Global emission of mercury to the atmosphere from anthropogenic sources in 2005 and projections to 2020

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ABSTRACT

This paper presents the 2005 global inventory of anthropogenic emissions to the atmosphere component of the work that was prepared by UNEP and AMAP as a contribution to the UNEP report *Global Atmospheric Mercury Assessment: Sources, Emissions and Transport* (UNEP Chemicals Branch, 2008).

It describes the methodology applied to compile emissions data on the two main components of the inventory – the 'by-product' emissions and the 'intentional use' emissions – and to geospatially distribute these emissions estimates to produce a gridded dataset for use by modelers, and the results of this work.

It also presents some initial results of work to develop (simplified) scenario emissions inventories for 2020 that can be used to investigate the possible implications of actions to reduce mercury emissions at the global scale.

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1. Introduction

Mercury is a global pollutant. Certain forms of mercury can be transported globally following releases to the environment from both natural and anthropogenic sources. Mercury is ubiquitous in the environment. Humans and wildlife throughout the world are exposed to mercury, often at levels that raise concern for health and environmental effects (e.g., AMAP, 2005; Mergler et al., 2007; Scheuhammer et al., 2007). An understanding of sources of mercury emissions to the atmosphere (the subject of this paper) and to aquatic environments is critical for the development of (cost-)effective strategies for reducing the negative impacts of this global pollutant.

Because it is a global pollutant, reducing the environmental and health risks from mercury requires international action. Mercury is one of the contaminants addressed under the Heavy Metals Protocol to the Convention on Long-range Transboundary Air Pollution that entered into force in 2003.

Mercury has also been on the agenda of the UNEP Governing Council since 2002. Under the UNEP 'mercury process' an ad-hoc Open Ended Working Group (OEWG) was established to review and assess options for enhanced voluntary measures and international legal instruments for mercury. A key part of the UNEP initiative has been obtaining best available information on mercury atmospheric emissions and trends, including, where possible, an analysis by country, region and sector; a consideration of factors driving such trends; and an analysis of applicable regulatory mechanisms. UNEP cooperated with the Arctic Monitoring and Assessment Programme (AMAP) working group under the Arctic Council to develop a mercury emission assessment. The results of this assessment (UNEP Chemicals Branch, 2008) were presented at the UNEP Governing Council at their meeting in February 2009. During that meeting, UNEP agreed a process to develop a legally-binding global instrument on mercury to be implemented by 2013.

This paper describes the emissions inventory that was prepared by UNEP and AMAP as a contribution to the UNEP assessment mentioned above (UNEP Chemicals Branch, 2008).

Information submitted to UNEP-Chemicals by Governments, intergovernmental and non-governmental organizations and available scientific information was used in the preparation of this inventory. Information compiled by the UNEP Global Mercury

Partnership (Mercury Air Transport and Fate Research Partnership area) (Pirrone and Mason, 2008) was also used, in particular in relation to natural sources of mercury and emissions associated with artisanal and small-scale gold mining.

In addition to the inventory of mercury emissions to the atmosphere from anthropogenic sources for the (reference) year of 2005, emission projections for the year 2020 based on three emissions scenarios are presented and discussed. Additional details on the work presented in this paper can be found in the *Technical Background Report to the Global Atmospheric Mercury Assessment* (AMAP/UNEP, 2008).

2. Anthropogenic sources of mercury to the atmosphere

Two groups of anthropogenic sources of mercury can be distinguished: primary anthropogenic sources and secondary anthropogenic sources. Primary anthropogenic sources are those where mercury of geological origin is mobilized and released to the environment. The two main source categories in this group are mining (both for mercury and for other minerals) and extraction and burning of fossil fuels which contain mercury as a trace contaminant. Secondary anthropogenic sources are those where emissions occur from the intentional use of mercury, including mercury use in industrial processes, in products, in dental applications, or in artisanal and small-scale gold mining (ASGM) operations. Emissions to the environment from both primary and secondary sources can occur via direct discharge of exhaust gases and effluents, and through the generation of mercury-containing wastes.

Of the primary anthropogenic sources of mercury, the principle sources are those where mercury is emitted as an unintentional 'by-product'. With the exception of mercury mining itself, the mercury emissions arise from mercury that is present as an 'impurity' in the fuel or raw material used. The main 'by-product' emissions are from sectors that involve combustion of coal or oil, production of pig iron and steel, production of non-ferrous metals, and cement production (e.g., Pacyna et al., 2006; Streets et al., 2005).

Stationary combustion of coal, and to a lesser extent other fossil fuels, associated with energy or heat production in major power plants, small industrial or residential heating units or small-scale residential heating appliances as well as various industrial processes, is the largest single source category of anthropogenic mercury emission to air. Although coal does not contain high concentrations of mercury, the amount of coal that is burned and the fact that emissions from coal-burning plants go mainly to the atmosphere mean that coal burning is the largest anthropogenic source of mercury emissions to the atmosphere (e.g., Pacyna et al., 2006).

Mining and industrial processing of ores, in particular in primary production of iron and steel and non-ferrous metal production (especially copper, lead and zinc smelting), release mercury as a result of both fuel combustion and mercury present as impurities in ores, and at mine sites through accelerating the exposure of tailings to natural weathering processes. Mining and processing of mercury itself is a relatively minor source. Production of gold, where mercury is both present in ores and used in some industrial processes to extract gold from lode deposits, however, can be a significant source (e.g., Swain et al., 2007).

The third major source of 'by-product' releases of mercury is associated with cement production, where mercury is released primarily as a result of the combustion of fuels (mainly coal but also a range of wastes) to heat cement kilns. Mercury-containing fly-ash is sometimes added to cement following the production process; however, it can be expected that this mercury will only gradually leach into the environment as cement products are 'weathered' over time.

A new focus of the work reported in this paper was an attempt to utilize improved basic data on mercury consumption as a basis for determining mercury in waste streams, and estimating associated mercury releases to the atmosphere. Emissions from intentional mercury use have been only poorly quantified in previous global emission inventories, and then only partially included (i.e., only for some sectors, such as waste incineration, and not for all regions).

Estimates of the global consumption of mercury by application and region in 2005 are presented in Fig. 1.

Artisanal and small-scale gold mining (ASGM) remains the largest global use sector for mercury. It reportedly continues to increase with the upward trend in the price of gold and is the largest source of environmental release from intentional use of mercury. ASGM is inextricably linked with issues of poverty and human health. According to the UNIDO/UNDP/GEF Global Mercury Project (Telmer, 2008), at least 100 million people in over 55 countries depend on ASGM – directly or indirectly – for their livelihood, mainly in Africa, Asia and South America. ASGM is

Global mercury consumption by application and by region in 2005 (note: East and Southeast Asia bar is split)

Mercury consumption, tonnes
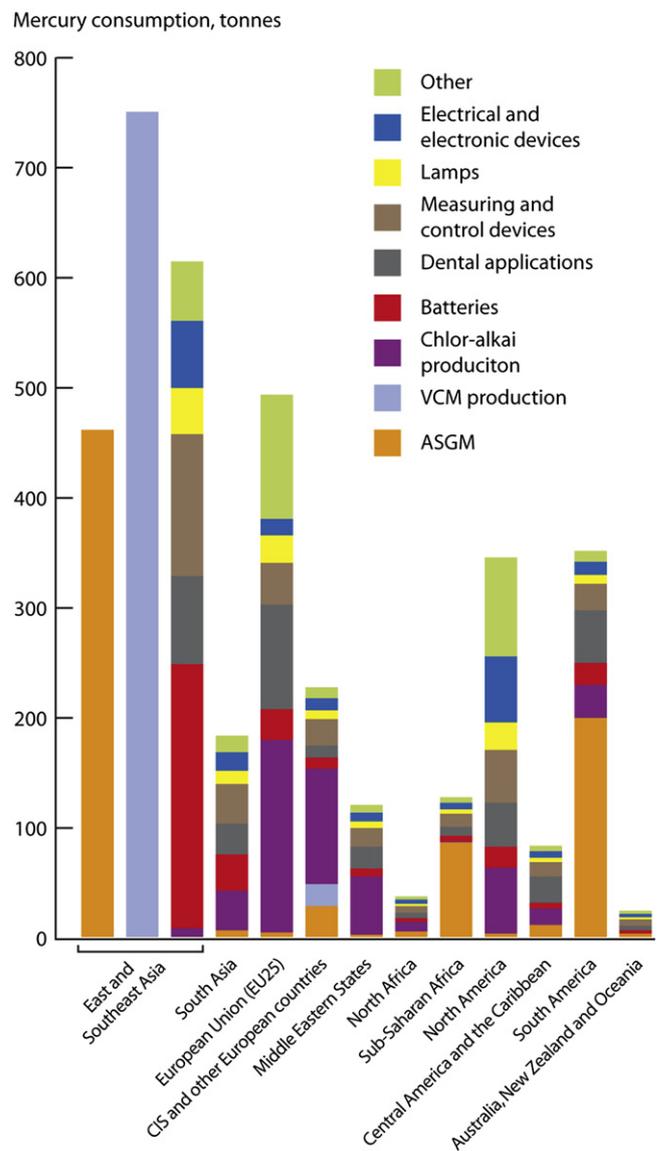
AMAP/IVL, 2008

Fig. 1. Global Hg consumption in the year 2005 (3798 tonnes) by application and by region (AMAP/UNEP, 2008).

responsible for an estimated 20–30% of the world's gold production.

The large and increasing use of mercuric chloride as a catalyst in the production of vinyl chloride monomer (VCM), notably in China, is another area of major concern, especially as it is not yet clear how much mercury – estimated to be several hundred tonnes per year – is released via flue gases, to the hydrochloric acid waste stream, and during the recycling of depleted catalyst (e.g., Swain et al., 2007).

The chlor-alkali industry is the third major mercury user worldwide. Many plant operators have phased out this technology and converted to the more energy-efficient and mercury-free membrane process, others have plans to do so, and still others have not announced any such plans. In many cases, governments have worked with industry representatives and/or provided financial incentives to facilitate the phase-out of mercury technology. Recently governments and international agencies have created partnerships with industry to address the management and releases of mercury from chlor-alkali facilities. Major issues still relate to the fate of stocks of mercury recovered from the chlor-alkali industry as the mercury process is phased out (e.g., EC, 1997).

The use of mercury in batteries, while still considerable, continues to decline. Many countries have implemented policies to mitigate the problems related to diffuse mercury releases such as those associated with disposal of mercury-containing batteries. While mercury use in Chinese batteries was confirmed to have been high through 2000, most Chinese manufacturers have reportedly now shifted to designs with lower mercury content, following international legislation and trends in customer demand in other parts of the world (NRDC, 2006).

Mercury can be released to the environment as a result of routine losses during handling of mercury in dental applications, and following cremation of human remains with dental mercury. Among others, Japan and the Nordic countries have implemented measures to greatly reduce the use of dental amalgams containing mercury. In these and some other higher income countries (e.g., United States) dental use of mercury is now declining as alternatives such as composites (most common), glass ionomers and compomers (modified composites) are introduced. However, the rate of decline varies widely; mercury use in dental applications is still significant in many countries, while in some countries (Sweden, Norway) it has almost ceased. In many lower income countries, changing diets and better access to dental care may actually increase mercury use temporarily.

A wide selection of mercury-containing measuring and control devices, including thermometers, barometers and manometers are still manufactured in various parts of the world, although mercury-free alternatives are available for nearly all such applications and increasingly being used. This change to mercury-free alternatives is being reinforced by legislation in some regions, such as Europe. The global estimate for mercury consumption in these applications is based heavily on Chinese production of sphygmomanometers and thermometers (SEPA, 2008). Over 270 tonnes of mercury were estimated to have been used in the production of only these two devices in 2004, with China responsible for about 80–90% of world production of these two products. Thermometers and sphygmomanometers are considered to represent around 80% of total mercury consumption in this sector.

Mercury-containing lamps (fluorescent tubes, compact fluorescent, high-intensity discharge lighting) remain the standard for energy-efficient lamps, where ongoing industry efforts to reduce the amount of mercury in each lamp are countered, to some extent, by the ever-increasing number of energy-efficient lamps purchased and installed around the world. There is no doubt that mercury-free alternatives, such as LEDs (light-emitting diodes), will become increasingly available, but for most applications the alternatives are still quite limited and/or quite expensive. In China alone, mercury used in the production of (mostly) fluorescent tubes and CFLs (compact fluorescent lamps) was estimated at 55 tonnes for 2004 (SEPA, 2008), which may be an underestimate. Many of these lamps are exported.

Owing to the RoHS Directive (for the restriction of the use of certain hazardous substances in electrical and electronic equipment) in Europe, and similar initiatives in Japan, China and California, among others, mercury-free substitutes for devices such as mercury switches and relays are being actively encouraged, and mercury consumption has declined substantially in recent years. At the same time, the US-based Interstate Mercury Education and Reduction Clearinghouse (IMERC) database demonstrates that mercury use in these devices remains significant.

The category 'other applications of mercury' in Fig. 1 has traditionally included the use of mercury and mercury compounds in such diverse applications as pesticides, fungicides, laboratory chemicals, pharmaceuticals, as a preservative in paints, traditional medicine, cultural and ritual uses, and cosmetics. However, there are some further applications that have recently come to light in which the consumption of mercury is also especially significant. The continued use of mercury catalysts in the production of polyurethane elastomers, where the catalysts remain in the final product, is one such use. Likewise, the use of considerable quantities of mercury in porosimetry has until recently escaped special notice, although in this case the rate of recycling appears to be quite high. The quantities of mercury consumed in these applications in the EU are estimated based on industry information (DG ENV, 2008).

3. Anthropogenic emissions of mercury to the atmosphere in 2005

The global inventory of mercury emissions to the atmosphere reported in this paper consists of two main components. The first component comprised the estimation of 'by-product' mercury releases resulting mainly from combustion of fossil fuels (primary ferrous and non-ferrous) metal production, and cement production. This component also included quantification of emissions from the chlor-alkali (caustic soda production) industry and from large-scale gold production, and from waste incineration in Europe and the United States. These emission sectors are essentially those that have been included in previous inventories of global anthropogenic emissions to air for the reference years 1990, 1995 and 2000 (Pacyna and Pacyna, 2002, 2005; Pacyna et al., 2003, 2006). The work involved the preparation of national emissions estimates (for the nominal reference year of 2005) for these main emission sectors, and the calculation of similar national estimates for emissions from these sectors in 2020 under certain defined scenarios.

The second component of the work addressed quantification of emissions from 'intentional use' sectors that had not previously been included in the global emissions inventories. Principal among these are emissions from ASGM activities, emissions from human cremation following use of mercury in dental amalgam, and emissions from intentional use of mercury in products, including resulting waste streams. The latter category also included emissions from secondary steel production, which are not generally included in the metal production sectors covered by the 'by-product' component. Estimates for (direct atmospheric) emissions from ASGM activities were taken from the report of Telmer and Veiga (2008). Releases from (intentional) mercury use in products were estimated using a modeling approach that has been applied in Europe and which, under this work was adapted for application at a global scale, and data on regional mercury consumption and product use of mercury compiled by the authors. These parts of the inventory work involved

preparation of emissions estimates for various regions of the globe. The resulting emissions estimates were then allocated (mainly on the basis of population) to individual countries in order to allow them to be combined with the national emissions estimates derived in the first part of the work. Until better information is available for these sources at the national level, this latter process is the best (only) approach available.

3.1. Methodology of emission estimates for by-product sources

Two methods were used for the calculation of global anthropogenic emissions of mercury from by-product sources for the (nominal) reference year of 2005:

- the first method involved the collection and compilation of emissions data from countries where such data are estimated by national emissions experts or reported to international programs and conventions.
- the second method consisted of estimating emissions on the basis of emission factors and statistical data on the production of industrial goods and/or the consumption of raw materials. These estimates were carried out by the authors of this paper.

In general, where data such as national reports were available, these were compared with the estimates derived using statistical data for verification. In the case of discrepancies, efforts were made to find explanations, allowing the most appropriate to be used in the global inventory compilation.

Main sources of emissions data used in the preparation of the 'by-product' component of the 2005 emissions inventory are listed in Table 1.

The collection of mercury emissions data elaborated by national experts as part of this inventory activity and/or reported to international programs/projects, and the author's own estimates for countries with no emissions data are indicated in Table 1 as 'This work'.

Estimates for Europe are prepared by national experts in 30 European countries and reported to the UN ECE EMEP program (UN ECE EMEP and EMEP Data), and used in the paper. In addition, emissions experts from Belgium, Bulgaria, Croatia, the Czech Republic, Denmark, Finland, France, Germany, Latvia, Moldova, the Netherlands, Norway, Romania, Slovakia, Sweden, Switzerland, and the United Kingdom provided estimates to UNEP-Chemicals. Finally,

Table 1
Source of information on 'by-product' mercury emissions to the atmosphere from anthropogenic sources in 2005.

Region	2005
Europe (excluding Russia)	UN ECE EMEP (http://www.emep.int)National data supplied by Belgium, Bulgaria, Croatia, the Czech Republic, Denmark, Finland, France, Germany, Latvia, Moldova, the Netherlands, Norway, Romania, Slovakia, Sweden, Switzerland, the United KingdomEU25 European Pollutant Emission Register (EPER)/European Pollutant Emissions and Transfer Register (E-PRTR), http://eper.eea.europa.eu/eper EU ESPREME project (http://espreme.ier.uni-stuttgart.de)
Russia	This work; ACAP (2005b)
Asia (excluding Russia)	National data provided by Cambodia, Japan, Philippines, Republic of Korea; This work
North America	USA: US EPA National Emissions Inventory (data for 2002) (http://www.epa.gov/ttn/chief/net/2002inventory.html) Canada: National Pollution Release Inventory (data for 2004 and 2005) (http://www.ec.gc.ca/pdb/npri/); This work
South America	National data from Chile, Peru; This work
Africa	National data from Burkina Faso, South Africa; This work
Australasia/ Oceania	National data for Australia; This work

information from the EU ESPREME project (Integrated Assessment of Heavy Metal Releases in Europe) was also used for comparison with the estimates provided by national experts (EU ESPREME, 2007).

Estimates for China were prepared by the authors of this paper. These estimates were then compared with the emissions data compiled by the UNEP Mercury Fate and Transport Partnership (F&TP) (Pirrone and Mason, 2008), by Streets et al. (2008) for emissions from coal combustion, and by Feng et al. (2008) for emissions from industrial processes. Combustion source estimates produced by the authors of this paper (ca. 385 tonnes in 2005) are somewhat higher than those derived by the F&TP (260 tonnes in 2003), whereas emissions from industrial activities (including metal production, cement production and caustic soda production) of 245 tonnes in 2005 are slightly lower than the estimate of 320 tonnes in 2003 in the F&TP report. In general, the differences between the estimates prepared in this work and those reported by Streets et al. (2008) and Feng et al. (2008) were considered to be within the range of estimation uncertainties, given that sectors and years were not always directly comparable.

Estimates for India were also prepared by the authors of this paper and compared with the emission data reported to the F&TP by Mukherjee et al. (2008). Mukherjee et al. (2008) used a value for coal mercury content of about 0.376 g tonne^{-1} (ppm), the highest of six reported (measured) values for mercury content in coal used in India. The use of this value resulted in an estimated emission from coal burning in India of ca. 121 tonnes. The average mercury content of most coals is between 0.1 and 0.2 ppm, and the authors of this paper considered it more reasonable to employ the geometric mean value (of 0.3 ppm) reported for mercury content in Indian coals for the emissions estimates presented in this paper.

Information from emissions reports provided by environmental protection authorities in Cambodia, Japan, the Philippines, and the Republic of Korea to UNEP-Chemicals was used in the reported work together with the authors' own estimates.

The emissions estimates prepared for Canada utilized information from the Canadian National Pollution Release Inventory. Estimates prepared within the ACAP mercury project (ACAP, 2005a) were also considered in this inventory. The ACAP estimates were used as a source for some Russian emissions sector estimates (ACAP, 2005b).

Emissions data for the United States were taken from the US EPA's National Emission Inventory for Hazardous Air Pollutants (NEI for HAPs Database). These data were for emissions in 2002; later data were not available for this work.

Information from emissions reports provided by environmental protection authorities in Chile and Peru to UNEP-Chemicals was used to estimate emissions in South America, together with the author's own estimates. Estimates for other countries in South America were made by the authors using the procedures outlined above.

South African emissions data were provided by the South African Mercury Assessment (SAMA) program (Leaner et al., 2008; Dabrowski et al., 2008) through the South African-Norwegian project on Mercury in South Africa (MERSA). Mercury emissions estimates for other countries in Africa are based on calculations made by the authors.

Information on mercury emissions in Australia provided by Nelson (2007) was used in the work reported here to estimate emissions in that country, together with the project's own estimates. Estimates for the other countries in Australasia/Oceania were prepared by the authors.

Emissions data provided by a number of national authorities (see Table 1) were checked for completeness and comparability. Checking for completeness mainly concerned checking for the inclusion of all relevant major (by-product) source categories which may emit mercury to the atmosphere. No major omissions were detected in this respect.

It is difficult to verify data obtained from national authorities. The following approach was therefore undertaken. Information on emissions of mercury from various sources were brought together with statistics on the production of industrial goods and/or the consumption of raw materials, and these two sets of data were used to calculate emission factors. Emission factors calculated in this manner were then compared with emission factors reported in the Joint EMEP/CORINAIR Atmospheric Emission Inventory Guidebook (UN ECE, 2000). In the majority of cases, emission factors estimated on the basis of national emissions data were within the range of emission factors proposed in the Guidebook.

Emissions estimates have been prepared in this work for a number of countries where national emissions data were not available (as described above). These estimates were produced using:

- statistical information on the consumption of raw materials and the production of industrial goods in 2005, including the UN Statistical Yearbook (UN, 2007); and
- emission factors for mercury, estimated by the authors of this work for the UN ECE Task Force on Emission Inventories in the period from 1997 until the present, as reported in the Atmospheric Emission Inventory Guidebook (see the relevant information in UN ECE, 2000) Examples of emission factors used in this paper are presented in Table 2.

Emission factors were multiplied by statistical data in order to obtain national emissions estimates for the sectors under consideration.

3.2. Methodology of emission estimates for 'intentional use' of mercury

Emissions from intentional use of mercury were calculated using distribution factors for the mercury consumed in the different products, and emission factors to air for releases of mercury from the different paths that apply for mercury in products. The general methodology applied is described in Kindbom and Munthe (2007).

Mercury consumption for various uses has been well studied in the EU and the United States. Apart from specific applications, however, mercury use for most other regions has been only roughly estimated in the past. The analysis reported here, therefore, refines previous estimates by correlating mercury consumption in products (especially batteries, lamps, measuring & control, electrical & electronic, and 'other') with regional economic activity, expressed as 'purchasing power parity' (PPP). Some two-thirds of global economic activity takes place in East and Southeast Asia, North America, and

Table 2
Emission factors for mercury, used to estimate the 2005 emissions.

Category	Unit	Emission factor
Coal combustion	g tonne^{-1} coal	
Power plants		0.1–0.3
Residential and commercial boilers		0.3
Oil combustion	g tonne^{-1} oil	0.001
Non-ferrous metal production		
Copper smelters	g tonne^{-1} Cu produced	5.0
Lead smelters	g tonne^{-1} Pb produced	3.0
Zinc smelters	g tonne^{-1} Zn produced	7.0
Cement production	g tonne^{-1} cement	0.1
Pig iron & steel production	g tonne^{-1} steel	0.04
Waste incineration	g tonne^{-1} wastes	
Municipal wastes		1.0
Sewage sludge wastes		5.0
Mercury production (primary)	kg tonne^{-1} ore mined	0.2
Gold production (large-scale)	g g^{-1} gold mined	0.025–0.027
Caustic soda production	g tonne^{-1} produced	2.5

the European Union (details available in UNEP, 2008). While there are some particular differences in consumption as regards different mercury-containing products, it is evident that these three regions are responsible for the majority of the mercury consumed in products and processes around the world. The analysis of the relative economic well-being of different regions may be used to roughly correlate each region's purchasing power with its consumption of mercury-containing products in cases where actual statistics are lacking. This approach was applied to the various regions and major uses of mercury, in order to obtain data for total mercury consumed worldwide by region and by major application. The summary of the results of this analysis has already been shown in Fig. 1.

All of the above mentioned uses give rise to mercury releases to air, water and land (waste). These releases may occur during all stages of the application; for example, for a mercury-containing product such as thermometers, releases can occur during raw material extraction, manufacturing, use, and disposal (UNEP-Chemicals, 2002). Estimates of product-related emissions have been made for the EU (Kindbom and Munthe, 2007) using a simple approach where emissions from the use and disposal of products were included. The Draft UNEP Toolkit (UNEP, 2005) provides a more complete method for estimating emissions from products and intentional use, but requires a detailed inventory of mercury uses and sources, which is still lacking in many countries. Product-related emissions of mercury to air are, in a limited number of cases, also included in national inventories as emissions from waste incineration or manufacturing facilities. For the global inventory presented here, the method applied by Kindbom and Munthe (2007) was employed to estimate product-related emissions. This method is assumed to provide conservative estimates of emissions from product use and disposal. For this reason, an upper-range emission value is also presented (see below).

The method presented by Kindbom and Munthe (2007) includes the following paths for distribution of the mercury contained in products: releases through breakage; metal scrap smelting; re-collection to safe storage; waste (incinerated, landfilled, recycled); and mercury remaining in products accumulated in society. The distribution factor assumptions for each of the distribution path in various countries were based on assessments of product-related mercury emissions to air in the European Union. The distribution factors developed in 2007 for the European Union were employed in the current study, and assumptions for other regions were based on these distribution factors.

The emission factors used for each of the paths of release of mercury to air from products are presented in AMAP/UNEP (2008). The emission factors are in principle the same as were used by Kindbom and Munthe (2007), with a few adjustments. In that study, emissions were accounted for annually on a 10-year time horizon (with a lower emission factor for the consecutive years). The emission factor for release through 'breakage' was doubled compared to the earlier study to account for this methodological difference. New emission factors have also been assigned for the further refinement of waste treatment introduced in the present study with regard to waste incineration divided into three groups, waste landfill into two groups and the added path of losses during waste recycling. The emission factors for large-scale, controlled waste incineration and for managed landfills were those used for waste treatment in the previous study covering the EU. The emission factor for losses during waste recycling and handling was derived from Barr Engineering Company (2001).

The emissions estimated using the method described above are considered to be conservative based on the selection of distribution and emission factors. Furthermore, they do not include emissions from the manufacturing step. To account for these and other potential underestimation of emissions during use and disposal, an

upper-range estimate is also presented. Unfortunately, very little information is available to provide a consistent estimate of an upper range. Examples of higher estimates of product-related emissions are Cain et al. (2007) and Maxson (2007) for dental amalgam emissions in the USA and EU, respectively. Additional information on large losses of mercury in the manufacturing step were submitted to UNEP as a part of the review process (e.g., Lennett, 2008). In the absence of specific information on potential higher emissions, a calculation of emissions using adjusted emission factor has been performed. In this calculation, emission factors for the categories 'released by breaking', and 'waste landfill' were increased by a factor of 3. The emission factor for waste incineration (different categories) was increased by 10%. These changes and the resulting emissions are assumed to represent both emissions from the complete life cycle of the product as well as assumed higher emission fluxes from the use and disposal steps.

Emissions from use of dental amalgam were estimated using available statistics on cremations and consumption of mercury in the dental sector. The estimates are limited to emissions to air from cremations and thus do not take into account any emissions during production, transport, handling and disposal of dental amalgam. Although some studies have indicated large losses of mercury in these steps (Maxson, 2007; Cain et al., 2007) the lack of information and overall uncertainties were judged to be so large that an estimate of the resulting emissions to air was not meaningful. The amount of mercury released in each cremation was estimated using previous estimates of the mercury content per person (2–5 g) for Europe and scaling to different regions using mercury consumption data for dental use in this region. The fact that human cremations are not practiced in some countries was taken into account.

The estimates of mercury emissions to air from its use in artisanal gold mining presented in this paper are entirely based on the work of Telmer and Veiga (2008). These authors have examined the available information on the use patterns, technological aspects and fate of mercury in a number of countries in different regions. Relatively reliable information is available from two countries (Brazil and Indonesia) where field studies and assessments have been performed in several regions. Partial information is available from an additional seven countries and information from the remaining around 60 countries where artisanal gold mining is practiced is scarce. The global estimate for emissions to air reported by Telmer and Veiga (2008) was distributed to individual countries on the basis of their estimated consumption of mercury in artisanal and small-scale operations (Telmer and Veiga, 2008).

3.3. Emission estimates for various anthropogenic source categories

Estimates of global emissions from by-product sources are summarized in Table 3.

The largest emissions to the global atmosphere of mercury as a by-product occur from combustion of fossil fuels, mainly coal in power plants and industrial and residential boilers. Various factors affect the emission of mercury to the atmosphere during combustion of fuels. The most important are: 1) the content of mercury in coal, and 2) the type and efficiency of control equipment that can remove mercury from exhaust gases. The amount of combusted fuel is, of course, a key factor. Emissions of mercury from coal combustion are between one and two orders of magnitude higher than emissions from oil combustion per tonne of fuel burned, depending on the country.

With regard to the non-ferrous metal industry, mercury emissions depend mainly on: 1) the content of mercury in non-ferrous metal ores that are predominantly used in primary smelting processes, or scrap used in secondary non-ferrous production, 2) the type of industrial technology employed in the production of

non-ferrous metals, and 3) the type and efficiency of emissions control installations.

Among various steel making technologies, the electric arc (EA) process produces the largest amounts of trace elements and their emission factors are about one order of magnitude higher than those for techniques such as basic oxygen (BO) and open hearth (OH) processes. Electric arc furnaces are used primarily to produce special alloy steels or to melt large amounts of scrap for reuse. However, the major source of atmospheric mercury related to the iron and steel industry is the production of metallurgical coke.

The fuel-firing kiln and clinker-cooling and handling systems are responsible for emissions of mercury in the cement industry. The content of mercury in fuel used in the kiln and the type and efficiency of control equipment (mostly electro-static precipitators (ESPs)) are the main parameters affecting mercury emissions.

The use of the mercury cell process to produce caustic soda in the chlor-alkali industry has decreased significantly over the past 15 years worldwide (http://www.eurochlor.org). Major points of mercury release in the mercury cell process of chlor-alkali production include: by-product hydrogen stream, end box ventilation air, and cell room ventilation air. Typical devices/techniques for removal of mercury at these points are: 1) gas stream cooling to remove mercury from hydrogen stream, 2) mist eliminators, 3) scrubbers, and 4) adsorption onto activated carbon and molecular sieves. Installation of these devices can remove mercury with an efficiency of more than 90%.

The calculated emissions of mercury to air from intentional use in products are summarized in Table 4, which presents emissions by product category in various regions, and Table 5, which presents the emissions in the various regions according to the distributed pathways. Both tables include the conservative estimate (C), based on the average of the regional minimum consumption, and the upper-range estimate (U) based on the regional maximum consumption of mercury.

Emissions from cremations and ASGM activities are presented in Table 6.

Summing the emissions from 'by-product' sectors, and the conservative emissions estimates from intentional use of mercury in products and artisanal mining, and emissions associated with cremations result in a global inventory of emissions of mercury to air from anthropogenic sources for the reference year of 2005 of ca. 1930 tonnes. Fig. 2 summarizes the emissions associated with various anthropogenic activities.

The combined 2005 global anthropogenic emissions inventory for by-product sectors, product use, cremation and artisanal mining can also be divided among the continents as summarized in Fig. 3.

Fig. 4 shows the breakdown by continent and the major emission sectors.

From Fig. 4 it is apparent that Asian countries contributed about 67% to the global mercury emissions from anthropogenic sources in 2005, followed by North America and Europe. This pattern is similar if by-product emission sectors only are considered. Russia, with its contribution of about 4% to global emissions is considered separately due to its territories in both Europe and Asia.

Combustion of fuels to produce electricity and heat is the largest source of anthropogenic mercury emissions in Europe, North America, Asia and Russia, and responsible for about 40–50% of the anthropogenic emissions in Oceania and Africa. However, in South America ASGM is responsible for the largest proportion of the emissions (>55%).

From the compiled inventory data, it is also possible to rank the countries by their emissions. Fig. 5 presents the sector-breakdown of emissions from the ten largest emitting countries.

China, with its more than 2000 coal-fired power plants, is the largest single emitter of mercury worldwide, by a large margin.

Table 3
Mercury by-product emissions to air in 2005 from anthropogenic sources worldwide in 2005 (in tonnes).

Continent	Stationary combustion	Non-ferrous metals production	Pig iron and steel production	Cement production	Gold production	Mercury production (primary sources)	Caustic soda production
Africa	37.3	2.1	1.6	10.9	8.9	0.0	0.1
Asia (excluding Russia)	622.1	90.0	24.1	137.7	58.9	8.8	28.7
Europe (excluding Russia)	76.6	9.4	9.4	18.8	0.0	0.0	6.3
North America	71.2	5.7	14.4	10.9	12.9	0.0	6.5
Oceania	19.0	6.1	0.8	0.4	10.1	0.0	0.2
Russia	46.0	5.2	2.6	3.9	4.3	0.0	2.8
South America	8.0	13.6	1.8	6.4	16.2	0.0	2.2
World	880.2	132.0	54.8	189.0	111.3	8.8	46.8

Power plant emissions are only a part of the total combustion emissions of mercury in China. Equally significant are emissions from combustion of poor quality coal mixed with various kinds of wastes in small residential units to produce heat and cook food in rural areas. With estimated by-product sector emissions exceeding 600 tonnes, China contributes about 40% to the global mercury by-product emissions, and this contribution may be even higher because mercury emission factors for non-ferrous metal production in China may be underestimated. China also has significant emissions from ASGM.

Together, three countries, China, the United States and India, are responsible for about 60% of the total estimated global emission inventory for 2005 (1115 out of 1930 tonnes).

The emission inventories compiled in this work comprise national emission totals for defined emission sectors. If transport and fate of emitted mercury is to be reliably modeled, it is important to know not only how much mercury is emitted but where these emissions occur (on a finer scale than the extent of a nations territorial extent). This is particularly so for large countries such as China, Russia and the United States. Work was therefore also conducted to geospatially distribute the global emissions inventories produced in the current work within a global 0.5 × 0.5° latitude/longitude grid. These gridded datasets are required as input to global transport models.

Most mercury emissions to air occur from 'point sources', whether these be power plant stacks, industrial units, or landfill sites. Even for activities that may be considered to be 'diffuse sources' such as artisanal mining operations, or emissions from breakage, the releases themselves will tend to be concentrated in specific general locations (e.g., mining communities or population centers). Where information is available on the location (e.g., latitude–longitude) of these point sources or release 'points', and also

Table 4
Conservative and upper-range emissions of mercury from product use by region and product category (tonnes).

Emissions	Batteries	Measuring and control devices	Lighting	Electrical devices	Other	Sum
Conservative and upper-range emissions estimates (C–U)	C–U	C–U	C–U	C–U	C–U	C–U
East and Southeast Asia	11–19	12–28	4–9	7–14	5–12	38–82
South Asia	1–2	4–10	1–5	2–3	2–4	11–24
European Union	2–3	3–6	2–4	2–3	10–17	20–32
CIS + oth European count	0.9–1	3–5	1–2	2–3	1–2	7–13
Middle Eastern States	0.1–0.3	1–3	0.4–1	1–2	0.5–1	3–8
North Africa	0.2–0.2	1–2	0.2–1	0.5–1	0.3–0,7	2–4
Sub-Saharan Africa	0.5–1	2–4	0.5–1	1–2	1–1	4–8
North America	2–2	5–9	2–4	9–14	9–17	27–45
Central America and the Caribbean	0.2–0.3	1–3	0.4	0.6	0.5	3.0
South America	0.6–1	2–5	1–2	1–3	1–2	5–12
Australia New Zealand and Oceania	0.1–0,2	0.3–1	0.1–0.2	0.3–0.4	0.2–0.3	1–2
Sum	20–31	33–74	13–28	26–47	29–58	120–237

Table 5
Conservative and upper-range emissions of mercury from product use by region and source category (tonnes).

Emissions	Release by breaking	Waste incineration	Waste landfill	Scrap metal	Waste recollected, recycling–handling	Sum
Conservative–upper-range emissions estimates (C–U)	C–U	C–U	C–U	C–U	C–U	C–U
East and Southeast Asia	2–6	16–18	16–47	2–3	3–10	39–89
South Asia	0.5–1	4–4	6–18	0.2–0.2	0.1–0.3	11–24
European Union	1–4	13–14	4–11	1–1	1–2	20–32
CIS + oth European count	0.3–1	4–4	2–7	0.3–0.3	0.2–0.4	7–13
Middle Eastern States	0.2–1	0.3–0.3	2–7	0.2–0.2	0–0	3–8
North Africa	0.1–0.2	1–1	1–3	0–0	0–0	2–4
Sub-Saharan Africa	0.2–0.4	2–3	2–5	0.1–0.1	0–0.1	4–8
North America	1–4	14–16	6–18	4–4	1–4	27–45
Central America and the Caribbean	0.2–0.5	1–1	2–6	0.1–0.1	0–0.1	3–7
South America	0.3–1	1–1	3–9	0.3–0.3	0–0.1	5–12
Australia New Zealand and Oceania	0.1–0.2	0.4–0.4	0.3–1	0.2–0.2	0.1–0,2	1–2
Sum	6–18	57–62	45–133	7–7	5–16	120–236

Table 6
Emissions of mercury from cremation and artisanal and small-scale gold mining by region (tonnes).

Region	Cremation emissions by region	Artisanal and small-scale gold mining by region
Central America and the Caribbean	0.4	5
East and Southeast Asia	16	233
Europe – EU, CIS and non-EU countries	3.75	4
Middle East	0.02	3
North America	1	6
Oceania	0.01	0.2
South America	1	64
South Asia	2.5	28
Sub-Saharan Africa	0.5	8
Total	26	350

on the amounts of mercury emitted (or for example, the proportion of the national emissions for a given sector that occur at the release points), then allocation of emissions estimates to geospatial grids is a simple matter. However, this information is generally not available.

In the absence of comprehensive information on the locations of emission sources, a common practice in the past has been to 'geo-distribute' the mercury emission according to the distribution of some suitable 'surrogate' parameter for which a spatial distribution is defined. Various 'surrogates' have been employed for distributing emission inventories (e.g., population, land-use, vegetation, wild-fires); however, for mercury, geospatial distribution of emissions has almost exclusively involved the use of population distribution (see Wilson et al., 2006). The underlying assumption is simple: the more people that are located in a given area, the more mercury is emitted in that area. This assumption can be justified for example for releases associated with use of mercury in products. Wastes tend to be incinerated or disposed of close to the population centers
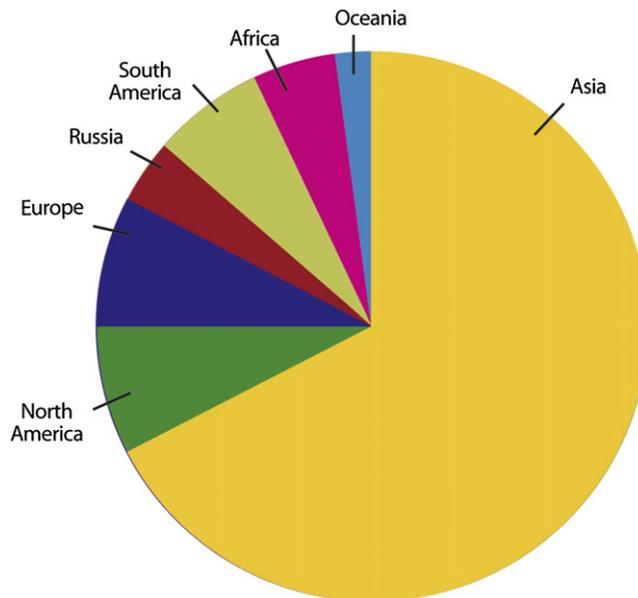

Fig. 3. Proportion of global anthropogenic emissions of mercury to air in 2005 from different regions (AMAP/UNEP, 2008).

where they are generated. Industrial activities and power generation are co-located with population centers, for obvious reasons, and all other things being equal, the more people the greater the 'activity' and the greater the emissions. However, there are obvious exceptions. An example is gold production, where emissions will tend to occur at the sites of extraction, and in most cases these are not the parts of the country with the highest population density (e.g., major cities). The limitations of the use of population as a 'distribution mask' for distributing mercury emissions are discussed by Wilson et al. (2006). A major focus of the work undertaken in connection with the 2005 global mercury anthropogenic emission inventory, reported here, was therefore to improve the geospatial distribution procedures. As a first step, several new 'distribution masks' were prepared in addition to global population
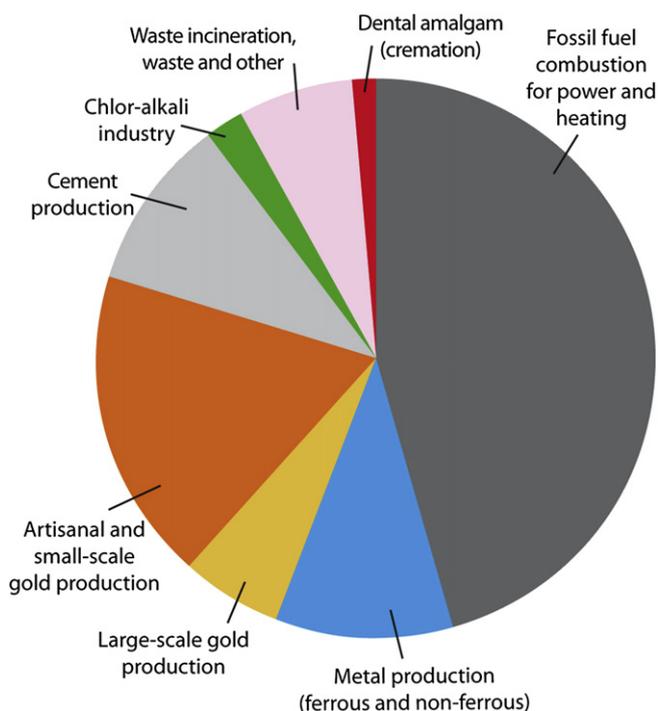
Fig. 2. Proportion of global anthropogenic emissions of mercury to air in 2005 from various sectors (AMAP/UNEP, 2008).
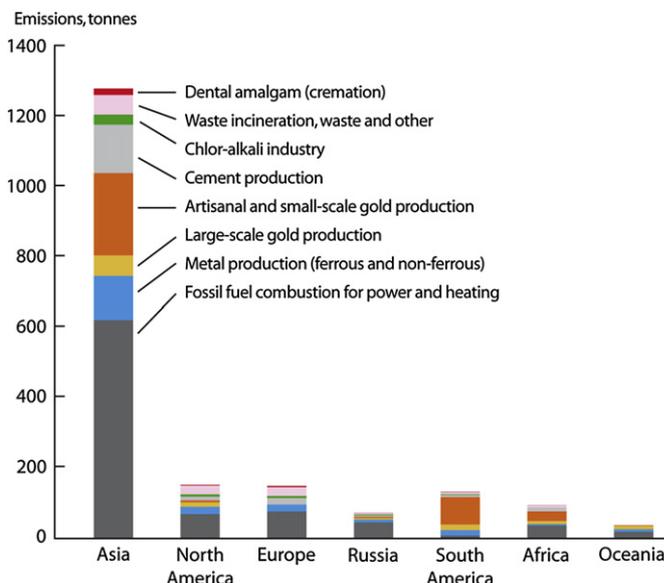
Fig. 4. Global anthropogenic emissions of mercury to air in 2005 from different continents by sector (AMAP/UNEP, 2008).
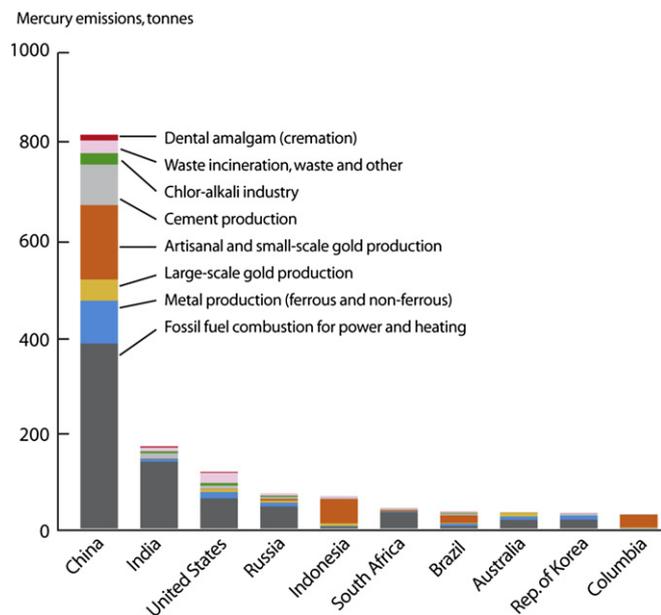
Mercury emissions, tonnes

Fig. 5. Emissions of mercury to air in 2005 from various anthropogenic sectors in the ten largest emitting countries (AMAP/UNEP, 2008).

masks; these included an 'urban population' mask, an 'industrial activity' mask, a major power plant mask, and a gold deposits mask. 'Distribution masks' are essentially a numerical matrix of scaling factors, where the matrix corresponds to the grid domain (in this case the $0.5 \times 0.5°$ global grid, comprising 259 200 grid cells) and the scaling factors are the proportion of the country's total value for the parameter concerned (e.g., total population) within that grid cell. These factors are then used as multipliers for the country's total 'area source' emissions for the sector concerned. The sector-specific gridded emissions inventories for 2005 can be conveniently mapped, as shown in Fig. 6 which presents the global distribution of anthropogenic emissions of mercury in 2005, following application of the geospatial distribution methodology described by the authors above and in AMAP/UNEP (2008).

4. Uncertainties in emission estimates

It is important to recognize that the emission estimates (both 'expert' estimates and officially reported emissions figures) presented above are just that – estimates. These estimates are based on a number of assumptions, where the methods used to produce the inventory are described. These include assumptions regarding mercury consumption, production and use of fossil fuels and other raw materials, emission factors, and technology. Further assumptions are made in order to allocate or distribute these emissions among regions, countries or even finer geographical units (e.g., geospatial distribution of emissions inventories to grid cells for modeling applications). All of the assumptions used are considered to represent the best option currently available for filling gaps in the knowledge required to produce a quantitative distributed global emission inventory for mercury. An obvious consequence of estimations based on assumptions is that the estimates have an associated degree of uncertainty.

Uncertainties in emissions estimates can be grouped depending on source type and category. For major source sectors, uncertainty ranges are presented in Tables 7 and 8. In general, the uncertainties reflect the extent to which emissions from a given source sector have been studied and the countries or regions where these studies have been undertaken.

The most accurate data on mercury emissions are those for combustion of coal in stationary sources, mainly electricity-generating power plants. This relates primarily to the accuracy of emission factors for mercury emitted from various types of coal, boiler and emission control measures applied in coal-fired power plants. Emission factors for mercury and other contaminants emitted during coal combustion have been developed on the basis of either direct measurements of mercury in the flue gas or material mass-balances for mercury entering the combustion zone in coal, and leaving the combustion zone in bottom ash, fly-ash, and flue gas.

The 2005 global emissions inventory presented in this paper represents the first attempt to quantify the global emissions of mercury to air from the major intentional use sectors (product use, cremations, and artisanal gold mining). There is thus very little information available for comparison with the results obtained in this work. As described above, the basis for these estimates is
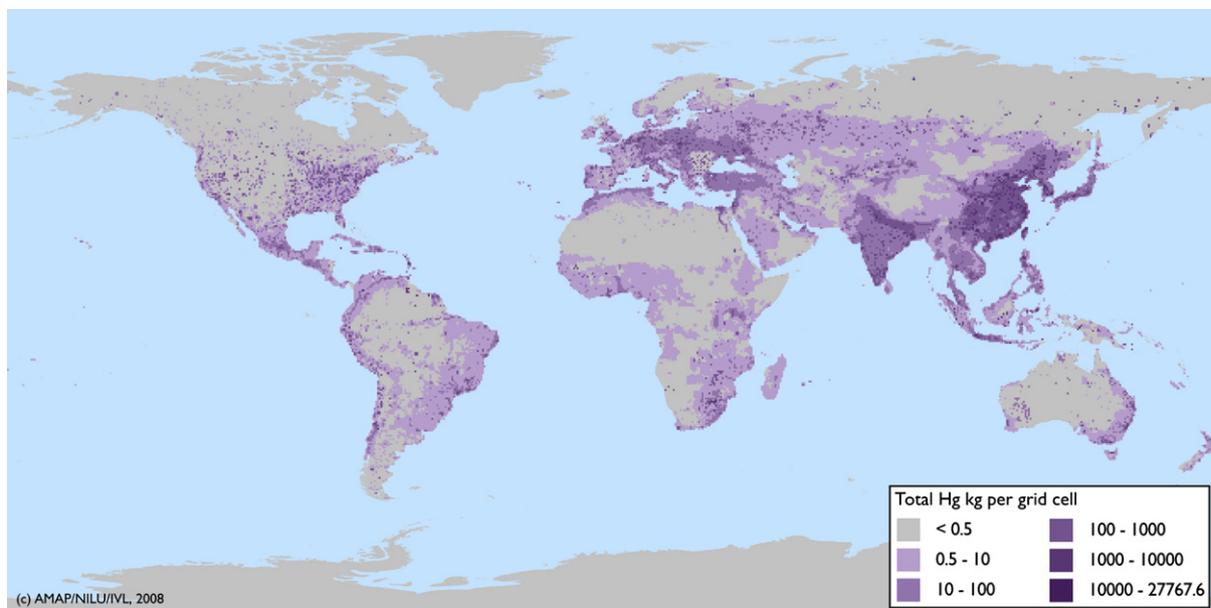

Fig. 6. Global distribution of anthropogenic emissions of mercury in 2005 (AMAP/UNEP, 2008).

Table 7
Uncertainty of mercury emissions estimates by source category.

Industrial source	Uncertainty (±%)
Stationary fossil fuel combustion	25
Non-ferrous metal production	30
Iron and steel production	30
Cement production	30
Waste disposal and incineration	As much as 3 times
Mercury and gold production	?

largely information on global (supply and demand and) consumption of mercury. These data are believed to be only moderately uncertain, although large uncertainties do exist for specific sectors and countries. For the 'distribution factors' used to assign mercury consumption between various product categories and the 'emission factors' used to estimate actual emissions from different categories, the uncertainties are large. For many of these factors, no specific information is available and the authors therefore had to apply their own expert judgment. It is thus not possible to provide a quantitative number for the uncertainties associated with the intentional use sectors, as is done above for the by-product emission sectors. For this reason 'upper-range' estimates are presented in Tables 4 and 5 together with the 'conservative' estimates that are incorporated in the 2005 inventory itself. For the purposes of assessing reliability of the estimates of emission from intentional use sectors, it is probably more relevant to consider the few values where emissions have been quantified using other methods (e.g., point source measurements or engineering estimates). For waste incineration (which is the dominant sector in the product-use emission category), nationally reported values are available from a few countries.

In connection with this work, the authors circulated a questionnaire with four questions on verification of emission estimates, missing sources and source categories, estimated completeness of reported official national inventories, and estimated inventories to national emission experts. A more detailed discussion of the results of this survey on uncertainties and verification procedures is presented by the authors in AMAP/UNEP (2008).

5. Emission scenarios and future trends

Future mercury emissions are dependent upon a great many variables, including the development of national and regional economies, development and implementation of technologies for reducing emissions, possible regulatory changes, and also factors connected to global climate change.

As a first attempt to gain insight into the possible implications for global anthropogenic emissions of mercury to the atmosphere, of taking (additional) actions vs. not taking (additional) actions to control emissions, three emissions scenarios were considered for a target year of 2020:

- The 'Status Quo' (SQ) scenario assumes that current patterns, practices and uses that result in mercury emissions to air will

Table 8
Uncertainty of mercury emissions estimates by continent.

Continent	Uncertainty (±%)
Africa	50
Asia	40
Australia	30
Europe	30
North America	27
South America	50

continue. Economic activity is assumed to increase, in various regions; however, emission control practices remain unchanged from those currently employed, leading to increased emissions in several sectors.
- The 'Extended Emissions Control' (EXEC) scenario assumes economic progress at a rate reflecting the future development of industrial technologies and emissions control technologies; that is, mercury-reducing technologies currently generally employed throughout Europe and North America would be implemented elsewhere. It further assumes that emissions control measures currently committed to in Europe to reduce mercury emissions to air or water would be implemented throughout the world. These include certain measures adopted under the LRTAP Convention Heavy Metals Protocol, EU Directives, and also agreements to meet IPCC Kyoto targets on reduction of greenhouse gases causing climate change (which will also result in reductions in mercury emissions).
- The 'Maximum Feasible Technological Reduction' (MFTR) scenario assumes implementation of all available solutions/measures, leading to the maximum degree of reduction of mercury emissions and mercury discharges to any environment; cost is taken into account but only as a secondary consideration.

These scenarios were applied to the data used to produce the 2005 inventory, to prepare three 'scenario emission inventories' for 2020; these inventories were geospatially distributed in a similar way to that described above for the 2005 global inventory to produce scenario datasets for use by modelers.

In the following discussion, the emissions scenarios for by-product sources and intentional use sectors are considered separately. In general, only the scenario results for by-product sources are considered robust at this time, in terms of the methodology employed to generate the scenario emissions estimates; future emissions from intentional use sectors are highly speculative.

For by-product sectors, emissions scenarios were estimated on the basis of information on emission factors elaborated within the EU projects ESPREME (Estimation of willingness-to-pay to reduce risks of exposure to heavy metals and cost–benefit analysis for reducing heavy metals occurrence in Europe; EU ESPREME) and DROPS (Development of macro and sectoral economic models to evaluate the role of public health externalities on society; EU DROPS), and statistical data on the production of industrial goods, consumption of raw materials, and incineration of wastes. Further details of the assumptions made within the ESPREME and DROPS projects for heavy metals, including mercury for the years 2010 and 2020 can be found from the above web resources and in AMAP/UNEP (2008). The EXEC scenario described in this paper is equivalent to the DROPS 'BAU + C 2020' (Business as Usual, with a component related to actions to address climate change) scenario in terms of assumptions for large combustion plants, iron and steel production, cement production and the chlor-alkali industry.

Emission factors developed and used within the ESPREME and DROPS projects are available from Theloke et al. (2008). Unabated emission factors are presented with the information on emission control efficiency for mercury and other heavy metals for all significant emission categories, and emissions control techniques. Using the unabated emission factors and the degree of emissions control, one may easily calculate the emission factors for a given emission source category and emission control method, such as those presented above as assumption for the 2020 emission scenarios.

The abated emission factors (unabated emission factor multiplied by the efficiency of emission control for a given emission control installation) were used to scale the 2005 emissions estimates developed as described in previous sections of this paper.

In the next step, assumptions regarding changes in the consumption of coal and the production of cement between the years 2005 and 2020, based on statistical information obtained from the Energy Information Administration (2007), were used to further scale the estimates to obtain the final estimated emissions in 2020 for the EXEC and MFTR scenarios.

For the SQ scenario, factors are abated at the same level as today, but otherwise no scaling was applied. Mercury emissions to air continue and increase as a result of the assumed increase in economic activity.

5.1. Scenario emission estimates for 'by-product' (plus chlor-alkali industry) sources

Scenario estimates of by-product sector emissions of mercury in 2020 for the three scenarios: SQ, EXEC and MFTR and different regions are presented in Fig. 7. The 2005 emission estimates are also presented in this figure for comparison. Details of scenario emission estimates for each source category in individual countries are included in AMAP/UNEP (2008).

If no major changes in the efficiency of emission control are introduced and economic activity continues to increase (the SQ scenario), significant increases in global anthropogenic mercury emissions (equivalent to about one quarter of the 2005 mercury emissions from these sectors) are projected in 2020. The largest increase in emissions of mercury is projected for stationary combustion, mainly from combustion of coal. A comparison of the 2020 emissions estimated from the EXEC scenario and the SQ scenario indicates that a further 1000 tonnes of mercury could be emitted globally on top of the projected emission of 850 tonnes (under the EXEC scenario) in 2020, if mercury continues to be emitted under the control measures and practices that are in operation today against a background of increasing population and economic growth in some regions. In other words, the

implementation of available measures and practices (the basic assumption of the EXEC scenario), implies a benefit of reducing mercury emissions by up to 1000 tonnes per year in the period to 2020 under the assumptions employed in this scenario discussion. Doing nothing to improve reduction of mercury emissions is projected to result in emissions in 2020 that are more than 100% above those envisaged under the EXEC scenario.

As might be expected, an even greater reduction in mercury emissions is projected if the 2020 SQ scenario is compared with the 2020 MFTR emission reduction scenario. In this comparison or projections, emissions of mercury in various industrial sectors, such as cement production and metal manufacturing by the year 2020 could be 2- to 3-fold higher if nothing is done to improve emission control.

Under the EXEC scenario, clear decreases in mercury emissions between 2005 and 2020 are projected for all continents. As might be expected, the largest emissions of mercury in 2020 are estimated for Asia. The 2005 emissions in China of almost 635 tonnes are projected to decrease in 2020 to between 380 tonnes (under the EXEC scenario) and 290 tonnes (under the MFTR scenario). This corresponds to a reduction in Chinese emissions of between 40 and 55%. This decrease assumes that by 2020, all Chinese power plants will be equipped with improved emission control installations. These projections also assume that consumption of coal will increase in China between 2005 and 2020 by a factor of 2 and industrial production by a factor of 1.5. It should be recognized that the projections described for China are based on rigorous implementation of emission reduction measures, particularly those concerning major improvement in the efficiency of installed emission controls. If the improvement is for example 50% lower than assumed under the scenarios, Chinese emissions will increase rather than decrease by 2020 (i.e., reductions due to controls would not compensate for the projected increase in emissions due to economic development). A more detailed pre-feasibility study
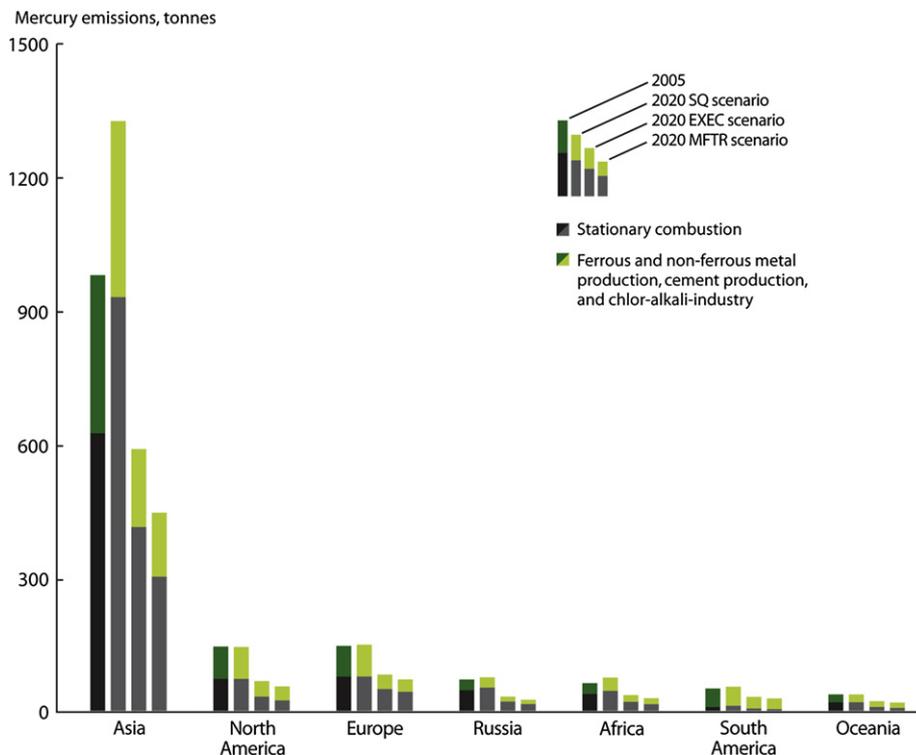

Fig. 7. Comparison of anthropogenic emissions (in tonnes per year) of mercury from the 'by-product' plus chlor-alkali sectors in 2005 and under the 2020 SQ, EXEC and MFTR scenarios (AMAP/UNEP, 2008).

would need to be carried out, however, on the potential for the improvement of efficiency of control equipment and its utilization in power stations and industrial plants in China and other countries, also addressing economic aspects, in order to define more accurately conclusions and eventual recommendations on how the potential improvement described above might be achieved.

For India, similar assumptions as those applied to China were made when scaling emission factors on the basis of projections for improvement of efficiency of emission control installations in Indian power stations and industrial plants by 2020.

The projected decreases in mercury emissions in Europe, North America, Australia, Japan and Russia are between 40 and 60%.

5.2. Emission scenario estimates for intentional use of mercury

Scenarios for future intentional use of mercury are highly uncertain due to the lack of consistent international agreements or policies to reduce mercury demand. In many countries and regions, large efforts are nevertheless being made to reduce mercury use in products and in industrial applications. The potential for reduction of use is also large since technologically and economically feasible alternatives are often available.

In AMAP/UNEP (2008), two future scenarios for mercury consumption in different categories were defined. The scenarios were based on a partly qualitative discussion of reduction potentials and ongoing activities to reduce demand. To take into account the unavoidable uncertainties, two different scenarios were considered: a 'Status Quo scenario' and EXEC ('Focused mercury reduction') scenario. For the Status Quo scenario, data on use and emissions presented by Pirrone and Mason (2008) were used. In addition, an MFTR scenario was developed, based on an overall assumption of 50% reduction of mercury use in comparison to the EXEC scenario. For ASGM, no change in consumption is assumed beyond that envisaged in the EXEC scenario. This assumption reflects the expected difficulties in managing this largely unregulated sector. Table 9 presents projected future trends for emissions from intentional use of mercury.

It should be noted that the scenarios presented above are hypothetical and the future trends in mercury consumption are highly dependent on the development of legislation or voluntary agreements to reduce mercury usage. The reduction potential is large, perhaps even larger than that reflected in the MFTR scenario in some cases, but actual compliance is difficult to estimate.

6. Concluding remarks

Global atmospheric emissions of mercury from human activities in 2005 were estimated to be approximately 1930 tonnes. Burning

Table 9
Emissions of mercury from intentional use in three 2020 emission scenarios.[a]

	SQ 2020	EXEC 2020	MFTR 2020
ASGM	330	164	164
VCM	N.A.	N.A.	N.A.
Batt	20	5	3
Dent	25	16	11
Meas	33	9	5
Lamp	13	9	5
Elec	26	11	6
Other	29	3	1
Sum	475	218	195

N.A. = not available.
[a] Emissions from mercury use in the chlor-alkali industry were considered under the by-product emission scenarios, where a complete phase-out of mercury use in this sector by 2010 is assumed.

of fossil fuels (primarily coal) is the largest single source of emissions from human sources, accounting for about 45% of the total anthropogenic emissions. Artisanal/small-scale gold mining was responsible for about 18%, with industrial gold production accounting for an additional 5–6% of global emissions from human activities. Other mining and metal production activities are responsible for about 10% of global anthropogenic releases to the atmosphere. Cement production releases a similar amount. Emissions from waste incineration and product-use sources are more difficult to estimate. These emissions could be considerably higher than the generally conservative estimates of 150 tonnes included in the 1930 tonnes global estimate.

Power plants are the largest single source in most countries with high mercury emissions, although in Brazil, Indonesia, Columbia, and some other countries (in South America, Asia and Africa in particular) artisanal/small-scale gold mining is the largest single source.

Geographically, about two-thirds of global anthropogenic releases of mercury to the atmosphere appear to come from Asian sources, with China as the largest contributor worldwide. The United States of America and India are the second and third largest emitters, but their combined total emissions are only about one-third of China's.

The uncertainties associated with estimates of mercury emissions are largely related to the application of various assumptions that are required to make up for a lack of actual measurement data. The figures for anthropogenic emissions are based on governmental emission data where available, combined with estimates for countries that did not provide such data. Some countries that are major mercury emitters did not provide national emissions reports. Other countries, such as South Africa and Japan, provided updated information and more accurate emissions estimates than were available in the past. Measurements made at major point sources such as power plants are few, but where available they were used as the basis for some emission estimates. The reliability of industrial activity statistics and other statistics used for the purposes of estimating emissions, and the accuracy of various assumptions about specific practices and technologies as they relate to mercury emissions are additional sources of uncertainty. Despite the uncertainties involved, the 2005 emissions inventory and its underlying data are considered to represent a robust inventory of contemporary global anthropogenic emissions of mercury to air, provide a picture of regional and national patterns and give insight into global trends.

Scenarios of future emissions have been prepared to help explore the prospects for reducing mercury emissions and the implications of not taking any action in this regard. These scenarios suggest that, if current trends in industrial development and resource use were to continue, mercury emissions in key selected sectors (those where mercury is an incidental pollutant and also the chlor-alkali industry) are likely to rise. However, if emission controls currently in place or planned in Europe were to be extended worldwide, considerable reductions in mercury emissions from these sectors in 2020 are projected. Under a scenario of maximum technologically feasible reduction measures, emissions from by-product sectors in 2020 are projected to further decline.

With the decision by UNEP to develop a global legally-binding instrument on mercury by 2013, work to improve emissions inventories and further develop scenario inventories is likely to receive much attention in the coming years. The information presented in this paper provides a contribution to this process, and one that can certainly be further developed if there is a demand for this.

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