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Atmospheric Mercury Footprints of Nations

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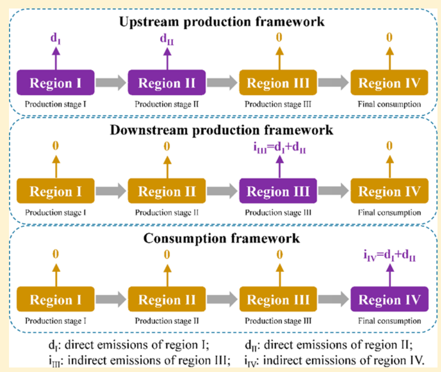
Supporting Information

ABSTRACT: The Minamata Convention was established to protect humans and the natural environment from the adverse effects of mercury emissions. A cogent assessment of mercury emissions is required to help implement the Minamata Convention. Here, we use an environmentally extended multi-regional input–output model to calculate atmospheric mercury footprints of nations based on upstream production (meaning direct emissions from the production activities of a nation), downstream production (meaning both direct and indirect emissions caused by the production activities of a nation), and consumption (meaning both direct and indirect emissions caused by final consumption of goods and services in a nation). Results show that nations function differently within global supply chains. Developed nations usually have larger consumption-based emissions than up- and downstream production-based emissions. India, South Korea, and Taiwan have larger downstream production-based emissions than their upstream production- and consumption-based emissions. Developed nations (e.g., United States, Japan, and Germany) are in part responsible for mercury emissions of developing nations (e.g., China, India, and Indonesia). Our findings indicate that global mercury abatement should focus on multiple stages of global supply chains. We propose three initiatives for global mercury abatement, comprising the establishment of mercury control technologies of upstream producers, productivity improvement of downstream producers, and behavior optimization of final consumers.



■ INTRODUCTION

Mercury releases to the atmosphere, the principle source to global ecosystems, have increased over the past decades.[1] Increased mercury in the atmosphere will lead to increased deposition and contamination that will impact wildlife and humans.[2,3] As the consequence of the increasing knowledge and awareness by scientists and the public on mercury-related human health issues, nations have signed the Minamata Convention in October 2013 to control and possibly reduce global anthropogenic mercury releases.[4]

Previous studies have compiled inventories for global atmospheric mercury emissions from direct anthropogenic sources at multiple time points (e.g., 1983–1992,[5] 1850–2008,[1] 1996–2009,[6] 1995,[7−9] 2000,[9,10] 2005,[11−13] 2007,[14] and 2010[15]) as well as inventories for specific processes (e.g., energy combustion,[16,17] biomass burning,[18] gold and silver mining,[19] and contaminated site releases[20]). Such "bottom-up" inventories provide quantitative information for decision making to control and reduce mercury emissions from direct anthropogenic sources, e.g., directing key direct emitters for the application of "best available technologies".

However, to mitigate mercury emissions at the global scale, it is also important to examine how mercury emissions have been driven by production and consumption activities across global supply chains. The international fragmentation of production separates stages of global supply chains (e.g., mining, processing, manufacturing, and consumption) into different nations. Atmospheric mercury emissions of upstream producers (e.g., mercury mining and artisanal gold mining in China) are usually induced by downstream producers (e.g., the production of computers and cell phones in South Korea) and final consumers (e.g., households in the U.S.A.). Only efforts in upstream producers are not enough to control global atmospheric mercury emissions if the demand of downstream producers and final consumers continues to increase. Thus, investigating mercury emissions of a nation should concern not only its direct emissions but also its indirect emissions accumulated through global supply chains, which can highlight both major direct emitters and major underlying drivers. Studies investigating major sources of mercury to the atmosphere have only investigated direct emissions of nations (e.g., from energy combustion and raw material production)

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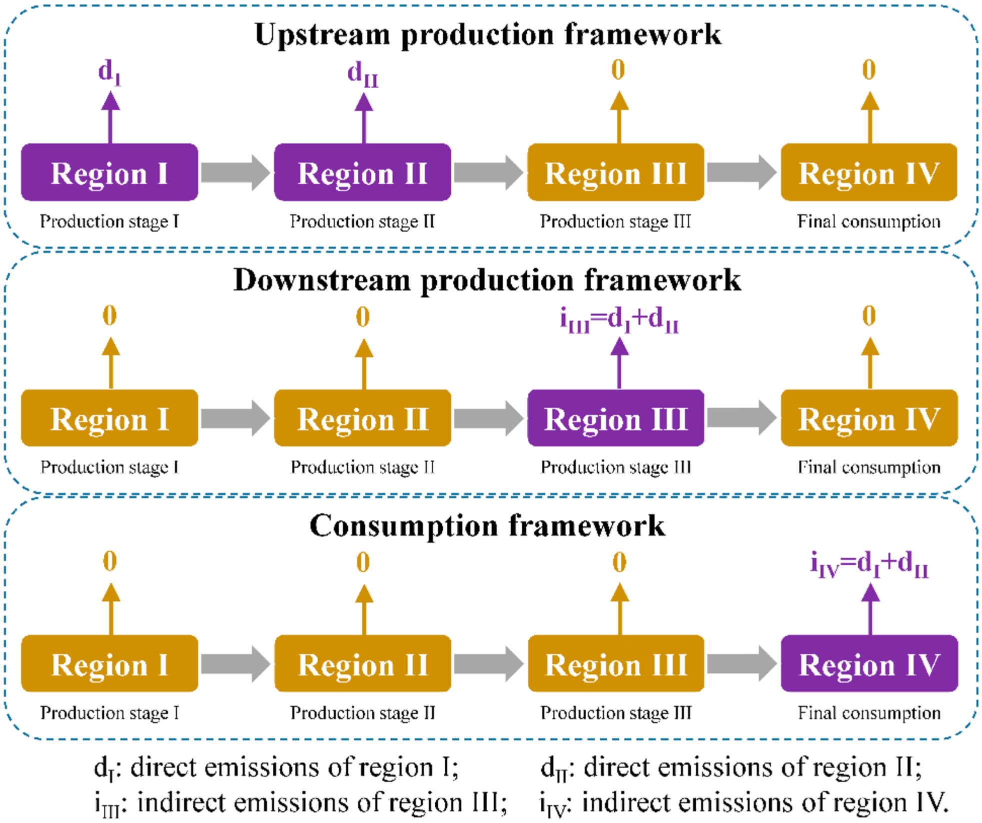

Figure 1. Three accounting frameworks based on upstream production, downstream production, and consumption. This graph takes a global supply chain with four regions as an example.

and ignored indirect emissions associated with intermediate inputs to the production of finally consumed products.

To solve this problem, this study calculates atmospheric mercury footprints of nations based on upstream production (meaning direct emissions from the production activities of a nation), downstream production (meaning both direct and indirect emissions caused by the production activities of a nation), and consumption (meaning both direct and indirect emissions caused by final consumption of goods and services in a nation). Detailed descriptions on these three accounting frameworks are shown in the following section. Our research hypothesis is, as a result of global trade, direct atmospheric mercury emissions in one nation are also attributable to the production and consumption in another nation. This study provides an alternative way of thinking about who is responsible for global mercury emissions.

■ METHODS AND DATA

Accounting Frameworks Based on Upstream Production, Downstream Production, and Consumption. Figure 1 uses a global supply chain with four regions to explain three accounting frameworks based on upstream production, downstream production, and consumption. Region I location is at the beginning of the supply chain; region II location is at the intermediate production stage; region III location is at the final production stage; and region IV location is at the final consumption stage. We assume that only region I (d_I emissions) and region II (d_{II} emissions) have direct mercury emissions to the atmosphere.

The upstream production framework allocates atmospheric mercury emissions to nations who directly emit mercury emissions to the atmosphere, i.e., direct atmospheric mercury emissions because of energy combustion and obtaining and processing raw materials (e.g., mercury mining, gold mining, and metal smelting). This framework is consistent with the "production-based framework" in the study by Peters.[21] We define this framework as upstream production in this study to distinguish from the second framework we proposed in next paragraph. The upstream production framework highlights regions I and II, who have direct emissions. It is widely used in existing "bottom-up" inventory analysis.

The downstream production framework allocates atmospheric mercury emissions to nations whose final production (final production here means the production of finally consumed goods and services) drives global mercury emissions. This framework tracks direct emissions from and indirect emissions embodied in intermediate inputs to the production of finally consumed products. This framework highlights region III, who produces finally consumed goods and services and locates at the downstream production stage of the supply chain. Region III does not have direct emissions but has indirect emissions ($i_{III} = d_I + d_{II}$) embodied in intermediate inputs to its production.

The consumption framework allocates atmospheric mercury emissions to nations who finally consume goods and services. It tracks emissions embodied in imports to satisfy domestic consumption but deducting emissions embodied in exports. This framework is consistent with the "consumption-based framework" in previous studies.[21,22] The consumption framework highlights region IV, who locates at the final consumption stage of the supply chain. Region IV does not have direct emissions. However, it has indirect emissions ($i_{IV} = d_I + d_{II}$)

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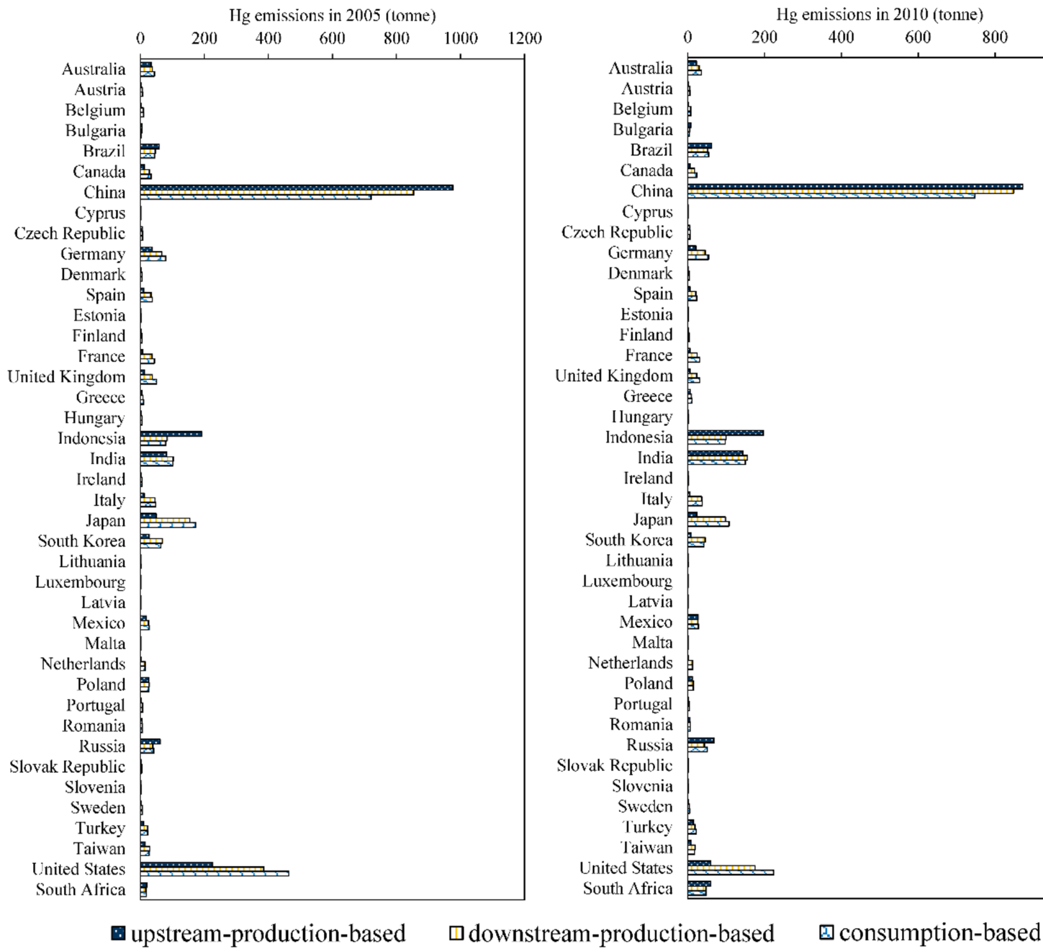

Figure 2. Atmospheric mercury footprints of nations by different accounting frameworks in 2005 and 2010.

embodied in its consumed products. The consumption in region IV induces emissions of the whole supply chain.

Environmentally Extended Multi-regional Input−Output Model. We use an environmentally extended multi-regional input−output (EE-MRIO) model[23] to calculate atmospheric mercury footprints of nations based on upstream production, downstream production, and consumption. The multi-regional input−output (MRIO) model captures domestic and international economic transactions of nations at the sector level. Treating sectoral environmental emissions as the satellite account of the MRIO model, we can construct the EE-MRIO model.

We calculate emission footprints of regions based on upstream production, downstream production, and consumption by eqs 1−3, respectively.

$$\text{upstream production-based footprints of region } r = \mathbf{F}x_r \tag{1}$$

$$\text{downstream production-based footprints of region } r = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}y_r \tag{2}$$

$$\text{consumption-based footprints of region } r = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}f^r \tag{3}$$

The row vector **F** represents the emission intensity for one unit of the total output of each sector, termed as direct intensity of sectors in this study. The column vectors x_r and y_r indicate total output and final demand of sectors in region r, respectively. The notation I represents the identity matrix. The matrix $(\mathbf{I} - \mathbf{A})^{-1}$ is usually named as the Leontief inverse matrix,[24] whose element l_{ij} indicates both direct and indirect requirements of products from sector i to produce one unit of final demand for sector j. The block matrix **A** is the direct requirement coefficient matrix (also named as technical matrix), whose element a_{ij} indicates the direct requirement of products from sector i to produce one unit of total output in sector j. The matrix $\mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}$ is termed as life cycle intensity of sectors in this study, meaning both direct and indirect emissions caused by unitary final demand of sectors. The column vector f^r represents product flows from all regions to the final demand of region r.

Data Sources. We use two sets of data sources: the global MRIO tables and sectoral atmospheric mercury emissions. We set the baseline year as 2010 and also calculate results in 2005 to investigate temporal changes.

We use global MRIO tables in 2005 and 2010 from the World Input−Output Database (WIOD, released in November 2013). These global MRIO tables contain 27 European Union countries and 13 other major nations,[25] and each nation is divided into 35 economic sectors. South Africa, a major direct emitter of global atmospheric mercury emissions,[12,15] is not separately listed in the WIOD. Hence, we separate South Africa from the rest of the world (RoW) in the WIOD. The separating methods are explained in detail in the Supporting Information. Finally, our global MRIO tables contain 41 major nations and the RoW (see Table S1 of the Supporting Information).

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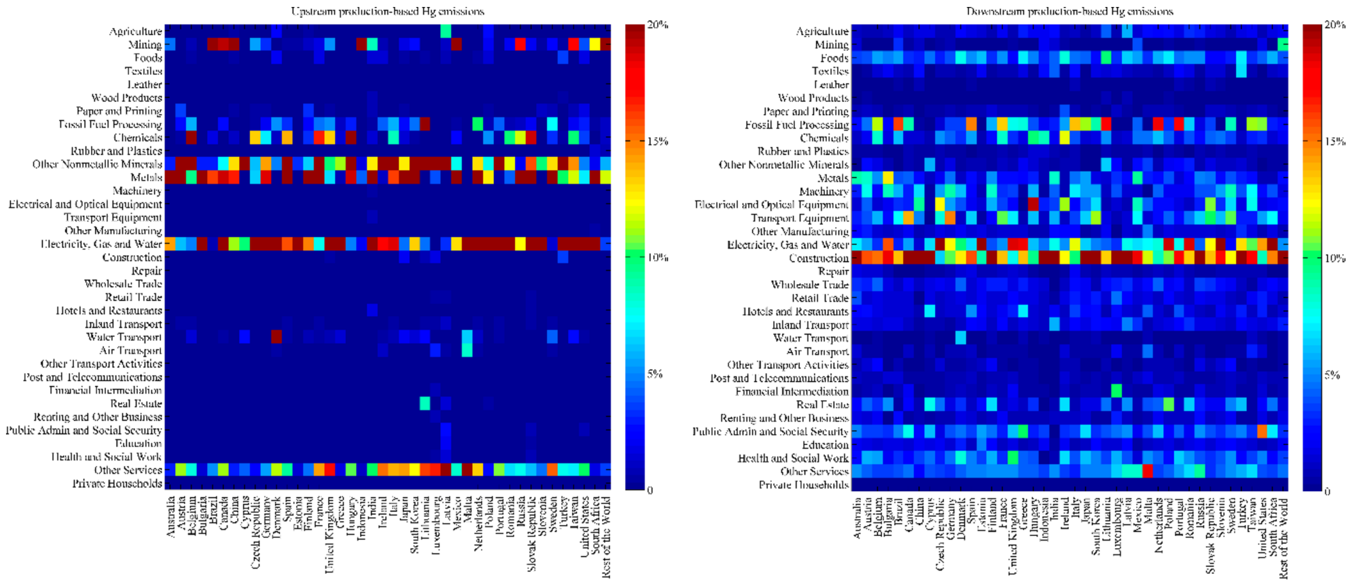

Figure 3. Up- and downstream production-based mercury emissions at the sector level in 2010. Sectoral values of a particular nation are normalized by its national total. Mercury emission quantities of the top 30 sectors in 2010 are shown in Table S4 of the Supporting Information.

Disaggregating the RoW and improving the sector resolution in future studies can improve the resolution of the global MRIO tables.

The system boundary of our atmospheric mercury emission inventories is consistent with that of the Arctic Monitoring and Assessment Programme (AMAP)/United Nations Environment Programme (UNEP).[12,15] Our inventories cover anthropogenic atmospheric mercury emissions from energy combustion, oil refining (not included in 2005 inventory), waste incineration, the production of non-ferrous metals (including copper, zinc, lead, aluminum, primary mercury, and large-scale gold but not including aluminum in 2005 inventory), pig iron and steel, cement, and caustic soda, and dental amalgam. Those are major anthropogenic sources for atmospheric mercury emissions.

Sectoral atmospheric mercury emissions from energy combustion are calculated by multiplying sectoral emission-relevant energy uses with related emission factors. The environmental account of the WIOD contains time-series data for sectoral emission-relevant energy uses from 1995 to 2009. Data for sectoral emission-relevant energy uses in 2005 are from the environmental account of the WIOD.[25] The WIOD, however, does not have data for sectoral emission-relevant energy uses in 2010. We first calculate growth rates from 2009 to 2010 by nations, sectors, and energy types based on the database of the International Energy Agency.[26] We then obtain the data for the sectoral emission-relevant energy uses of each nation in 2010 using its growth rates to scale up those data in 2009 from the WIOD.[25] Atmospheric mercury emission factors for various types of energy sources are from previous studies.[12,14,15] In particular, there are differences in emission factors for 2005 and 2010. The 2005 inventory of the AMAP/UNEP uses the same emission factors for all nations,[12] while most emission factors in its 2010 inventory are nation-specific.[15]

Atmospheric mercury emissions from oil refining, waste incineration, artisanal and small-scale gold mining, the production of non-ferrous metals, pig iron and steel, cement, and caustic soda, and dental amalgam are from the "bottom-up" inventories of the AMAP/UNEP.[12,15] Atmospheric mercury emissions from artisanal and small-scale gold mining are obtained from the Mercury Watch database.[27]

RESULTS

Atmospheric Mercury Footprints of Nations. The global production system discharged 2655 tonnes of anthropogenic mercury to the atmosphere in 2005 and 2446 tonnes in 2010. Because the AMAP/UNEP used different methods and mercury emission factors for 2005 and 2010 inventories,[12,15] total global mercury emissions in 2005 are not comparable to the 2010 figure. For the 2010 inventory, 1358 tonnes (56% of global total) are from Asia and Pacific (including China, India, Japan, South Korea, Australia, Taiwan, Turkey, Indonesia, and Russia), 66 tonnes (3% of global total) are from North America (including Canada and the United States), 154 tonnes (6% of global total) are from 27 European Union countries, 89 tonnes (4% of global total) are from Latin America (including Brazil and Mexico), and 779 tonnes (32% of global total) are from the RoW.

Figure 2 shows that nations function differently within global supply chains. Developing nations (e.g., Brazil, China, Indonesia, and South Africa) mainly produce basic materials and semi-manufactured goods (e.g., mineral ores and metals). Their products are mainly used for downstream production instead of directly entering final consumption. Production activities of those nations mainly locate at upstream production stages of global supply chains. Their downstream production-based emissions are smaller than upstream production-based emissions. In addition, atmospheric mercury emissions caused by their consumption are lower than those caused by their upstream production. For example, China, the largest contributor to global atmospheric mercury emissions, caused 872 tonnes of upstream production-based emissions (36% of global total), 848 tonnes of downstream production-based emissions (35% of global total), and 748 tonnes of consumption-based emissions (31% of global total) in 2010. On the other hand, developed nations (e.g., the United States, Japan, Germany, and United Kingdom) mainly produce finished products (e.g., services) that directly enter final

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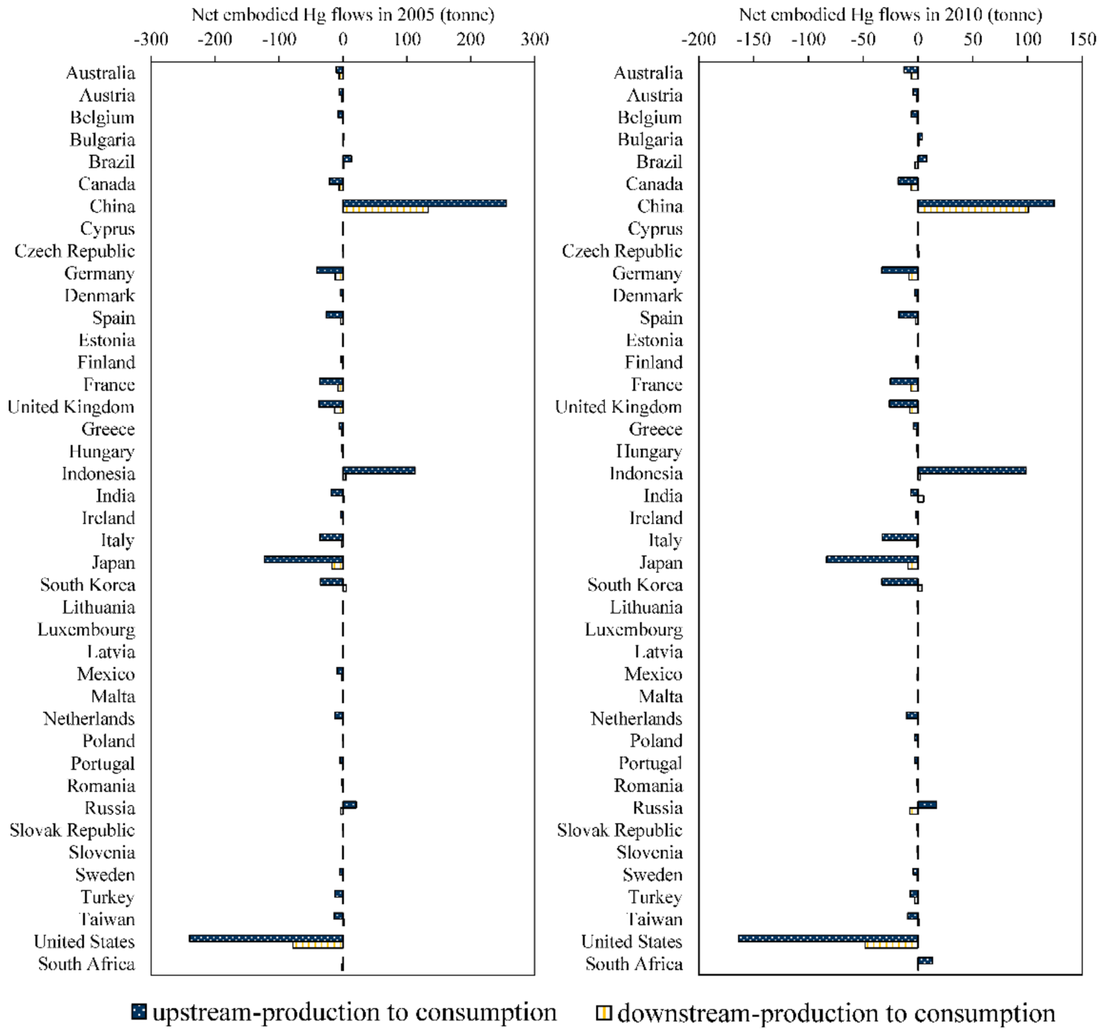

Figure 4. Trade balance of embodied atmospheric mercury for nations in 2005 and 2010. Positive values mean that emissions embodied in exports are larger than those embodied in imports, and negative values mean that emissions embodied in exports are smaller than those embodied in imports.

consumption. These nations mainly locate at downstream production and consumption stages of global supply chains. They have relatively larger emissions caused by downstream production and consumption and lower emissions as a result of upstream production. For example, the United States causes 60 tonnes of upstream production-based emissions (2% of global total) but 176 tonnes of downstream production-based emissions (7% of global total) and 224 tonnes of consumption-based emissions (9% of global total) in 2010.

Moreover, we observe that India, South Korea, and Taiwan have larger downstream production-based emissions than upstream production- and consumption-based emissions. They mainly produce finished products (e.g., electrical and optical equipment), importing basic materials abroad and exporting manufactured finished products to the consumption of other nations. This finding reflects the importance of the downstream production framework to investigate emission footprints of nations, besides upstream production and consumption frameworks in previous studies.[21,22] If India, South Korea, and Taiwan improve their productivity using less inputs of products (especially mercury-intensive inputs) from upstream providers but still fulfilling the demand of final consumers, induced emissions of upstream providers will be reduced. Thus, nations with large downstream emissions can contribute to global mercury reductions through productivity improvement instead of only emission intensity reductions.

We further disaggregate results based on the up- and downstream production frameworks in 2010 to the sector level (Figure 3), by diagonalizing the column vectors x_r and y_r in eqs 1 and 2, respectively. We observe that the production of basic materials (e.g., electricity, non-metallic mineral products, metals, mineral ores, and chemicals) and other services is the major contributor to mercury emissions based on the upstream production framework. The top two direct emitters are mining and quarrying in RoW (561 tonnes in 2010) and the same sector in China (456 tonnes in 2010) (see Table S4 of the Supporting Information). On the other hand, the production of finished products (e.g., foods, processed fossil fuels, machinery, equipment, electricity, construction, and services) is the major contributor to mercury emissions based on the downstream production framework. These finished products have relatively small direct mercury emissions (except for electricity) but large indirect accumulation of mercury emissions embodied in intermediate product inputs. For example, the construction in China, a major destination of mercury-intensive basic materials of China, has only 1 tonne of direct mercury emissions but 386

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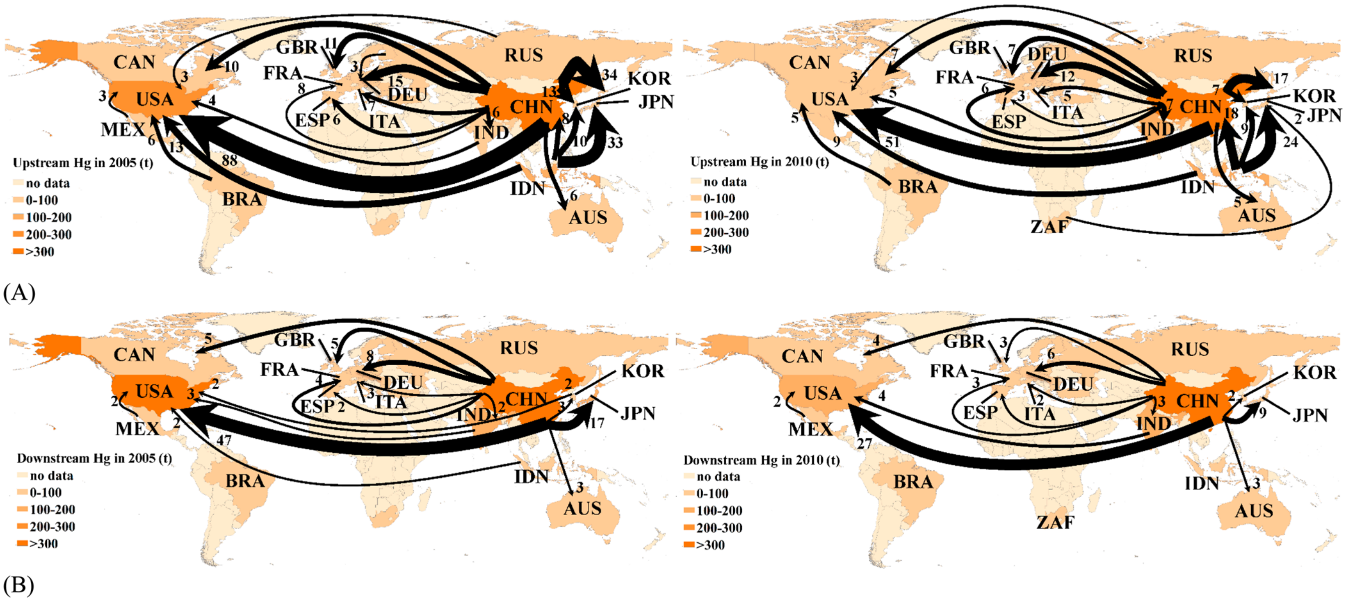

Figure 5. Major net international transfers of embodied atmospheric mercury emissions across different stages of global supply chains in (left graphs) 2005 and (right graphs) 2010. The background color of world maps indicates the value of (A) upstream and (B) downstream production-based atmospheric mercury emissions of nations. The width of arrows indicates the value of net international transfers of embodied mercury (in tonnes). The abbreviations represent nations listed in Table S1 of the Supporting Information.

tonnes of indirect mercury emissions in 2010 (see Table S4 of the Supporting Information).

Transfers of Embodied Mercury within Global Supply Chains. International trade causes the transfer of embodied atmospheric mercury (meaning atmospheric mercury embodied in exchanged goods and services). Figure 4 shows the trade balance of embodied atmospheric mercury of each nation in 2005 and 2010. Trade balance here means emissions embodied in exports minus those embodied in imports. China, Indonesia, Russia, and South Africa are primary exporters of embodied mercury, and United States, Japan, South Korea, and major European countries are primary importers. Figure 5 shows that embodied atmospheric mercury is mainly moving from developing nations (e.g., China, India, and Indonesia) to developed nations (e.g., United States, Japan, and Germany).

Figure 5A shows the transfer of embodied mercury from the upstream production stage to the consumption stage of global supply chains. About 893 tonnes of mercury (37% of global total) is directly emitted by upstream producers into the atmosphere in 2010 because of the production of goods and services that are finally consumed in a different nation. Embodied mercury is mainly transferred from China to the United States, European countries, and Japan as well as from India and Mexico to the United States. China is the largest exporter of embodied mercury, with 224 tonnes (26%) of its direct mercury emissions exported in 2010. This exported mercury is mainly discharged during the production of mineral ores, metals, electricity, and other non-metallic mineral products of China (Figure 6A). About 26% of the direct mercury emissions of China in 2010 are caused by the consumption of other nations, while 74% of those are caused by the consumption of itself. In addition, the consumption of China caused 100 tonnes of direct mercury emissions in other nations in 2010, only counting 13% of the consumption-based mercury emissions of China. This finding means that the majority of global mercury emissions caused by the consumption of China happens in China. The United States is the largest importer of embodied mercury. Only 10% (6 tonnes) of direct mercury emissions of the United States are caused by the consumption of other nations in 2010, while 76% (170 tonnes) of direct mercury emissions caused by the consumption of the United States occur abroad. Results in 2005 indicate similar findings.

Figure 5B shows the transfer of embodied mercury from the downstream production stage to the consumption stage of global supply chains. About 301 tonnes of mercury emissions (12% of global total) are caused by downstream producers during the production of bilateral-traded products to satisfy the final consumption of a different nation in 2010. China is the largest exporter of downstream production-based emissions. About 13% (113 tonnes) of downstream production-based emissions of China are caused by the consumption of other nations in 2010, while only 2% of downstream production-based emissions caused by the consumption of China occur abroad. The downstream production-based emissions of China are mainly transferred to other nations by embodying in the bilateral trade of equipment, machinery, textiles, metals, chemicals, rubber and plastics, and other non-metallic mineral products (Figure 6B). The United States is the largest importer of downstream production-based emissions. Only 7% (11 tonnes) of downstream production-based emissions of the United States are caused by the consumption of other nations in 2010, while 27% (60 tonnes) of downstream production-based emissions caused by the consumption of the United States occur abroad.

In particular, we observe that embodied mercury transfer from Russia to the United States is significant from the upstream production stage to the consumption stage but is not so significant from the downstream production stage to the consumption stage. Such finding indicates that, although mercury embodied in the bilateral trade from Russia to the United States is relatively small, indirect trade of embodied mercury from Russia to the United States (e.g., embodied

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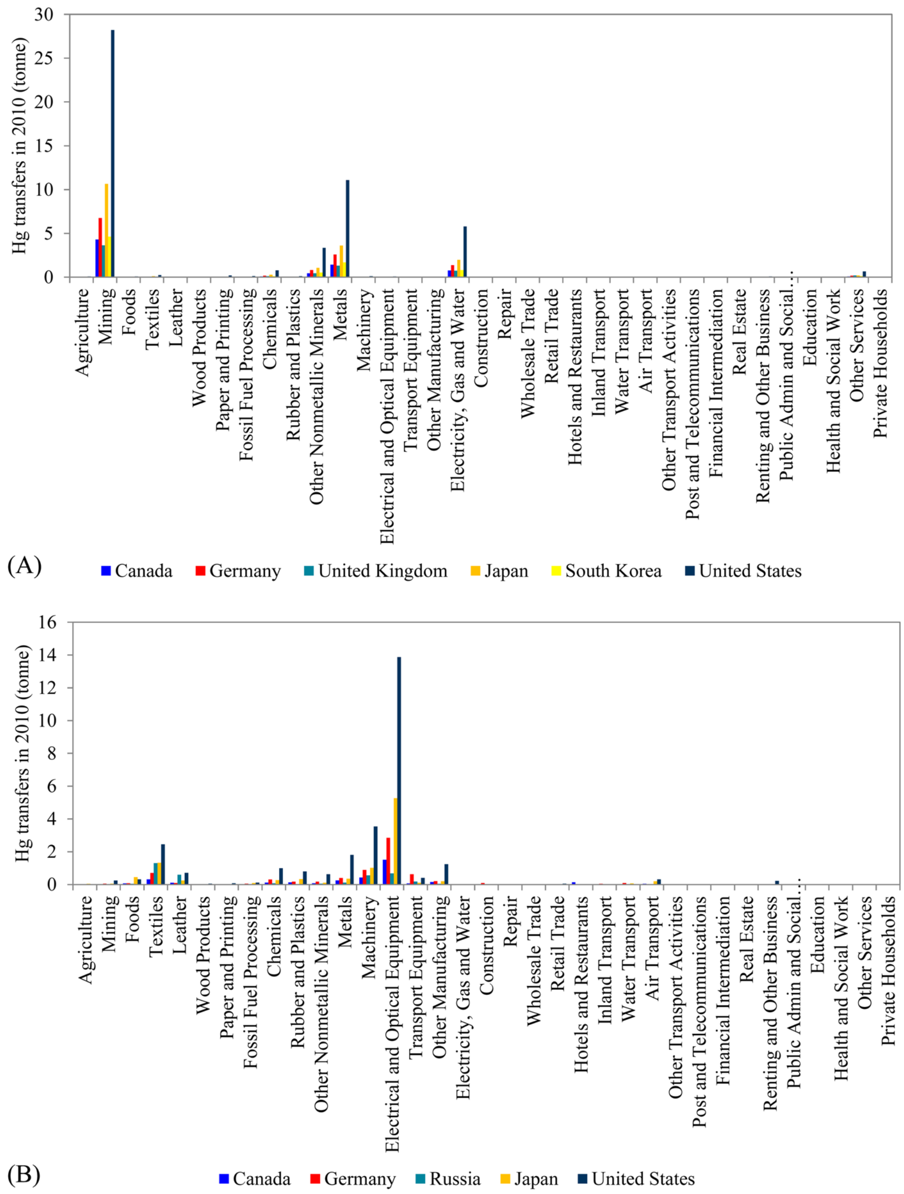

Figure 6. Transfers of embodied atmospheric mercury from China to major destination nations based on the (A) upstream and (B) downstream production frameworks in 2010.

mercury exported from Russia to China and then from China to the United States) is large.

■ POLICY IMPLICATIONS

Previous studies investigate atmospheric mercury emissions of nations based on the upstream production framework, which is limited to direct sources within geographic boundaries. We find that international trade makes mercury footprints of a particular nation go beyond its geographic boundary. Measures controlling global mercury emissions should focus on multiple stages of global supply chains, i.e., all upstream production, downstream production, and consumption stages. Collaborations among nations at different stages should also be encouraged. Details are discussed in the following sections.

Actions at Multiple Stages of Global Supply Chains. Three accounting frameworks that we proposed in this study provide the guidance for controlling global mercury emissions at different stages of global supply chains. They provide two new viewpoints (i.e., downstream production and consumption) to investigate drivers of global mercury emissions, besides traditional upstream production viewpoint.

The upstream production framework highlights nations and sectors with large direct emissions. This framework identifies the focus for traditional mercury control actions, e.g., “best available technologies”, including flue-gas desulfurization, activated carbon injection, and mercury-free gold extraction method.[28,29] These advanced mercury control technologies should be used during the production of basic materials (e.g., electricity, non-metallic mineral products, metals, mineral ores, and chemicals), especially in developing nations (e.g., China, Indonesia, India, Brazil, and South Africa).

The downstream production framework highlights nations and sectors with large total (both direct and indirect) emissions. Most of these sectors (e.g., machinery, equipment, construction, and services) have small direct mercury emissions but large indirect accumulation of mercury emissions. They are usually out of the attention of traditional mercury removal technologies because of their small direct emissions. Because

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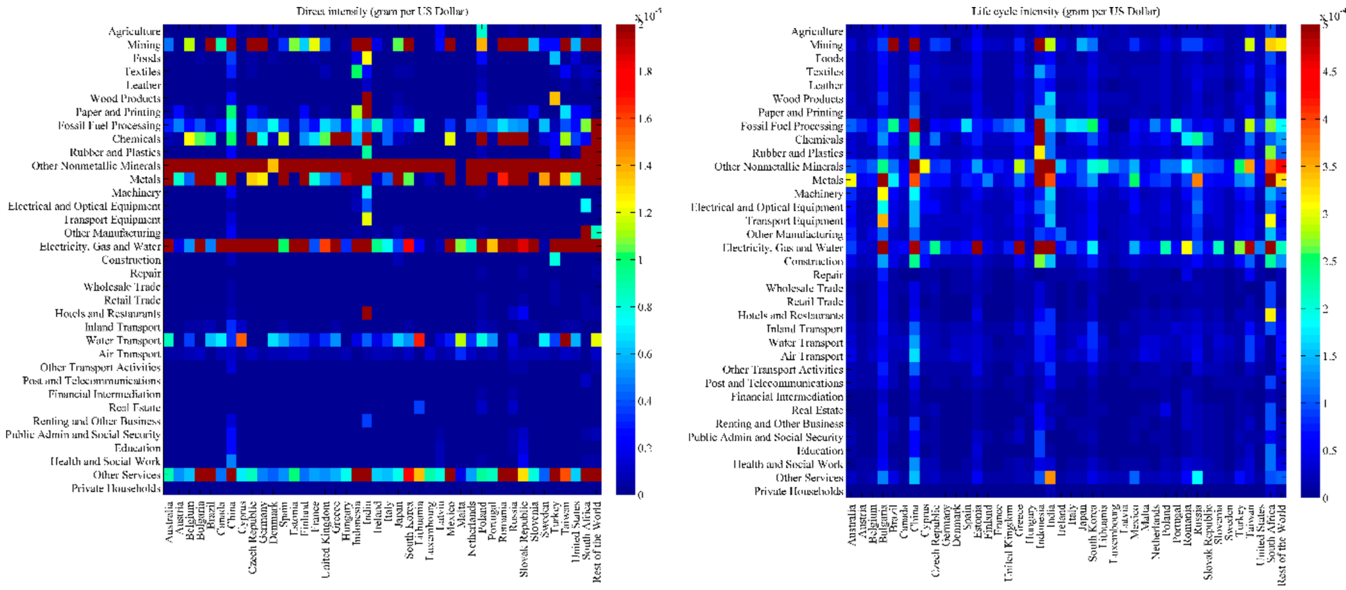

Figure 7. Intensity of atmospheric mercury emissions for unitary sectoral total output in 2010. Direct intensity of a particular sector means direct emissions caused by one unit of its total output. Life cycle intensity of a particular sector means both direct and indirect emissions caused by one unit of its final demand. Mercury emission intensities of the top 30 sectors in 2010 are shown in Table S5 of the Supporting Information.

those sectors have small direct mercury emissions, the focus of action in these sectors should not be placed on mercury control technologies. Instead, actions should focus on productivity improvement in those sectors. Improving their productivity using less inputs of products (especially mercury-intensive inputs) from upstream providers but still fulfilling the demand of final consumers can reduce their indirect emissions (i.e., their induced emissions of upstream providers). In addition, using less inputs of products means less production costs and more economic profits. Thus, productivity improvement in major contributors based on the downstream production framework is double-gain.

The consumption framework highlights nations whose consumption drives large upstream mercury emissions, which are mainly developed nations (e.g., the United States, Japan, Germany, and United Kingdom) in this study. Changing their consumption behaviors (e.g., choosing products that are less mercury-intensive from the whole life cycle) can influence up- and downstream production stages within global supply chains. Thus, actions based on the consumption framework should focus on the optimization of consumption behaviors through economic instruments (e.g., tax and subsidy on consumed goods and services).

Collaborations among Different Stages of Global Supply Chains. We observe that developed nations (e.g., the United States, Japan, and Germany) are in part responsible for mercury emissions of developing nations (e.g., China, India, and Indonesia). Figure 7 shows that developing nations have relatively larger direct mercury intensity than developed nations, indicating that developing nations have less pollution abatement technologies than developed nations. Transferring advanced mercury abatement technologies from developed nations to developing nations (especially to their enterprises producing mineral ores, chemicals, other non-metallic mineral products, metals, electricity, and other services) is a promising way to reduce global mercury emissions. Technology transfers can reduce upstream production-based emissions (i.e., direct emissions) of upstream producers by improving end-of-pipe mercury removal efficiency. Subsequently, indirect emissions embodied in inputs from upstream producers to downstream producers and final consumers will be reduced, meaning that technology transfers can reduce downstream production-based emissions of downstream producers and consumption-based emissions of final consumers.

Figure 7 also shows that life cycle (both direct and indirect) mercury intensity of developing nations is relatively larger than developed nations. This finding means that indirect mercury embodied in intermediate inputs of downstream producers (e.g., producing foods, textiles, equipment, machinery, and services) in developing nations is larger than that in developed nations, indicating lower productivity of downstream producers in developing nations. Transferring advanced production technologies from developed nations to these downstream producers in developing nations can improve their productivity and then reduce induced emissions of upstream providers.

In addition, higher direct and life cycle mercury intensity of developing nations also implies their lower marginal cost of mercury abatement. Establishing a global mercury emission trading scheme is a promising option to promote technology transfers from developed nations to developing nations, who are both pursuing lower cost mercury abatement.

■ ASSOCIATED CONTENT

Supporting Information

More information on methods and data as well as additional results on atmospheric mercury footprints of nations. This material is available free of charge via the Internet at http://pubs.acs.org. Detailed data supporting figures in this article can be downloaded from http://www.gmos.eu/sdi.

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Notes

The authors declare no competing financial interest.

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