Legacy impacts of all-time anthropogenic emissions on the global mercury cycle

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Received 6 November 2012; revised 28 February 2013; accepted 28 March 2013; published 9 May 2013.

Elevated mercury (Hg) in marine and terrestrial ecosystems is a global health concern because of the formation of toxic methylmercury. Humans have emitted Hg to the atmosphere for millennia, and this Hg has deposited and accumulated into ecosystems globally. Here we present a global biogeochemical model with fully coupled atmospheric, terrestrial, and oceanic Hg reservoirs to better understand human influence on Hg cycling and timescales for responses. We drive the model with a historical inventory of anthropogenic emissions from 2000 BC to present. Results show that anthropogenic perturbations introduced to surface reservoirs (atmosphere, ocean, or terrestrial) accumulate and persist in the subsurface ocean for decades to centuries. The simulated present-day atmosphere is enriched by a factor of 2.6 relative to 1840 levels, consistent with sediment archives, and by a factor of 7.5 relative to natural levels (2000 BC). Legacy anthropogenic Hg re-emitted from surface reservoirs accounts for 60% of present-day atmospheric deposition, compared to 27% from primary anthropogenic emissions, and 13% from natural sources. We find that only 17% of the present-day Hg in the surface ocean is natural and that half of its anthropogenic enrichment originates from pre-1950 emissions. Although Asia is presently the dominant contributor to primary anthropogenic emissions, only 17% of the surface ocean reservoir is of Asian anthropogenic origin, as compared to 30% of North American and European origin. The accumulated burden of legacy anthropogenic Hg means that future deposition will increase even if primary anthropogenic emissions are held constant. Aggressive global Hg emission reductions will be necessary just to maintain oceanic Hg concentrations at present levels.


1. Introduction

Hg cycles naturally through geochemical reservoirs, but human activities such as mining and more recently fossil fuel combustion have been increasing the Hg flux from the deep mineral reservoir to the atmosphere for millennia [Nriagu, 1993, 1994; Lacerda, 1997; Camargo, 2002]. Here we present a global biogeochemical model of Hg that dynamically couples the ocean, atmosphere, and terrestrial reservoirs. We force the model with a historical inventory of anthropogenic emissions [Streets et al., 2011], quantify the resulting present-day enrichment of the various global Hg reservoirs, and discuss implications for the future.

Hg liberated from the deep mineral reservoir naturally (e.g., volcanoes) or by human activities cycles between the atmosphere and surface reservoirs (ocean and terrestrial ecosystems) on timescales of years to decades [Mason et al., 1994; Mason and Sheu, 2002; Selin et al., 2008]. It is eventually transferred to recalcitrant soil pools [Smith-Downey et al., 2010] and the deep ocean [Gill and Fitzgerald, 1988; Sunderland and Mason, 2007] over centuries and back to the deep mineral reservoir over millennia [Andren and Nriagu, 1979]. Anthropogenic enrichment of the ocean is of particular interest because Hg exposure for most human populations is from methylmercury in marine fish [Johansen et al., 2004; Sunderland, 2007; Kim and Lee, 2010].

Sedimentary and ice core records provide evidence of a two- to five-fold enrichment in present-day atmospheric Hg deposition relative to preindustrial (ca. 1840) levels [Fitzgerald et al., 1998; Schuster et al., 2002; Biester et al., 2007; Lindberg et al., 2007]. This reflects growing emissions in Europe and North America over the nineteenth and twentieth centuries, compounded by growth in Asian emissions over the past decades [Pacyna et al., 2003, 2006;...
from the deep mineral reservoir to the atmosphere by geogenic or anthropogenic emissions is viewed as an external forcing since the residence time of Hg in the deep mineral reservoir is ~1 billion years [Andren and Nriagu, 1979]. Burial from the deep ocean returns Hg to the deep mineral reservoir.

[7] Figure 1 provides a schematic of the box model. Mass transfer between model reservoirs is represented by a system of coupled first-order differential equations:

$$\frac{dm}{dt} = Km + s$$  (1)

where m is a seven-element vector of reservoir masses (Mg of Hg), s is a vector describing the external forcing (Mg a⁻¹) from the deep mineral reservoir (0 for all reservoirs except for the atmosphere), and K is a 7 × 7 matrix of first-order time-invariant rate coefficients kij (a⁻¹) describing the flow from reservoir i to reservoir j. Thus, kij=Fij/mi, where Fij (Mg a⁻¹) is the flow (sink) from reservoir i to reservoir j and mi (Mg) is the mass of reservoir i. The flows are not thought to be limited by Hg, so the assumption of first-order behavior is reasonable. We derive values of kij from literature estimates of present-day masses and flows, as summarized in Table 1 and described below. Estimates in Table 1 account for Hg speciation (Hg(0), Hg(II), and particulate Hg), but here we only track total Hg.

[8] The physical and chemical processes driving the flows Fij are unlikely to have changed significantly over the Holocene, supporting the use of time-invariant kij. An exception may be the rate of atmospheric oxidation of Hg(0), which determines the rate coefficient for transfer from the atmosphere to the surface reservoirs (1.5 a⁻¹ in Figure 1, corresponding to an atmospheric lifetime of 8 months). Atmospheric oxidant levels may have been affected by human activities, but the resulting atmospheric lifetime of Hg is unlikely to have changed by more than a factor of 2 from present to preindustrial or over the Holocene [Thompson et al., 1993; Parrella et al., 2012] and is therefore short relative to the decadal and longer timescales of interest here. Changing the preindustrial atmospheric lifetime of Hg by a factor of 2 in our model has an inverse effect on the simulated atmospheric reservoir amount but has no effect on any other model results including the preindustrial-to-present enrichment factor for atmospheric deposition.

2. Model Description

[4] We develop a fully coupled, seven-reservoir box model of the global Hg cycle by building on previous models that focused on individual components of the cycle [Sunderland and Mason, 2007; Selin et al., 2008; Soerensen et al., 2010; Holmes et al., 2010; Smith-Downey et al., 2010]. Much of these previous works used the GEOS-Chem global 3-D model for atmospheric Hg coupled to 2-D surface reservoirs (http://geos-chem.org). Our seven-box model allows full coupling of the ocean, atmosphere, and terrestrial reservoirs for millennium-scale simulations. The seven reservoirs include the atmosphere, ocean (surface, subsurface, and deep), and terrestrial ecosystems (fast terrestrial, slow soil, and armored soil), as described below. Hg transferred

Figure 1. Rate coefficients kij (a⁻¹) driving our seven-reservoir global biogeochemical box model for Hg. kij defines the first-order transfer from reservoir i to reservoir j as Fij = kijmi, where Fij (Mg a⁻¹) is the Hg flow from reservoir i to reservoir j and mi (Mg) is the mass of Hg in reservoir i. Values of kij are derived from best estimates of present-day flows and masses from the literature (Table 1) and are assumed to be constant in time. The red arrow represents the external forcing by primary emissions (geogenic or anthropogenic) from the deep mineral reservoir. Geogenic emissions are constant (90 Mg a⁻¹), and anthropogenic emissions are time dependent (Figure 2).

Wu et al., 2006; Pacyna et al., 2010; Streets et al., 2011]. However, pre-1850 anthropogenic emissions were also large [Nriagu, 1993; Streets et al., 2011], as shown by long-term peat and sediment records [Roos-Barralough et al., 2002, 2006; Cooke et al., 2009; Elbaz-Poulichet et al., 2011]. This historical anthropogenic Hg continues to cycle through biogeochemical reservoirs, representing a legacy of Hg enrichment in the environment.

[5] Understanding how the legacy of historical anthropogenic emissions impacts the present-day Hg cycle is necessary for projecting future changes. Global anthropogenic emissions are expected to increase in the future in the absence of directed efforts to control Hg [Streets et al., 2009]. The new global Hg treaty negotiated by the United Nations Environment Program (UNEP) aims to reduce anthropogenic sources [United Nations Environment Program (UNEP), 2013]. Here we examine how the global ocean, atmosphere, and terrestrial ecosystems will respond to future changes in emissions.

2.1. Atmosphere

[5] We adopt the present-day atmospheric reservoir and deposition estimates from the GEOS-Chem simulation of Holmes et al. [2010] (Table 1), which show no systematic biases against observations. The atmospheric reservoir is 5000 Mg, and the total deposition is 6900 Mg a⁻¹, corresponding to an atmospheric lifetime of 0.7 years. Other literature estimates give a range of 4600–5600 Mg for the atmospheric reservoir, 4200–9000 Mg a⁻¹ for total deposition, and 0.5–1.5 years for atmospheric lifetime [Slemr et al., 1985; Lindqvist and Rodhe, 1985; Mason et al., 1994; Shia et al., 1999; Mason and Sheu, 2002; Lamborg et al., 2002b; Seigneur et al., 2004; Selin et al., 2008; Amos et al., 2012].
### Table 1. Present-Day Hg Reservoirs and Flows\(^a\)

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Flow (Mg a(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere: 5000 Mg</td>
<td>3900</td>
</tr>
<tr>
<td>Hg(II) deposition to ocean</td>
<td>40</td>
</tr>
<tr>
<td>Hg(0) deposition to ocean</td>
<td>1500</td>
</tr>
<tr>
<td>Hg(II) deposition to land(^b)</td>
<td>1500</td>
</tr>
<tr>
<td>Surface ocean: 2900 Mg</td>
<td></td>
</tr>
<tr>
<td>Hg(0) evasion</td>
<td>3000</td>
</tr>
<tr>
<td>Particle settling to subsurface ocean</td>
<td>3300</td>
</tr>
<tr>
<td>Water transfer to subsurface ocean</td>
<td>5100</td>
</tr>
<tr>
<td>Subsurface ocean: 130,000 Mg</td>
<td></td>
</tr>
<tr>
<td>Particle settling to deep ocean</td>
<td>480</td>
</tr>
<tr>
<td>Water transfer to surface ocean</td>
<td>7100</td>
</tr>
<tr>
<td>Water transfer to deep ocean</td>
<td>340</td>
</tr>
<tr>
<td>Deep ocean: 220,000 Mg</td>
<td></td>
</tr>
<tr>
<td>Burial to deep sediments</td>
<td>210</td>
</tr>
<tr>
<td>Water transfer to subsurface ocean</td>
<td>180</td>
</tr>
<tr>
<td>Fast terrestrial pool: 9600 Mg</td>
<td></td>
</tr>
<tr>
<td>Evasion due to respiration of organic carbon</td>
<td>460</td>
</tr>
<tr>
<td>Photocatalytic re-emission of deposited Hg</td>
<td>850</td>
</tr>
<tr>
<td>Biomass burning</td>
<td>290</td>
</tr>
<tr>
<td>Transfer to slow pool</td>
<td>330</td>
</tr>
<tr>
<td>Transfer to armored pool</td>
<td>10</td>
</tr>
<tr>
<td>River runoff to surface ocean(^c)</td>
<td>365</td>
</tr>
<tr>
<td>Slow soil pool: 35,000 Mg</td>
<td></td>
</tr>
<tr>
<td>Evasion due to respiration of organic carbon</td>
<td>250</td>
</tr>
<tr>
<td>Biomass burning</td>
<td>8</td>
</tr>
<tr>
<td>Transfer to fast pool</td>
<td>210</td>
</tr>
<tr>
<td>River runoff to surface ocean</td>
<td>10</td>
</tr>
<tr>
<td>Armored soil pool: 190,000 Mg</td>
<td></td>
</tr>
<tr>
<td>Evasion due to respiration of organic carbon</td>
<td>25</td>
</tr>
<tr>
<td>Biomass burning</td>
<td>4</td>
</tr>
<tr>
<td>Transfer to fast pool</td>
<td>15</td>
</tr>
<tr>
<td>River runoff to surface ocean</td>
<td>5</td>
</tr>
<tr>
<td>Deep mineral reservoir: 3 \times 10(^{11}) Mg</td>
<td>90</td>
</tr>
<tr>
<td>Geogenic emission</td>
<td>90</td>
</tr>
<tr>
<td>Anthropogenic emission(^d)</td>
<td>2000</td>
</tr>
</tbody>
</table>

\(^a\)The best estimates of present-day reservoirs \(m_i\) and flows \(F_i\) given in this table are used to derive the rate coefficients \(k_{ij} = F_i/m_j\) in Figure 1. References are Holmes et al. (2010) for the atmosphere and biomass burning, Soerensen et al. (2010) for the surface ocean, Sunderland and Mason (2007) for the subsurface/deep ocean and river runoff, Smith-Downey et al. (2010) for the terrestrial/soil pools, and Andren and Nriagu (1979) and Perrone et al. (2010) for the deep mineral reservoir.  
\(^b\)Partitioned 50% to the fast terrestrial pool, 32% to the slow soil pool, and 18% to the armored soil pool following Smith-Downey et al. (2010).  
\(^c\)All Hg(0) deposition is delivered to the fast terrestrial pool.  
\(^d\)Extending down to the base of the ocean mixed layer.  
\(^e\)Extending from the base of the ocean mixed layer down to the depth of the permanent thermocline.  
\(^f\)Total biomass burning is 300 Mg a\(^{-1}\) [Holmes et al., 2010] and is apportioned as 95% from vegetation (fast terrestrial pool) and 5% from the three soil pools (fast, slow, and armored) based on carbon content [Smith-Downey et al., 2010].  
\(^g\)Total river runoff is 380 Mg a\(^{-1}\) [Sunderland and Mason, 2007] and is partitioned among the soil pools in the same manner as biomass burning.  
\(^h\)Anthropogenic emissions are time dependent (see Figure 2a). The value 2000 Mg a\(^{-1}\) corresponds to the year 2008 from Streets et al. (2011).  

## 2.2. Ocean

We partition the ocean into three reservoirs: (1) the surface ocean extending to the depth of the permanent thermocline (1500 m based on Sunderland and Mason [2007]), and (3) the deep ocean extending to the sea floor. Our surface ocean budget, including air-sea exchange, is based on the GEOS-Chem simulation of Soerensen et al. [2010], which uses a global mean mixed layer depth of 54 m based on observations [Montegut et al., 2004]. Subsurface and deep ocean reservoirs are estimated from vertical Hg profile data following Sunderland and Mason [2007].

Hg flows/sinks from ocean reservoirs include evasion to the atmosphere, settling of particulate matter including eventual burial in deep-sea sediments, and vertical transport of seawater. Particle settling is based on carbon export fluxes (ocean rain) using the parameterization of Antia et al. [2001] and global ocean productivity from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data (see Soerensen et al. [2010] and Sunderland and Mason [2007] for details). Burial to deep ocean sediments returns Hg to the deep mineral reservoir. Sunderland and Mason [2007] estimated the present-day range in burial to be 180–260 Mg a\(^{-1}\). Model results are relatively insensitive (<10%) to this range.

## 2.3. Terrestrial Ecosystems

Terrestrial Hg is partitioned into three reservoirs based on the Global Terrestrial Mercury Model (GTMM) of Smith-Downey et al. [2010]: fast terrestrial reservoir, slow soil, and armored soil. The fast terrestrial reservoir includes vegetation, litter, labile organic carbon soil pools, and ice and snow-covered terrestrial surfaces [Smith-Downey et al., 2010]. Slow and armored soil pools are defined by long turnover times for organic carbon mineralization, with armored soils being the most recalcitrant. GTMM is based on the association of Hg with organic carbon and uses soil carbon pools and turnover times from the Carnegie Ames Stanford Approach (CASAB) biogeochemical model for carbon [Potter et al., 1993; van der Weerf et al., 2003].

Hg from terrestrial reservoirs is transferred to the atmosphere by respiration of organic carbon, photoreduction, and biomass burning; and to the surface ocean by river runoff. Hg emissions associated with organic carbon decomposition (740 Mg a\(^{-1}\)) are from Smith-Downey et al. [2010]. Global estimates of photoreduction are in the range 260–1100 Mg a\(^{-1}\) [Selin et al., 2008; Smith-Downey et al., 2010; Holmes et al., 2010]. We adopt a value of 850 Mg a\(^{-1}\) to balance emissions and deposition in our atmospheric budget. Global biomass burning emission estimates range from 300 [Holmes et al., 2010] to 675 Mg a\(^{-1}\) [Friedli et al., 2009]. We use 300 Mg a\(^{-1}\) here, but a larger biomass burning source could be equivalently accommodated in our model by decreasing the photoreduction source. We assume that 95% of the biomass burning source is from the fast terrestrial reservoir (which includes vegetation), and the remaining 5% is partitioned among the fast, slow, and armored soils based on their respective soil organic carbon content, following Smith-Downey et al. [2010]. River runoff is 380 Mg a\(^{-1}\) from Sunderland and Mason [2007] and is partitioned among terrestrial pools in the same manner as biomass burning.

## 2.4. Geogenic Emission

We define geogenic emission as Hg liberated from the deep mineral reservoir by volcanic activity, crustal degassing, and weathering [Nriagu and Becker, 2003]. Andren and Nriagu [1979] estimated the size of the deep mineral reservoir to be 3 \times 10\(^{11}\) Mg. Estimates of geogenic range from ~1 to 1000 Mg a\(^{-1}\) [Varekamp and Buseck, 1986; Ferrara et al., 2000; Nriagu and Becker, 2003; Pyle and Mather, 2003; Bagnato et al., 2011], but little confidence is placed in the extrema of this range [Pyle and...
We use 90 Mg a\(^{-1}\) \(\text{CO}_1\) from Pirrone et al. [2010], which is consistent with the estimate of Bagnato et al. [2011] (95 Mg a\(^{-1}\) \(\text{CO}_1\)) derived from atmospheric observations of volcanic plumes.

2.5. Anthropogenic Emissions

[15] We force the model from 2000 BC to 2008 AD with primary anthropogenic emissions of total Hg, as shown in Figure 2a. “Primary” refers to direct transfer from the deep mineral reservoir to the atmosphere. Streets et al. [2011] gave a best estimate of 2000 Mg a\(^{-1}\) for 2008 emissions (referred to here as “present-day”), a total of 215 Gg for 1850–2008 emissions with decadal information on emission sectors and source regions, and a pre-1850 total of 137 Gg without temporal information. Based on the work of Nriagu [1993] and Streets et al. [2011], we estimate that 111 Gg of that total was emitted between 1570 and 1850, mainly in association with silver mining in Spanish America. The remaining 26 Gg is emitted before 1570 AD.

[16] Sediment cores [Cooke et al., 2009; Elbaz-Poulichet et al., 2011] and archeological evidence [Goldwater, 1972 and references therein; Nriagu, 1979 and references therein] suggest more than 3500 years of Hg releases from human activity. We initiate anthropogenic Hg emissions in 2000 BC based on use of Hg as pigment as far back as 2500–1600 BC by the Greeks, reports of quicksilver found in a tomb dating to ~2000 BC, and use of Hg (as quicksilver and cinnabar) by the Assyrians as early as 1900 BC [Goldwater, 1972]. We assume a linear increase in emissions from 2000 BC until 1570 AD, a step increase at 1570 AD due to silver production in Spanish America [Nriagu, 1993, 1994; Camargo, 2002], and constant emissions between 1570 and 1850 AD. Model results are insensitive to the details of this emission schedule, as discussed in section 3.

[17] Streets et al. [2009] projected future Hg emissions out to 2050 using the International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) scenarios [Nakicenovic, 2000]. The A1B business-as-usual scenario features continued growth in emissions such that primary anthropogenic emissions in 2050 are a factor of 3.6 higher than present-day. The most optimistic SRES scenario (B1) has effectively constant emissions relative to present-day levels [Streets et al., 2009]. These scenarios assume no direct policy intervention for Hg control, but some level of intervention may be anticipated in light of the recent Hg treaty negotiated by UNEP [UNEP, 2013]. To illustrate the potential benefit of emission controls, we consider a “mercury controls” scenario where primary anthropogenic emissions decline by 2050 to 50% of their present-day value. Achieving this level of reduction would require implementation of Hg-specific control technologies across multiple sectors (fuel combustion, mining, waste incineration, and
industry). We also consider a “zero emissions” scenario where primary anthropogenic emissions are completely eliminated as of 2015. This bounds the maximum achievable global benefit from regulating emissions. Business-as-usual is assumed between 2008 and 2015, and all scenarios take effect in 2015.

### Table 2. Hg Reservoir Masses and Historical Anthropogenic Enrichments

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Natural</th>
<th>Preindustrial (1840)</th>
<th>Present Day</th>
<th>All Time</th>
<th>Modern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>700</td>
<td>2,000</td>
<td>5,300</td>
<td>7.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Terrestrial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast</td>
<td>1,900</td>
<td>4,800</td>
<td>11,000</td>
<td>5.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Slow</td>
<td>9,800</td>
<td>24,000</td>
<td>50,000</td>
<td>5.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Armored</td>
<td>170,000</td>
<td>180,000</td>
<td>210,000</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Ocean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>530</td>
<td>1,300</td>
<td>3,100</td>
<td>5.9</td>
<td>2.3</td>
</tr>
<tr>
<td>Subsurface</td>
<td>26,000</td>
<td>67,000</td>
<td>140,000</td>
<td>5.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Deep</td>
<td>95,000</td>
<td>130,000</td>
<td>200,000</td>
<td>2.1</td>
<td>1.5</td>
</tr>
</tbody>
</table>

*Ratio of present-day to natural reservoir mass.

3. Historical Reconstruction and Uncertainty

#### 3.1. Historical Reconstruction and Model Evaluation

[18] We first apply the model to simulate natural steady state conditions, defined by solving (1) for \( \frac{dn}{dt} = 0 \) with \( s = 90 \text{ Mg a}^{-1} \) as the constant geogenic source. Table 2 shows the resulting natural distribution of Hg between reservoirs. From this initial condition, we force the model with historical anthropogenic emissions (2000 BC–present), shown in Figure 2a. Table 2 shows the resulting preindustrial (1840) and present-day reservoir masses.

[19] Figure 3 depicts our simulated present-day global budget. Reservoir masses and flows are comparable to the literature values of Table 1 used to construct the model, even though these literature values were used only to constrain the first-order rate coefficients in the model. This demonstrates consistency between present-day anthropogenic enrichments and our historical inventory of anthropogenic emissions. It provides an independent check because we do not impose a preindustrial-to-present enrichment in atmospheric deposition unlike previous reconstructions [Mason et al., 1994; Mason and Sheu, 2002; Seigneur et al., 2004; Selin et al., 2008; Smith-Downey et al., 2010]. The present-day
ammonia Hg reservoir is simulated to be 5300 Mg, within
the range of 4600–5600 Mg constrained by observations (see
section 2.1). The mean ocean concentration above the
thermocline (surface + subsurface) is 1.4 pM, consistent with
the range of 0.5–2.5 pM given by Mason et al. [2012] from
compiled observations. We find a modern (preindustrial-to-
present) enrichment factor of 2.6 for atmospheric deposition,
which is consistent with sediment core data, indicating
that atmospheric Hg deposition has increased by 2 to 5 times
relative to preindustrial levels [Lamborg et al., 2002a;
Biester et al., 2007; Drevnick et al., 2012]. We conclude that
our box model provides a realistic representation of the
present-day budget of Hg in the different geochemical
reservoirs and a plausible reconstruction of the historical
anthropogenic enrichment.

3.2. Uncertainty in Natural Processes
[20] We applied perturbation analysis to examine how
uncertainties in individual model terms affect simulated
anthropogenic enrichments of the different Hg reservoirs,
using the three observational constraints defined above:
(1) present-day atmospheric reservoir (4600–5600 Mg),
(2) present-day surface + subsurface ocean concentration
(0.5–2.5 pM), and (3) preindustrial-to-present enrichment
factor in atmospheric deposition (2–5). We find that the
simulated preindustrial-to-present enrichment factor is
most sensitive to uncertainties in geogenic emissions and
oceanic evasion. The magnitude of geogenic emissions
dictates the natural Hg loading and the resulting relative
enrichment from primary anthropogenic emissions. Based
on the observational constraints and reasonable estimates
for primary anthropogenic emissions, geogenic emissions
are unlikely to be more than 4 times larger than our adopted
value of 90 Mg a\(^{-1}\) and could be smaller. Larger geogenic
emissions decrease the relative anthropogenic enrichment
and vice versa.

[21] Oceanic evasion is the largest single input of Hg to
the atmosphere and is a major removal pathway of Hg from
the surface ocean (Table 1 and Figure 3). Qureshi et al.
[2011] highlighted the uncertainty in ocean evasion and its
influence on the global biogeochemical cycle of Hg.
Removal of Hg from the surface ocean is a competitive
process between evasion and export to the subsurface ocean
by particle scavenging. If evasion rates decrease, the net transfer
from the subsurface ocean increases while atmospheric deposition
decreases, and there is an associated increase in the relative
anthropogenic enrichment of atmospheric deposition. To
be consistent with both the present-day atmospheric reservoir
and the preindustrial-to-present enrichment in atmospheric
deposition, we find that the rate coefficient of ocean evasion
in our model must be within ±30% of our best estimate from
Figure 1.

[22] Perturbations to the rate coefficients for terrestrial
cycling have less effect on our model results than geogenic
emissions or oceanic evasion, in terms of the three observa-
tional constraints above. This is because, as discussed
below, Hg perturbations to surface reservoirs propagate
principally to the ocean. We see from Figure 3 that the
terrestrial reservoirs are only weakly coupled to one
another and instead exchange principally with the atmo-
sphere. However, such a result is contingent on the mecha-
nistic basis for our terrestrial Hg model that presumes a
strong association of Hg with organic matter [Smith-
Downey et al., 2010]. Better understanding of terrestrial
cycling of Hg is needed.

3.3. Uncertainty in Anthropogenic Emissions
[23] Streets et al. [2011] gave uncertainties in the range of
-30% to +60% for 1920–2008 anthropogenic emissions,
with somewhat larger uncertainties before 1920. We
estimate an uncertainty range of -50% and +300% for pre-
1850 emissions, with additional uncertainty in the timing
of these emissions. We conducted sensitivity simulations to
investigate the effect of these uncertainties using the same
time three observational constraints as above to guide the analy-
sis. We find that the timing and initiation (between 2000
and 500 BC) of pre-1570 anthropogenic emissions has no
significant effect on model results because these emissions
are small (best estimate of 26 Gg) and the associated Hg
has been transferred by now to the deep ocean, armored soil,
and deep mineral reservoir. Simulated all-time enrichment
and the present-day budget (Figure 3) are also insensitive
(<5%). We find also little sensitivity to the timing of
1570–1850 AD anthropogenic emissions. The simulated
preindustrial-to-present enrichment in atmospheric deposi-
tion decreases from a factor of 2.6 to 2.4 if the timing is
shifted (based on Nriagu [1993]) to release 70% of these
emissions during 1700–1850 AD rather than 50%.

[24] The magnitude of all-time anthropogenic emissions has
more impact on model results. We conducted sensitivity simulations following the lower or upper envelope of the
historical range of emission uncertainties (see above). The
resulting ranges for the lower-upper envelope of emissions are 4100–9000 Mg for the present-day atmospheric reser-
voir, 1.1–2.6 pM for the present-day surface + subsurface
ocean concentration, and 2.9–2.0 for the preindustrial-to-
present enrichment factor in atmospheric deposition. The
upper envelope is unrealistic, as reflected by its large
overestimate of the present-day atmospheric reservoir. The
lower envelope is within the uncertainty of observational
constraints and will be used below to provide a lower limit
on anthropogenic influence (section 5). The all-time anthro-
pogenic emissions for the lower envelope amount to 232 Gg,
as compared to 352 Gg for our best estimate.

4. Timescales for Hg Cycling and Response to Perturbations
4.1. Eigenanalysis of Characteristic Timescales
[25] Understanding the timescales involved in Hg
biogeochemical cycling is critical to interpreting the
effects of anthropogenic perturbations. Residence times
\(t_r = 1/\sum k_{ij}\) for individual reservoirs in our seven-box
model provide a first estimate of these timescales but do
not account for the coupling between reservoirs. Eigenanalysis of the \(7 \times 7\) mass transfer matrix \(K = (k_{ij})\) in
equation (1) identifies the true timescales of the coupled
system [Prather, 1996]. Each eigenvector \(x_p\), \((p \in [1, 7])\) with
eigenvalue \(\lambda_p\) represents a normal mode of the model, and
any perturbation to that mode decays exponentially with a
characteristic timescale \(-1/\lambda_p\).
Figure 4. Normal modes of the Hg biogeochemical model. Each column describes an eigenvector of the mass transfer matrix $K$ and represents a normal mode of the system. Perturbation to a normal mode decays exponentially with a timescale equal to the inverse of the corresponding eigenvalue. These timescales are displayed above the modes. The elements of the eigenvectors indicate the coupling between reservoirs associated with each timescale. For example, Mode 1 (0.2 years) describes a strong coupling between the surface and subsurface ocean reservoirs, and a weak coupling with the atmosphere. Mode 2 (0.8 years) describes a strong coupling between the atmosphere and subsurface ocean. Mode 3 (6 years) and 4 (70 years) couple respectively the fast and slow terrestrial pools to the subsurface ocean via the atmosphere and surface ocean. Mode 5 (200 years) couples the subsurface and deep ocean by vertical seawater mixing. Mode 6 (1000 years) describes the return of Hg to the deep mineral reservoir by burial from the deep ocean. Mode 7 (6000 years) describes the ultimate decay of the perturbation by transfer from the armored soil reservoir to the deep mineral reservoir via ocean burial.

Figure 5. Characteristic timescales (years) for Hg biogeochemical cycling derived from eigenanalysis of our seven-compartment box model (see section 4.1). The arrows indicate the principal reservoirs coupled over each timescale. These couplings often involve a combination or succession of transfers through intermediate reservoirs. More details are presented in Figure 4.
transferred away from the reservoir of origin on a timescale of months (surface ocean and atmosphere) to a decade (fast terrestrial). In all three cases, the transfer of Hg is principally to the subsurface ocean due to the fast timescales coupling the subsurface ocean to all three surface reservoirs (Figure 5).

[30] Even when the initial release is to the fast terrestrial reservoir, we find that most of the Hg ends up in the subsurface ocean on a timescale of a decade. In our model, terrestrial Hg can be transferred to the surface ocean either by re-emission to the atmosphere (photoreduction, respiration of organic matter, and biomass burning) and subsequent deposition, or by river runoff. Cycling through the atmosphere is the dominant pathway (Figure 3). Transfer of Hg from the fast terrestrial reservoir to more recalcitrant soil pools is slow in comparison.

[31] Even though the armored soil is the dominant Hg reservoir under natural (i.e., steady state) conditions (Table 2), we find that a Hg perturbation to the surface reservoirs propagates principally to the ocean. Regardless of the location of the pulse of origin, after 1000 years, we find that 40% is in the ocean, 20% is in the soil, and 40% has been returned to the deep mineral reservoir (Figure 6). The preferential long-lived reservoir for the perturbed system is the deep ocean, imposing a continued legacy on the subsurface/surface ocean reservoirs through vertical exchange of seawater. The implication of our work is that in the decades following release to the atmosphere, surface ocean, or terrestrial ecosystem, a large fraction of anthropogenic Hg will end up in the subsurface ocean.

5. Anthropogenic Enrichment and the Importance of Legacy Hg

[32] Table 2 shows that the present-day anthropogenic enrichment of the surface and subsurface ocean is similar to that in the atmosphere, reflecting the short timescales for coupling of these reservoirs. Even the deep ocean shows a factor of 2 enrichment. We find that the present-day atmospheric Hg reservoir (and deposition) is enriched 7.5 times relative to natural levels (Table 2 and Figure 3). Modeled enrichment is still 5.8 for the lower bound of anthropogenic emissions (section 3.3). This enrichment is larger than the observed three–fold anthropogenic enrichment from sediment cores that extend back to the mid-nineteenth century [Biester et al., 2007; Lindberg et al., 2007] and reflects anthropogenic Hg emissions prior to 1850 (section 2.5). Several long-term archives corroborate the importance of
The contribution from natural Hg is defined by steady state in our biogeochemical model without anthropogenic emissions. The primary anthropogenic contribution to deposition is from direct emissions (Figure 2a), while the legacy contribution is from anthropogenic Hg previously deposited and then re-emitted by surface reservoirs. The contribution from legacy Hg is calculated as total deposition minus primary anthropogenic emissions and natural emissions. For the ocean reservoirs, we partition the anthropogenic contribution by time period (left column) and region (right column). “Rest of world” includes Africa, the Middle East, and Oceania.

6. Implications for the Future

We project future changes in the Hg cycle under four illustrative emission trajectories (section 2.5 and Figure 2a): (1) the business-as-usual A1B scenario of Streets et al. [2009] with continued increases in global emissions, (2) constant future emissions, (3) 50% decrease of emissions by 2050 (“mercury controls”), and (4) zero future anthropogenic emissions as a bounding case. These scenarios are assumed to take effect in 2015.

Figure 2c shows the atmospheric deposition for each of the four future emission scenarios. Primary anthropogenic emissions increase by 2000 Mg a\(^{-1}\) between 2015 and 2050 under A1B, but atmospheric deposition increases by 4600 Mg a\(^{-1}\). Even if primary anthropogenic emissions stay constant between 2015 and 2050, atmospheric deposition increases by 30%. Under these scenarios, new anthropogenic Hg is being added to the pool of legacy Hg faster than it can be sequestered into longer-lived reservoirs, and the legacy contribution to deposition grows as a result. Corbitt et al. [2011] projected that atmospheric deposition would remain at present-day levels under the B1 scenario of Streets et al. [2009] (effectively constant emissions), but they assumed the legacy Hg pool to remain constant. Our work
Figure 8. Change in reservoir masses relative to 2015 under a scenario of zero primary anthropogenic emissions after 2015.

highlights the importance of accounting for changing legacy Hg when modeling the future atmosphere.

[38] We find that a decrease in Hg emission is needed just to maintain Hg deposition at its present-day level. Under our hypothetical “mercury controls” scenario with 50% decrease in primary anthropogenic emissions by 2050, deposition begins to decrease by 2020 as the legacy contribution stabilizes (reflecting a balance between new anthropogenic Hg inputs and transfer to the longer-lived reservoirs). In this scenario, primary emissions decrease by 1400 Mg a$^{-1}$ from 2015 to 2050 while deposition decreases by 1200 Mg a$^{-1}$.

[39] To illustrate the timescales required for dissipation of anthropogenic influence, Figure 8 shows the time-dependent responses of the atmosphere and ocean Hg reservoirs to complete elimination of anthropogenic Hg emissions from 2016 on. We previously pointed out the immediate 30% decrease in the atmosphere. There is also an immediate 10% decline in the surface ocean that is dampened relative to the atmosphere by the persistent legacy influence from the subsurface ocean. Subsequent decline in the surface ocean is more gradual, with 65% of the initial loading remaining in 2100. The subsurface ocean begins to slowly decrease after a decade, mostly by transfer to the deep ocean, but the anthropogenic signal persists for centuries. The deep ocean reservoir continues to increase throughout the 21st century even in the absence of primary anthropogenic emissions.

[40] Future Hg concentrations in the surface + subsurface ocean are of particular concern because they are critical for determining the reservoir available for oceanic methylmercury production [Mason et al., 2012] and associated concentrations in pelagic marine fish. Under the business-as-usual emissions trajectory, Hg concentrations in the combined surface + subsurface ocean will increase by 40% (relative to present day) by 2050. Under the “mercury controls” scenario, the Hg concentration in the surface + subsurface will still increase by 20%. Our results suggest that stabilization of ocean concentrations at present-day levels will require more aggressive reductions in primary anthropogenic emissions than is usually recognized.

7. Conclusions

[41] We have developed a seven-compartment biogeochemical box model to describe the global cycling of mercury (Hg) between the atmosphere, ocean, and terrestrial reservoirs. The model is based on our best current understanding from observations and process models and is described by first-order rate constants ordinary differential equations (coupled ODEs) for the transfer of Hg between compartments. We forced the model with time-dependent historical emissions (2000 BC–present), initializing from natural steady state, and showed consistency with observational constraints for the present-day budget and anthropogenic enrichments. We used the model to analyze the timescales involved in Hg cycling and to quantify the impact of legacy anthropogenic Hg in the present-day global budget and under various future emission scenarios.

[42] We find that characteristic timescales for Hg global biogeochemical cycling range from less than a year for coupling between the subsurface/surface ocean and the atmosphere to thousands of years for transfer from the armored soil to the deep mineral pool via the deep ocean. The subsurface ocean, extending from the base of the ocean mixed layer down to the permanent thermocline, plays a central role in the global biogeochemical cycling of Hg. A perturbation to the surface reservoirs (atmosphere, ocean, and fast terrestrial) propagates to the subsurface ocean on a timescale of years to decades and persists there for decades to centuries. Under natural conditions, terrestrial reservoirs contain a larger Hg inventory than the ocean. However, perturbations to surface reservoirs first propagate to the deep ocean because transfer of Hg to the armored soil reservoir is extremely slow and persist in the deep ocean for centuries to millennia with upwelling causing a sustained effect on the surface and subsurface ocean. The persistence of Hg in the ocean is of particular environmental consequence because of the importance of marine fish as source of methylmercury exposure for humans and wildlife.

[43] Atmospheric deposition in the model increases by a factor of 2.6 from 1840 to present, consistent with sediment archives. This factor of 3 has been regarded in previous studies as the anthropogenic enrichment relative to natural conditions, but in fact, the anthropogenic perturbation to the Hg cycle extends back for millennia. We find that all-time anthropogenic Hg emissions have enriched the present-day atmosphere, surface ocean, and deep ocean by factors of 7.5, 5.9, and 2.1, respectively, relative to natural conditions. This is a much larger relative anthropogenic perturbation than is usually recognized.

[44] Model results show that most (60%) of present-day Hg atmospheric deposition is legacy anthropogenic Hg re-emitted from surface reservoirs. Natural emissions and primary anthropogenic emissions contribute 13% and 27% to present-day deposition, respectively. Over half of the anthropogenic enrichment of the surface ocean is from pre-1950 emissions, and most of the anthropogenic enrichment of the deep ocean is from pre-1900 emissions. Although Asia accounts for 65% of present-day primary anthropogenic emissions [Streets et al., 2011], Hg of Asian
anthropogenic origin only accounts for 30% of present-day atmospheric deposition and 17% of the surface ocean reservoir. By contrast, North America and Europe together account for 30% of the surface ocean reservoir.

[45] Understanding how the legacy of past anthropogenic emissions contributes to present-day Hg enrichment is essential for anticipating the effectiveness of future Hg emission reduction strategies. If anthropogenic emissions continue to rise, the resulting growth in atmospheric deposition will be greater than the increase in primary emissions due to sustained growth of the legacy component. Even if emissions stay constant, atmospheric deposition will continue to increase because new anthropogenic Hg will add to the surface + subsurface ocean reservoir faster than Hg can be transferred from that reservoir to the deep ocean. Our work shows that projecting future atmospheric deposition under changing emissions requires a full accounting of the coupling between the biogeochemical reservoirs. Aggressive reduction in primary anthropogenic emissions will be needed just to maintain oceanic Hg concentrations at present-day levels.

[46] We investigated the response of the global Hg cycle to zeroing primary anthropogenic emissions after 2015 as a bound on the maximum global benefits to be expected from regulating emissions. We find a nearly instantaneous 30% decrease in atmospheric deposition and 10% decrease in the surface ocean reservoir. Subsequent declines are slower, limited by the timescale for transfer to the deep ocean. By 2100, there is a 55% decrease in atmospheric deposition and 35% decrease in surface ocean loading. The subsurface ocean responds more slowly to the elimination of primary anthropogenic emissions and, by 2100, has decreased by 25%.

[47] Our analysis focused on the global background. However, Hg concentrations in the surface ocean and terrestrial reservoirs vary depending on local environmental conditions, and many historic Hg problems have occurred as site-specific contamination issues from point sources. Ecosystem-scale studies indicate large variability in biotic Hg response to total Hg loading, depending on conditions facilitating methylmercury production [Harris et al., 2007; Knightes et al., 2009]. The global information provided here needs to be combined with site-specific understanding of the factors driving biological exposures.

[48] Our analysis points to the need for improved, empirically constrained estimates of ocean evasion, geogenic emissions, and primary anthropogenic emissions. Whether or not organic carbon serves as the best analogue for modelling terrestrial Hg cycling also deserves further investigation. Ocean evasion and terrestrial cycling influence the fate and accumulation of Hg. Geogenic emissions determine the natural environmental burden of Hg and hence the impact of all-time anthropogenic Hg emissions, which may also be inferred from mult millennia sedimentary records. Improved estimates of these quantities will allow us to better estimate the impact of present-day and future anthropogenic Hg emissions and more confidently establish the effectiveness of implemented regulation.

[49] Acknowledgments. We thank Jeroen Sonke and an anonymous reviewer for their thoughtful comments. We acknowledge financial support from NSF Atmospheric Chemistry (ATM0961357), NSF Chemical Oceanography (OCE1130549), and the Electric Power Research Institute (EPRI).

H.M.A. acknowledges support from NSF GRFP. We thank Anne Soensren and Mauricio Santillana for thoughtful discussions.

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