Global Change and Mercury Cycling: Challenges for Implementing a Global Mercury Treaty

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Abstract

The Minamata Convention aims to protect human health and the environment from anthropogenic emissions and releases of mercury. The provisions of the Minamata Convention are examined to assess their influence on global biogeochemical cycling of mercury. Though the Convention's scope covers all major categories of atmospheric emissions, the degree to which it will affect future emissions trajectories remains unclear. A box model analysis shows that future global biogeochemical cycling under projected technological provisions would mainly result in avoided increases, and that estimated differences in atmospheric concentrations resulting from policies would be on the order of 1-2% per year. Present experience suggests that scientific knowledge at present is not sufficient to attribute causes to changes of this magnitude. Enhancements to capacity to measure the effectiveness of the Minamata Convention are suggested, including both measurement and modeling.

1. Introduction

Numerous policy actions have been taken at national and international level over the past several decades to reduce mercury contamination in the environment, with the goal of preventing toxic impacts on ecosystems and human health [1]. This now includes a global treaty to reduce mercury pollution, the 2013 Minamata Convention [2,3]. A global agreement on mercury has the potential to reduce harms to both humans and the environment, but it is as yet unclear whether and how much implementation of the Minamata Convention will lead to environmental improvements. Measuring the effectiveness of environmental policy implementation requires both understanding the baseline status in the absence of policy and evaluating the changes introduced by policy action.

A major scientific basis for negotiating a global-scale mercury treaty has been that human influences have dramatically altered the global biogeochemical cycle of mercury relative to a pre-industrial baseline [4]. Previous scientific work has focused on identifying human influences on global biogeochemical cycling of mercury [5-7], and its potential response to policy action. For example, Sunderland and Selin [8] argued that aggressive anthropogenic emission reductions are needed to reduce methylmercury exposures and associated health impacts on humans and wildlife. Corbitt et al. [9] calculated the impact of future global emission scenarios on mercury deposition, with a goal of informing future policy development and effectiveness evaluation. Mason et al. [10] suggest that methylmercury in fish should respond on timescales of years or decades to changes in atmospheric mercury inputs achieved by regulatory control strategies at global scale.

With the finalization of Minamata Convention in January 2013, it is now possible to evaluate existing global-scale mercury policies. While aspects of the Minamata Convention could have a range of benefits on local, regional and global scales, I evaluate here its potential impact on the amount of mercury entering the global environment, focusing on the issue of global biogeochemical cycling as an issue of specific interest to the scientific community. In section 2, present mercury emissions and uses with likely changes under Convention provisions are compared. In section 3, a box model is used to quantify potential biogeochemical cycle changes expected given likely emission changes. Section 4 explores whether the necessary scientific knowledge about the mercury cycle is sufficient to evaluate the effectiveness of a mercury treaty at addressing the global budget of mercury, considering uncertainties in our ability to measure and attribute changes in mercury cycling, particularly in the context of ongoing climate change. Section 5 then reviews mechanisms in the Minamata Convention for research and effectiveness evaluation. Comparing with the experience of the Stockholm Convention on Persistent Organic Pollutants (POPs), which has similar provisions, I evaluate how scientific input into the Minamata Convention is likely to occur as it is implemented, identifying research and information needs that would support evaluation of the effectiveness of a treaty, including the use of modeling to inform future decision-making. Section 6 concludes by discussing potentiall overall impacts of the Minamata Convention.

2. Quantifying mercury reductions from the Minamata Convention

The Minamata Convention addresses a comprehensive set of global issues regarding mercury. Substantive provisions of the Convention cover the entire life-cycle of mercury. In addition to the potential influence of the treaty on direct mercury emissions to the atmosphere, the Minamata Convention through its life-cycle approach also controls mercury upstream, by restrictions on production, trade, use and consumption. The Convention will enter into force after it is ratified by fifty countries, which based on experience from previous environmental agreements such as the Stockholm Convention, will be in 2015 at the earliest, given that countries must fulfill domestic legislative requirements in order to ratify. In this section, the Convention's treatment of atmospheric emissions by source category is evaluated. Due to the long (6-12 month) lifetime of mercury in the atmosphere, it can travel globally, meaning that atmospheric emissions directly affect the global biogeochemical cycle. Amounts of mercury controlled during other phases of its life cycle are then addressed, their possible impact on global biogeochemical cycling is assessed.

2.1. Atmospheric emissions

Atmospheric emissions of mercury from human activities are the major known pathway for human-mobilized mercury to enter the global biogeochemical cycle. Table 1 summarizes the total emissions to the atmosphere from the latest available inventory [11], and identifies whether and how these sectors are subject to control by the Minamata Convention. The source inventory identifies two major categories of atmospheric mercury emissions: by-product or unintentional emissions, and intentional uses. By-product or unintentional emissions come from sources such as fossil fuels, production of ferrous and non-ferrous metals, large-scale gold production, and cement production, mercury mining, oil refining, and contaminated sites. Emissions from intentional uses of mercury result from artisanal and small-scale gold mining, chlor-alkali production, consumer product waste, and cremation/dental amalgam. These two major categories are addressed differently in the mercury treaty. As shown in Table 1, the percentage of known atmospheric mercury emission that is within the scope of the mercury treaty is 96%; the remaining 4% is not addressed by any provision. As discussed below, however, most of these categories are not associated with quantitative limits or reductions.

2.1.1. By-product or unintentional emissions: In the Minamata Convention, by-product or unintentional emissions are addressed in three separate articles of the treaty, which focus on point sources (Article 8), mercury supply (mining, Article 3), and contaminated sites (Article 12). Point sources represent about half of the 1960 Mg y^{-1} atmospheric emission of mercury directly released from human activities (Table 1), and they are addressed by Article 8 and associated annex D. The specific point sources covered by the relevant article of the Minamata Convention are coal-fired power plants, coal-fired industrial boilers, melting and roasting processes used in the production of non-ferrous metals (lead, zinc, copper and industrial gold)·, waste incineration facilities, and cement clinker production facilities. Coal burning (all uses) is the largest of the sources controlled by treaty provisions on atmospheric emissions from point sources, totaling 474 Mg y^{-1}. Production of non-ferrous metals results in 290 Mg y^{-1} emissions total, of which 97 Mg y^{-1} comes from industrial gold, and the remainder from lead, zinc, copper, and aluminum. Aluminum production, which wass included in global inventories for the first time for 2010, is not included in the treaty, though it is the smallest contributor of these (around 2% of the total non-ferrous metal emission, or 6 Mg y^{-1}) [11]. Consumer product waste is estimated to contribute 96 Mg y^{-1}, and cement production 173 Mg y^{-1}. Atmospheric emissions from point sources not included in the treaty come from oil and gas burning (10 Mg y^{-1}), and oil refining (16 Mg y^{-1}).

Provisions for point sources in the Minamata Convention thus apply to sources that total 1027 Mg y^{-1}. However, the Convention does not set quantitative limits or reduction thresholds on these sources. In negotiations of the agreement, while some countries (such as European Union states) supported strict controls on atmospheric emissions from point sources, others (such as India and China) preferred a voluntary approach. Given the different capacities of countries to implement mercury-specific technologies, countries agreed that the Convention would not include mandatory, quantitative reduction targets worldwide. Instead, the article aims to control, and where feasible reduce emissions. This means that emissions are allowed to (and likely will) increase in many countries beyond present levels. The requirements in the article involve an approach based on defining “best available techniques” (BAT) for emissions control. The definition of BAT, included in the text of the Convention, takes into account both the technical and economic availability of technologies to control emissions, and BAT is specific to countries and facilities.

Provisions in the Minamata Convention treat new and existing point sources of mercury differently. BAT is required to be implemented for new sources, beginning five years after the entry into force of the Convention for the party. This date is thus variable, but would be 2020 at the earliest if entry into force is in 2015. Requirements for existing sources are more flexible, and begin ten years after entry into force for that party (no earlier than 2025). Parties may choose from a menu of options to control mercury from these sources, including using BAT, setting emission limit values, quantified goals, or alternative measures that would reduce emissions. This means that emissions of mercury from point sources presently in the inventory (1027 Mg y^{-1} noted above) would not be subject to controls until 2025, and any new sources could add to this total before 2020.

Mercury mining also releases mercury to the environment, and thus results in unintentional emission. The Minamata Convention includes, in Article 3 on mercury supply and trade, provisions to stop new mining of mercury, and to eliminate existing mining by fifteen years after its entry into force for a party (2030 at the earliest). This should prevent the direct emissions from mining (12 Mg y^{-1}). The additional benefit of mercury mining in controlling mercury from entering the product stream is discussed below.

The Convention addresses contaminated sites, which emit 83 Mg y^{-1} to the atmosphere, in Article 13. The Convention asks parties to develop strategies for identifying them, according to guidance to be developed. Oil refining (16 Mg y^{-1}) is not covered by the Minamata Convention. In addition, several unintentional emission categories not quantified in the inventory are also not covered, including secondary metals production, biofuels production and combustion, and oil and gas extraction/transport/processing. The size of these sources is at present unknown.

2.1.2. Intentional uses of mercury: The largest source of atmospheric mercury emissions comes from mercury's intentional use in artisanal and small-scale gold mining (ASGM), according to UNEP. ASGM is addressed in a standalone article of the Minamata Convention (Article 7). Estimates vary for the total amount of ASGM mercury use, as well as the total amount emitted to the atmosphere. The total amount of mercury consumed in ASGM worldwide was previously estimated at approximately 1000 Mg y^{-1}, of which 70% was thought to be released to waterways and 30% emitted to the atmosphere [12]. The resulting atmospheric release estimate of 300 Mg y^{-1} would make up approximately 17% of present-day anthropogenic emission to the atmosphere. However, the most recent UNEP emissions inventory (released in 2013) resulted in an increased estimate of mercury uses in ASGM: 727 Mg y^{-1} emitted to the atmosphere (uncertainty range between 410-1040 Mg y^{-1}), and at least 800 Mg y^{-1} released to water. While very uncertain, the UNEP estimate makes ASGM the largest source to the atmosphere.

Requirements are included in the Minamata Convention for all parties that have "more than insignificant" ASGM activities; however, "insignificant" is not specifically defined. Those parties are required to develop an implement a national action plan, and review it every three years. These national plans need to include, among other requirements: national objectives and reduction targets; actions to eliminate certain processes that result in high levels of emission; steps to facilitate the formalization or regulation of the ASGM sector; strategies for managing mercury trade; public health and communication strategies; and strategies to reduce emissions and releases of mercury from all ASGM activities.

Industrial processes that use mercury result in emissions to the atmosphere, and they are addressed in Article 5 of the Minamata Convention and associated Annex B. Mercury use in chlor-alkali production (28 Mg y^{-1}) is to be phased out by 2025, and mercury use in acetaldehyde production (not quantified by the inventory) by 2018. New facilities are not allowed, so growth of emissions in this sector should not occur. For other processes (vinyl chloride monomer production, sodium or potassium methylate or ethylate, and production of polyurethane using mercury-containing catalysts) parties must take measures to restrict the use of mercury. Exemptions to the phase-out requirements may be requested for a maximum of two five-year periods.

Consumer product waste was estimated to contribute 96 Mg y^{-1} to total global atmospheric emissions in 2010. This number is very uncertain: UNEP gives an uncertainty range of 24-330 Mg y^{-1} for this estimate. Previous estimates have varied: Swain et al. [13] estimated that 1300 Mg y^{-1} of mercury are disposed of annually from products in use, with 40 Mg y^{-1} entering the atmosphere from product use, 110 Mg y^{-1} from product disposal, and 120 Mg y^{-1} from manufacturing (totaling 270 Mg y^{-1}, at the high end of the UNEP uncertainty range).

In its article on wastes (Article 11), the Convention requires parties to manage mercury waste in an environmentally sound manner, which would help prevent mercury products from entering the environment. In addition, incineration is covered under point source requirements. A final category in the inventory is dental amalgam: UNEP estimates that cremation results in 4 Mg y^{-1} of atmospheric emission. Dental amalgam is to be phased down in the Minamata Convention, under provisions addressing mercury in products, with no particular date set.

2.2. Provisions addressing mercury life-cycle

In addition to provisions that directly address atmospheric emission categories, several requirements of the Minamata Convention address mercury from a life-cycle perspective, focusing on upstream controls. Table 2 estimates the total amount of mercury in these categories and associated provisions under the treaty. While these add up to quantities of mercury greater than those involved in atmospheric emissions, the impact of their reduction on the global biogeochemical cycle is indirect, and thus not easily quantified. Mercury in use or contained in products can enter the environment through evasion, or upon disposal, when these products become wastes. The contribution of this product mercury is addressed in emission inventories by using a simple material flow analysis approach [14]. Some of this mercury will affect local ecosystems, but some will transport on a global scale. Given that the amount of mercury historically mined is on the order of 1 Tg [15], this represents a potentially large source. For comparison, the total amount of mercury estimated to be emitted to the atmosphere over time is 350 Gg [16]. The importance of product mercury to the global biogeochemical cycle is an area of ongoing research: for example, Streets et al. [16] suggest that historical legacy from products may be influencing the global cycle, but there are as yet no quantitative estimates.

The total amount of mercury mined in 2009 was 1920 Mg y^{-1} [17]. Mining represents primary production of mercury, which is released from geological sources. Annual consumption (demand) of mercury, excluding ASGM use, is estimated to be 3850 Mg [14]; the difference between mining and demand is supplied by stocks or recycling. The Minamata Convention includes requirements to limit or phase out mercury use in several products and processes. With respect to products, which are addressed in Article 4, the Convention covers batteries, switches and relays, lamps, cosmetics, pesticides/biocides, and measuring devices such as barometers and thermometers [14]. Total quantities of mercury used in these sectors are listed in Table 2. Manufacture, import or export of certain types of these products that use mercury are to be prohibited by 2020. The Convention does not cover all products in each associated category: for example, among others, button zinc silver oxide and air batteries with a mercury content < 2% are excluded and certain types of lamps, such as compact fluorescent lamps, are allowed with a maximum mercury content. Mercury used in dental amalgam, as noted above, is to be phased down, with no particular date set.

Restricting uses of mercury used in industrial processes prevents not only atmospheric emissions from that sector, but also prevents the total amount of mercury used in that process from being a potential source to the environment, For example, the total use of mercury in chlor-alkali processes was 504 Mg y^{-1}, much larger than estimated atmospheric emission of 29 Mg. Atmospheric emissions from vinyl chloride monomer production and acetaldehyde production have not been estimated, but the total use of mercury in this sector was 770 Mg y^{-1} in 2005.

Provisions on both products and processes allow for possible exemptions to phase-outs upon countries' request, which could extend phase-out dates for a maximum of two five-year periods with the agreement of the Conference of Parties. The inclusion of products and processes to be phased out under the Convention is periodically reviewed; thus, future sources can be included.

The Minamata Convention also includes a separate article (Article 9) on releases of mercury to water and land from point sources. (Within the Convention, the term emissions specifically applies to air emissions, and the term releases is applied to land and water). Unlike emissions to the atmosphere, releases to land and water do not immediately circulate globally. Releases from point sources have been estimated at 185 Mg y^{-1}, from AGSM 800 Mg y^{-1}, from contaminated sites 8-34 Mg y^{-1}, and from deforestation 260 Mg y^{-1}, though these estimates are very uncertain and do not comprehensively cover potential sources [11]. Nevertheless this suggests that the total amount of releases is of at least the same order of magnitude as atmospheric emissions, although the total amount does not circulate globally. Releases are addressed in part by articles on AGSM and products; Article 9 addresses releases from point sources not covered by other Convention provisions. For those sources, parties are required to take measures to control releases, selecting from a list of options including release limit values, BAT, multi-pollutant strategies, or alternative measures. Parties are also required to establish an inventory of releases.

3. The Global Biogeochemical Cycle of Mercury under Policy

Addressing whether the provisions of the Minamata Convention could influence the global biogeochemical cycle of mercury requires a quantitative comparison of the magnitude of the stocks and flows of mercury in the current global environment with business-as-usual projections and likely changes due to the Convention. I use the information presented in section 2 to discuss potential estimates of the future atmospheric emissions (in approximately 2050) that may result from global policy action under the Minamata Convention. A six-box model of the global mercury cycle is then used to calculate likely changes with and without global policy.

There are only two sectors in which the influence of treaty requirements on emissions can be quantified directly. If relevant countries with emissions become parties and comply with mercury treaty requirements, emissions from chlor-alkali and mercury mining (totaling 40 Mg y^{-1}) will be eliminated before 2050. In other sectors, this calculation is more indirect. For AGSM provisions, while requirements are not specified in the Convention, UNIDO has estimated that a 50% reduction in ASGM mercury use is feasible by 2017 [18], which would total 350 Mg y^{-1} in reduced emission if fully implemented. For upstream activities such as product restrictions, and other sources such as contaminated sites, it is not feasible to calculate quantitative estimates of mercury prevented from entering the environment.

For point sources, as discussed above, it can be assumed that requirements will not lead to reductions before 2025; under business-as-usual projections, mercury emissions could increase until then. Beyond 2025, the potential for atmospheric emission mitigation due to a global mercury treaty, as discussed above, depends on what technologies will be considered available for mercury controls and implemented domestically. Streets et al. [19], based on scenarios from the Intergovernmental Panel on Climate Change (IPCC), address the potential of changes in technologies to alter year 2050 mercury emissions to the atmosphere. They project total emissions in 2050 to be in the range 2390-4860 Mg y^{-1}. Much of the difference between their scenarios can be explained by differing assumptions about pollution controls in Asia, in particular the penetration of flue-gas desulfurization (FGD). The higher end can be viewed as a scenario without mercury policy, and with high growth. This suggests that, if a global agreement leads to adoption of FGD technologies in rapidly-developing countries such as China, mercury emissions could be at the lower end of this range. Assuming that FGD is a widely-adopted available technology encouraged and facilitated by global policy actions by 2050, and global total emissions were at the low end of the range given by Streets et al., this would mean an increase of 469 Mg y^{-1}. Streets notes that lower emissions (1670-3480 Mg y^{-1}) are possible with deployment of more advanced technologies such as activated carbon injection, but this technology would not meet BAT criteria in most countries in the near term. This more technologically optimistic view would mean a reduction by 2050 of 251 Mg y^{-1} of atmospheric emissions relative to the present day. Relative to the highest-emission projection of Streets et al., however, this would correspond to avoided emission of 2470-3190 Mg y^{-1}.

As most of the emissions changes described by Streets et al. [19] relate to technologies for point sources, and this is by far the largest category of potential change as shown by the analysis above and in Table 1, their estimates are used here to constrain the order of magnitude for the potential of the Minamata Convention to reduce emissions to 2050. Based on a best estimate of trajectories with and without mercury policy, a simple box model is used to calculate the order-of-magnitude influence of these potential changes on the global biogeochemical cycle. Figure 1 summarizes potential trajectories of mercury into the future, showing the potential global biogeochemical cycle of mercury in the present-day and in 2050 with anthropogenic emissions of 1670 and 4700 Mg y^{-1}, based on a six-box dynamic model of the mercury cycle. These values are chosen for modeling, as they are the highest and lowest emissions values in 2050 from atmospheric projections [19], representing the largest range of potential influence for policy on the global biogeochemical cycle.

The six-box model is a dynamic simulation based on present-day biogeochemical cycles and reservoir timescales based on values from the GEOS-Chem global mercury simulation [6,20,21]. First-order processes are assumed for all fluxes. The simulation is initialized in year 1450 with geogenic emissions only. Anthropogenic emissions gradually increase to 200 Mg y^{-1} in 1800, and follow the trajectory of historical emissions outlined by Streets et al. [16], with a peak in 1890 at 2500 Mg y^{-1}, a decline to 600 Mg y^{-1} in the mid-20th century, and an increase to present-day level of 1900 Mg y^{-1}. Emissions changes for 2050 scenarios are linearly interpolated from 2012 to 2050; though no treaty requirements would be technically required before 2025, a linear trajectory takes into account that countries may phase in regulations over time.

In the present-day base case, the magnitude of anthropogenic disruption of the global biogeochemical cycle of mercury is constrained by lake sediment cores, which show an enhancement of a factor of 3-5 in mercury deposition relative to the preindustrial atmosphere [7]. Correspondingly, less than a third of mercury emitted to the atmosphere is from natural sources, including geogenic and volcanic sources [22]. About a third is present-day direct anthropogenic emissions: the remainder is historical or "legacy" mercury, or the mercury previously mobilized by human activities and residing in surface land and ocean reservoirs. This means that decreases in direct human emissions have a small initial influence on the total amount of mercury circulating globally in the biogeochemical cycle, as the timescales involved are long. Correspondingly, however, this means that human emissions have a long-lasting impact on the global cycle, since emitted mercury continues to circulate for decades to centuries.

The effect on the system of these long timescales is shown in Figure 2. As shown in Figure 2b, the lower emission scenario results in 2050 atmospheric and surface ocean concentrations of mercury roughly consistent with the present-day, while concentrations increase by 75% (atmosphere) and 50% (surface ocean) in the higher emission scenario (Figure 2c). The difference between these two scenarios corresponds to a change on the order of 1-2% per year in atmospheric concentrations.

Sensitivity analyses were conducted with the box model to assess the influence of uncertainties in past emission estimates on projected trajectories. In particular, the estimated peak of emissions in the late 1800s due to the North American gold rush is not prominent in lake sediment core records [23], and previous model analyses have argued that atmospheric emissions estimates for that period have been too high [24]. In a model run without the late 1800s emission peak, concentrations of mercury in the atmosphere, surface ocean, and intermediate oceans as estimated by the box model are 9%, 14%, and 19% lower, respectively, in 2005. This is within the uncertainty of total budget numbers, as discussed below. Quantitative differences between 2005 and 2050 in the same three boxes, however, are driven by the projected trajectory of emissions in that period, and are identical to the results presented above.

4. Measurement and Monitoring of Global Biogeochemical Cycling

Monitoring the effectiveness of policy requires better knowledge of and ability to explain baseline levels in the global biogeochemical cycle in the absence of policy, and track potential changes. Monitoring atmospheric mercury and mercury deposition provides a key indicator of the amount of mercury entering ecosystems, as most mercury in non-contaminated areas comes from the atmosphere.

Measurement constraints on the global biogeochemical cycle of mercury include atmospheric concentrations, deposition measurements, ocean concentrations, and land-atmosphere and ocean-atmosphere fluxes. While the availability of measurement constraints has increased dramatically in the last decade, our ability to constrain mercury fluxes remains limited. Atmospheric measurement networks were reviewed in 2010 by Sprovieri et al. [25], who argued that existing measurement networks were insufficient due to lack of speciated and deposition measurements, long-term measurements co-located with other pollutants, free tropospheric measurements in both Northern and Southern hemisphere, and sites characterizing inter-hemispheric transport and background trends. Much information is available from Northern hemisphere terrestrial sites in the U.S. and Europe, where wet deposition data are also available from long-term networks. Tropical and southern hemisphere concentrations, as well as dry deposition and land-atmosphere fluxes, are less well-characterized. The largest uncertainties in the global biogeochemical cycle involve the influence of legacy mercury, which continues to affect the global biogeochemical cycle for timescales of decades to centuries.

As shown in the previous section, projected changes in atmospheric mercury driven by different anthropogenic emission trajectories alone range from 0-75%, or up to 2% per year. Recent experience suggests that scientific analysis is not able at present to identify the causes of changes in atmospheric mercury of similar order of magnitude to those projected by the box model. Slemr et al. [26] reported a 20% decline in atmospheric mercury between 1995-2010, that is, a rate between 1.4-2.7% per year, at sites in both the northern and southern hemisphere (Cape Point, South Africa and Mace Head, Ireland). Mercury has also been decreasing at 0.6% a year at Alert in the Arctic [27]. It has been argued that the declining trends in atmospheric mercury measured in both hemispheres reflect an overall global decline in atmospheric mercury, though the sparse network limits our availability to quantify the global baseline levels with necessary precision. Figure 2 shows source attribution results at Cape Point and Mace Head from the GEOS-Chem global chemical transport model for mercury [20,21,28]. As shown in the figure, anthropogenic, ocean, and land-based sources contribute 19 (29), 56 (42) and 20 (24)% to total concentrations at Cape Point (Mace Head). A 20% change in concentration would thus require a factor of 2-3 change in individual source terms, which is inconsistent with current estimates. To date, no conclusive evidence has emerged to explain the recent decline, but several possible explanations have been suggested, including: decreases in anthropogenic emission; the acceleration of the oxidizing capacity in the atmosphere; the decrease of emissions from the legacy of historical mercury use (e.g., Hg-containing products) and emissions; changing emissions from the oceans and the land [29]; and other possible factors such as climate change [26]. The lack of scientific consensus about the causes of the recent declines in atmospheric mercury suggests that identifying the cause of changes of similar magnitude (0.5-2% per year) in the future requires improved scientific knowledge.

Not included in our simple box model are potential changes in other fluxes, such as changes in the mobilization of mercury from land and ocean. Global climate change is one factor that could complicate interpretation of data relevant to global biogeochemical cycling of mercury. Changes in meteorology could change the mobilization of mercury from environmental reservoirs. One of the largest influences due to changing climate could be mercury from biomass burning, which has been estimated to emit ≈600 Mg to the atmosphere annually [6,18,30]. Increases in wildfires, particularly in northern latitudes where biomass stocks are high in mercury, could increase mobilization of mercury from surface reservoirs to the atmosphere [13,31]. This could further complicate attribution of changes.

5. Research, Monitoring and Evaluation under the Minamata Convention

It was shown above that the global-scale monitoring network for background mercury levels is not at present capable of clearly identifying whether the Minamata Convention leads to changes in global biogeochemical cycling of mercury. The Convention, however, includes provisions to enhance research, development, monitoring, and effectiveness evaluation. Here, the scope and likely impact of these provisions are reviewed, and strategies are recommended to enhance monitoring and related analysis programs, including modeling.

5.1. Scope and Impact of Potential Minamata Convention Activities

The Minamata Convention includes separate articles on Research, Development and Monitoring and Effectiveness Evaluation. Provisions on research, development and monitoring would encourage scientific research and exchange of information on mercury in the environment. Building on existing monitoring networks and research, the text focuses on providing information on: use, consumption, and anthropogenic emissions of mercury to air, and releases to water and land;

modeling and monitoring of mercury in humans, biota and the environment; impact assessments; mercury cycling including long-range transport and fate, taking into account historic and natural sources; information about mercury in trade and commerce; and techniques for mercury-free products, processes and practices. At the first meeting of the Conference of the Parties, which will occur after the Convention's entry into force, arrangements must be established for providing comparable monitoring data on the presence and movement of mercury in the environment, as well as trends and levels of mercury in biota and vulnerable populations. Effectiveness evaluation of the Minamata Convention is envisioned to begin no later than six years after entry into force of the Convention, and will incorporate scientific information on monitoring results and trends.

To envision the type of global monitoring that might be conducted under the Minamata Convention, it is useful to examine the Stockholm Convention on Persistent Organic Pollutants (POPs). The text of the articles on research and effectiveness in the Minamata Convention closely parallel similar articles in the Stockholm Convention. During negotiations of the Minamata Convention, some parties cited the Stockholm Convention specifically as a good model for selecting indicators and evaluation criteria for monitoring progress in addressing global environmental contamination [32].

A key scientific component of the effectiveness evaluation of the Stockholm Convention is the Global Monitoring Plan, which was established at the second conference of parties in 2006 [33]. It was agreed that this monitoring plan would initially focus on air monitoring and human exposure in breast milk or blood serum as core data. One critical element of the monitoring plan is its global coverage: The first effectiveness evaluation of the Stockholm Convention was completed at the fourth Conference of Parties (COP-4) to the Stockholm Convention in 2009. At that meeting, parties agreed that the information presented as part of the global monitoring report [34] could be used as a baseline for future comparisons. It is expected that subsequent effectiveness evaluations will be conducted at six-year intervals, which would mean the next evaluation would be in 2015. At COP-4, an ad hoc working group was established to identify how information from national reports and global monitoring could be used in effectiveness evaluation procedures [35]. With respect to measuring the Stockholm Convention's effectiveness at protecting human health and the environment, the ad hoc working group recommended three indicators: changes in levels of POPs in air, humans, and other environmental media, as available.

Climate change is also a complicating factor in assessing the baseline status and trends of POPs in the environment. Similar to processes affecting mercury, changes in climate could affect mobilization, transport, and exposure to POPs. Recent work has suggested that remobilization of POPs into the Arctic atmosphere from surface reservoirs as a result of climate change has already begun over the past two decades [36]. The first Global Monitoring Report stressed the need to consider possible climate effects in interpreting POPs trend data in air and humans. To provide the

Convention with scientific information on climate and POPs, an expert group was established in 2010. The expert group report noted that some of the POPs regulated under the Convention may not be declining as rapidly, or may increase in some regions, due to climate impacts [37].

In summary, ten years after the Stockholm Convention was completed, despite extensive efforts at effectiveness evaluation, the influence of its provisions on long-range transport of POPs remains uncertain. This is in part due to the difficulty of the scientific problem of attributing changes in environmental levels to treaty mechanisms. However, it also shows the limitations of potential monitoring programmes under global environmental treaties, which lack substantial funding mechanisms to encourage new research, and the pace of implementation in global environmental agreements.

5.2. Potential enhancements to improve monitoring and evaluation

If, as in the Stockholm Convention, initial monitoring for the Minamata Convention focuses on levels in the atmosphere and in humans, more research is needed to define a global baseline and interpret changes over time. As noted above, existing monitoring programs do not provide the long-term, comparable data required for defining trends, and targeted scientific research is necessary to better understand global biogeochemical cycling. With increasing policy emphasis on controlling the emission of mercury to ecosystems, numerous scientists have called for increasing efforts to monitor and evaluate changes of mercury in the environment to improve our ability to quantify sources of mercury to the atmosphere [10,38,39]. In the context of designing a program to monitor global background mercury trends, special attention should be paid to three areas, described further below: (1) mercury speciation, (2) spatial and temporal coverage, and (3) integrating measurements and modeling.

5.2.1. Mercury Speciation. While discussions about mercury during international negotiations have largely not distinguished among its forms in the environment, different species of mercury act very differently in the global environment. In the atmosphere, mercury is present as elemental (Hg(0)), reactive (Hg(II)), and particulate mercury (Hg(P)). The lifetime of elemental mercury in the atmosphere is 6-12 months, while reactive and particulate mercury remain in the atmosphere only for days to weeks [6]. This means that while elemental mercury travels globally, reactive and particulate mercury mostly deposit to local and regional areas (though some Hg(II) could reduce to Hg(0), for example in power plant plumes [40]). Streets et al. [19] note that the fraction of emissions as Hg(0) will likely change, and projects a decreasing Hg(0) fraction in most scenarios; FGD, however, controls primarily Hg(II). Corbitt et al. [9] derive a source-receptor function for the policy effectiveness of Hg(0) and Hg(II) emission reduction at reducing deposition in other global regions, and show that Hg(0) controls would be roughly twice as effective as Hg(II) controls. Because the chemistry and transformations of Hg(0), Hg(II) and Hg(P) in the atmosphere are still uncertain [41], monitoring atmospheric levels should measure all three species [38], and a global monitoring plan should take this into account in emission and concentration analysis.

In addition to considering different forms of inorganic mercury, methylmercury, as discussed above, is formed in the environment and, though of primary policy concern for human health, is not directly controlled by policies. People are exposed to methylmercury primarily through fish consumption, either from local waters or open-ocean fish [42]. Because methylmercury is produced in the environment, its dynamics can differ from those of inorganic mercury. For example, methylmercury concentrations in Arctic biota have increased by an order of magnitude since the year 1500 [5]. As the quantity of mercury deposited to ecosystems has gone up by only a factor of 3-5 [6,22], the remaining change has been hypothesized to be due to climate, ecosystem and/or food web changes that influence methylation and/or bioaccumulation [5]. A substantial degree of uncertainty remains in quantifying the processes of methylation, in ways that will complicate interpretation of mercury trends in humans and biota. Mason et al. [10] however, suggest that most methylmercury accumulating in ocean fish is derived from in situ production within the upper ocean waters (1000 m), with the source of inorganic mercury to the open ocean being primarily atmospheric deposition. This suggests that monitoring changes in global biogeochemical cycling can provide information on the drivers of methylmercury concentrations, but methylmercury may respond more rapidly than the global cycle to human-induced changes.

5.2.2. Spatial and temporal coverage. Defining appropriate spatial and temporal coverage for mercury monitoring will be particularly important to discern changes in biogeochemical cycling. Mercury has a variety of timescales, ranging from local to global [43,44]. Because Hg(II) and Hg(P) are shorter-lived in the atmosphere, that they show more regional variability; thus, monitoring that shows declines in deposition could be due to global or local influences [45]. In recent decades, process-driven variability, including both climate changes and changes in uptake of mercury in biota, may be large enough to obscure source-driven trends in mercury levels in the Arctic [5]. The timescales of responses of mercury concentrations and ecosystems to changes in deposition can range from years to centuries [44,46]. Improved temporal and spatial coverage of comparable measurements, especially in remote areas and the free troposphere, could improve our ability to characterize hemispheric background levels of mercury and identify signatures from sources in comparison to modeling techniques.

5.2.3. Integrating measurement and modeling. Because even effective policy action may at least initially result in global background levels of mercury in the environment that are unchanging, as discussed above, interpretation of trends could benefit from the application of global and regional-scale modeling.

These strategies will help identify changes. However, the analysis above suggests that the largest potential benefit of the Minamata Convention would be in avoiding increases in emissions. Thus, counterfactual analyses will be necessary for effectiveness evaluation. However, modeling of mercury is limited by incomplete knowledge of atmospheric chemical mechanisms [41], oceanic processes [47], and regional-scale phenomena [48,49] The ability to discern and attribute trends would require improved process-based modeling of global mercury transport and fate, and the application of integrated assessment modeling that includes estimates of emissions policies and technologies.

6. Conclusion: Impacts of the Minamata Convention beyond biogeochemical cycling

The overall requirements of the Minamata Convention on emissions that affect global biogeochemical cycling of mercury are not easily quantifiable. The main provisions that would directly affect global levels are those on atmospheric emissions from point sources, and their stringency will depend heavily on which technologies are identified as available in various countries. More intensive efforts will also be needed on monitoring and evaluation, as present-day networks are not sufficient to explain projected changes in atmospheric concentrations.

While the official requirements of the Minamata Convention suggest that future mercury emissions will follow business-as-usual projections at least until 2025, the official requirement may underestimate the potential influence of the treaty. International treaties can alter countries' behavior through raising awareness, creating shared norms, and providing technical and financial assistance. These factors could encourage countries to strengthen domestic controls, even in the absence of specific treaty requirements [50]. Since few penalties exist for non-compliance in global environmental treaties [51], these informal mechanisms can be critically important.

The potential changes to 2050 in global biogeochemical cycling as a result of a mercury treaty as projected here are small, but the potential avoided emissions large. This suggests that lack of environmental improvement on near-term timescales may not be evidence for an ineffective treaty, but also may show that progress may require more ambitious action. As others have previously noted, the timescales of responses to mercury emissions reductions can be long [9,44]. Correspondingly, however, this means that actions (or inactions) today have influence decades to centuries in the future, by influencing future legacy mercury [8]. In addition, it suggests that a flexible framework to address global mercury emissions, including adoption of new mercury control technologies as they become economically viable in various regions, will be required to fully address the mercury problem.

While the focus here has been on measuring the influence of policies and climate change on the global biogeochemical cycle of mercury, there are several additional areas of possible (in fact, more likely) benefits from a global treaty for mercury exposure that are not addressed here. Actions on ASGM, products, and mercury waste could have substantial impacts in minimizing local-scale exposure to mercury, particularly in developing countries and among specific populations such as miners and their families. Technical and financial assistance mobilized as part of a global treaty process can enhance the capacities of countries to address mercury risks domestically, including import-export, regulations, and cleanup. The co-benefits to urban and regional air pollution (and thus to human health) of installing emissions control technologies such as FGD could be large. These and other potential benefits should also be assessed and quantified in the implementation and evaluation process.

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Tables

Table 1. Anthropogenic Mercury Emissions to the Atmosphere and Associated Treaty Provisions. Categories of atmospheric emissions are taken from UNEP [11] and information from the Minamata Convention.

Category	**Total budget (Mg) (Uncertainty range)**	**Covered by Minamata Convention**	**Convention requirements**
By-product or unintentional emission			
Coal burning (all uses)	474 (304-678)	YES	Best available technology approach after 5-10 years
Oil and natural gas burning	9.9 (4.5-16.3)	NO	
Primary production of ferrous metals	45.5 (20.5-241)	NO	
Primary production of non-ferrous metals (Al, Cu, Pb, Zn)	193 (82-660)	YES (97%), except for Al	Best available technology approach after 5-10 years
Large-scale gold production	97.3 (0.7-247)	YES	Best available technology approach after 5-10 years
Cement production	173 (65.5-646)	YES	Best available technology approach after 5-10 years
Mine production of mercury	11.7 (6.9-17.8)	YES	Bans primary mining after 15 years
Oil refining	16 (7.3-26.4)	NO	
Contaminated sites	82.5 (70-95)	YES	Endeavour to develop strategies to identify, assess; cooperation
Intentional uses			
Artisanal and small-scale gold mining	727 (410-1040)	YES	Implement national plan
Chlor-alkali industry	28.4 (10.2-54.7)	YES	Phase-out by 2025
Consumer product waste	95.6 (23.7-330)	YES	Articles on products, wastes; incineration covered under point sources
Cremation (dental amalgam)	3.6 (0.9-11.9)	YES	Phase-down
Total emission	1960 (1010-4070)	1880 (96%)	

Table 2. Quantities of mercury use subject to treaty provisions. Product use estimates are from 2005.

Category	**Total budget (Mg) (Uncertainty range)**	**Convention provision**	**Date (estimated)**	**Citation, notes**
Production (Primary)	1920 (variation from 1,150-1920 from 2005-2009)	Mining to be eliminated after 15 years	(2030)	[17]
Use				
Chlor-alkali production	504	Phase-out	2025	[14]
Acetaldehyde, VCM	770	Acetaldehyde eliminated; VCM to	2018 (acetaldehyde)	[14]

		be restricted		
Batteries	365	Certain batteries to be phased out	2020	[14]
Switches and relays	189	Certain switches/relays to be phased out	2020	[14]
Lamps	122	Certain lamps to be phased out	2020	[14]
Measuring Devices	328	Certain measuring devices to be phased out	2020	[14]
Compounds and other applications	330	Certain cosmetics, pesticides, biocides, antiseptics	2020	[14]
Dental amalgam	321	Phase-down	n/a	[14]

Figure Legends

Figure 1. Percentage source contributions to surface Hg(0) at a) Mace Head and b) Cape Point stations, from the GEOS-Chem model.

Figure 2. Global biogeochemical cycles of mercury for (a) present-day, (b) emission of 1670 Mg y^{-1} ***in 2050, and (c) emission of 4700 Mg*** y^{-1} ***in 2050, based on a dynamic 6-box global biogeochemical cycle simulation. Fluxes in Mg*** y^{-1}***, stocks in Mg.***

Figures

Figure 1. Percentage source contributions to surface Hg(0) at a) Mace Head and b) Cape Point stations, from the GEOS-Chem model.

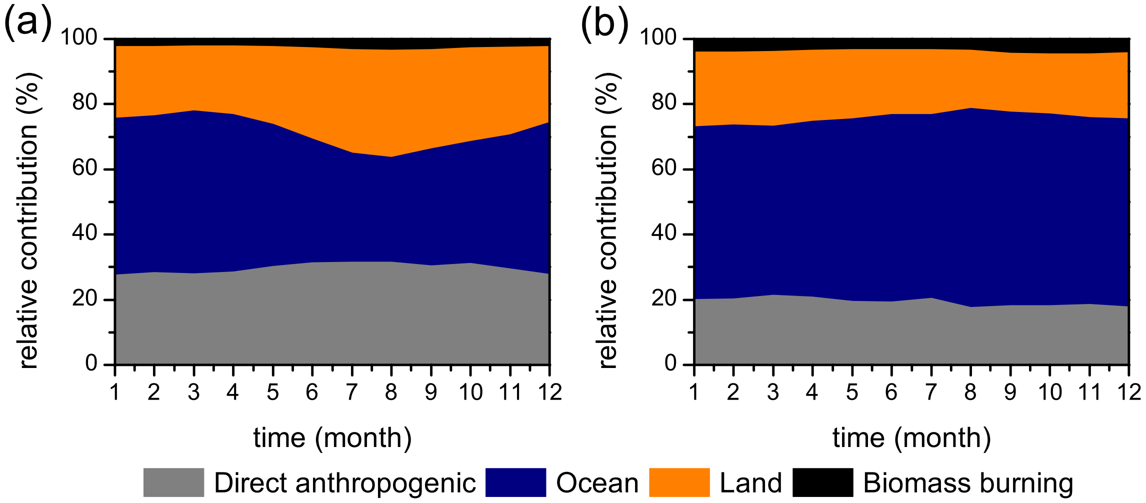

Figure 2. Global biogeochemical cycles of mercury for (a) present-day, (b) emission of 1670 Mg y^{-1} in 2050, and (c) emission of 4700 Mg y^{-1} in 2050, based on a dynamic 6-box global biogeochemical cycle simulation. Fluxes in Mg y^{-1}, stocks in Mg.