality assurance and quality control across Arctic studies to ensure comparability of measurements;
- Prioritize ecosystem level studies that evaluate 1) transport pathways delivering Hg to the Arctic, particularly the Arctic Ocean, 2) the role of climate change on the Hg cycle, and 3) exposure pathways for wildlife;
- Apply isotope-based models to estimate the relative contribution of diet items to Hg exposure in humans, as a valuable complement to traditional dietary exposure assessment;
- Prioritize Hg isotope measurements of abiotic matrices that support interpretation of transport and fate studies, including compound specific isotope analysis;
- Track change using specimen bank archives of Arctic fish and wildlife tissues to measure multi-decadal time series of Hg isotopes in key bioindicator species; and
- Integrate AMAP Hg isotope measurements with other regional monitoring to support future Minamata Convention effectiveness evaluations

7.7 Closing

Through this scoping initiative, there were three main outcomes that advance applications of Hg isotopes in AMAP monitoring.

8. References

- Aarhus University. 2024. Scientists in search of the sources of mercury pollution in the Arctic. <https://tech.au.dk/en/about-the-faculty/news/show/artikel/scientists-in-search-of-the-sources-of-mercury-pollution-in-the-arctic>.
- AMAP. 1998. AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xii+859 pp.
- AMAP. 2003. Chapter 5: Biological Monitoring: Human Tissue Levels of Environmental Contaminants. In AMAP Assessment 2002: Human Health in the Arctic, edited by AMAP, Oslo, Norway: Arctic Monitoring and Assessment Programme, pp 31–51.
- AMAP. 2011. AMAP Assessment 2011: Mercury in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xiv + 193 pp.
- AMAP. 2018. AMAP Assessment 2018: Biological Effects of Contaminants on Arctic Wildlife and Fish. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. vii+84pp.
- AMAP. 2021a. AMAP Assessment 2021: Mercury in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. viii + 324 pp.
- AMAP. 2021b. AMAP Assessment 2021: Human Health in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. x+240 pp.
- AMAP. 2021c. 2021 AMAP Mercury Assessment. Summary for Policy Makers. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. 15 pp.
- Araujo BF et al. 2022. Mercury isotope evidence for Arctic summertime re-emission of mercury from the cryosphere. *Nature Communications*. 13(1). <https://doi.org/10.1038/s41467-022-32440-8>
- ATSDR. 2024. Toxicological Profile for Mercury. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. <https://www.atsdr.cdc.gov/ToxProfiles/tp46.pdf>.
- Basu N et al. 2018. A state-of-the-science review of mercury biomarkers in human populations worldwide between 2000 and 2018. *Environmental Health Perspectives*. 126(10). <https://doi.org/10.1289/EHP3904>
- Basu N et al. 2023. Our evolved understanding of the human health risks of mercury. *Ambio*. 52(5):877–896. <https://doi.org/10.1007/s13280-023-01831-6>
- Beasley DMG et al. 2014. Full Recovery from a Potentially Lethal Dose of Mercuric Chloride. *Journal of Medical Toxicology*. 10(1):40–44. <https://doi.org/10.1007/s13181-013-0311-1>
- Bergquist BA. 2018. Mercury Isotopes. In: White WM, editor. *Encyclopedia of Geochemistry*. Encyclopedia of Earth Sciences Series. Springer International Publishing: p 900–906. https://doi.org/10.1007/978-3-319-39193-9_122-1
- Bergquist BA, Blum JD. 2007. Mass-dependent and -independent fractionation of Hg isotopes by photoreduction in aquatic systems. *Science*. 318(5849):417–420. <https://doi.org/10.1126/science.1148050>
- Besnard L et al. 2021. Foraging depth depicts resource partitioning and contamination level in a pelagic shark assemblage: Insights from mercury stable isotopes. *Environmental Pollution*. 283:117066. <https://doi.org/10.1016/j.envpol.2021.117066>
- Besnard L et al. 2025. Using Carbon, Nitrogen, Sulfur, and Mercury Isotopes to Trace Elasmobranch Foraging Habitats in Contrasting Biogeochemical Environments. *Environmental Science & Technology*. 59(32):16972–16984. <https://doi.org/10.1021/acs.est.5c01680>
- Biswas A et al. 2008. Natural mercury isotope variation in coal deposits and organic soils. *Environmental Science and Technology*. 42(22):8303–8309. <https://doi.org/10.1021/es801444b>
- Blum JD, Bergquist BA. 2007. Reporting of variations in the natural isotopic composition of mercury. *Analytical and Bioanalytical Chemistry*. 388(2):353–359. <https://doi.org/10.1007/s00216-007-1236-9>
- Blum JD, Johnson MW. 2017. Recent developments in mercury stable isotope analysis. *Reviews in Mineralogy and Geochemistry*. 82:733–757. <https://doi.org/10.2138/rmg.2017.82.17>
- Blum JD, Sherman LS, Johnson MW. 2014. Mercury isotopes in earth and environmental sciences. *Annual Review of Earth and Planetary Sciences*. 42:249–269. <https://doi.org/10.1146/annurev-earth-050212-124107>
- Bolea-Fernandez E et al. 2019. High-precision isotopic analysis sheds new light on mercury metabolism in long-finned pilot whales (*Globicephala melas*). *Scientific Reports*. 9(1). <https://doi.org/10.1038/s41598-019-43825-z>
- Bonsignore M et al. 2015. Tracing mercury pathways in Augusta Bay (southern Italy) by total concentration and isotope determination. *Environmental Pollution*. 205:178–185. <https://doi.org/10.1016/j.envpol.2015.05.033>
- Brooks SB et al. 2006. The mass balance of mercury in the springtime arctic environment. *Geophysical Research Letters*. 33(13). <https://doi.org/10.1029/2005GL025525>
- Cai H, Chen J. 2016. Mass-independent fractionation of even mercury isotopes. *Science Bulletin*. 61(2):116–124. <https://doi.org/10.1007/s11434-015-0968-8>
- Campeau A et al. 2022. Sources of riverine mercury across the Mackenzie River Basin; inferences from a combined Hg–C isotopes and optical properties approach. *Science of the Total Environment*. 806. <https://doi.org/10.1016/j.scitotenv.2021.150808>
- Cao Q et al. 2024. Mercury isotope fractionation and mercury source analysis in coal. *Science of The Total Environment*. 954:176286. <https://doi.org/10.1016/j.scitotenv.2024.176286>
- Charrier J et al. 2024. Mercury compound distribution and stable isotope composition in the different compartments of seabird eggs: The case of three species breeding in East Greenland. *Chemosphere*. 363. <https://doi.org/10.1016/j.chemosphere.2024.142857>
- Chen J, Hintelmann H, Feng X, Dimock B. 2012. Unusual fractionation of both odd and even mercury isotopes in precipitation from Peterborough, ON, Canada. *Geochimica et Cosmochimica Acta*. 90:33–46. <https://doi.org/10.1016/j.gca.2012.05.005>
- Chételat J et al. 2022. Climate change and mercury in the Arctic: Abiotic interactions. *Science of the Total Environment*. 824. <https://doi.org/10.1016/j.scitotenv.2022.153715>
- Chételat J et al. 2024. River influence on mercury bioaccumulation in the coastal food web of Eeyou Istchee, James Bay, Canada. *FACETS*. 9:1–13. <https://doi.org/10.1139/facets-2023-0121>
- Chételat J et al. 2026. The Athabasca River regulates methylmercury burdens of waterbirds breeding downstream. *Scientific Reports*. 16(1). <https://doi.org/10.1038/s41598-026-35970-z>
- Chételat J, Ackerman JT, Eagles-Smith CA, Hebert CE. 2020. Methylmercury exposure in wildlife: A review of the ecological and physiological processes affecting contaminant concentrations and their interpretation. *Science of the Total Environment*. 711. <https://doi.org/10.1016/j.scitotenv.2019.135117>
- Clarkson TW, Magos L. 2006. The toxicology of mercury and its chemical compounds. *Critical Reviews in Toxicology*. 36(8):609–662. <https://doi.org/10.1080/10408440600845619>
- Crowther ER et al. 2023. Coupling of nitric acid digestion and anion-exchange resin separation for the determination of methylmercury isotopic composition within organisms. *Analytical and Bioanalytical Chemistry*. 415(5):759–774. <https://doi.org/10.1007/s00216-022-04468-8>
- Day RD et al. 2012. Mercury stable isotopes in seabird eggs reflect a gradient from terrestrial geogenic to oceanic mercury reservoirs. *Environmental Science and Technology*. 46(10):5327–5335. <https://doi.org/10.1021/es2047156>
- Demers JD et al. 2018. Hg isotopes reveal in-stream processing and legacy inputs in East Fork Poplar Creek, Oak Ridge, Tennessee, USA. *Environmental Science: Processes and Impacts*. 20(4):686–707. <https://doi.org/10.1039/c7em00088a>

- doi.org/10.1039/c7em00538e
- Demers JD, Blum JD, Zak DR. 2013. Mercury isotopes in a forested ecosystem: Implications for air-surface exchange dynamics and the global mercury cycle. *Global Biogeochemical Cycles*. 27(1):222–238. <https://doi.org/10.1002/gbc.20021>
- Desforges J-P et al. 2022. Anthropogenic and Climatic Drivers of Long-Term Changes of Mercury and Feeding Ecology in Arctic Beluga (*Delphinapterus leucas*) Populations. *Environmental Science and Technology*. 56(1):271–281. <https://doi.org/10.1021/acs.est.1c05389>
- Dietz R et al. 2011. Temporal trends and future predictions of mercury concentrations in Northwest Greenland polar bear (*Ursus maritimus*) hair. *Environmental Science and Technology*. 45(4):1458–1465. <https://doi.org/10.1021/es1028734>
- Dietz R et al. 2021. Analysis of narwhal tusks reveals lifelong feeding ecology and mercury exposure. *Current Biology*. 31(9):2012–2019. e2. <https://doi.org/10.1016/j.cub.2021.02.018>
- Dietz R, Outridge P, Hobson KA. 2009. Anthropogenic contributions to mercury levels in present-day Arctic animals-A review. *Science of the Total Environment*. 407(24):6120–6131. <https://doi.org/10.1016/j.scitotenv.2009.08.036>
- Douglas TA, Blum JD. 2019. Mercury Isotopes Reveal Atmospheric Gaseous Mercury Deposition Directly to the Arctic Coastal Snowpack. *Environmental Science and Technology Letters*. 6(4):235–242. <https://doi.org/10.1021/acs.estlett.9b00131>
- Du B et al. 2018. Use of Mercury Isotopes to Quantify Mercury Exposure Sources in Inland Populations, China. *Environmental Science and Technology*. 52(9):5407–5416. <https://doi.org/10.1021/acs.est.7b05638>
- Du B et al. 2021. Use of mercury isotopes to quantify sources of human inorganic mercury exposure and metabolic processes in the human body. *Environment International*. 147:106336. <https://doi.org/10.1016/j.envint.2020.106336>
- Enrico M et al. 2016. Atmospheric Mercury Transfer to Peat Bogs Dominated by Gaseous Elemental Mercury Dry Deposition. *Environmental Science & Technology*. 50(5):2405–2412. <https://doi.org/10.1021/acs.est.5b06058>
- Estrade N, Carignan J, Sonke JE, Donard OFX. 2009. Mercury isotope fractionation during liquid-vapor evaporation experiments. *Geochimica et Cosmochimica Acta*. 73(10):2693–2711. <https://doi.org/10.1016/j.gca.2009.01.024>
- Feng C et al. 2015. Specific Pathways of Dietary Methylmercury and Inorganic Mercury Determined by Mercury Speciation and Isotopic Composition in Zebrafish (*Danio rerio*). *Environmental Science & Technology*. 49(21):12984–12993. <https://doi.org/10.1021/acs.est.5b03587>
- Feng X et al. 2008. Human Exposure To Methylmercury through Rice Intake in Mercury Mining Areas, Guizhou Province, China. *Environmental Science & Technology*. 42(1):326–332. <https://doi.org/10.1021/es071948x>
- Gačnik J, Živković I, Horvat M. 2025. Mercury isotopes in the atmosphere: Synthesis, perspectives and analytical considerations. *TrAC Trends in Analytical Chemistry*. 189:118257. <https://doi.org/10.1016/j.trac.2025.118257>
- Gambardella N et al. 2025. The role of prokaryotic mercury methylators and demethylators in Canadian Arctic thermokarst lakes. *Scientific Reports*. 15(1):7173. <https://doi.org/10.1038/s41598-025-89438-7>
- Gantner N, Hintelmann H, Zheng W, Muir DC. 2009. Variations in stable isotope fractionation of Hg in food webs of Arctic lakes. *Environmental Science and Technology*. 43(24):9148–9154. <https://doi.org/10.1021/es901771r>
- Garnier J et al. 2025. Mercury isotope constraints on artisanal and small-scale gold mining source contributions and redox cycling in the Yanomami Indigenous Territory. *Journal of Hazardous Materials*. 498:139892. <https://doi.org/10.1016/j.jhazmat.2025.139892>
- Ghosh S, Xu Y, Humayun M, Odom L. 2008. Mass-independent fractionation of mercury isotopes in the environment. *Geochemistry, Geophysics, Geosystems*. 9(3). <https://doi.org/10.1029/2007GC001827>
- Gleason JD et al. 2017. Sources and cycling of mercury in the paleo Arctic Ocean from Hg stable isotope variations in Eocene and Quaternary sediments. *Geochimica et Cosmochimica Acta*. 197:245–262. <https://doi.org/10.1016/j.gca.2016.10.033>
- Gong W et al. 2025. Modelling Arctic lower-tropospheric ozone: processes controlling seasonal variations. *Atmospheric Chemistry and Physics*. 25(15):8355–8405. <https://doi.org/10.5194/acp-25-8355-2025>
- Goodsite ME, Plane JMC, Skov H. 2004. A Theoretical Study of the Oxidation of Hg⁰ to HgBr₂ in the Troposphere. *Environmental Science & Technology*. 38(6):1772–1776. <https://doi.org/10.1021/es034680s>
- Gratz LE, Keeler GJ, Blum JD, Sherman LS. 2010. Isotopic composition and fractionation of mercury in Great Lakes precipitation and ambient air. *Environmental Science and Technology*. 44(20):7764–7770. <https://doi.org/10.1021/es100383w>
- Grégoire DS et al. 2021. Stable Isotope Fractionation Reveals Similar Atomic-Level Controls during Aerobic and Anaerobic Microbial Hg Transformation Pathways. *Applied and Environmental Microbiology*. 87(18):1–13. <https://doi.org/10.1128/AEM.00678-21>
- Ha E et al. 2017. Current progress on understanding the impact of mercury on human health. *Environmental Research*. 152:419–433. <https://doi.org/10.1016/j.envres.2016.06.042>
- He S et al. 2025. Stable Isotopes Reveal the Contribution of Glacier Melting to Mercury Budget in Tibetan Rivers. *Environmental Science & Technology Letters*. 12(1):85–91. <https://doi.org/10.1021/acs.estlett.4c01008>
- Hilgendag IR et al. 2022. Mercury biomagnification in benthic, pelagic, and benthopelagic food webs in an Arctic marine ecosystem. *Science of The Total Environment*. 841:156424. <https://doi.org/10.1016/j.scitotenv.2022.156424>
- Hintelmann H. 2012. Chapter 4: Use of stable isotopes in mercury research. In: *Mercury in the Environment: Pattern and Process*. University of California Press; p 55–71
- Hintelmann H, Lu S. 2003. High precision isotope ratio measurements of mercury isotopes in cinnabar ores using multi-collector inductively coupled plasma mass spectrometry. *Analyst*. 128(6):635–639. <https://doi.org/10.1039/b300451a>
- Holmes CD, Jacob DJ, Yang X. 2006. Global lifetime of elemental mercury against oxidation by atomic bromine in the free troposphere. *Geophysical Research Letters*. 33(20). <https://doi.org/10.1029/2006GL027176>
- Hughes-Allen L et al. 2024. A 14,000-Year Sediment Record of Mercury Accumulation and Isotopic Signatures From Lake Malaya Chabyda (Siberia). *Journal of Geophysical Research: Biogeosciences*. 129(10). <https://doi.org/10.1029/2023JG007863>
- Janssen SE, Schaefer JK, Barkay T, Reinfelder JR. 2016. Fractionation of Mercury Stable Isotopes during Microbial Methylmercury Production by Iron- and Sulfate-Reducing Bacteria. *Environmental Science and Technology*. 50(15):8077–8083. <https://doi.org/10.1021/acs.est.6b00854>
- Jiskra M et al. 2017. Source tracing of natural organic matter bound mercury in boreal forest runoff with mercury stable isotopes. *Environmental Science: Processes and Impacts*. 19(10):1235–1248. <https://doi.org/10.1039/c7em00245a>
- Jiskra M et al. 2019. Insights from mercury stable isotopes on terrestrial-atmosphere exchange of Hg(0) in the Arctic tundra. *Biogeosciences*. 16(20):4051–4064. <https://doi.org/10.5194/bg-16-4051-2019>
- Jiskra M et al. 2021. Mercury stable isotopes constrain atmospheric sources to the ocean. *Nature*. 597(7878):678–682. <https://doi.org/10.1038/s41586-021-03859-8>
- Jiskra M, Wiederhold JG, Bourdon B, Kretzschmar R. 2012. Solution Speciation Controls Mercury Isotope Fractionation of Hg(II) Sorption to Goethite. *Environmental Science & Technology*. 46(12):6654–6662. <https://doi.org/10.1021/es3008112>
- Korbas M et al. 2010. The Chemical Nature of Mercury in Human Brain Following Poisoning or Environmental Exposure. *ACS Chemical Neuroscience*. 1(12):810–818. <https://doi.org/10.1021/cn1000765>
- Kritee K et al. 2007. Mercury stable isotope fractionation during reduction of Hg(II) to Hg(0) by Mercury resistant microorganisms. *Environmental Science and Technology*. 41(6):1889–1895. <https://doi.org/10.1021/es062019t>
- Kritee K, Barkay T, Blum JD. 2009. Mass dependent stable isotope fractionation of mercury during mer mediated microbial degradation

- of monomethylmercury. *Geochimica et Cosmochimica Acta*. 73(5):1285–1296. <https://doi.org/10.1016/j.gca.2008.11.038>
- Kritee K, Blum JD, Reinfelder JR, Barkay T. 2013. Microbial stable isotope fractionation of mercury: A synthesis of present understanding and future directions. *Chemical Geology*. 336:13–25. <https://doi.org/10.1016/j.chemgeo.2012.08.017>
- Kwon SY et al. 2012. Absence of fractionation of mercury isotopes during trophic transfer of methylmercury to freshwater fish in captivity. *Environmental Science and Technology*. 46(14):7527–7534. <https://doi.org/10.1021/es300794q>
- Kwon SY et al. 2016. Quantifying mercury isotope dynamics in captive Pacific bluefin tuna (*Thunnus orientalis*). *Elementa*. 2016. <https://doi.org/10.12952/journal.elementa.000088>
- Kwon SY et al. 2020. Mercury stable isotopes for monitoring the effectiveness of the Minamata Convention on Mercury. *Earth-Science Reviews*. 203. <https://doi.org/10.1016/j.earscirev.2020.103111>
- Kwon SY, Blum JD, Chirby MA, Chesney EJ. 2013. Application of mercury isotopes for tracing trophic transfer and internal distribution of mercury in marine fish feeding experiments. *Environmental Toxicology and Chemistry*. 32(10):2322–2330. <https://doi.org/10.1002/etc.2313>
- Laffont L et al. 2009. Anomalous Mercury Isotopic Compositions of Fish and Human Hair in the Bolivian Amazon. *Environmental Science & Technology*. 43(23):8985–8990. <https://doi.org/10.1021/es9019518>
- Laffont L et al. 2011. Hg Speciation and Stable Isotope Signatures in Human Hair As a Tracer for Dietary and Occupational Exposure to Mercury. *Environmental Science & Technology*. 45(23):9910–9916. <https://doi.org/10.1021/es202353m>
- Le Croizier G et al. 2020. The Twilight Zone as a Major Foraging Habitat and Mercury Source for the Great White Shark. *Environmental Science & Technology*. 54(24):15872–15882. <https://doi.org/10.1021/acs.est.0c05621>
- Lee BJ et al. 2020. Internal dynamics of inorganic and methylmercury in a marine fish: Insights from mercury stable isotopes. *Environmental Pollution*. 267:115588. <https://doi.org/10.1016/j.envpol.2020.115588>
- Lee JH, Kwon SY, Lee H, et al. 2021. Climate-Associated Changes in Mercury Sources in the Arctic Fjord Sediments. *ACS Earth and Space Chemistry*. 5(9):2398–2407. <https://doi.org/10.1021/acsearthspacechem.1c00095>
- Lee JH, Kwon SY, Yin R, et al. 2021. Spatiotemporal Characterization of Mercury Isotope Baselines and Anthropogenic Influences in Lake Sediment Cores. *Global Biogeochemical Cycles*. 35(10):e2020GB006904. <https://doi.org/10.1029/2020GB006904>
- Lepak RF et al. 2020. Resolving Atmospheric Mercury Loading and Source Trends from Isotopic Records of Remote North American Lake Sediments. *Environmental Science and Technology*. 54(15):9325–9333. <https://doi.org/10.1021/acs.est.0c00579>
- Lepak RF et al. 2022. Using Carbon, Nitrogen, and Mercury Isotope Values to Distinguish Mercury Sources to Alaskan Lake Trout. *Environmental Science & Technology Letters*. 9(4):312–319. <https://doi.org/10.1021/acs.estlett.2c00096>
- Li M et al. 2014. Assessing sources of human methylmercury exposure using stable mercury isotopes. *Environmental Science and Technology*. 48(15):8800–8806. <https://doi.org/10.1021/es500340r>
- Li M, Schartup AT, et al. 2016. Environmental Origins of Methylmercury Accumulated in Subarctic Estuarine Fish Indicated by Mercury Stable Isotopes. *Environmental Science and Technology*. 50(21):11559–11568. <https://doi.org/10.1021/acs.est.6b03206>
- Li M, von Stackelberg K, et al. 2016. Insights from mercury stable isotopes into factors affecting the internal body burden of methylmercury in frequent fish consumers Blum JD, Mason R, editors. *Elementa: Science of the Anthropocene*. 4:000103. <https://doi.org/10.12952/journal.elementa.000103>
- Li M et al. 2020. Selenium and stable mercury isotopes provide new insights into mercury toxicokinetics in pilot whales. *Science of the Total Environment*. 710. <https://doi.org/10.1016/j.scitotenv.2019.136325>
- Li M-L et al. 2022. Internal Dynamics and Metabolism of Mercury in Biota: A Review of Insights from Mercury Stable Isotopes. *Environmental Science and Technology*. 56(13):9182–9195. <https://doi.org/10.1021/>
- acs.est.1c08631
- Li P et al. 2008. Mercury exposure in the population from Wuchuan mercury mining area, Guizhou, China. *Science of The Total Environment*. 395(2):72–79
- Li X et al. 2021. Isotope signatures of atmospheric mercury emitted from residential coal combustion. *Atmospheric Environment*. 246:118175. <https://doi.org/10.1016/j.atmosenv.2020.118175>
- Lim AG et al. 2020. A revised pan-Arctic permafrost soil Hg pool based on Western Siberian peat Hg and carbon observations. *Biogeosciences*. 17(12):3083–3097. <https://doi.org/10.5194/bg-17-3083-2020>
- Lim SH et al. 2024. Near surface oxidation of elemental mercury leads to mercury exposure in the Arctic Ocean biota. *Nature Communications*. 15(1). <https://doi.org/10.1038/s41467-024-51852-2>
- Liu Y et al. 2024. Atmospheric Hg(0) dry deposition over environmental surfaces: Insights from mercury isotope fractionation. *Eco-Environment & Health*. 3(4):543–555. <https://doi.org/10.1016/j.eehl.2024.04.009>
- Madigan DJ et al. 2018. Mercury Stable Isotopes Reveal Influence of Foraging Depth on Mercury Concentrations and Growth in Pacific Bluefin Tuna. *Environmental Science & Technology*. 52(11):6256–6264. <https://doi.org/10.1021/acs.est.7b06429>
- Mailloux RJ, Yumvihoze E, Chan HM. 2015. Superoxide anion radical (O₂⁻) degrades methylmercury to inorganic mercury in human astrocytoma cell line (CCF-STTG1). *Chemico-Biological Interactions*. 239:46–55. <https://doi.org/10.1016/j.cbi.2015.06.028>
- Martins BM, Hintelmann H, Pilote M, Vieira G, et al. 2025. Recent advances in the study of mercury biogeochemistry in Arctic permafrost ecosystems. *Science of The Total Environment*. 959:178176. <https://doi.org/10.1016/j.scitotenv.2024.178176>
- Martins BM, Hintelmann H, Pilote M, Cesário R, et al. 2025. Seasonal patterns of mercury dynamics in thermokarst lakes from sporadic permafrost. *Environmental Pollution*. 384:127030. <https://doi.org/10.1016/j.envpol.2025.127030>
- Masbou J et al. 2015. Hg Stable Isotope Time Trend in Ringed Seals Registers Decreasing Sea Ice Cover in the Alaskan Arctic. *Environmental Science and Technology*. 49(15):8977–8985. <https://doi.org/10.1021/es5048446>
- Masbou J et al. 2018. Hg-Stable Isotope Variations in Marine Top Predators of the Western Arctic Ocean. *ACS Earth and Space Chemistry*. 2(5):479–490. <https://doi.org/10.1021/acsearthspacechem.8b00017>
- Masbou J et al. 2025. Mercury compound-specific stable isotope fractionation in high-altitude lake ecosystems of the Bolivian Altiplano. *Science of The Total Environment*. 983:179630. <https://doi.org/10.1016/j.scitotenv.2025.179630>
- Mason RP, Reinfelder JR, Morel FMM. 1996. Uptake, toxicity, and trophic transfer of mercury in a coastal diatom. *Environmental Science and Technology*. 30(6):1835–1845. <https://doi.org/10.1021/es950373d>
- McKinney MA et al. 2022. Climate change and mercury in the Arctic: Biotic interactions. *Science of the Total Environment*. 834. <https://doi.org/10.1016/j.scitotenv.2022.155221>
- McKinney MA, Atwood TC, Pedro S, Peacock E. 2017. Ecological Change Drives a Decline in Mercury Concentrations in Southern Beaufort Sea Polar Bears. *Environmental Science & Technology*. 51(14):7814–7822. <https://doi.org/10.1021/acs.est.7b00812>
- Morlighem M et al. 2017. BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation. *Geophysical Research Letters*. 44(21):11,051–11,061. <https://doi.org/10.1002/2017GL074954>
- Mu C et al. 2019. Carbon and mercury export from the Arctic rivers and response to permafrost degradation. *Water Research*. 161:54–60. <https://doi.org/10.1016/j.watres.2019.05.082>
- Nagano M, Yasutake A, Miura K. 2010. Demethylation of Methylmercury in Human Neuroblastoma, Glioblastoma and Liver Cells. *Journal of Health Science*. 56(3):326–330. <https://doi.org/10.1248/jhs.56.326>
- Obrist D et al. 2017. Tundra uptake of atmospheric elemental mercury drives Arctic mercury pollution. *Nature*. 547(7662):201–204. <https://doi.org/10.1038/nature22997>
- Olson C et al. 2018. Mercury in Active-Layer Tundra Soils of Alaska: Concentrations, Pools, Origins, and Spatial Distribution.

- Global Biogeochemical Cycles. 32(7):1058–1073. <https://doi.org/10.1029/2017GB005840>
- Olson CL, Jiskra M, Sonke JE, Obrist D. 2019. Mercury in tundra vegetation of Alaska: Spatial and temporal dynamics and stable isotope patterns. *Science of the Total Environment*. 660:1502–1512. <https://doi.org/10.1016/j.scitotenv.2019.01.058>
- Osterkamp TE, Burn CR. 2003. PERMAFROST. In: Holton JR, editor. *Encyclopedia of Atmospheric Sciences*. Academic Press; p 1717–1729. <https://doi.org/10.1016/B0-12-227090-8/00311-0>
- Otosaka IN et al. 2023. Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. *Earth System Science Data*. 15(4):1597–1616. <https://doi.org/10.5194/essd-15-1597-2023>
- Outridge PM et al. 2018. Updated Global and Oceanic Mercury Budgets for the United Nations Global Mercury Assessment 2018. *Environmental Science & Technology*. 52(20):11466–11477. <https://doi.org/10.1021/acs.est.8b01246>
- Peng X et al. 2023. Active Layer Thickness and Permafrost Area Projections for the 21st Century. *Earth's Future*. 11(8):e2023EF003573. <https://doi.org/10.1029/2023EF003573>
- Perrot V et al. 2016. Natural Hg isotopic composition of different Hg compounds in mammal tissues as a proxy for in vivo breakdown of toxic methylmercury. *Metallomics*. 8(2):170–178. <https://doi.org/10.1039/c5mt00286a>
- Pinzone M et al. 2024. Dynamics of mercury stable isotope compounds in Arctic seals: New insights from a controlled feeding trial on hooded seals *Cystophora cristata*. *Environmental Pollution*. 358. <https://doi.org/10.1016/j.envpol.2024.124450>
- Point D et al. 2011. Methylmercury photodegradation influenced by sea-ice cover in Arctic marine ecosystems. *Nature Geoscience*. 4(3):188–194. <https://doi.org/10.1038/ngeo1049>
- Poulin BA et al. 2021. Isotope Fractionation from In Vivo Methylmercury Detoxification in Waterbirds. *ACS Earth and Space Chemistry*. 5(5):990–997. <https://doi.org/10.1021/acsearthspacechem.1c00051>
- Reiersen L-O, Vorkamp K, Kallenborn R. 2024. The role of the Arctic Monitoring and Assessment Programme (AMAP) in reducing pollution of the Arctic and around the globe. *Environmental Science and Ecotechnology*. 17. <https://doi.org/10.1016/j.ese.2023.100302>
- Renedo M et al. 2020. Contrasting Spatial and Seasonal Trends of Methylmercury Exposure Pathways of Arctic Seabirds: Combination of Large-Scale Tracking and Stable Isotopic Approaches. *Environmental Science and Technology*. 54(21):13619–13629. <https://doi.org/10.1021/acs.est.0c03285>
- Rodríguez-González P et al. 2009. Species-Specific Stable Isotope Fractionation of Mercury during Hg(II) Methylation by an Anaerobic Bacteria (*Desulfobulbus propionicus*) under Dark Conditions. *Environmental Science & Technology*. 43(24):9183–9188. <https://doi.org/10.1021/es902206j>
- Roffler GH et al. 2025. Switching to marine prey leads to unprecedented mercury concentrations in a population of coastal Alaska wolves. *Science of The Total Environment*. 980:179542. <https://doi.org/10.1016/j.scitotenv.2025.179542>
- Rosera TJ et al. 2020. Isolation of methylmercury using distillation and anion-exchange chromatography for isotopic analyses in natural matrices. *Analytical and Bioanalytical Chemistry*. 412(3):681–690. <https://doi.org/10.1007/s00216-019-02277-0>
- Rosera TJ et al. 2022. Methylmercury Stable Isotopes: New Insights on Assessing Aquatic Food Web Bioaccumulation in Legacy Impacted Regions. *ACS ES and T Water*. 2(5):701–709. <https://doi.org/10.1021/ACSESTWATER.1C00285>
- Rothenberg SE et al. 2017. Stable Mercury Isotopes in Polished Rice (*Oryza sativa* L.) and Hair from Rice Consumers. *Environmental Science & Technology*. 51(11):6480–6488. <https://doi.org/10.1021/acs.est.7b01039>
- Rua-Ibarz A et al. 2019. Tracing Mercury Pollution along the Norwegian Coast via Elemental, Speciation, and Isotopic Analysis of Liver and Muscle Tissue of Deep-Water Marine Fish (*Brosme brosme*). *Environmental Science & Technology*. 53(4):1776–1785. <https://doi.org/10.1021/acs.est.8b04706>
- Schuster PF et al. 2011. Mercury Export from the Yukon River Basin and Potential Response to a Changing Climate. *Environmental Science & Technology*. 45(21):9262–9267. <https://doi.org/10.1021/es202068b>
- Schuster PF et al. 2018. Permafrost Stores a Globally Significant Amount of Mercury. *Geophysical Research Letters*. 45(3):1463–1471. <https://doi.org/10.1002/2017GL075571>
- Senn DB et al. 2010. Stable Isotope (N, C, Hg) Study of Methylmercury Sources and Trophic Transfer in the Northern Gulf of Mexico. *Environmental Science & Technology*. 44(5):1630–1637. <https://doi.org/10.1021/es902361j>
- Sherman LS et al. 2010. Mass-independent fractionation of mercury isotopes in Arctic snow driven by sunlight. *Nature Geoscience*. 3(3):173–177. <https://doi.org/10.1038/ngeo758>
- Sherman LS et al. 2015. The use of Pb, Sr, and Hg isotopes in Great Lakes precipitation as a tool for pollution source attribution. *Science of the Total Environment*. 502:362–374. <https://doi.org/10.1016/j.scitotenv.2014.09.034>
- Sherman LS, Blum JD, Douglas TA, Steffen A. 2012. Frost flowers growing in the Arctic ocean-atmosphere-sea ice-snow interface: 2. Mercury exchange between the atmosphere, snow, and frost flowers. *Journal of Geophysical Research Atmospheres*. 117(3). <https://doi.org/10.1029/2011JD016186>
- Sherman LS, Blum JD, Franzblau A, Basu N. 2013. New insight into biomarkers of human mercury exposure using naturally occurring mercury stable isotopes. *Environmental Science and Technology*. 47(7):3403–3409. <https://doi.org/10.1021/es305250z>
- Shi M et al. 2023. The efficiency of Hg cold vapor generation and its influence on Hg isotope analysis by MC-ICP-MS. *Journal of Analytical Atomic Spectrometry*. 38(5):1076–1087. <https://doi.org/10.1039/D3JA00056G>
- Skov H et al. 2004. Fate of Elemental Mercury in the Arctic during Atmospheric Mercury Depletion Episodes and the Load of Atmospheric Mercury to the Arctic. *Environmental Science & Technology*. 38(8):2373–2382. <https://doi.org/10.1021/es030080h>
- Smith CN, Kesler SE, Blum JD, Rytuba JJ. 2008. Isotope geochemistry of mercury in source rocks, mineral deposits and spring deposits of the California Coast Ranges, USA. *Earth and Planetary Science Letters*. 269(3–4):399–407. <https://doi.org/10.1016/j.epsl.2008.02.029>
- Smith CN, Kesler SE, Klau B, Blum JD. 2005. Mercury isotope fractionation in fossil hydrothermal systems. *Geology*. 33(10):825–828. <https://doi.org/10.1130/G21863.1>
- Sommar JO et al. 2025. Atmospheric Mercury: Recent advances in theoretical, computational, experimental, observational and isotopic understanding to decipher its complex redox transformations in the upper and lower atmosphere and interaction with Earth surface reservoirs. *EGUsphere*. 2025:1–94. <https://doi.org/10.5194/egusphere-2024-4190>
- Søndergaard J et al. 2025. Stable isotopes unveil ocean transport of legacy mercury into Arctic food webs. *Nature Communications*. 16(1). <https://doi.org/10.1038/s41467-025-60356-6>
- Song Z et al. 2025. Atmospheric source of mercury to the ocean constrained by isotopic model. *Nature Communications*. 16(1):5752. <https://doi.org/10.1038/s41467-025-60981-1>
- Sonke JE et al. 2023. Mercury Stable Isotope Composition of Lichens and Mosses from Northern Eurasia Reveals Hg Deposition Pathways and Sources. *ACS Earth and Space Chemistry*. 7(1):204–211. <https://doi.org/10.1021/acsearthspacechem.2c00297>
- Sonke JE et al. 2026. The Global Observation System for Mercury dataset for mercury stable isotope signatures in environmental media. *Scientific Data*. 13(1):688. <https://doi.org/10.1038/s41597-026-07035-3>
- St. Pierre KA et al. 2018. Unprecedented Increases in Total and Methyl Mercury Concentrations Downstream of Retrogressive Thaw Slumps in the Western Canadian Arctic. *Environmental Science & Technology*. 52(24):14099–14109. <https://doi.org/10.1021/acs.est.8b05348>
- Štok M et al. 2019. Mercury speciation and mercury stable isotope composition in sediments from the Canadian Arctic Archipelago. *Science of the Total Environment*. 671:655–665. <https://doi.org/10.1016/j.scitotenv.2019.03.424>
- Štok M, Baya PA, Hintelmann H. 2015. The mercury isotope composition of Arctic coastal seawater. *Comptes Rendus - Geoscience*. 347(7–8):368–376. <https://doi.org/10.1016/j.crte.2015.04.001>

- Sun J et al. 2025. High precision analysis of mercury isotopes at ultra-low concentrations using dry cold vapor generation-MC-ICP-MS. *Journal of Analytical Atomic Spectrometry*. 40(8):2251–2260. <https://doi.org/10.1039/d5ja00220f>
- Sun R et al. 2014. Mercury Stable Isotope Signatures of World Coal Deposits and Historical Coal Combustion Emissions. *Environmental Science & Technology*. 48(13):7660–7668. <https://doi.org/10.1021/es501208a>
- Sun R et al. 2016. Historical (1850–2010) mercury stable isotope inventory from anthropogenic sources to the atmosphere Blum JD, Mason R, editors. *Elementa: Science of the Anthropocene*. 4:000091. <https://doi.org/10.12952/journal.elementa.000091>
- Sun R et al. 2019. Modelling the mercury stable isotope distribution of Earth surface reservoirs: Implications for global Hg cycling. *Geochimica et Cosmochimica Acta*. 246:156–173. <https://doi.org/10.1016/j.gca.2018.11.036>
- Sunderland EM. 2007. Mercury Exposure from Domestic and Imported Estuarine and Marine Fish in the U.S. Seafood Market. *Environmental Health Perspectives*. 115(2):235–242
- Sunderland EM, Li M, Bullard K. 2018. Decadal changes in the edible supply of seafood and methylmercury exposure in the United States. *Environmental Health Perspectives*. 126(1). <https://doi.org/10.1289/EHP2644>
- Szponar N et al. 2020. Isotopic Characterization of Atmospheric Gaseous Elemental Mercury by Passive Air Sampling. *Environmental Science & Technology*. 54(17):10533–10543. <https://doi.org/10.1021/acs.est.0c02251>
- Treu G et al. 2018. Correlations between hair and tissue mercury concentrations in Icelandic arctic foxes (*Vulpes lagopus*). *Science of The Total Environment*. 619–620:1589–1598. <https://doi.org/10.1016/j.scitotenv.2017.10.143>
- Tsui MT-K, Blum JD, Kwon SY. 2020. Review of stable mercury isotopes in ecology and biogeochemistry. *Science of the Total Environment*. 716. <https://doi.org/10.1016/j.scitotenv.2019.135386>
- UNEP. 2019. Global Mercury Assessment 2018. United Nations Environment (UNEP), Geneva, Switzerland. <https://wedocs.unep.org/handle/20.500.11822/29831>.
- UNEP. 2021. Guidance on monitoring of mercury and mercury compounds to support evaluation of the effectiveness of the Minamata Convention. Produced by the United Nations Environment Programme (UNEP). Document UNEP/MC/COP4/INF/12. https://minamataconvention.org/sites/default/files/documents/information_document/4_INF12_MonitoringGuidance.English.pdf.
- Vermilyea AW et al. 2017. Continuous proxy measurements reveal large mercury fluxes from glacial and forested watersheds in Alaska. *Science of The Total Environment*. 599–600:145–155. <https://doi.org/10.1016/j.scitotenv.2017.03.297>
- Vonk JE et al. 2015. Reviews and syntheses: Effects of permafrost thaw on Arctic aquatic ecosystems. *Biogeosciences*. 12(23):7129–7167. <https://doi.org/10.5194/bg-12-7129-2015>
- Wang S et al. 2019. Direct detection of atmospheric atomic bromine leading to mercury and ozone depletion. *Proceedings of the National Academy of Sciences*. 116(29):14479–14484. <https://doi.org/10.1073/pnas.1900613116>
- WHO. 2018. Assessment of prenatal exposure to mercury: human biomonitoring survey. The first survey protocol. World Health Organization, Regional Office for Europe, Copenhagen, Denmark. <https://iris.who.int/server/api/core/bitstreams/eeb623e2-99eb-465c-9d42-b3aa11bbb16c/content>.
- Wiederhold JG et al. 2013. Mercury isotope signatures as tracers for Hg cycling at the new idria Hg mine. *Environmental Science and Technology*. 47(12):6137–6145. <https://doi.org/10.1021/es305245z>
- Yuan S et al. 2022. Event-Based Atmospheric Precipitation Uncovers Significant Even and Odd Hg Isotope Anomalies Associated with the Circumpolar Vortex. *Environmental Science & Technology*. 56(17):12713–12722. <https://doi.org/10.1021/acs.est.2c02613>
- Zdanowicz CM et al. 2016. Historical variations of mercury stable isotope ratios in Arctic glacier firn and ice cores. *Global Biogeochemical Cycles*. 30(9):1324–1347. <https://doi.org/10.1002/2016GB005411>
- Zhang C, Sun R. 2026. Atmospheric mercury stable isotopes: Advances in mercury cycle tracing and projections of future trends. *Earth-Science Reviews*. 272:105348. <https://doi.org/10.1016/j.earscirev.2025.105348>
- Zhang L, Yin Y, Li Y, Cai Y. 2022. Mercury isotope fractionation during methylmercury transport and transformation: A review focusing on analytical method, fractionation characteristics, and its application. *Science of the Total Environment*. 841. <https://doi.org/10.1016/j.scitotenv.2022.156558>
- Zheng W et al. 2021. Mercury stable isotopes reveal the sources and transformations of atmospheric Hg in the high Arctic. *Applied Geochemistry*. 131. <https://doi.org/10.1016/j.apgeochem.2021.105002>
- Zheng W, Hintelmann H. 2009. Mercury isotope fractionation during photoreduction in natural water is controlled by its Hg/DOC ratio. *Geochimica et Cosmochimica Acta*. 73(22):6704–6715. <https://doi.org/10.1016/j.gca.2009.08.016>
- Zheng W, Obrist D, Weis D, Bergquist BA. 2016. Mercury isotope compositions across North American forests. *Global Biogeochemical Cycles*. 30(10):1475–1492. <https://doi.org/10.1002/2015GB005323>
- Zhou J et al. 2021. Vegetation uptake of mercury and impacts on global cycling. *Nature Reviews Earth and Environment*. 2(4):269–284. <https://doi.org/10.1038/s43017-021-00146-y>
- Zhou Z, Wang H, Li Y. 2023. Mercury stable isotopes in the ocean: Analytical methods, cycling, and application as tracers. *Science of the Total Environment*. 874. <https://doi.org/10.1016/j.scitotenv.2023.162485>
- Zolkos S et al. 2020. Mercury Export from Arctic Great Rivers. *Environmental Science and Technology*. 54(7):4140–4148. <https://doi.org/10.1021/acs.est.9b07145>

Appendices

Appendix 1

List of laboratories in Arctic countries and observer countries with specialized expertise to measure Hg isotopes.

Appendix 2

$\Delta^{199}\text{Hg}$ values in Arctic abiotic matrices.

$\delta^{202}\text{Hg}$ values in Arctic abiotic matrices.

$\Delta^{200}\text{Hg}$ values in Arctic abiotic matrices.

Appendix 3

Published studies with Hg isotope data for Arctic biota.

Appendix 1

Table A1.1. List of laboratories in Arctic countries and observer countries with specialized expertise to measure Hg isotopes.

Country	Institution	Laboratory Name	City, Province or State	Web Page/Contact Email
Canada	Trent University	Water Quality Centre	Peterborough, ON	Web: https://www.trentu.ca/wqc/facilities-services/services Email: waterqualitycentre@trentu.ca
Canada	University of Toronto	Department of Earth Sciences	Toronto, ON	Email: bergquist@es.utoronto.ca
China	Tianjin University	School of Earth System Science	Tianjin	Email: ruoyu.sun@tju.edu.cn
Denmark	Aarhus University	ECOS Trace Metal & Isotope Geochemistry Laboratory	Roskilde	Web: https://ecos.au.dk/en/researchconsultancy/themes/facilities Email: js@ecos.au.dk
France	Géosciences Environnement Toulouse	Géochimie des Isotopes Stables	Toulouse	Web: https://www.get.omp.eu/gis/ Email: jeroen.sonke@get.omp.eu
France	The University of Pau and Pays de l'Adour (UPPA)	The Institute of Analytical Sciences and Physico-Chemistry for Environment and Materials (IPREM)	Pau	Web: https://iprem.univ-pau.fr/en/home.html Email: david.amouroux@univ-pau.fr
South Korea	Pohang University of Science and Technology	Environmental & Health Assessment Lab	Pohang-si	Email: saeyunk@postech.ac.kr
United States of America	University of New Hampshire	Department of Earth Sciences	Durham, NH	Email: Jason.Demers@unh.edu
United States of America	US Geological Survey	M3 Research Laboratory	Madison, WI	Web: https://www.usgs.gov/labs/m3-research-laboratory/lab-capabilities Email: m3research@usgs.gov
United States of America	Brooks Applied Labs	n/a	Seattle, WA	Web: https://brooksapplied.com/services/stable-isotope-ratio-testing/

Appendix 2

Table A2.1. $\Delta^{199}\text{Hg}$ values in Arctic abiotic matrices.

Media		Chemical form	$\Delta^{199}\text{Hg}$ (%) Median, mean or interquartile range	Location (time period)	Source
Water	Coastal	THg (filtered)	0.12 to 0.37	Canadian Arctic Archipelago	Štok et al. (2015)
	River	D-THg	0.09 to 1.27	Makenzie River	Campeau et al. (2022)
		P-THg	-0.36 to 0.26	Makenzie River	Campeau et al. (2022)
	Stream	THg	-0.42 to -0.33	N Sweden	Jiskra et al. (2017)
Sediment	Marine	THg	-0.18 to 0.12	Arctic Ocean, all sections	Gleason et al. (2017)
		THg	-0.05 $\pm$ 0.06	Arctic Ocean, Holocene	Gleason et al. (2017)
	Lake	THg	-0.12 to 0.12	Alaska	Lepak et al. (2020)
		THg	-0.37 to 0.74 (mean 0.09)	NE Canada	Gantner et al. (2009)
		THg	-0.15 to 0.70	Siberia	Hughes-Allen et al. (2024)
Air		Hg(0)	-0.20, -0.28 to -0.08	Zeppelin	Araujo et al. (2022)
		Hg(0)	-0.31, -0.38 to -0.15	Alert	Araujo et al. (2022)
		Hg(0)	-0.21, -0.31 to 0.10	Villum	Araujo et al. (2022)
			Range: -0.50 to 1.32	Zeppelin, Alert, Villum	Araujo et al. (2022)
		THg (g)	-0.11 & -0.22	Barrow (Alaska)	Sherman et al. (2010)
		Hg(0)	-0.28 to -0.19	Toolik Field station (Alaska)	Obrist et al. (2017), as reported in Douglas & Blum (2019)
		THg (g)	-0.62 to -0.29	Beaufort Sea (Alaska)	Lim et al. (2024)
Snow	Surface	THg	-2.41 to -2.63	Barrow (Alaska)	Sherman et al. (2010)
			-1.01 & -0.97	Barrow (Alaska)	Sherman et al. (2012)
	Drifted	THg	-3.84 to -5.08	Barrow (Alaska)	Sherman et al. (2010)
	Snowfall	THg	-0.95 & -1.20	Barrow (Alaska)	Sherman et al. (2010)
		THg	0.32	Greenland	Chen et al. (2012)
Ice	New frost flowers	THg	0.77 $\pm$ 0.13	Barrow (Alaska)	Sherman et al. (2012)
	Aged frost flowers	THg	0.10 $\pm$ 0.05	Barrow (Alaska)	Sherman et al. (2012)
	Glacier/firn	THg	-1.09 to 0.29	Canada, industrial era	Zdanowicz et al. (2016)
	Glacier/firn	THg	-0.35 to 2.44	Canada, pre-industrial era (>200 y BP)	Zdanowicz et al. (2016)
Brine			-0.39 & -0.41	Barrow (Alaska)	Sherman et al. (2012)
Soil	Boreal	THg	-0.48 to -0.24	N Sweden	Jiskra et al. (2015)
	Peat	THg	-0.19 to 0.02	Alaskan Arctic coast	Douglas & Blum (2019)
Litter	Boreal	THg	-0.44 $\pm$ 0.03	N Sweden	Jiskra et al. (2015)

Table A.2.2. $\delta^{202}\text{Hg}$ values in Arctic abiotic matrices.

Media		Chemical form	$\Delta^{199}\text{Hg}$ (‰) Median, mean or interquartile range	Location (time period)	Source
Water	Coastal	THg (filtered)	-2.85 to -1.1	Canadian Arctic Archipelago	Štok et al. (2015)
	River	D-THg	-1.77 to 0.15	Mackenzie River	Campeau et al. (2022)
		P-THg	-2.12 to -1.55	Mackenzie River	Campeau et al. (2022)
	Stream	THg	-2.29 to -1.99	N Sweden	Jiskra et al. (2017)
Sediment	Marine	THg	-2.34 to -0.78	Arctic Ocean, all sections	Gleason et al. (2017)
		THg	-1.38 $\pm$ 0.22	Arctic Ocean, Holocene	Gleason et al. (2017)
	Lake	THg	-1.29 to -0.85	Alaska	Lepak et al. (2020)
		THg	-0.94 $\pm$ 0.11	Ellesmere Island (NE Canada)	Gantner et al. (2009)
		THg	-1.23 $\pm$ 0.41	Cornwallis Island (NE Canada)	Gantner et al. (2009)
		THg	-1.02 $\pm$ 0.32	Kent Peninsula (NE Canada)	Gantner et al. (2009)
		THg	-1.75 to -0.5	Siberia	Hughes-Allen et al. (2024)
Air		Hg(0)	0.57 (0.45 to 0.75)	Zeppelin	Araujo et al. (2022)
		Hg(0)	0.66 (0.47 to 0.85)	Alert	Araujo et al. (2022)
		Hg(0)	0.54 (0.39 to 0.64)	Villum	Araujo et al. (2022)
		THg (g)	-0.12 & 0.15	Barrow (Alaska)	Sherman et al. (2010)
		Hg(0)	0.55 to 0.80	Toolik Field station (Alaska)	Obrist et al. (2017), as reported in Douglas & Blum (2019)
		THg (g)	0.40 to 0.72	Beaufort sea (Alaska)	Lim et al. (2024)
Snow	Surface	THg	-0.49 to 0.70	Barrow (Alaska)	Sherman et al. (2010)
			0.63 & 0.69	Barrow (Alaska)	Sherman et al. (2012)
	Drifted	THg	0.40 to 0.57	Barrow (Alaska)	Sherman et al. (2010)
	Snowfall	THg	-0.05 & 0.54	Barrow (Alaska)	Sherman et al. (2010)
		THg	-1.35	Greenland	Chen et al. (2012)
Ice	Glacier/firn	THg	-2.02 to 0.14	Canada, industrial era	Zdanowicz et al. (2016)
	Glacier/firn	THg	-2.48 to 1.99	Canada, pre-industrial era (>200 y BP)	Zdanowicz et al. (2016)
Brine			-0.19 & -0.39	Barrow (Alaska)	Sherman et al. (2012)
Soil	Peat deposits	THg	-1.3 to -1.1	Point Barrow (Alaska)	Biswas et al. (2008)
	Boreal	THg	-2.56 to -1.55	N Sweden	Jiskra et al. (2015)
	Peat	THg	-1.39 to -0.81	Alaskan Arctic coast	Douglas & Blum (2019)
Litter	Boreal	THg	-2.35 $\pm$ 0.09	N Sweden	Jiskra et al. (2015)

Table A.2.3. $\Delta^{200}\text{Hg}$ values in Arctic abiotic matrices.

Media		Chemical form	$\Delta^{199}\text{Hg}$ (‰) Median, mean or interquartile range	Location (time period)	Source
Water	Coastal	THg (filtered)	0.05 to 0.52	Canadian Arctic Archipelago	Štrok et al. (2015)
Air		Hg(0)	-0.08, -0.10 to -0.07	Zeppelin	Araujo et al. (2022)
		Hg(0)	-0.07, -0.09 to -0.05	Alert	Araujo et al. (2022)
		Hg(0)	-0.09, -0.13 to -0.03	Villum	Araujo et al. (2022)
		Hg(0)	-0.09 to -0.04	Toolik Field Station (Alaska)	Obrist et al. (2017), as reported in Douglas & Blum (2019)
		THg (g)	-0.05 to -0.04	Beaufort Sea (Alaska)	Lim et al. (2024)
Air	Hg(0) uptake endmember	THg	-0.05, -0.08 to -0.03	Northern hemisphere	Jiskra et al. (2022) as cited in Hughes-Allen et al. (2024)
Precipitation	Wet deposition end member	THg	0.14, 0.09 to 0.2	Northern hemisphere	Jiskra et al. (2022) as cited in Hughes-Allen et al. (2024)
Water	Stream	THg	-0.12 to -0.01	N Sweden	Jiskra et al. (2017)
Snow	Surface	THg	-0.12 to 0.01	Barrow (Alaska)	Sherman et al. (2010)
			-0.11 & -0.02	Barrow (Alaska)	Sherman et al. (2012)
Brine			-0.20 & -0.01	Barrow (Alaska)	Sherman et al. (2012)
Ice	Glacier/firn	THg	0.07 to 0.62	Canada, industrial era	Zdanowicz et al. (2016)
	Glacier/firn	THg	-0.06 to 0.57	Canada, pre-industrial era (>200 y BP)	Zdanowicz et al. (2016)

References for Appendix 2

- Araujo BF et al. 2022. Mercury isotope evidence for Arctic summertime re-emission of mercury from the cryosphere. *Nature Communications*. 13(1). <https://doi.org/10.1038/s41467-022-32440-8>
- Biswas A et al. 2008. Natural mercury isotope variation in coal deposits and organic soils. *Environmental Science and Technology*. 42(22):8303–8309. <https://doi.org/10.1021/es801444b>
- Campeau A et al. 2022. Sources of riverine mercury across the Mackenzie River Basin; inferences from a combined Hg–C isotopes and optical properties approach. *Science of the Total Environment*. 806. <https://doi.org/10.1016/j.scitotenv.2021.150808>
- Chen J, Hintelmann H, Feng X, Dimock B. 2012. Unusual fractionation of both odd and even mercury isotopes in precipitation from Peterborough, ON, Canada. *Geochimica et Cosmochimica Acta*. 90:33–46. <https://doi.org/10.1016/j.gca.2012.05.005>
- Douglas TA, Blum JD. 2019. Mercury Isotopes Reveal Atmospheric Gaseous Mercury Deposition Directly to the Arctic Coastal Snowpack. *Environmental Science and Technology Letters*. 6(4):235–242. <https://doi.org/10.1021/acs.estlett.9b00131>
- Gantner N, Hintelmann H, Zheng W, Muir DC. 2009. Variations in stable isotope fractionation of Hg in food webs of Arctic lakes. *Environmental Science and Technology*. 43(24):9148–9154. <https://doi.org/10.1021/es901771r>
- Gleason JD et al. 2017. Sources and cycling of mercury in the paleo Arctic Ocean from Hg stable isotope variations in Eocene and Quaternary sediments. *Geochimica et Cosmochimica Acta*. 197:245–262. <https://doi.org/10.1016/j.gca.2016.10.033>
- Hughes-Allen L et al. 2024. A 14,000-Year Sediment Record of Mercury Accumulation and Isotopic Signatures From Lake Malaya Chabyda (Siberia). *Journal of Geophysical Research: Biogeosciences*. 129(10). <https://doi.org/10.1029/2023JG007863>
- Jiskra M et al. 2017. Source tracing of natural organic matter bound mercury in boreal forest runoff with mercury stable isotopes. *Environmental Science: Processes and Impacts*. 19(10):1235–1248. <https://doi.org/10.1039/c7em00245a>
- Lepak RF et al. 2020. Resolving Atmospheric Mercury Loading and Source Trends from Isotopic Records of Remote North American Lake Sediments. *Environmental Science and Technology*. 54(15):9325–9333. <https://doi.org/10.1021/acs.est.0c00579>
- Lim SH et al. 2024. Near surface oxidation of elemental mercury leads to mercury exposure in the Arctic Ocean biota. *Nature Communications*. 15(1). <https://doi.org/10.1038/s41467-024-51852-2>
- Obrist D et al. 2017. Tundra uptake of atmospheric elemental mercury drives Arctic mercury pollution. *Nature*. 547(7662):201–204. <https://doi.org/10.1038/nature22997>
- Sherman LS et al. 2010. Mass-independent fractionation of mercury isotopes in Arctic snow driven by sunlight. *Nature Geoscience*. 3(3):173–177. <https://doi.org/10.1038/ngeo758>
- Sherman LS, Blum JD, Douglas TA, Steffen A. 2012. Frost flowers growing in the Arctic ocean-atmosphere-sea ice-snow interface: 2. Mercury exchange between the atmosphere, snow, and frost flowers. *Journal of Geophysical Research Atmospheres*. 117(3). <https://doi.org/10.1029/2011JD016186>
- Štrok M, Baya PA, Hintelmann H. 2015. The mercury isotope composition of Arctic coastal seawater. *Comptes Rendus - Geoscience*. 347(7–8):368–376. <https://doi.org/10.1016/j.crte.2015.04.001>
- Zdanowicz CM et al. 2016. Historical variations of mercury stable isotope ratios in Arctic glacier firn and ice cores. *Global Biogeochemical Cycles*. 30(9):1324–1347. <https://doi.org/10.1002/2016GB005411>

Appendix 3

Table A.3.1. Published studies with mercury isotope data for Arctic biota.

Biota	Ecosystem	Tissue	Sampling period	Region	Location	Source
Zooplankton: (mostly cladocerans and copepods) and fish: 11 species	Freshwater & Marine	Whole organisms	1998-2002	Subarctic, mostly outside AMAP area	Lake Ontario, Shipiskan Lake, Labrador Sea, Cli Lake, Northwest Territories, Canada	Jackson et al., (2008)
Fish: Arctic char (<i>Salvelinus alpinus</i>) and zooplankton, chironomids, insects	Freshwater	Bulk zooplankton and chironomids Arctic char muscle	2005-2007	High Arctic	10 lakes in Ellesmere Island, Cornwallis Island, Kent Peninsula, and Ungava Peninsula, Pingualuk, Canada	Gantner et al., (2009)
Birds: Common murre (<i>Uria aalge</i>) and thick-billed murre (<i>Uria lomvia</i>).	Marine	Sea bird eggs	1999–2002	Arctic	3 nesting sites in Alaska	Point et al., (2011)
Birds: Common murre (<i>Uria aalge</i>) Thick-billed murre (<i>Uria lomvia</i>)	Marine	Sea bird eggs	2008-2009	Arctic	Norton Sound & Bering Sea, Alaska	Day et al., (2012)
Humans (<i>Homo sapiens</i>) and Pilot whales (<i>Globicephala melas</i>)	Marine	Muscle (whales) Hair (humans)	2006 (whales) 1998 (hunters)	Subarctic, on the limit of the AMAP area	Faroe Islands, North Atlantic	Li et al., (2014)
Ringed seals (<i>Pusa hispida</i>)	Marine	Liver	1988-2002	Arctic	Barrow & Nome, Alaska	Masbou et al., (2015)
Invertebrates: blue mussel, (<i>Mytilus edulis</i>), fish: 16 species	Freshwater & Marine	Muscle	2014-2015	Subarctic, on the limit of the AMAP area	Lake Melville and Labrador Sea, Canada	Li et al., (2016)
Beluga whales (<i>Delphinapterus leucas</i>), Polar bears (<i>Ursus maritimus</i>), Ringed seals (<i>P. hispida</i>)	Marine	Liver	1988-2002	Arctic	Alaska	Masbou et al., (2018)
Fish: Tusk (<i>Brosme brosme</i>)	Marine	Liver and muscle	2013-2015	subarctic	Norwegian coast	Rua Iberz et al., (2019)
Sea birds: Little auk (<i>Alle alle</i>)	Marine	Blood and feathers	2015-2016	Arctic, subarctic	5 Arctic colonies, Hooker iskand, Bjørn øya, East Greenland, Spitsbergen and NW Greenland.	Renedo et al., (2020)
Pilot whales (<i>G. melas</i>), fish: blue whiting (<i>Micromesistius poutassou</i>), greater argentine (<i>Argentina silus</i>), and oceanic squid (<i>Todarodes sagittatus</i>)	Marine	Brain, kidney, liver, heart, and muscle	2016	Subarctic	Faroe islands, North Atlantic	Li et al., (2020)
Fish: Lake trout (<i>Salvelinus namaycush</i>), Sockeye salmon (<i>Oncorhynchus nerka</i>) and plankton	Freshwater	Bulk plankton samples Fish muscle	2011-2016	Subarctic	Lake Clark and Katmai, Alaska:	Lepak et al., (2022)
Hooded seal (<i>Cystophora cristata</i>)	Marine	Kidney, liver, hair and muscle	2012-2014	Subarctic	Greenland Sea	Pinzone et al., (2024)
Fish: Arctic cod (<i>Boreogadus saida</i>) and zooplankton	Marine		2022	Arctic	Bering Strait, the Chukchi Sea, and the Beaufort Sea, Alaska	Lim et al., (2024)
Birds: Common eider (<i>Somateria mollissima</i>), black-legged kittiwake (<i>Rissa tridactyla</i>) and the little auk (<i>A. alle</i>)	Marine	Egg yolk, albumen, membrane, and shell	2020	Arctic, subarctic	East Greenland	Charrier et al., (2024)
Birds: Common eider (<i>S. mollissima</i>)	Marine	Liver & muscle	2014-2017 & 2021	Subarctic	Hudson Bay and James Bay, Canada	Chételat et al.,(2024)
Fish: Atlantic bluefin tuna (<i>Thunnus thynnus</i>)	Marine	Spleen, kidney, stomach, intestine, gonad, gill, liver, brain, heart, bile, muscle and Pyloric cecum	August-October 2019/2020	Subarctic	Bergen, Norway	Wiech et al., (2024)

Biota	Ecosystem	Tissue	Sampling period	Region	Location	Source
Arctic char (<i>S. alpinus</i>), sculpin (<i>Myoxocephalus scorpius</i>) ringed seal (<i>P. hispida</i>), polar bear (<i>U. maritimus</i>), glaucous gull (<i>Larus hyperboreus</i>)	Marine, freshwater, terrestrial	Liver, muscle, hair	1983-2024 and long-term (>2500 years) time series in peat	Arctic, subarctic	Greenland Coast	Sondergaard et al., (2025)
Fish: European hake (<i>Merluccius merluccius</i>)	Marine	Muscle, fillet samples	2019–2022	Subarctic	Norwegian Coast	Zhu et al., (2025)

References for Appendix 3

- Charrier J et al. 2024. Mercury compound distribution and stable isotope composition in the different compartments of seabird eggs: The case of three species breeding in East Greenland. *Chemosphere*. 363. <https://doi.org/10.1016/j.chemosphere.2024.142857>
- Chételat J et al. 2024. River influence on mercury bioaccumulation in the coastal food web of Eeyou Istchee, James Bay, Canada. *FACETS*. 9:1–13. <https://doi.org/10.1139/facets-2023-0121>
- Day RD et al. 2012. Mercury stable isotopes in seabird eggs reflect a gradient from terrestrial geogenic to oceanic mercury reservoirs. *Environmental Science and Technology*. 46(10):5327–5335. <https://doi.org/10.1021/es2047156>
- Gantner N, Hintelmann H, Zheng W, Muir DC. 2009. Variations in stable isotope fractionation of Hg in food webs of Arctic lakes. *Environmental Science and Technology*. 43(24):9148–9154. <https://doi.org/10.1021/es901771r>
- Jackson TA, Whittle DM, Evans MS, Muir DCG. 2008. Evidence for mass-independent and mass-dependent fractionation of the stable isotopes of mercury by natural processes in aquatic ecosystems. *Applied Geochemistry*. 23(3):547–571. <https://doi.org/10.1016/j.apgeochem.2007.12.013>
- Lepak RF et al. 2022. Using Carbon, Nitrogen, and Mercury Isotope Values to Distinguish Mercury Sources to Alaskan Lake Trout. *Environmental Science and Technology Letters* 9(4):312–319. <https://doi.org/10.1021/acs.estlett.2c00096>
- Li M et al. 2014. Assessing sources of human methylmercury exposure using stable mercury isotopes. *Environmental Science and Technology*. 48(15):8800–8806. <https://doi.org/10.1021/es500340r>
- Li M et al. 2016. Environmental Origins of Methylmercury Accumulated in Subarctic Estuarine Fish Indicated by Mercury Stable Isotopes. *Environmental Science and Technology*. 50(21):11559–11568. <https://doi.org/10.1021/acs.est.6b03206>
- Li M et al. 2020. Selenium and stable mercury isotopes provide new insights into mercury toxicokinetics in pilot whales. *Science of the Total Environment*. 710. <https://doi.org/10.1016/j.scitotenv.2019.136325>
- Lim SH et al. 2024. Near surface oxidation of elemental mercury leads to mercury exposure in the Arctic Ocean biota. *Nature Communications*. 15(1). <https://doi.org/10.1038/s41467-024-51852-2>
- Masbou J et al. 2015. Hg Stable Isotope Time Trend in Ringed Seals Registers Decreasing Sea Ice Cover in the Alaskan Arctic. *Environmental Science and Technology*. 49(15):8977–8985. <https://doi.org/10.1021/es5048446>
- Masbou J et al. 2018. Hg-Stable Isotope Variations in Marine Top Predators of the Western Arctic Ocean. *ACS Earth and Space Chemistry*. 2(5):479–490. <https://doi.org/10.1021/acsearthspacechem.8b00017>
- Pinzone M et al. 2024. Dynamics of mercury stable isotope compounds in Arctic seals: New insights from a controlled feeding trial on hooded seals *Cystophora cristata*. *Environmental Pollution*. 358. <https://doi.org/10.1016/j.envpol.2024.124450>
- Point D et al. 2011. Methylmercury photodegradation influenced by sea-ice cover in Arctic marine ecosystems. *Nature Geoscience*. 4(3):188–194. <https://doi.org/10.1038/ngeo1049>
- Renedo M et al. 2020. Contrasting Spatial and Seasonal Trends of Methylmercury Exposure Pathways of Arctic Seabirds: Combination of Large-Scale Tracking and Stable Isotopic Approaches. *Environmental Science and Technology*. 54(21):13619–13629. <https://doi.org/10.1021/acs.est.0c03285>
- Rua-Ibarz A et al. 2019. Tracing Mercury Pollution along the Norwegian Coast via Elemental, Speciation, and Isotopic Analysis of Liver and Muscle Tissue of Deep-Water Marine Fish (*Brosme brosme*). *Environmental Science and Technology* 53(4):1776–1785. <https://doi.org/10.1021/acs.est.8b04706>
- Søndergaard J et al. 2025. Stable isotopes unveil ocean transport of legacy mercury into Arctic food webs. *Nature Communications*. 16(1). <https://doi.org/10.1038/s41467-025-60356-6>
- Wiech M et al. 2024. Organ-specific mercury stable isotopes, speciation and particle measurements reveal methylmercury detoxification processes in Atlantic Bluefin Tuna. *Journal of Hazardous Materials*. 473:134699. <https://doi.org/10.1016/j.jhazmat.2024.134699>
- Zhu Y et al. 2025. Distribution and trophic transfer of mercury and selenium in European hake (*Merluccius merluccius*) from the Northeast Atlantic Ocean: A stable isotope approach. *Journal of Hazardous Materials*. 494:138564. <https://doi.org/10.1016/j.jhazmat.2025.138564>

Acronyms and Abbreviations

AMAP	Arctic Monitoring and Assessment Programme
AMDE	Atmospheric mercury depletion event
BrCl	Bromine monochloride
CVG	Cold vapour generator
GEM	Gaseous elemental mercury
H ₂ O	Water
H ₂ O ₂	Peroxide
HCl	Hydrochloric acid
Hg	Mercury
Hg(II)	Divalent inorganic mercury
Hg(0)	Elemental mercury
^{xxx} Hg	Mercury stable isotope (where xxx is isotope 198, 199, 200, 201, 202, or 204)
δ ^{xxx} Hg	Delta mercury isotope value (where xxx is isotope 198, 199, 200, 201, 202, or 204)
Δ ^{xxx} Hg	Capital delta mercury isotope value (where xxx is isotope 198, 199, 200, 201, 202, or 204)
HNO ₃	Nitric acid
MC-ICP-MS	Multicollector Inductively Coupled Plasma Mass Spectrometry
MDF	Mass dependent fractionation
MeHg	Methylmercury
MIE	Magnetic isotope effect
MIF	Mass independent fractionation
N ₂	Nitrogen gas
NIST	National Institute of Standards and Technology
PHg	Particulate mercury
RGM	Reactive gaseous mercury
SnCl ₂	Stannous chloride
SRM	Standard reference material
SSB	Sample-standard bracketing
TGM	Total gaseous mercury
THg	Total mercury
Tl	Thallium
UN	United Nations
UNEP	United Nations Environment Programme

Arctic Monitoring and Assessment Programme

The Arctic Monitoring and Assessment Programme (AMAP) was established in June 1991 by the eight Arctic countries (Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden and the United States) to implement parts of the Arctic Environmental Protection Strategy (AEPS). AMAP is now one of six working groups of the Arctic Council, members of which include the eight Arctic countries, the six Arctic Council Permanent Participants (Indigenous Peoples' organizations), together with observing countries and organizations.

AMAP's objective is to provide 'reliable and sufficient information on the status of, and threats to, the Arctic environment, and to provide scientific advice on actions to be taken in order to support Arctic governments in their efforts to take remedial and preventive actions to reduce adverse effects of contaminants and climate change'.

AMAP produces, at regular intervals, assessment reports that address a range of Arctic pollution and climate change issues, including effects on health of Arctic human populations. These are presented to Arctic Council Ministers in 'State of the Arctic Environment' reports that form a basis for necessary steps to be taken to protect the Arctic and its inhabitants.

This report has been subject to a formal and comprehensive peer review process. The results and any views expressed in this series are the responsibility of those scientists and experts engaged in the preparation of the reports.

The AMAP Secretariat is located in Tromsø, Norway. For further information regarding AMAP or ordering of reports, please contact the AMAP Secretariat (The Fram Centre, P.O. Box 6606 Stakkevollan, N-9296 Tromsø, Norway) or visit the AMAP website at www.amap.no.

AMAP Secretariat

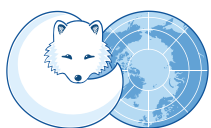
The Fram Centre,
P.O. Box 6606 Stakkevollan,
N-9296 Tromsø, Norway

T +47 21 08 04 80

F +47 21 08 04 85

www.amap.no

ISBN - 978-82-8440-000-6



ARCTIC COUNCIL

AMAP
Arctic Monitoring and
Assessment Programme

