Science of the Total Environment 722 (2020) 137832

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

The mercury science-policy interface: History, evolution and progress of the Minamata Convention

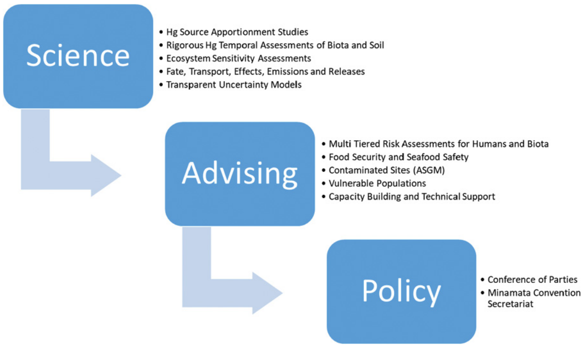
Michael S. Bank *

Department of Contaminants and Biohazards, Institute of Marine Research, Bergen, Norway
Department of Environmental Conservation, University of Massachusetts, Amherst, MA, USA

HIGHLIGHTS

- The Minamata Convention on Mercury (MCM) entered into force in August 2017.
- Hg post depositional processes and ecosystem sensitivity are important themes.
- Hg models have important limitations and increased transparency is needed.
- Valid temporal assessments of Hg in biota need to evaluate concomitant changes in food webs.
- The MCM will benefit from treating Hg pollution as a food security issue.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 November 2019
Received in revised form 4 March 2020
Accepted 8 March 2020
Available online 10 March 2020

Keywords:
Mercury
Minamata Convention
Science
Policy

ABSTRACT

Mercury (Hg) pollution is an important environmental and public health issue that has garnered significant interest from policy makers and the global regulatory community. Consumption of seafood is the primary mechanism of methyl Hg (MeHg) exposure in humans, globally, and marine fish represent an important linkage between atmospheric dynamics, aquatic biogeochemistry and trophic transfer of this highly neurotoxic and easily assimilated form of Hg. Hg policies and management are highly interdisciplinary and at their foundation are relatively well established scientific principles related to Hg methylation, MeHg cycling and bioaccumulation, and subsequent trophic transfer to humans; however, certain fine-scale aspects of these processes remain poorly understood. After several years of intergovernmental negotiations the Minamata Convention on Mercury (MCM) entered into force in August 2017. Anthropogenic releases (water) and emissions (air) of Hg, human exposure, and environmental health are of considerable importance within the framework and policies outlined in the MCM. Additionally, the overall risk of Hg from artisanal and small-scale gold mining (ASGM) is considered a significant source of human exposure and commonly occurs in low and middle income countries, where miners use elemental Hg to extract gold from ore. Here I outline the history, evolution and progress of the MCM as it relates to the science-policy interface and offer a brief synthesis of the state of Hg science in the context of modeling, temporal assessments of Hg trends and global environmental change and ecosystem sensitivity.

1. Introduction

Mercury (Hg) pollution is an environmental and public health issue that is of global concern, and in August 2017 the United Nations Minamata Convention on Mercury (MCM) entered into force. The

---

* Institute of Marine Research, P.O. Box 1870 Nordnes, Bergen 5005, Norway.
E-mail address: Michael.Bank@hi.no.

https://doi.org/10.1016/j.scitotenv.2020.137832

primary goal of the convention is to reduce emissions (air) and releases (water) of anthropogenic Hg and to protect the environment and human health. Sources of Hg include atmospheric emissions from coal and industrial processes, including cement production, as well as artisanal and small-scale gold mining (ASGM) activities (minamataconvention.org). All emissions to the atmosphere have the potential to be distributed globally, and to be deposited to any surface of the Earth. Although elemental Hg can be readily deposited to surfaces, it also has the potential to be emitted back to the atmosphere, and this cycle can occur many times. Deposition is facilitated by oxidation of elemental Hg to a variety of gaseous oxidized forms depending on the chemistry of the air (Sprovieri et al., 2005). These Hg (II) compounds have high deposition velocities, are deposited readily, and then enter ecosystems, where they are more easily methylated than elemental Hg (Hu et al., 2013). Methylation of inorganic mercury to the more toxic and bioavailable organic forms, provides an efficient pathway into food webs. Because Hg is bioaccumulated in organisms, and biomagnified in food webs this results in high exposures for those consuming organisms at high tropic levels. In addition, pristine ecosystems are impacted by Hg deposition, resulting in impact to organisms remote from any direct sources of Hg (Fitzgerald et al., 1998).

Recent summaries of Hg science and policy (Bank et al., 2014; Evers et al., 2016; Gustin et al., 2016; Platjouw et al., 2018; Basu, 2018; Chen et al., 2018; Selin et al., 2018; Kwon et al., 2020) have identified many relevant biomonitoring needs and scientific advances that have furthered our understanding of the Hg cycle, which is inherently complex. Here I provide an overview of the history, evolution and progress of mercury science and policy in the context of the MCM. Specifically I outline and focus on three major avenues of Hg research that are highly relevant to the MCM including: a) temporal assessments of Hg in fish and wildlife, b) Hg stable isotopes and source apportionment modeling, and c) the interaction between atmospheric mercury and ecosystem sensitivity. Recent advances in human health have been covered elsewhere (Basu et al., 2018; Eagles-Smith et al., 2018; Budnik and Casteleyen, 2019).

2. History of mercury policy related to the Minamata Convention on mercury

Members of the scientific community, from academia, government, and industry, along with environmental regulators have played a critical role in the establishment of the MCM. Furthermore, regional scientists and policymakers from the Arctic monitoring and assessment working group (AMAP) were also critical to the development of the MCM and associated texts (Platjouw et al., 2018). Collectively these efforts represent a significant organizational and global diplomatic achievement (Bank et al., 2019). Fig. 1 outlines the timeline and the history of the MCM along with the associated intergovernmental negotiations and diplomatic events. A critical year for the MCM was 2013, when the treaty was agreed upon during the 5th session of the Intergovernmental Negotiating Committee in January at Geneva, Switzerland. Later that year, in October, the MCM was fully adopted at the Diplomatic Conference held in Kumamoto, Japan (Fig. 1, minamataconvention.org; Platjouw et al., 2018).

The MCM (Article 1), by design, is focused on protecting human health and the environment from anthropogenic emissions and releases of mercury. Moreover, the MCM was successful in highlighting the challenges of this ubiquitous pollutant by addressing the issue at global, regional, and local scales (minamataconvention.org). The MCM (Article 7) also outlines the importance of mercury in supply and trade and the implications of ASGM with regard to environmental and public health (minamataconvention.org). ASGM is of considerable importance considering that approximately 1000 tons of Hg from tailings and vaporization are released each year, and that between 10 and 19 million people from >70 countries (Fig. 2) use Hg in the ASGM process (Esdaile and Chalker, 2018). However, these estimates and predictions are highly uncertain and not well constrained (Streets et al., 2009) and the biogeochemical effects of ASGM may occur at more local scales than global ones especially when compared to more globally relevant sources including long-range Hg atmospheric deposition from coal-fired plants and cement factories. There is scientific evidence to support the insignificance of ASGM as a global source and not observed as predicted by Streets et al. (2009) in the ocean or remote terrestrial locations. Data from sediment cores collected in remote areas (Fitzgerald et al., 2005) and from global ocean inventories (Lamborg et al., 2014) suggest that ASGM is not a significant global air-ocean perturbance in comparison to long range hemispheric transport of Hg from anthropogenic sources identified above. Further research on this topic is desperately needed in order to fill these important knowledge gaps and to identify the spatial scale and extent of the ASGM problem within the context of the global mercury cycle.

The MCM exists at the science-policy interface that is inherently complex, because providing scientific advice to policy makers often occurs within an interdisciplinary framework that involves political and social spheres. Moreover, there can be no guarantees that policymakers will actually accept and follow sound scientific advice that is provided to them (Gluckman, 2016). Fortunately, several aspects of the MCM are based on sound scientific evidence and support with regard to the major drivers of Hg pollution to the environment as well as human exposure regimes, however critical questions still remain. For example, it is fairly well established that the Hg cycle interacts with and is interwoven with the carbon and selenium cycles, and that climate change and other perturbations need to be considered when evaluating Hg pollution regimes (Obrist et al., 2018). However, details on these processes are still poorly understood despite considerable focus on these integrated topics of the Hg cycle.

3. Recent scientific advances relevant to the Minamata convention on mercury

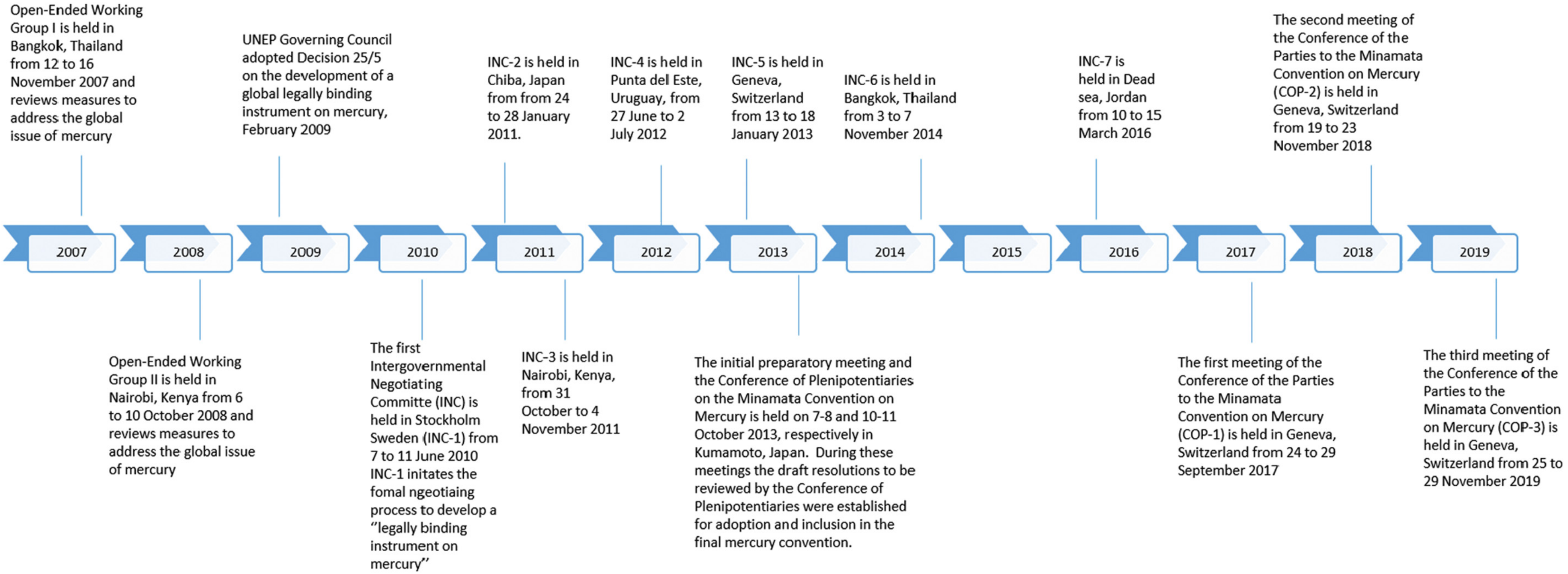
Several recent advances in mercury research relevant to the MCM are outlined in this special issue as well as in a companion Hg special issue of *Science of the Total Environment* published in 2019 (Bank et al., 2019) and in other sources (Chen et al., 2018, Eagles-Smith et al., 2018; Obrist et al., 2018; Hsu-Kim et al., 2018; Selin et al., 2018).

3.1. Temporal assessment of mercury in fish and wildlife and the Minamata Convention on mercury

Effectiveness evaluation (Article 22) of the MCM is foundational to its success. An important component of this evaluation is to identify temporal trends of Hg in selected environmental matrices. The Conference of Parties is ultimately responsible for deciding which matrices will be used in the MCM effectiveness evaluation and air, soils, seawater and biota have been identified as potential indicators. Biota Hg data are often collected by existing regional and national biomonitoring programs, and will be essential to a robust and statistically sound global monitoring program in support of the MCM.

Temporal assessments of Hg exist for a wide array of organisms (Braune, 2007; Braune et al., 2014; Braune et al., 2016; Vo et al., 2011; Wang et al., 2019), although temporal data for seafood species (Cross et al., 2015; Drevnick et al., 2015; Lee et al., 2016), and for marine fish in general, are lacking (Grieb et al., 2019) despite their important linkages with seafood safety, food security, and ocean and human health (Knowlton, 2004).

In a recent review paper Wang et al. (2019) reported that temporal patterns of Hg in biota were often not reflective of the concomitant atmospheric Hg deposition and suggested that the cumulative and interactive effects of legacy Hg, local and regional processes, as well as climate change were likely responsible for this lack of accordance between biota and atmospheric Hg data. To account for this divergence in atmospheric and biotic Hg concentrations, Wang et al. (2019) further



Open-Ended Working Group I is held in Bangkok, Thailand from 12 to 16 November 2007 and reviews measures to address the global issue of mercury

Open-Ended Working Group II is held in Nairobi, Kenya from 6 to 10 October 2008 and reviews measures to address the global issue of mercury

UNEP Governing Council adopted Decision 25/5 on the development of a global legally binding instrument on mercury, February 2009

The first Intergovernmental Negotiating Committe (INC) is held in Stockholm Sweden (INC-1) from 7 to 11 June 2010 INC-1 initates the fomal ngeotiaing process to develop a "legally binding instrument on mercury"

INC-2 is held in Chiba, Japan from from 24 to 28 January 2011.

INC-3 is held in Nairobi, Kenya, from 31 October to 4 November 2011

INC-4 is held in Punta del Este, Uruguay, from 27 June to 2 July 2012

INC-5 is held in Geneva, Switzerland from 13 to 18 January 2013

The initial preparatory meeting and the Conference of Plenipotentiaries on the Minamata Convention on Mercury is held on 7-8 and 10-11 October 2013, respectively in Kumamoto, Japan. During these meetings the draft resolutions to be reviewed by the Conference of Plenipotentiaries were established for adoption and inclusion in the final mercury convention.

INC-6 is held in Bangkok, Thailand from 3 to 7 November 2014

INC-7 is held in Dead sea, Jordan from 10 to 15 March 2016

The first meeting of the Conference of the Parties to the Minamata Convention on Mercury (COP-1) is held in Geneva, Switzerland from 24 to 29 September 2017

The second meeting of the Conference of the Parties to the Minamata Convention on Mercury (COP-2) is held in Geneva, Switzerland from 19 to 23 November 2018

The third meeting of the Conference of the Parties to the Minamata Convention on Mercury (COP-3) is held in Geneva, Switzerland from 25 to 29 November 2019

Fig. 1. Timeline and history of the negotiations process and the evolution of the Minamata Convention on Mercury. Data are from minamataconvention.org.

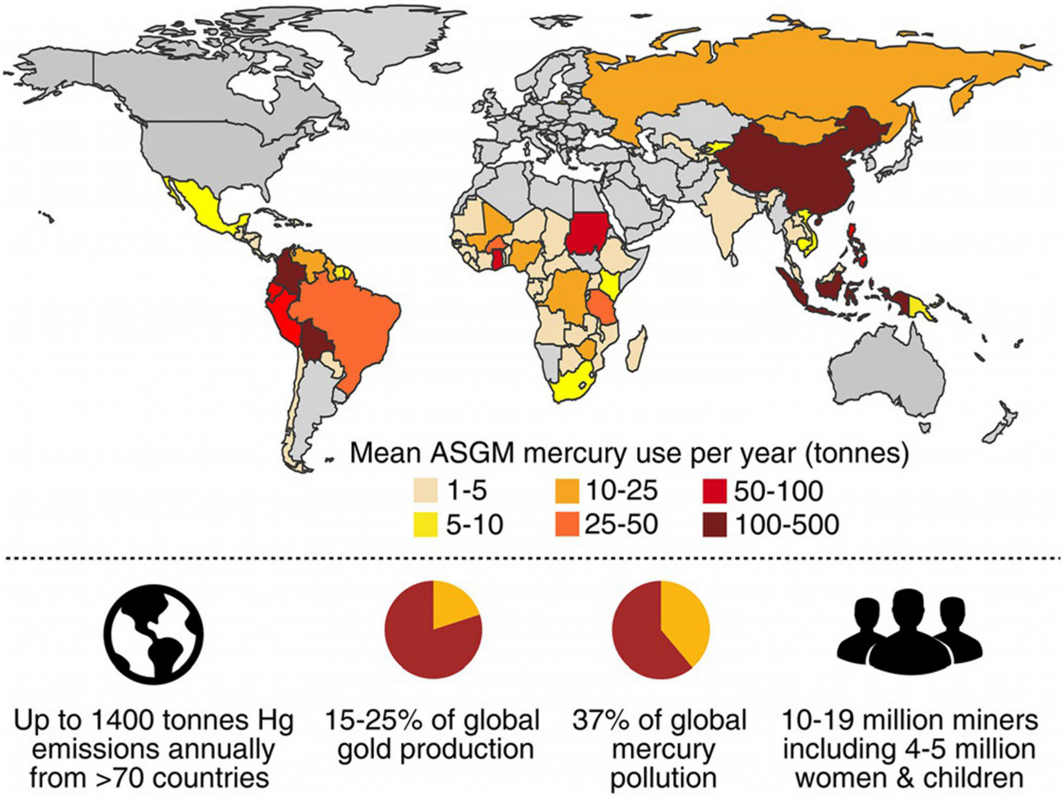


Fig. 2. Estimated annual mercury use in artisanal and small-scale gold mining (ASGM). Figure reproduced from Esdaile and Chalker (2018) and used with permission (Attribution-Non Commercial 4.0 International, Creative Commons BY-NC 4.0 https://creativecommons.org/licenses/by-nc/4.0/).

recommended that the effectiveness evaluation of the MCM will require a comprehensive biomonitoring program that measures multiple taxa across trophic levels and throughout different regions of the world. Additionally, the importance of changes in species diet or the food web must be accounted for in order for temporal analyses of Hg in biota to be truly valid, and to differentiate between source driven and process driven Hg bioaccumulation trends over time (Braune et al., 2014; Braune et al., 2016). Despite their limitations, the use of bulk carbon and nitrogen stable isotope signatures will be important with regard to tracking changes in the food web concomitantly with Hg data (Braune et al., 2014), and compound specific stable isotope analysis of amino acids can mitigate potential limitations of these analytical tools, and offer higher resolution assessments of both energy sources (C) and trophic position (N) (Ishikawa, 2018).

3.2. Stable isotopes, source apportionment modeling and the Minamata Convention on mercury

Mercury has seven stable isotopes that may be measured in high precision. Use of isotopic data can provide valuable insights into the sources fate, transport, and pathways of Hg and MeHg in complex and heterogeneous environments (Berquist and Blum, 2007; Hintelmann, 2012; Basu, 2018). Source apportionment (SA) modeling has important implications for the MCM effectiveness evaluation (Article 23; Kwon et al., 2020) and global monitoring programs (Article 22), but these isotopic analyses may be limited by higher costs and lower laboratory throughput compared to Hg and MeHg concentration measurements. That said, Hg isotope data can provide a framework for SA assessment of Hg and MeHg on a wide array of environmental samples, and will be critical for identifying origins of different geochemical pools of Hg and MeHg from natural and anthropogenic sources, including the atmosphere, across spatial gradients. Furthermore, Hg SA models can be conducted temporally in soils and biota to track changes in isotopic signatures (Lepak et al., 2019) allowing for the development of a high resolution assessment of the effectiveness of the MCM in the context of a global Hg monitoring program (Kwon et al., 2020).

3.3. Atmospheric mercury, ecosystem sensitivity and the Minamata Convention on mercury

The atmospheric and post deposition processes (Wang et al., 2010; Gustin et al., 2016), including Hg methylation and demethylation kinetics, are highly complex and these are important factors governing the bioaccumulation of Hg in biota and overall source-receptor dynamics (Bank, 2012). Moreover, atmospheric loadings do not always translate into equal rates of exposure and bioaccumulation of MeHg and Hg in biota due to differences in ecosystem sensitivity and its subsequent effects on Hg methylation, demethylation, and the overall bioaccumulation regime (Bank et al., 2005). For example, empirical studies have shown that ecosystems may have higher deposition of total Hg, but significantly lower overall MeHg and total Hg bioaccumulation in terrestrial biota (Bank et al., 2005; Shanley et al., 2019). Conversely, experimental investigations have reported a linear relationship between increasing inorganic Hg loading and MeHg bioaccumulation in biota (Orihel et al., 2007). Other experimental research has demonstrated the importance of differential availability of Hg geochemical pools on MeHg bioaccumulation, and have shown that MeHg loadings from atmospheric sources and terrestrial runoff were more important than MeHg formed *in situ* in sediments (Jonsson et al., 2014). Furthermore, field studies by Hammerschmidt and Fitzgerald (2005, 2006) reported strong relationships between atmospheric Hg loadings and MeHg concentrations in both mosquitoes species and largemouth bass (*Micropterus salmoides*), suggesting this phenomenon can occur in biota at broad spatial scales, across trophic levels and in a wide array of habitats and under varying biogeochemical conditions. Collectively, these studies demonstrate that the findings from studies addressing atmospheric loadings, ecosystem sensitivity, Hg methylation, and trophic transfer and bioaccumulation of Hg vary considerably, and have significant uncertainties. This makes it difficult for policy makers and decision makers to come to consensus. These groups will likely benefit from a more holistic, weight of evidence perspective and one that considers post-depositional processes (Wang et al., 2010) with regard to the development of robust monitoring programs using harmonized data sampling protocols (Bank et al., 2014) in support of the MCM (Wang et al., 2019) effectiveness evaluation.

4. Modeling and the Minamata Convention on mercury

"*All models are wrong, but some are useful*" is an important concept put forward by the renowned British statistician George Box (Box, 1976). The reason that this aphorism is so important is that policy makers do not often realize that models rely on hypotheses and, at times, completely unrealistic assumptions. Modeling of Hg in different ecosystem reservoirs is highly uncertain (Selin, 2014; Gustin et al., 2016), and in comparison to other pollutants, such as nitrogen or sulfur, Hg models often do not have strong model validation, are limited in scale or rely on extremely small sample sizes to describe large ecosystems such as marine environments (Schartup et al., 2019). Under the MCM these uncertainties will likely increase due to regulation of emissions and releases, as well as changes in atmospheric chemistry and biogeochemical conditions related to natural and legacy sources of Hg (Kwon and Selin, 2016). Moreover, simply using Hg and MeHg data from the literature is also problematic due to a lack of sampling and measurement standardization, biases associated with missing values and limited geographical coverage, non-linear correlations, multifactorial effects (as opposed to unifactorial) and the major issues associated with the transfer of biases and errors from the original sources to the final synthesis. Additionally, even a small violation of the assumptions or deviation from the basic principles of a meta-analysis can lead to misleading conclusions (Greco et al., 2013).

Factors related to climate and ecosystem change (Jonsson et al., 2017), food web dynamics (Braune et al., 2014; Braune et al., 2016), post depositional processes (Wang et al., 2010), and the overall inherent complexities of source-receptor dynamics (Bank, 2012), collectively, presents some critical challenges for the MCM effectiveness evaluation. Furthermore, Hg inventories tend to be incredibly coarse, including those used in the Minamata initial assessments, and thus, these low resolution estimates are also a considerable source of uncertainty for source-receptor models especially since reporting among countries can be inconsistent. Collectively all of the uncertainties combined are significant and represent a substantial degree of experiment wide and prediction errors especially for Hg modeling efforts at regional and global scales. In all fairness, and from an honest broker perspective (Platjouw et al., 2018), policymakers must take note of model uncertainties and recognize that these efforts do not truly reflect reality and have limited or no ability to forecast future Hg conditions and regimes. Additionally, the Hg modeling community will also need to be more transparent with regard to reporting Hg model hypotheses, assumptions and their high degree of uncertainty when communicating with policymakers and the MCM secretariat.

5. Conclusions

Mercury pollution is inherently a chemistry problem (Esdaile and Chalker, 2018), but also an important seafood safety and food security issue. New ways of thinking about this important environmental contaminant will be required in order to address this issue more holistically within the framework of MCM especially considering the incredibly short time frame, of six years, for the initial effectiveness evaluation. Establishing MCM regional centers of excellence similar to the Basel and Stockholm Convention Centers will likely enhance capacity building and transfer of available technology to parties from developing countries (Bank et al., 2014). Such centers would require a diverse set of expertise in order to meet the challenges of the implementation of the MCM with regard to providing technical assistance capacity building and support for biomonitoring programs.

Since Hg cycling and exposure dynamics are highly complex, multi-tiered risk assessments that focus on ecological health and human health separately will be required to meet their objectives. Fish consumption advisories and overall Hg exposure guidance will vary for the general human population in comparison to vulnerable populations such as ASGM miners, subsistence fishers, and individuals from indigenous communities that rely on wild food for sustenance. Additionally, the MCM should continue its focus on contaminated sites and vulnerable human populations as priorities. In general Hg science and policy will likely benefit from furthering the development of Hg research at the food-environment nexus (Sedlak, 2019) and integrating seafood safety and food security themes and approaches into the framework of the MCM.

Finally, Hg science and policy has come a long way over the last 30 years with important advancements made in understanding atmospheric chemistry, methylation and demethylation dynamics, Hg stable isotope SA modeling, sampling and analytical advancements and food web studies in heterogeneous environments. Hg is the only element on the periodic table to have its own environmental convention highlighting the importance of the Hg pollution issue. As a scientific community it is critical that Hg scientists use more integrated approaches (Basu, 2018), in order to advance policy relevant science and to serve as a resource for capacity building in developing countries and to support the conference of parties and the implementation of the MCM.

CRediT authorship contribution statement

Michael S. Bank: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Visualization, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by financing provided by the Norwegian Ministry of Trade, Industry and Fisheries to M.S.B.

References

Bank, M.S. (Ed.), 2012. Mercury in the Environment: Pattern and Process. University of California, Berkeley, CA USA (360 pages).

Bank, M.S., Loftin, C.S., Jung, R.E., 2005. Mercury bioaccumulation in northern two-lined salamanders from streams in the Northeastern United States. Ecotoxicology 14, 181–191.

Bank, M.S., Vignati, D.A., Vigon, B., 2014. United Nations Environment Programme's Global Mercury Partnership: science for successful implementation of the Minamata Convention. Environ. Toxicol. Chem. 33, 1199–1201.

Bank, M.S., Rinklebe, J., Feng, X., Xiaoyu, X., Lin, J., 2019. Mercury cycling and bioaccumulation in a changing environment. Sci. Total Environ. 670, 345.

Basu, N., 2018. The Minamata Convention on Mercury and the role for the environmental sciences community. Environ. Toxicol. Chem. 37, 2951–2952.

Basu, N., Horvat, M., Evers, D.C., Zastenskaya, I., Weihe, P., Tempowski, J., 2018. A state-of-the-science review of mercury biomarkers in human populations worldwide between 2000 and 2018. Environ. Health Perspect. 126. https://doi.org/10.1289/EHP3904.

Berquist, B.A., Blum, J.D., 2007. Mass-dependent and independent fractionation of hg isotopes by photoreduction in aquatic systems. Science 318, 417–420.

Box, G.E.P., 1976. Science and statistics. J. Am. Stat. Assoc. 71, 791–799.

Braune, B.M., 2007. Temporal trends of organochlorines and mercury in seabird eggs from the Canadian Arctic, 1975 to 2003. Environ. Pollut. 148, 599–613.

Braune, B.M., Gaston, A.J., Hobson, K.A., Gilchrist, G.G., Mallory, M.L., 2014. Changes in food web structure alter trends in mercury uptake at two seabird colonies in the Canadian Arctic. Environ. Sci. Technol. 48, 13246–13252.

Braune, B.M., Gaston, A.J., Mallory, M.L., 2016. Temporal trends of mercury in eggs of five sympatrically breeding seabird species in the Canadian Arctic. Environ. Pollut. 2016 (214), 124–131.

Budnik, L.T., Casteleyen, L., 2019. Mercury pollution in modern times and its socio-medical consequences. Sci. Total Environ. 654, 720–734.

Chen, C.Y., Driscoll, C.T., Eagles-Smith, C.A., Eckley, C.S., Gay, D.A., Hsu-Kim, H., Keane, S.E., Kirk, J.L., Mason, R.P., Obrist, D., Selin, H., Selin, N.E., Thompson, M.R., 2018. A critical time for mercury science to inform global policy. Environ. Sci. Technol. 52, 9556–9561.

Cross, F.A., Evans, D.W., Barber, R.T., 2015. Decadal declines of mercury in adult bluefish (1972–2011) from the Mid-Atlantic Coast of the USA. Environ. Sci. Technol. 49, 9064–9072.

Drevnick, P.E., Lamborg, C.H., Horgan, M.J., 2015. Increase in mercury in Pacific yellowfin tuna. Environ. Toxicol. Chem. 34, 931–934.

Eagles-Smith, C.A., Silbergeld, E.K., Basu, N., Bustamante, P., Diaz-Barriga, F., Hopkins, W.A., Kidd, K.A., Nyland, J.F., 2018. Modulators of risk to wildlife and humans in the context of rapid global change. Ambio 47, 170–197.

Esdaile, L.J., Chalker, J.M., 2018. The mercury problem in artisanal and small-scale gold mining. Chem. Eur. J. 24, 6905.

Evers, D.S., Keane, S.E., Basu, N., Buck, D., 2016. Evaluating the effectiveness of the Minamata Convention on Mercury: principles and recommendations for next steps. Sci. Total Environ. 569–570, 888–903.

Fitzgerald, W.F., Engstrom, D.R., Mason, R.P., Nater, E.A., 1998. The case for atmospheric mercury contamination in remote areas. Environ. Sci. Technol. 32, 1–7.

Fitzgerald, W.F., Engstrom, D.R., Lamborg, C.H., Tseng, C.-M., Balcom, P.H., Hammerschmidt, C.R., 2005. Modern and historic atmospheric mercury fluxes in northern Alaska: global sources and arctic depletion. Environ. Sci. Technol. 39, 557–568.

Gluckman, P., 2016. The science–policy interface. Science 353, 969.

Greco, T., Zangrillo, A., Biondi-Zoccal, G., Landoni, G., 2013. Meta-analysis pitfalls and hints. Heart Lung Vessel 5, 219–225.

Grieb, T.M., Fisher, N.S., Karimi, R., Levin, L., 2019. An assessment of temporal trends in mercury concentrations in fish. Ecotoxicology, 1–11 https://doi.org/10.1007/s10646-019-02112-3.

Gustin, M.S., Evers, D.C., Bank, M.S., Hammerschmidt, C.R., Pierce, A., Basu, N., Blum, J., Bustamante, P., Chen, C.Y., Driscoll, C.T., Horvat, M., Jaffe, D., Pacyna, J., Pirrone, N., Selin, N., 2016. Importance of integration and implementation of emerging and future mercury research into the minamata convention. Environ. Sci. Technol. 50, 2767–2770.

Hammerschmidt, C.R., Fitzgerald, W.F., 2005. Methylmercury in mosquitoes related to atmospheric mercury deposition and contamination. Environ. Sci. Technol. 39, 3034–3039.

Hammerschmidt, C.R., Fitzgerald, W.F., 2006. Methylmercury in freshwater fish linked to atmospheric mercury deposition. Environ. Sci. Technol. 40, 7764–7770.

Hintelmann, H.H., 2012. Use of Stable Isotopes in Mercury Research. Pages 55–72 in M.S. Bank (Editor) Mercury in the Environment: Pattern and Process. University of California, Berkeley, CA USA (360 pages).

Hu, H., Lin, H., Zheng, W., Tomanicek, S.J., Johs, A., Feng, X., Elias, D.A., Liang, L., Gu, B., 2013. Oxidation and methylation of dissolved elemental mercury by anaerobic bacteria. Nat. Geosci. 6, 751–754.

Hsu-Kim, H., Eckley, C.S., Achá, D., Feng, X., Gilmour, C.C., Jonsson, S., Mitchell, C., 2018. Challenges and opportunities for managing aquatic mercury pollution in altered landscapes. Ambio 47 (2), 141–169. https://doi.org/10.1007/s13280-017-1006-7.

Ishikawa, N.F., 2018. Use of compound-specific nitrogen isotope analysis of amino acids in trophic ecology: assumptions, applications, and implications. Ecol. Res. 33, 825–837.

Jonsson, S., Skyllberg, U., Nilsson, M.B., Lundberg, E., Andersson, A., Björn, E., 2014. Differentiated availability of geochemical mercury pools controls methylmercury levels in estuarine sediment and biota. Nat. Commun. 5, 4624.

Jonsson, S., Andersson, A., Nilsson, M.B., Skyllberg, U., Lundberg, E., Schaefer, J.K., Åkerblom, S., Björn, E., 2017. Terrestrial discharges mediate trophic shifts and enhance methylmercury accumulation in estuarine biota. Sci. Adv. 3, e1601239.

Knowlton, N., 2004. Ocean health and human health. Environ. Health Perspect. 112, A262.

Kwon, S.Y., Selin, N.E., 2016. Uncertainties in atmospheric mercury modeling for policy evaluation. Curr. Pollut. Rep. 2, 103. https://doi.org/10.1007/s40726-016-0030-8.

Kwon, S.Y., Blum, J.D., Yin, R., Tsui, M.T.K., Yang, Y.-H., Choi, J.W., 2020. Mercury stable isotopes for monitoring the effectiveness of the Minamata Convention on Mercury. Earth Sci. Rev. 203, 103111.

Lamborg, C.H., Hammerschmidt, C.R., Bowman, K.L., Swarr, G.J., Munson, K.M., Ohnemus, D.C., Lam, P.J., Heimbürger, L.-E., Rijkenberg, M.J.A., Saito, M.A., 2014. A global ocean inventory of anthropogenic mercury based on water column measurements. Nature 512, 65–68.

Lee, C.S., Lutcavage, M.E., Chandler, E., Madigan, D.J., Cerrato, R.M., Fisher, N.S., 2016. Declining mercury concentrations in bluefin tuna reflect reduced emissions to the North Atlantic Ocean. Environ. Sci. Technol. 50, 12825–12830.

Lepak, R.F., Hoffman, J.C., Janssen, S.E., Krabbenhoft, D.P., Ogorek, J.M., DeWild, J.F., Tate, M.T., Babiarz, C.L., Yin, R., Murphy, E.W., Engstrom, D.R., Hurley, J.P., 2019. Mercury source changes and food web shifts alter contamination signatures of predatory fish from Lake Michigan. Proc. Natl. Acad. Sci. 116, 23600–23608. https://doi.org/10.1073/pnas.1907484116.

Minamataconvention.org. Minamata Convention on Mercury (website). Accessed November 11, 2019.

Obrist, D., Kirk, J.L., Zhang, L., Sunderland, E.M., Jiskra, M., Selin, N.E., 2018. A review of global environmental mercury processes in response to human and natural perturbations: changes of emissions, climate, and land use. Ambio 47, 116–140.

Orihel, D.M., Paterson, M.J., Blanchfield, P.J., Bodaly, R.A., Hintelmann, H., 2007. Experimental evidence of a linear relationship between inorganic mercury loading and methylmercury accumulation by aquatic biota. Environ. Sci. Technol. 41, 4952–4958.

Platjouw, F.M., Steindal, E.H., Borch, T., 2018. From arctic science to international law: the road towards the Minamata Convention and the role of the arctic council. Arct. Rev. Law Polit. 9, 226–243.

Schartup, A.T., Thackray, C.P., Qureshi, A., Dassuncao, C., Gillespie, K., Hanke, A., Sunderland, E.M., 2019. Climate change and overfishing increase neurotoxicant in marine predators. Nature 572, 648–650.

Sedlak, D.L., 2019. The food-environment nexus. Environ. Sci. Technol. 53, 6597–6598.

Selin, N.E., 2014. Global change and mercury cycling: challenges for implementing a global mercury treaty. Environ. Toxicol. Chem. 33, 1202–1210.

Selin, H., Keane, S.E., Wang, S., Selin, N.E., Davis, K., Bally, D., 2018. Linking science and policy to support the implementation of the Minamata Convention on Mercury. Ambio 47, 198–215.

Shanley, J.B., Marvin-DiPasquale, M., Lane, O., et al., 2019. Resolving a paradox—high mercury deposition, but low bioaccumulation in northeastern Puerto Rico. Ecotoxicology https://doi.org/10.1007/s10646-019-02108-z.

Sprovieri, F., Pirrone, N., Landis, M.S., Stevens, R.K., 2005. Oxidation of gaseous elemental mercury to gaseous divalent mercury during 2003 polar sunrise at Ny-Alesund. Environ. Sci. Technol. 39, 9156–9165.

Streets, D.G., Zhang, Q., Wu, Y., 2009. Projections of global mercury emissions in 2050. Environ. Sci. Technol. 43, 2983–2988.

Vo, A.T.E., Bank, M.S., Shine, J.P., Edwards, S.V., 2011. Temporal increase in organic mercury in an endangered pelagic seabird assessed by century-old museum specimens. Proc. Natl. Acad. Sci. 108, 7466–7471.

Wang, F., Macdonald, R.W., Stern, G.A., Outridge, P.M., 2010. When noise becomes the signal: chemical contamination of aquatic ecosystems under a changing climate. Mar. Pollut. Bull. 60, 1633–1635.

Wang, F., Outridge, P.M., Feng, X., Meng, B., Heimbürger-Boavida, L.E., Mason, R.P., 2019. How closely do mercury trends in fish and other aquatic wildlife track those in the atmosphere? – implications for evaluating the effectiveness of the Minamata Convention. Sci. Total Environ. 674, 58–70.