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CRITICAL REVIEW

Science and strategies to reduce mercury risks: a critical review

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Despite decades of scientific research and policy actions to control mercury, exposure to toxic methylmercury continues to pose risks to humans and the environment. This article critically reviews the linkages between scientific advancements and mercury reduction policies aimed at reducing this risk, focusing on the challenges that mercury poses as an issue that crosses both spatial and temporal scales. Scientific aspects of the mercury issue at various spatial and temporal scales are reviewed, and policy examples at global, national and local scale are analysed. Policy activity to date has focused on the mercury problem at a single level of spatial scale, and on near-term timescales. Efforts at the local scale have focused on monitoring levels in fish and addressing local contamination issues; national-scale assessments have addressed emissions from particular sources; and global-scale reports have integrated long-range transport of emissions and commercial trade concerns. However, aspects of the mercury issue that cross the political scale (such as interactions between different forms of mercury) as well as contamination problems with long timescales are at present beyond the reach of current policies. It is argued that these unaddressed aspects of the mercury problem may be more effectively addressed by (1) expanded cross-scale policy coordination on mitigation actions and (2) better incorporating adaptation into policy decision-making to minimize impacts.

1. Introduction

Mercury is a substance of continuing scientific and policy interest. While mercury has always been present in the Earth system, both natural events and a vast range of human activities over centuries have mobilized the element in ways that pose environmental and human health risks. Human exposure to mercury, which can accumulate in fish as methylmercury, can cause developmental delays and neurological damage, especially in the offspring of women exposed to methylmercury during pregnancy.[1] It has been estimated that over 300 000 newborns in the US are exposed in utero to levels of methylmercury associated with increased risks of neurodevelopmental impacts.[2] Similarly, a study in the Philippines showed that over 70% of workers in gold mining or mineral processing areas had signs of mercury intoxication.[3]

Similar to other traditional environmental contamination issues, much of the scientific investigation into the environmental behavior of mercury and how mercury affects humans aims to inform policy-making. Mercury-related research is carried out over a range of disciplines, including chemistry, biology, toxicology and public health. Regulatory agencies at a variety of different political scales have developed mercury policies over time in the context of increasing scientific knowledge of processes

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Environmental impact

This paper is a critical review focusing on multi-level understanding of environmental risk from mercury pollution. Through case studies, it addresses the linkages between scientific advancements and mercury reduction policies aimed at reducing this risk, focusing on the challenges that mercury poses as an issue that crosses both spatial and temporal scales. The case studies show that policy activities to date have focused on near-term timescales at local, national and global spatial scales. Aspects of the mercury issue that cross political scale (such as interactions between different forms of mercury) and contamination problems with long timescales are not covered by current policies. The paper concludes that these unaddressed aspects of the mercury problem may be more effectively addressed by (1) expanded cross-scale policy coordination on mitigation actions and (2) better incorporating adaptation into policy decision-making to minimize impacts. Assessment of science-policy linkages in this area is critical to better understanding mercury as an environmental problem.

in the environment and ecological and human effects. Yet, environmental problems remain. For example, recent regulatory efforts at local scale have identified the challenge of addressing impacts from out-of-region emission sources.[4] This paper reviews and assesses the scope of local, national and global policies, and their intersection with developing scientific understanding of physical characteristics of the mercury problem.

The current status of mercury science and policy, further challenges and gaps in linking scientific knowledge to policy action on the mercury issue are identified, towards the goal of more effectively addressing environmental mercury contamination problems. The analysis is based on a critical review of the peer-reviewed scientific literature, as well as examination of the background documents and regulatory reports for the selected empirical cases. Section 2 reviews the characteristics of the mercury issue with particular attention to their physical and temporal scales. Section 3 presents, *via* empirical case studies, a sampling of the types of scientific investigations that have informed policy-making in local, national and international political forums. Section 4 draws insights from these case studies to assess the prospects for better linking science and policy across scales, and identifies challenges for future science and policy in this area. It is argued that neither scientists nor policy decision-makers have fully addressed the cross-scale nature of the mercury problem, which has important both temporal and spatial dimensions. Further, because of the nature of mercury as a problem at multiple levels of temporal and spatial scales, it is suggested that addressing societal concerns about mercury contamination requires both (1) expanded cross-scale policy coordination on mitigation actions and (2) better incorporating adaptation into policy decision-making to minimize impacts.

2. Temporal and spatial scales of mercury science and policy

The attributes of the mercury problem operate on multiple timescales and spatial scales, incorporating natural systems, human exposure, and policy responses. This section reviews the relevant scales characteristic of the mercury problem, first assessing temporal, then spatial scales. In contrast to previous reviews of mercury science alone, the discussion here focuses on the scales characteristic of science-policy interactions. A third subsection addresses how human exposure from environmental mercury responds to and integrates influences from across these spatial and temporal scales.

2.1. Temporal scales

The mercury problem exists on timescales ranging from days to millennia. Table 1 lists a range of timescales (both scientific and policy-relevant) characteristic of the mercury problem, from longest to shortest.

The longest timescale of the mercury pollution problem (the timescale for mercury to return to deep-ocean sediments, Table 1) reflects that mercury makes up one of Earth's biogeochemical cycles. As it is an element, mercury has been circulating in the environment, as a result of emissions from geological sources such as volcanoes, throughout Earth's history. Slow processes characterize this natural biogeochemical behavior, in which mercury emitted to the atmosphere cycles through the atmosphere, ocean and terrestrial system for centuries to millennia before it returns to deep-ocean sediments.[5]

Human societies have known of mercury as a useful element for millennia (human uses of mercury, Table 1, 1000+ years), and have used it intentionally in a variety of products and processes.[7] A large quantity of mercury was historically used in gold mining, and mercury continues to be used in small-scale artisanal gold mining primarily in developing countries.[15] Since the beginning of the industrial revolution (about 250 years ago, Table 1), however, humans have mobilized increasing amounts of mercury from long-term sedimentary storage into the atmosphere, both through intentional uses and as a byproduct of industrial activities such as coal burning. Mercury has been used in products including thermometers, barometers, paints, soaps, pharmaceuticals, and dental fillings.[11] This increase in environmental mercury has been measured as a three- to five-fold increase in atmospheric deposition by records in sediment cores[16] and ice cores such as the record from Wyoming, USA.[17]

Mercury (of either anthropogenic or natural origin) previously deposited to the land and oceans can remobilize to the atmosphere.[13] Continuing emissions from land and ocean surfaces that are enhanced as a result of past anthropogenic activities have been referred to as "legacy" emissions.[5] While changes in mercury concentrations in the surface ocean are rapid (Table 1), intermediate and deep ocean changes can take decades to centuries.[6] These subsurface ocean timescales vary in different ocean basins, due to their size and characteristics. Recent studies have illustrated that ocean mercury concentrations are likely not yet at steady state with respect to present-day deposition levels. The time for the deep Pacific to reach steady-state with respect to mercury concentrations has been estimated at >1500 years, while the corresponding time for the deep Atlantic is 50–100 years.[13] The contribution of legacy emissions to ocean concentrations may continue to increase in the future.[18] In the land system, soils can serve as a long-term sink for mercury (on the order of 100–200 years).[18] However, recent results from isotope measurements have shown that recently deposited mercury can be rapidly re-mobilized to the atmosphere on seasonal timescales[19] (listed as 0.5 year in Table 1). This process has been termed "rapid re-emission" or "prompt recycling".[5]

Upon deposition to aquatic ecosystems, mercury is converted to methylmercury by biological activity in anaerobic environments such as wetlands, and thus converted into a form more toxic to humans. Methylators of mercury include sulfate-reducing and iron-reducing bacteria.[20,21] Biotic and abiotic reactions convert methylmercury, Hg(II) and Hg(0) in aquatic systems.[22] Much of the research into aquatic cycling of mercury has been conducted in freshwater ecosystems. A recent model study examining the response of methylmercury in predatory fish to changes in atmospheric deposition in multiple ecosystem types showed an initial response over one to three decades, followed by a slower approach to steady-state concentrations over a timescale from decades to centuries.[9] The results for one type of ecosystem for this initial response (to 20% of steady-state values) and long-term response (to 80% of steady-state) are listed in Table 1. This behaviour is a result of ecosystem characteristics such as watersheds or lake water stratifications. Recent research has also shown that newly deposited mercury may be more

Table 1 Timescales of mercury in environmental and human systems

System	Timescale/years	Reference
Timescale for return to deep-ocean sediment	10 000	5
Deep Ocean (Pacific)	>1500	6
Human uses of elemental mercury	1000+	7
Legacy emissions from land sources (slow responses)	100–500	5
Industrial age and associated emissions	250+	8
Slow fish response to deposition change (seepage lake), 80% of steady-state[a]	100	9
Deep Ocean (Atlantic), time to steady-state	50–100	6
Power plant lifetime	41	10
Time to establish regulations on power plant mercury, US[b]	11+	11
Lifetime of mercury-containing products	10+	12
Rapid fish response to deposition change (seepage lake), 20% of steady-state[a]	10–12	9
Projected Hg treaty conference of parties meeting frequency	2	
Surface ocean, lifetime[c]	0.6	5
Atmospheric lifetime (Hg(0))[c]	0.5–2	13
Land source "prompt recycling"	<0.5	5
MeHg half-life in human body	0.2	14
Atmospheric lifetime (Hg(II))[c]	0.003	5

[a] Response time to 80% of steady-state value for increase in atmospheric deposition. [b] Time between announcement of intent to regulate and final rule; process still pending. [c] e-Folding lifetime.

available for methylation than mercury already resident in ecosystems.[23] There is less known about mercury dynamics and methylmercury production in the open ocean, where marine fish may be influenced.[24] A current scientific challenge is identifying where in the ocean methylation occurs: in sediments or estuaries nearer to the coast, or farther away from shore in the water column or deep ocean.[25,26] This challenge is intensified as mercury measurements are difficult; lack of a standardized analytical procedure for methylmercury means that literature values should be interpreted with caution.

Human sources of mercury can also exhibit different lifetimes. Point sources such as coal-fired power plants can last for several decades; the average age of a coal-fired power plant in the United States is 40+ years (Table 1).[10] Mercury-containing products (such as thermometers, thermostats or medical equipment) can remain in use for decades or longer.[12] Disposal of mercury-containing articles can subsequently become area sources to the atmosphere, with timescales characteristic of land sources.

2.2. Spatial scales

In addition to temporal scale, the mercury problem exists on multiple spatial scales. Characteristic spatial scales of the mercury problem are listed in Table 2, from longest to shortest.

Transport of mercury through the atmosphere links temporal and spatial scale, because air is a transport medium. The longer the lifetime of any species in the air, the farther it may travel *via* atmospheric currents. The transport distance of mercury is complex, however, because of the existence of multiple forms of mercury in the atmosphere (Fig. 1). The elemental form of mercury (Hg(0)) is emitted from both natural and anthropogenic sources. Hg(0) has an atmospheric lifetime of about 6 months to a year (Table 1), which means that it can transport on a global scale *via* air currents (listed as 110 000 km in Table 2 based on typical wind speeds of 7 m s^{-1}). Anthropogenic sources of mercury, such as coal-fired power plants, can emit mercury as Hg (0) or in two other forms, Hg(II) (divalent mercury), and Hg(P) (particulate mercury).[30] The latter two are more soluble, and can reach ecosystems through wet and dry deposition. Thus, they have a lifetime of days to weeks in the atmosphere because they are efficiently deposited to the surface (0.003 years for Hg(II), Table 1). Thus, Hg(II) and Hg(P) will deposit locally and regionally upon their formation in the atmospheric boundary layer (listed as 660 km in Table 2, calculated based on Hg(II) lifetime and typical wind speed). Hg(I) species are not considered significant.

Hg(0), Hg(II) and Hg(P) also interact in the atmosphere; these interactions are illustrated in Fig. 1. Hg(0) can oxidize to Hg(II);

Table 2 Spatial scales of mercury in environmental and human systems

System	Spatial scale/km	Reference
Surface Atlantic, model area/km^2	6.16×10^9	6
Polar Bear, home range size/km^2	125 100	27
Transport distance, Hg(0)	110 000+	Calculated from Table 1[a]
Tuna migratory distance	12 000	28
Watershed area, coastal plain river model ecosystem/km^2	2190	9
Average food transport distance, US	1640	29
Transport distance, Hg(II)	660	Calculated from Table 1[a]
Watershed area, seepage lake model ecosystem/km^2	0.81	9

[a] Assuming average wind speed of 7 m s^{-1}.

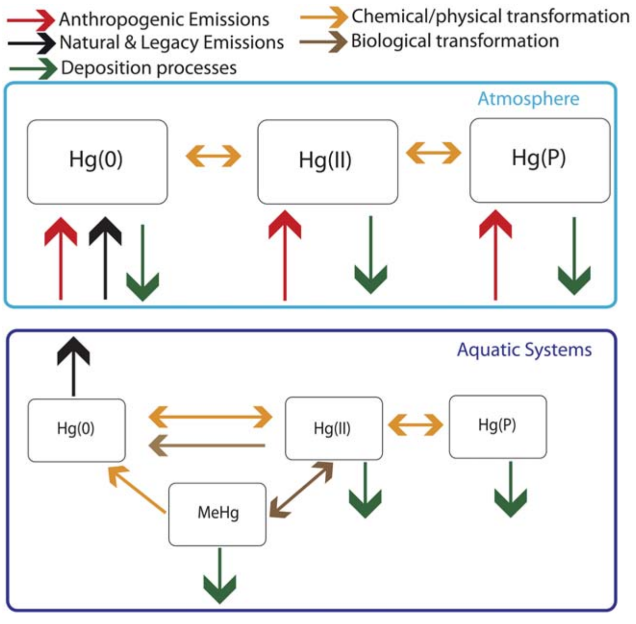

Fig. 1 Interactions of mercury species in the atmosphere and in aquatic systems. Shown are transformations between mercury species and emissions/deposition processes. MeHg = methylmercury.

Hg(II) can form Hg(P) in the atmosphere; and Hg(II) can also be reduced to Hg(0) in the background atmosphere or potentially in power plant plumes. These interactions serve to link regional-scale transport with intercontinental transport issues, and also have an influence on local-scale. Many of the atmospheric processes involved are not well-understood. Bullock *et al.*[31] examined the performance of an ensemble of regional models at predicting measured wet deposition on a weekly basis in the United States, and found that models differed substantially, and there was a strong influence of different boundary conditions on US deposition results, showing that cross-scale interactions are very uncertain and can be important on local-to-regional scale as well.

The transport and fate of mercury in ecosystems can also vary in their spatial scale. Oceans are large basins, for example on the order of 10^9 km^2 for the Atlantic. Watersheds can vary dramatically in size: the watershed area of modeled ecosystems used in the study of Knightes *et al.*[9] ranged from 0.8 km^2 to 2190 km^2. Organisms which accumulate methylmercury can travel over a large area. For example, tuna can migrate thousands of kilometres, while the home range of a polar bear is over 100 000 km^2.

2.3. Human exposure on spatial and temporal scales

Human exposure to mercury can occur on a variety of temporal and physical scales. In general, the form of mercury of most concern with regard to human and environmental exposure due to its toxic properties is methylmercury. Fig. 1 shows the chemical/physical and biological interactions of different mercury species in aquatic systems, including methylmercury.

Exposure over short timescales to high levels of elemental forms of mercury, mainly through inhalation of mercury vapor, can cause neurological problems such as tremors, memory loss, neuromuscular changes, and potentially death. These exposures are characteristic of occupational settings. Another potential route of occupational and public exposure to lower levels of elemental mercury is through the use of dental amalgams.[32] General population exposure and potential health effects of elemental mercury through typical exposures have generally not been associated with recent present-day policy activity. These exposures are well below those associated with potential effects.[33] Thus, the focus of discussion here is on environmental exposure to methylmercury.

Most present-day environmental exposure to methylmercury in the general population occurs mostly by eating contaminated fish. Exposure to high levels of methylmercury causes neurological impacts including sensory disturbances, ataxia, and tremor.[34] Consuming fish contaminated with methylmercury, even at low levels, also causes neurological impacts (particularly to the offspring of exposed individuals).[1] Some studies suggest that methylmercury exposure can also lead to cardiovascular impacts.[35] Recent scientific analyses, including epidemiological studies in the Faroe Islands and New Zealand, have drawn attention to the dangers of methylmercury exposure even at relatively low doses, which led to IQ deficits in the children of women who consumed elevated amounts of mercury during pregnancy.[36]

Consumers are exposed to methylmercury through eating both locally caught fish and fish from the commercial market, which are often open-ocean marine fish. Concentrations of methylmercury in fish combine mercury from local and long-distance sources, present-day and historical sources, and these concentrations can change on timescales ranging from years to decades or more.[37] The dose of methylmercury to any individual fish consumer depends on both the concentration of mercury in a fish and the amount and variety of fish that a person consumes. This exposure pattern thus also has spatial and temporal characteristics. Fish consumption patterns differ from place to place, and can change due to personal preferences, economic or market forces, or policy interventions. Consumers might choose to consume freshwater fish from local waterways, or marine fish caught thousands of kilometres from their homes.[38] Consumer preferences can also change over time.

Another aspect of exposure analysis is the spatial and temporal variation in mercury concentrations. Table 3 shows typical concentrations of mercury in environmental and human systems, illustrating the broad ranges of concentrations found in different media. While concentrations of mercury in the atmosphere are generally low, the atmosphere serves as a transport medium to

Table 3 Typical concentrations of mercury in environmental and human systems [μg g^{-1} unless otherwise noted]

System	Concentration/μg g^{-1}	Reference
Atmosphere (surface, Hg(0))[a]	1.6 (ng m^{-3})	39
Human hair, general population	0.1–1	1
Human hair, high fish consumers	1–15+	1
US EPA RfD, hair equivalent	1	40
Swordfish, mean	0.9	41
Light tuna (canned), mean	0.1	41
Albacore tuna, (canned), mean	0.35	41

[a] At northern hemisphere midlatitude sites.

distribute mercury worldwide. Bioaccumulation of methylmercury in ecosystems leads to higher concentrations and biota, but substantial variations remain both within and among species. For example, different types of tuna have very different mean mercury concentrations (Table 3).

3. Policy responses at multiple scales: addressing environmental exposures

As illustrated in the previous sections, mercury causes pollution problems that have a variety of characteristic temporal and spatial scales. Because mercury risks to human health and the environment take multiple forms and occur on multiple spatial and temporal scales, as described above, they need to be abated by different kinds of policy responses across different scales of social organization from the local to the global. Policy actions at local, national and global scales have addressed various aspects of the mercury pollution problem. Cross-scale policy efforts intersect with cross-scale scientific issues in multiple ways. However, many of these interactions and their implications for both policy and science have been subject to only limited analysis. Yet, these are important aspects of improving our understanding of mercury as a pollutant as well as the development of effective policy, and worthy of much more scholarly attention.

Early regulatory efforts on mercury focused on acute or occupational exposures, primarily to elemental mercury. These policy efforts were focused on short-term, local-scale and occupational exposures. For example, in 1925, the International Labour Organization included mercury and associated dangers in its convention on workman's compensation and associated diseases.[42] In the 1940s, numerous US states banned the use of mercury in hat-making, which was responsible for high levels of occupational exposure.[43] The dangers posed by methylmercury received increased policy attention as a result of high-profile poisoning incidents. In Minamata, Japan in the 1950s, methylmercury released to local waterways poisoned fish consumed by the local population, subsequently causing neurological damage later termed "Minamata Disease".[44] Scientific investigations into the Minamata incident provided early knowledge of methylmercury toxicity and effects. Regulations that addressed mercury before the 1990s primarily dealt with mercury found in products or wastes.

From the 1990s onward, local, national and international policies have increasingly focused on addressing exposure to mercury from environmental sources, specifically methylmercury exposure due to fish consumption. These policy efforts have addressed mercury on a broader spatial scale. As noted above, fish consumption and exposure to a particular consumer integrates influences from a variety of different spatial and temporal scales, meaning that the scope of the mercury problem lies under different authorities. These authorities have begun to respond in different ways to aspects of the mercury problem.

In addressing contamination of local waterways, some US states have taken action to reduce their mercury emissions. To control the regional transport of mercury from specific sources, a number of national governments, including the United States and many European countries, have instituted regulations on specific mercury sources. European countries (*e.g.* Sweden) and the US State of California have limited mercury in products at the scale of economic markets. To deal with contamination of shared waterways and longer-range transport, transnational cooperation has occurred in regional contexts (such as the European Union, the Arctic, and the Baltic Sea region).[45] A global mercury treaty is currently being negotiated.[46]

The three cases below explore in more detail the intersection between policy efforts and scientific information at different levels of spatial and temporal scale. These cases are: locally focused regulations in the Northeast US; national-level policies in the US; and global treaty negotiations under the auspices of the United Nations Environment Programme.

3.1. Local action: The Northeast USA

An example of local action on mercury linking scientific research and policy making comes from the Northeast US. The effects of mercury contamination and exposure are typically seen most readily at local scale. The scientific research mobilized in support of subnational mercury regulation has focused on ecosystem-level measurement and monitoring of deposition and fish concentrations in freshwater systems. These detailed, local studies have informed and evaluated action in Northeastern US states.

The Northeast is one of a few US regions that have been at the forefront of regulatory action on mercury (another is the Great Lakes region). In particular, regulation in the state of Massachusetts illustrates progress within the local level. Massachusetts has focused on environmental mercury regulation at the state level since the early 1990s.[47] While Massachusetts has succeeded in cutting mercury emissions, deposition has not fallen proportionally, and the fish in water bodies in Massachusetts continue to exceed guidelines.[48] Recent policy activities, and supporting scientific analyses, have acknowledged the need for addressing out-of-region emission sources.[4]

Massachusetts along with the other five New England states and five eastern Canadian provinces developed a Regional Mercury Action Plan, which was adopted in 1998. The goal of the plan was the virtual elimination of release of anthropogenic mercury, with emissions 50% below 1996 levels by 2003.[49] Implementing this action plan, Massachusetts developed a Zero Mercury Strategy in the early 2000s, with a goal of the virtual elimination of the release as well as the use of anthropogenic mercury (going beyond the regional goal).[47] Massachusetts also set an additional goal of a 75% reduction in mercury emissions by 2010 (data on this target are not yet available). Massachusetts is also one of the handful of US states that has begun to implement regulations on the utility sector (which was until recently unregulated at the national level). Massachusetts regulations required 85% capture of mercury from utility sources by 2008, and require 95% capture by 2012.[50] Available data indicate that power plants have so far complied with this requirement.[51]

Concurrent with these policy actions to reduce overall emissions from major regional sources, the Northeast states have developed an extensive effort in monitoring progress and ecosystem conditions. Massachusetts established a comprehensive fish monitoring network for mercury in 1994, implemented by the Department of Environmental Protection. Results from this network showed statistically significant mercury declines in fish between 1999 and 2004.[52] In addition, mercury concentrations in sewage sludge decreased by more than a factor of two over 2004–2006, coincident with the implementation of regulations requiring mercury waste separators in dental offices.[53]

In 2007, the Northeast states developed a proposal for a Mercury Total Maximum Daily Load (TMDL) under the US Clean Water Act.[4] Under the Clean Water Act (section 303(d)), states are required to identify those water bodies that fail to meet quality standards, and are further required to assess the daily amount of each pollutant they can assimilate without violating the standard. This process of identification, assessment, and potential regulation (of contributions from point source pollution) is referred to as the TMDL process. The development of the Northeast Regional TMDL is an example of how the region has engaged the cross-scale dynamics of the mercury issue, and the potential limits of action within the region. The mercury TMDL, proposed by the Northeast states together in 2007, aims to reduce mercury concentrations in regional freshwater fish to meet water quality standards.[4]

In the process of developing the TMDL, state authorities in Massachusetts, Connecticut, New Hampshire, Maine, Vermont, Rhode Island, and New York, as well as relevant regional organizations such as the New England Interstate Water Pollution Control Commission (NEIWPCC) and The Clean Air Association of the Northeast States (NESCAUM) relied on model results to assess the relative contributions of in-region and out-of-region sources. The TMDL notes explicitly that achieving the TMDL is dependent on implementing mercury controls at both the national and international levels. Model runs conducted under this process estimated that with 1998 emissions data, 43% of anthropogenic mercury deposited in the Northeast US was attributed to sources within the region. With 2002 emissions data (after decreases due to regional policies), 19% of deposited mercury originated from within the region.[4]

The TMDL sets goals for reductions within the region as well as outside the region, in an attempt to address the cross-scale nature of the problem. Regional goals were consistent with the regional mercury action plan described above—a 50% reduction between 1998 and 2003 (which was exceeded), and a 75% reduction from 2003 to 2010 (final data not yet available). Re-evaluation of the target will occur presently for a third phase. For out-of-region sources, the TMDL document recommended national-level actions to reduce power plant emissions by 90 percent based on a "Maximum Achievable Control Technology" (MACT) standard, discussed further in the next section.[4] Of course, the Northeast region does not have the political mandate to enact or enforce out-of-region controls.

While the Northeast case is generally seen as a successful implementation of regional policy, it also shows the limitations of at least some local-level action at a particular scale in dealing with the multifaceted mercury problem. State regulations focus on subnational spatial scales, and address and monitor mercury trends in local ecosystems on timescales up to a decade. In the Massachusetts case, this is illustrated by the timescales of mercury reduction policy goals as well as the monitoring conducted to evaluate these policies (local fish concentrations over a 5–10 year timeframe). Local action, however, has only addressed this element of the multifaceted mercury problem. Addressing other characteristics of the mercury problem, such as reducing deposition from long-range sources, minimizing local-scale consumption of high-mercury marine fish from the global market, and reducing mercury levels in slow-responding local ecosystems have been beyond the scope of local action.

Authorities' lack of reach to address sources in areas beyond their boundaries limits the ability of local authorities to address mercury deposition from these sources. Thus, local policies can only address characteristics of the mercury problem that intersect with local spatial scales. The TMDL document notes specifically, "The Northeast region's ability to achieve the calculated TMDL allocations is dependent on the adoption and effective implementation of national and international programs to achieve necessary reductions in mercury emissions. Given the magnitude of the reductions required to implement the TMDL, the Northeast cannot reduce in-region sources further to compensate for insufficient reductions from out-of-region sources."[4] That is, the ability to meet local policy goals can be directly dependent on supportive regulatory action that needs to be taken in external places and/or at broader levels of social organization.

Another limitation of local policy-making, similar to other policy efforts, lies on the temporal dimension. Policy-making is implemented over years, not centuries. In the policy context, policy-makers establish "long-term" goals for the next decade. First, with election cycles between 2 and 6 years, different administrations may have very different priorities and preferred strategies, meaning that policies could change substantially every few years. Second, governments can only regulate present-day emission sources, and potentially change the likelihood of future sources to emit. They cannot regulate what happened in the past, and their ability to influence the future diminishes with time. Thus, ecosystems that have mercury levels that remain high due to elevated emissions in the past, long timescale processes, and the continuing presence of legacy emissions are beyond the temporal reach of local policies. Minimizing present-day exposure from these sources thus requires adaptation strategies, such as shifts in fishing or dietary patterns. Following the Intergovernmental Panel on Climate Change, adaptation refers to adjustments in either natural or human systems in response to external stimuli, as opposed to mitigation, which is anthropogenic intervention to reduce emissions at their source or increase sinks.[54] The NEG/ECP action plan included an action item on outreach and education, but few explicit policies in the mercury area have focused on adaptation.

3.2. National politics: US Clean Air Mercury Rule

At the US national level, regulatory science provided to support policy action to reduce mercury emissions centers on tracing the pathway from regulated source to impacts. This involves linking emissions, deposition, conversion to methylmercury, and an analysis of the benefits of regulatory action, usually conducted by US EPA scientists. Similar to the local level, this approach focuses on one element of the problem, and centers on building a comprehensive case to address it. The national scale in the United States addresses the mercury contamination problem at a scale that takes into account atmospheric transport on the order of several days, and regulation of sources that cross state lines. (In other, smaller countries, such as many European countries, this level of scale is covered by international policies within the continent.)

US emissions of mercury have decreased dramatically since the 1980s. Decreases in some mercury emissions in the US were a result of co-benefits from sulfur emissions controls such as flue gas desulfurization or the use of electrostatic precipitators on power plants.[55] In the late 1990s, mercury emissions from municipal and medical waste incineration were regulated (under section 129 of the federal Clean Air Act). As a result of these actions, US mercury emissions decreased from 220 tons in 1990 to 115 tons in 1999.[56] The major remaining unregulated US source of anthropogenic mercury emissions is the power sector. In recent years, proposals to regulate mercury from the power sector have been politically controversial.

In the US Clean Air Act amendments of 1990, mercury was listed specifically as a hazardous air pollutant. In the 1990s, litigation under the Clean Air Act initiated by an environmental group, the Sierra Club, which resulted in an agreement by the EPA to regulate mercury from utility sources. As a result of this process, in December 2000, EPA determined that it was "appropriate and necessary" to regulate power-plant emissions of mercury under the Clean Air Act, which is the necessary first step in proposing regulations under the relevant section (112) of the Clean Air Act. Just over three years later, in January 2004, EPA proposed a rule which gave two options for regulating mercury. The first, which reflected the Clean Air Act procedure, applied a "Maximum Achievable Control Technology" (MACT) standard, a technology-based approach which would require minimum performance for both new and existing sources.

At the same time, however, the EPA under the George W. Bush administration (2001 to 2009) proposed an alternative approach, called the Clean Air Mercury Rule (CAMR), based on a "cap-and-trade" program.[56] The cap-and-trade regulatory approach has been used in the EPA's acid rain program as a flexible alternative to plant-by-plant technological regulations. Regulators set a nation-wide cap and require allowances or permits for each unit of emissions; emitters can then trade these permits in an economic market. Cap-and-trade approaches are considered more economically efficient than top-down regulations, as the trading program allows reductions to occur where they are cheapest.[57] However, the approach does allow the possibility of some plants reducing dramatically, and others continuing the same levels of emission.

The tradeoffs inherent in a cap-and-trade approach illustrate how a national-level policy can be limited in its local efficacy when dealing with a multifaceted issue such as mercury. Specifically, characteristics of the mercury problem that fall at different spatial scales can be left unaddressed. Opponents of a cap-and-trade approach argued that since mercury can deposit locally, allowing plants to adopt uneven levels of mercury reductions would not solve local mercury problems. They also argued that the total amount of mercury reduction under the rule was insufficient. In 2008, in response to legal challenges from states, environmental and public health organizations, the D.C. Circuit court vacated the rule on procedural grounds. Under the Obama administration (2009 onwards), the EPA has reversed course, once again finding that regulation under the Clean Air Act is "appropriate and necessary," and released a new proposal in March 2011 to regulate emissions using a "Maximum Achievable Control Technology" standard.[11]

The scientific characteristics of the mercury issue covered by regulation at the national level are illustrated by the regulatory impact analysis prepared for CAMR. The regulatory impact analysis was an extensive effort to combine and channel scientific information on the mercury problem, specifically focusing on the effects of mercury from power generation sources.[58] The Regulatory Impact Analysis focused specifically on point sources (which are in operation over a timescale of decades), and the impact of transport and deposition of mercury emissions from these sources (which affect the US as a whole).

The spatial extent of national policies is illustrated by the use of atmospheric modeling in the CAMR regulatory impact assessment and by the benefits analysis conducted. The regional Community Multiscale Air Quality model (CMAQ)[59] was used to assess scenarios for deposition for input into exposure and cost-benefit analyses. Because the modeling domain of CMAQ is limited to the United States, initial and boundary conditions for CMAQ came from the GEOS-Chem global chemical transport model for mercury.[60] However, it was beyond the scope of the analysis to address the implications of controlling or regulating mercury from beyond US borders, though, as noted before, deposition estimates in the US are sensitive to model characterization of boundary conditions, and that these cross-border impacts are an area of scientific uncertainty.[61]

Thus, national policies could not affect mercury problems characteristic of spatial scales larger than national. The chapter on fish consumption in the Regulatory Impact Analysis acknowledges the spatial limitations of its source-specific approach. It notes that the benefits analysis, focusing on recreational freshwater anglers, represents only 13% of total fish consumption in the US. These fish are largely imported or caught outside US waters, and thus were unlikely to be affected by US regulations on power plant emissions.

The temporal limitations of national policy-making become clear with a more detailed look at the timescales of ecosystem response to changes in deposition. As discussed in Section 2.1, mercury is methylated by bacterial activity in anaerobic environments such as wetlands. The CAMR regulatory impact analysis assumed that changes in deposition would be linearly related to changes in fish methylmercury concentrations, and acknowledges that ecosystems can respond slowly to changes in inputs. Thus, sensitivity analysis considered benefits of the regulation taking into account lag times of 5–50 years between changes in deposition and changes in fish concentration. Taking into account the influence of legacy emissions on present-day deposition, recent work has shown that these sources could continue to contribute to elevated methylmercury fish concentrations in some ecosystems over much longer timescales, centuries to millennia.[37] For this reason, similar to the local scale, addressing the mercury problem at national scale requires adaptation as well as mitigation.

3.3. Global negotiations: ongoing challenges under UNEP

Global activities on mercury focus on multiple aspects of the mercury problem. Policy action is based on the premise that mercury is a global challenge that crosses international borders. This includes long-distance transport of environmental mercury through the atmosphere, but also mercury use in products and in international trade. Additional efforts at the global level focus on capacity building to assist developing countries in implementing an eventual agreement. Science supporting global mercury regulations is geared towards building consensus for global actions, and on identifying and characterizing potential mercury reduction technologies especially in developing country contexts.

International cooperation on mercury dates back to at least the 1970s, with initiatives including regional cooperation and marine policy considerations.[45] Early international action on mercury was developed in the context of cooperation in hazardous substance management in regional seas such as the Baltic.[45] Movement towards a global, legally binding treaty controlling mercury emissions began in the early 2000s. In February 2001, the United Nations Environment Programme (UNEP) Governing Council initiated a process to assess whether mercury was of global concern. The resulting Global Mercury Assessment, which was released in late 2002, concluded that there was sufficient evidence of significant adverse impacts on human health and the environment from environmental releases of mercury to warrant global action to address these adverse impacts.[32]

After receiving the scientific assessment, the UNEP Governing Council took up the question of what, if any, future action should be taken at a global level on mercury first in 2003. At the time, several countries (including the European Union) argued that a global, legally binding treaty was necessary to manage mercury, but others, notably the United States, did not agree that a legal agreement was necessary. Other countries that were hesitant to begin global negotiations included India and China.[62] As a compromise, UNEP initiated a global mercury programme, which focused on technical assistance and capacity building through voluntarily funded partnerships. Among the activities conducted under the global mercury programme were a series of awareness-raising workshops held in developing countries, the development of training materials, and an initiative to assess the scientific issues surrounding the fate and transport of mercury. Meanwhile, at the biennial meetings of the UNEP Governing Council, global policy makers took up the question of negotiating a mercury treaty again in 2005 and 2007, but each time the idea could not garner consensus.

In 2009, however, a change in position of the United States (under President Barack Obama) enabled the UNEP Governing Council to come to consensus, and the UNEP Governing Council agreed to begin to negotiate a global, legally binding mercury treaty. The US under the prior administration of President George W. Bush had opposed new environmental treaty-making, preferring instead voluntary approaches conducted by only willing participants. The Obama administration, in contrast, is in favor of more multilateral diplomatic approaches to environmental problems. Already in 2007, the UNEP Governing Council had established an *ad hoc* open-ended working group to prepare for possible negotiations of a legally binding instrument; a mandate for negotiations was agreed in 2009. Negotiations began in the summer of 2010, with the aim of adopting a treaty in 2013.

The spatial reach of global policies is best illustrated by the 2002 Global Mercury Assessment and the 2008 Global Atmospheric Mercury Assessment. The 2008 report, requested by the UNEP governing council as background information for negotiations, covers the latest knowledge of atmospheric mercury emissions and current results from global-scale modeling as an update to the 2002 report. The newer report built on the results of an earlier voluntary partnership on mercury fate and transport.[55] The modeling work and analyses focus on intercontinental transport. As these global assessments form the basis for the negotiating mandate, they serve to define the scope of the global mercury problem.

Policies to be considered by the global negotiators include measures to reduce mercury supply, limit intentional uses of mercury, and limit releases to air, water and land. In addition, as in many international environmental agreements, global negotiators will need to address concerns such as technical and financial assistance to developing countries for implementation, potential mechanisms for implementation and enforcement, and institutional arrangements. Measures currently under negotiation, among others, include the degree to which export of mercury will be restricted, whether there will be targets and timetables for reduction of mercury emissions, and how stringent restrictions will be on mercury-added products. While these sorts of measures could potentially have substantial local benefits in many countries that do not currently have domestic regulations, the reason for negotiating a global agreement (as noted in the assessment reports) is to address the elements of the mercury problem that cannot effectively be addressed on a country-by-country basis.

Along a temporal dimension, global treaty-making occurs on decadal timescales. A previous example of a treaty on hazardous substances, the Stockholm Convention on Persistent Organic Pollutants, came under global discussion in the mid-1990s.[63] The treaty was adopted in 2001, and entered into force in 2004, a decade-long gap between the beginning of discussion and a legally binding treaty. The process of the mercury agreement, even if it proceeds as planned, will be even longer—while initial discussions began in 2002, a treaty will enter into force no earlier than 2015 or 2016. Conferences of parties to environmental treaties, which have the ability to change or modify treaty language, generally occur every year or two after the treaty has entered into force (Table 1). Thus, the policies and standards put into place by international agreements, while slow to take shape, can easily persist over decadal timescales.

4. Future challenges for policy-relevant science: linking temporal and spatial scale

As described above, policy makers at multiple levels of scale have attempted to address mercury due to concern about human and environmental exposures. Policy activities to date have been conducted at levels of spatial scale corresponding to typical governmental organization (local, national/regional, international). Policy actions to reduce mercury emissions and manage risks associated with mercury exposure are proceeding at multiple political scales simultaneously, each covering a different aspect of a connected, regional-to-global scientific issue. In addition, the temporal scales of the mercury problem range from days (local transport and deposition of industrial emissions), months (intercontinental transport), years (short-term ecosystem dynamics and fish accumulation), decades (longer-term ecosystem dynamics, fish dietary patterns, consumption patterns), to centuries and longer (global biogeochemical cycling). These temporal scales also match imperfectly with the timescales of policy. More effective governance of mercury risks would require better taking into account the multiscale characteristics of the mercury problem.

Fig. 2 illustrates the overlap between policy efforts to address mercury and the scientific characteristics of the mercury issue, organized by spatial and temporal scale. Aspects of mercury as a pollution problem (both environmental and human) are shown in black text, and classified as to their temporal scale (*x*-axis) and their physical scale features (*y*-axis), based on the information presented in Section 2 and Tables 1–2. Fig. 2 also shows the spatial and temporal scale of existing policy efforts (blue ovals) and their intersections with scientific issues at particular scale, based on the analysis in Section 3. The figure thus shows that current policies to address mercury cover mostly the shorter-term behavior of mercury, at levels of scale that correspond to existing political institutions.

At the local level, detailed studies of the direct effects of mercury on ecosystems link monitoring and evaluation with source-level controls. In general, as shown from the Northeast US case, this strategy can be effective at dealing with mercury forms such as Hg(II) and Hg(P) which travel short distances from source to receptor. However, local-level policy-science interaction has limited ability to address issues of mercury from beyond the region. This is best illustrated by the recognition in the context of the TMDL development process that local-scale policies cannot control out-of-region sources. At the US national level, policies have thoroughly documented pathways from emissions through to exposure and effects, but have also been limited by their necessary focus on specific categories of controllable sources. At a similar level of scale, this would reflect regional processes among smaller countries (for example in the European Union context). Globally, scientific assessment efforts

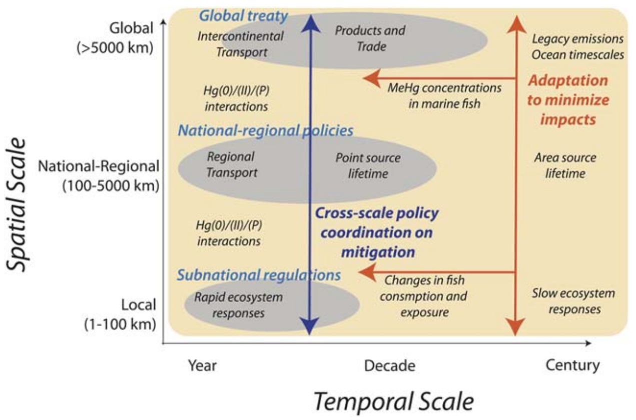

Fig. 2 An illustration of scientific aspects of the mercury issue, and political actions to address mercury, organized by spatial and temporal scale. Scientific aspects of the mercury issue are in black text. The scope of existing policies is denoted by shaded blue ovals. Scientific aspects falling outside the blue ovals are not well-covered by current policies. In order to address these aspects of the mercury issue, two strategies are suggested (arrows): cross-scale policy coordination to address near-term issues falling between the spatial coverage of existing policies (blue arrows); and policies emphasizing adaptation to address mercury impacts from long temporal-scale issues (red arrows).

have been comprehensive, but the role of science in international actions tends to focus on agenda-setting and technical approaches rather than comprehensive science-policy linkages. There has been limited interaction and coordination among these political and scientific scales.

Some elements of the mercury issue, which crosses scales, fall between the scope of these political efforts. For example, policies to address mercury have not specifically addressed the different species of mercury emitted from sources. Controlling Hg(0) or forms such as Hg(II) and Hg(P) will have dramatically different benefits in terms of where mercury deposition and associated exposures could be reduced. All three cases above dealt with mercury as a general category, and did not differentiate by species. It is the conversion of mercury among these species, which occurs *via* atmospheric processes, that makes global emissions important at local scales and local emissions important at global scales. In addition, in considering the entire pathway from emissions to exposure, many elements of this pathway cross scales. A consumer in an urban area in the United States might consume fish contaminated with mercury from a local waterway, and also fish bought in the supermarket which accumulated mercury during Pacific Ocean migrations. No one policy level can address all of the sources of exposure to this one consumer.

Along a temporal dimension, policies by definition deal with near-term decisions. Regulatory action can be implemented within timescales of a year, and regulations can be phased in over a decade or more. As noted above, point sources such as power plants can have lifetimes of decades. However, though policies can be more or less forward-looking, today's policies can have only an indirect effect on issues that have characteristic timescales of centuries.

Local and national policies can be long-lasting, and establish goals for emissions over a decade or more. However, future policy-makers can modify or change these policies—indeed, this is necessary to address environmental problems effectively as scientific understanding changes. Local and national policies can change on short timescales, but several examples exist of decadal goals and implementation (for example, the Massachusetts mercury strategy described above). While international treaty-making is a slow process, they tend to be long-lasting. However, no policy-maker can credibly regulate a century into the future (or longer) or change the past (with its accumulated "legacy" emissions).

Two types of solutions emerge for the spatial and temporal challenges associated with the mercury problem. These are illustrated in Fig. 2 by the red and blue arrows. First, to address the elements of the mercury issue that fall between the spatial scales of policy-making, better coordination among political levels is necessary. Increasingly, the interactions between scientific scales and political scales in environmental problems have also become the topic of research.[64] Previous research has noted that mercury is a multi-scale problem, and that in order to effectively address it, action at a variety of political scales is necessary.[45] However, this analysis shows clearly that in addition to self-contained action at multiple scales, coordination among scales is critical to addressing those aspects of the mercury problem that fall between the mandates of political levels. A growing literature studying international environmental agreements notes the increasing development of linkages between political organizations at different levels of scale, termed vertical linkages.[65] From a political perspective, several potential solutions have been proposed to facilitate these cross-scale linkages, including creating regional organizations that link local implementation to international policies.[66] This is an ongoing area of active research, and this analysis links these developments in policy sciences to the physical characteristics of an environmental problem.

Second, to address environmental and earth systems problems that occur on timescales longer than the usual political actions, a two-pronged approach is necessary, that combines forward-looking mitigation strategies with adaptation. In the case of mercury, adaptation involves actions that minimize human or environmental exposure to methylmercury other than controlling the direct anthropogenic emissions fraction. At present, the major active policy action in the adaptation arena for mercury involves dietary advice on eating contaminated fish.[67] Other adaptation strategies could include fishing limits or bans or ecosystem interventions to limit mercury revolatilization or methylmercury conversion. However, there is a clear need for more research to inform better, policy-focused adaptation strategies for mercury.

Making effective policy across scales on environmental issues is an ongoing challenge that is only beginning to be addressed by both the policy and research communities. From a scientific perspective, regulatory developments provide a critical demand-side push for further relevant investigations. Despite decades of policy action and research, mercury remains on political agendas as an environmental problem; it is unlikely to be solved without attention by both scientists and regulators to these cross-scale interactions and connections. This analysis suggests that the mercury regime is best conceptualized as a science-policy system with multiple driving forces and interactions at multiple scales. Cross-scale policy coordination and adaptation to minimize impacts are two strategies that could successfully create solutions not only for mercury, but also may apply to other environmental issues that cross spatial and temporal scales.

References

1 D. Mergler, H. A. Anderson, L. H. M. Chan, K. R. Mahaffey, M. Murray, M. Sakamoto and A. H. Stern, *Ambio*, 2007, **36**, 3–11.
2 K. R. Mahaffey, H. R. P. Clickner and C. B. Joseph, *Environ. Health Perspect.*, 2003, **562**, 562–570.
3 S. Böse-O'Reilly, S. Maydl, G. Drasch and G. Roider, *Mercury as a Health Hazard Due to Gold Mining and Mineral Processing Activities in Mindanao Philippines Final Report*, UNIDO Project DP/PHI/98/005, Munich, 2000.
4 Connecticut Department of Environmental Protection, Maine Department of Environmental Protection, Massachusetts Department of Environmental Protection, New Hampshire Department of Environmental Services, New York State Department of Environmental Conservation, Rhode Island Department of Environmental Management, Vermont Department of Environmental Conservation and New England Interstate Water Pollution Control Commission, *Northeast Regional Mercury Total Maximum Daily Load*, 2007, http://www.mass.gov/dep/water/resources/mertmdl.pdf, accessed 26 November 2010.
5 N. E. Selin, D. J. Jacob, R. M. Yantosca, S. Strode, L. Jaeglé and E. M. Sunderland, *Global Biogeochem. Cycles*, 2008, **22**, GB2011.
6 E. M. Sunderland and R. P. Mason, *Global Biogeochem. Cycles*, 2007, **21**, GB4022.
7 J. O. Nriagu, *Production and Uses of Mercury*, Elsevier, New York, 1979.
8 E. B. Swain, P. M. Jakus, G. Rice, F. Lupi, P. A. Maxson, J. M. Pacyna, A. Penn, S. J. Spiegel and M. M. Veiga, *Ambio*, 2007, **36**, 45–61.
9 C. D. Knightes, E. M. Sunderland, M. C. Barber, J. M. Johnston and R. B. AmbroseJr, *Environ. Toxicol. Chem.*, 2009, **28**, 881–893.
10 U.S. Energy Information Administration, *Existing Electric Generating Units in the United States (By Energy Source)*, http://www.eia.gov/cneaf/electricity/page/capacity/capacity.html, accessed 1 June 2011.
11 U.S. Environmental Protection Agency, *Fed. Regist*, 2011, **76**, 24976–25147.
12 K. Kindbom and J. Munthe, *Product-related Emissions of Mercury to Air in the European Union*, IVL Swedish Environmental Research Institute, Gothenburg, 2007, http://www.unece.org/env/lrtap/TaskForce/tfhm/fourth meetingdocs/Products_Hg_Emissions.pdf, accessed 1 June 2011.
13 R. P. Mason and G. R. Sheu, *Global Biogeochem. Cycles*, 2002, **16**, 1093.
14 U.S. Environmental Protection Agency, *Mercury Study Report to Congress Volume V: Health Effects of Mercury and Mercury Compounds EPA-452/R-97–007*, 1997, http://www.epa.gov/ttn/oarpg/t3/reports/volume5.pdf, accessed 1 June 2011.
15 M. M. Veiga and J. J. Hinton, *Nat. Resour. Forum*, 2002, **26**, 15–26.
16 W. F. Fitzgerald, D. R. Engstrom, C. H. Lamborg, C.-M. Tseng, P. H. Balcom and C. R. Hammerschmidt, *Environ. Sci. Technol.*, 2005, **39**, 557–568.
17 P. Schuster, D. Krabbenhoft, D. Naftz, L. Cecil, M. Olson, J. Dewild, D. D. Susong, J. Green and M. Abbott, *Environ. Sci. Technol.*, 2002, **36**, 2303–2310.
18 D. F. Grigal, *J. Environ. Qual.*, 2003, **32**, 393–405.
19 H. Hintelmann, R. Harris, A. Heyes, J. P. Hurley, C. A. Kelly, D. P. Krabbenhoft, S. Lindberg, J. W. M. Rudd, K. J. Scott and V. L. S. Louis, *Environ. Sci. Technol.*, 2002, **36**, 5034–5040.
20 E. J. Kerin, C. C. Gilmour, E. Roden, M. T. Suzuki, J. D. Coates and R. P. Mason, *Appl. Environ. Microbiol.*, 2006, **72**, 7919.
21 C. C. Gilmour, E. A. Henry and R. Mitchell, *Environ. Sci. Technol.*, 1992, **26**, 2281–2287.
22 D. Engstrom, *Proc. Natl. Acad. Sci. U. S. A.*, 2007, **104**, 16394–16395.
23 R. C. Harris, J. W. M. Rudd, M. Amyot, C. L. Babiarz, K. G. Beaty, P. J. Blanchfield, R. A. Bodaly, B. A. Branfireun, C. C. Gilmour, J. A. Graydon, A. Heyes, H. Hintelmann, J. P. Hurley, C. a. Kelly, D. P. Krabbenhoft, S. E. Lindberg, R. P. Mason, M. J. Paterson, C. L. Podemski, A. Robinson, K. a. Sandilands, G. R. Southworth, V. L. St Louis and M. T. Tate, *Proc. Natl. Acad. Sci. U. S. A.*, 2007, **104**, 16586–16591.
24 E. M. Sunderland, D. P. Krabbenhoft, J. W. Moreau, S. A. Strode and W. M. Landing, *Global Biogeochem. Cycles*, 2009, **23**, 1–14.
25 C. R. Hammerschmidt and W. F. Fitzgerald, *Geochim. Cosmochim. Acta*, 2006, **70**, 918–930.
26 M. Monperrus, E. Tessier, D. Point, K. Vidimova, D. Amouroux, R. Guyoneaud, A. Leynaert, J. Grall, L. Chauvaud and G. Thouzeau, *Estuarine, Coastal Shelf Sci.*, 2007, **72**, 485–496.
27 S. H. Ferguson, M. K. Taylor, E. W. Born, A. Rosing-Asvid and F. Messier, *Ecol. Lett.*, 1999, **2**, 311–318.
28 F. J. Mather, J. M. J. Mason and C. A. Jones, *Historical Document: Life History and Fisheries of Atlantic Bluefin Tuna Technical Memorandum NMFS-SEFSC*, National Oceanic and Atmospheric Administration (NOAA), 1995.
29 C. L. Weber and H. S. Matthews, *Environ. Sci. Technol.*, 2008, **42**, 3508–3513.
30 E. G. Pacyna, J. M. Pacyna, F. Steenhuisen and S. Wilson, *Atmos. Environ.*, 2006, **40**, 4048–4063.
31 O. R. Bullock, D. Atkinson, T. Braverman, K. Civerolo, A. Dastoor, D. Davignon, J. Y. Ku, K. Lohman, T. C. Myers, R. J. Park, C. Seigneur, N. E. Selin, G. Sistla and K. Vijayaraghavan, *J. Geophys. Res.*, 2009, **114**, 1–12.
32 United Nations Environment Programme (UNEP), *Global Mercury Assessment*, Inter-Organisation Programme for the Sound Management of Chemicals, Geneva, 2002.
33 T. W. Clarkson, *Environ. Health Perspect.*, 2002, **110**(suppl. 1), 11–23.
34 M. Harada, *Crit. Rev. Toxicol.*, 1995, **25**, 1–24.
35 H. A. Roman, T. L. Walsh, B. A. Coull, E. Dewailly, E. Guallar, D. Hattis, K. Marien, J. Schwartz, A. H. Stern, J. K. Virtanen and G. Rice, *Environ. Health Perspect.*, 2011, **119**, 607–614.

36 P. Grandjean, P. Weihe, R. F. White, F. Debes, S. Araki, K. Yokoyama, K. Murata, N. Sørensen, R. Dahl and P. J. Jørgensen, *Neurotoxicol. Teratol.*, 1997, **19**, 417–428.
37 N. E. Selin, E. M. Sunderland, C. D. Knightes and R. P. Mason, *Environ. Health Perspect.*, 2010, **118**, 137–143.
38 E. M. Sunderland, *Environ. Health Perspect.*, 2007, **115**, 235–242.
39 C. D. Holmes, D. J. Jacob, E. S. Corbitt, J. Mao, X. Yang, R. Talbot and F. Slemr, *Atmos. Chem. Phys.*, 2010, **10**, 12037–12057.
40 U.S. Environmental Protection Agency, *Methylmercury (MeHg) (CASRN 22967-92-6)*, http://www.epa.gov/iris/subst/0073.htm, accessed 1 June 2011.
41 U.S. Food and Drug Administration, *Mercury Levels in Commercial Fish and Shellfish (1990–2010)*, http://www.fda.gov/food/foodsafety/product-specificinformation/seafood/foodbornepathogenscontaminants/methylmercury/ucm115644.htm, accessed 1 June 2011.
42 International Labour Organization, *Workmen's Compensation (Occupational Diseases) Convention*, Geneva, 1925.
43 R. P. Wedeen, *Am. J. Ind. Med.*, 1989, **16**, 225–233.
44 H. Imura, in *Environmental Policy in Japan*, ed. H. Imura, M. Schreurs and E. Elgar, Cheltenham, UK, 2005.
45 N. E. Selin and H. Selin, *Rev. Eur. Community Int. Environ. Law*, 2006, **15**, 258–269.
46 M. Ashton, P. M. Kohler and K. Xia, *Earth Negotiations Bulletin*, 2011, **28**(7), 1–15.
47 Commonwealth of Massachusetts, *Massachusetts Zero Mercury Strategy*, Boston, MA, 2000, http://www.mass.gov/dep/toxics/stypes/zerohg.pdf, accessed 1 June 2011.
48 N. C. Kamman, N. M. Burgess, C. T. Driscoll, H. A. Simonin, W. Goodale, J. Linehan, R. Estabrook, M. Hutcheson, A. Major, A. M. Scheuhammer and D. A. Scruton, *Ecotoxicology*, 2005, **14**, 163–180.
49 C. M. Smith and L. J. Trip, *Ecotoxicology*, 2005, **14**, 19–35.
50 Commonwealth of Massachusetts, in *Code of Massachusetts Regulations*, vol. 310, CMR 7.29.
51 Northeast States for Coordinated Air Use Management, *Technologies for Control and Measurement of Mercury Emissions from Coal-Fired Power Plants in the United States*, NESCAUM, Boston, 2010, http://www.nescaum.org/documents/hg-control-and-measurement-techs-at-us-pps_201007.pdf, accessed 26 November 2010.
52 M. S. Hutcheson, J. Rose, C. M. Smith, C. R. West, O. Pancorbo, J. Sullivan and B. Eddy, *Massachusetts Fish Tissue Mercury Studies: Long-term Monitoring Results, 1999–2004*, Boston, MA, 2006. http://www.mass.gov/dep/toxics/stypes/hgtrend.pdf.
53 S. King, S. Hochbrunn, P. Miller, J. Graham, T. Goldberg, A. Wienert and M. Wilcox, *Environ. Manag.*, 2008, 9–13.
54 *Climate Change 2007: Impacts, Adaptation and Vulnerability*, ed. M. Parry, O. Canziani, J. Palutikof, P. van der Linden and C. Hanson, Cambridge University Press, Cambridge, UK, 2007.
55 United Nations Environment Programme, *The Global Atmospheric Mercury Assessment: Sources, Emissions and Transport*, UNEP, Geneva, 2008.
56 U.S. Environmental Protection Agency, *Fed. Regist.*, 2004, **69**, 4652–4752.
57 A. D. Ellerman, P. L. Joskow and D. Harrison, Emissions trading in the U.S.: Experience, Lessons and Considerations for Greenhouse Gases, Pew Center for Global Climate Change, Washington, DC, 2003.
58 U.S. Environmental Protection Agency, *Regulatory Impact Analysis of the Clean Air Mercury Rule: Final Report*, Research Triangle Park, NC, 2005, http://www.epa.gov/ttn/atw/utility/ria_final.pdf, accessed 1 June 2011.
59 O. R. Bullock and K. A. Brehme, *Atmos. Environ.*, 2002, **36**, 2135–2146.
60 N. E. Selin, D. J. Jacob, R. J. Park, R. M. Yantosca, S. Strode, L. Jaeglé and D. Jaffe, *J. Geophys. Res.*, 2007, **112**, D02308.
61 O. R. Bullock, D. Atkinson, T. Braverman, K. Civerolo, A. Dastoor, D. Davignon, J.-y. Ku, K. Lohman, T. C. Myers, R. J. Park, C. Seigneur, N. E. Selin, G. Sistla and K. Vijayaraghavan, *J. Geophys. Res.*, 2008, **113**, 1–17.
62 A. Appleton, M. Ashton, T. Kantai, W. Mwangi, K. Ripley and A. A. Vavilov, *Earth Negotiations Bulletin*, 2009, **16**(78), 1–16.
63 H. Selin and N. Eckley, *International Environmental Assessments: Politics, Law and Economics*, 2003, **3**, 17–42.
64 H. Bulkeley, *Polit. Geogr.*, 2005, **24**, 875–902.
65 O. Young, *The Institutional Dimensions of Environmental Change: Fit, Interplay, and Scale*, MIT Press, Cambridge, MA, 2002.
66 H. Selin, *Global Governance of Hazardous Chemicals: Challenges of Multilevel Management*, MIT Press, Cambridge, MA, 2010.
67 U.S. Food and Drug Administration and U.S. Environmental Protection Agency, *What You Need to Know About Mercury in Fish and Shellfish*, 2004. http://water.epa.gov/scitech/swguidance/fishshellfish/outreach/upload/2004_05_24_fish_MethylmercuryBrochure.pdf, accessed 26 November 2010.