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REVIEW

Mercury emissions in China: a general review

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Abstract
This paper provides a general review of the research status of mercury emissions in China. Global surveys rank Asia as the region with the largest share of global mercury emissions, accounting for almost half. China contributes about one-third of the world's mercury emissions, which is 600–800 t per year. And thus, it plays a vital role in reducing global mercury emissions. Data since 2003 has been surveyed. Mercury emissions in China have risen in the beginning and then declined. There are differences in the composition of mercury emissions sources between China and the world, in which coal combustion and non-ferrous metals smelting contribute more than 50% of the emissions in China. Although mercury emission standards in China are close to those of the European Union and the United States, annual mercury emissions in China are four times higher than those of the United States. Mercury emissions in China are concentrated in the central and eastern regions now, but the annual mercury emissions are increasing in the western regions, which may be related to the construction of industrial parks.

Keywords Mercury emissions inventory · Mercury distribution · Emission standard · Mercury emission trend

Introduction

Mercury, the only heavy metal pollutant in the atmosphere that exists mainly in gaseous form, has been widely studied, as it can survive and travel long distances in the atmosphere [1, 2] and has bioaccumulation effects [3]. Different from other heavy metal pollutants that are bound to particulate matter, mercury exists in the atmosphere in three forms [4]: gaseous elemental mercury, gaseous oxidized mercury, and particulate-bound mercury. Gaseous elemental mercury emissions account for more than 60% of total mercury emissions. The shelf life of this form of emissions is 0.5–2 years, enabling it to spread globally [5–7]. Mercury is converted to methyl mercury in aquatic ecosystems, which is neurotoxic, causing damage to human health and organisms [8].

Various sources contribute to mercury emissions [9, 10]. Due to the different ratio of different pollution sources to total emissions differs, the required measures to deal with the pollution also differ [11–13]. For this reason, a mercury emissions inventory is required to show the status of mercury emissions [6, 14]. This inventory has been undertaken by the United Nations Environment Programme (UN Environment) every 5 years since 2002. Recent report suggests that in 2015 [15], the total global mercury emissions to air from anthropogenic sources amounted to 2220 t, and were approximately 20% higher than the updated estimates for 2010 only 5 years earlier. Stationary combustion of fossil fuels and biomass is responsible for about 24% of the estimated global emissions, primarily from burning coal (21%).

In 2013, the Minamata Convention on Mercury was signed by 128 countries, including China [16]. Even though China is the country with the highest mercury emissions in the world [17, 18], its inventory statistics for mercury emissions have been studied only in the past decade. In this time, attention has turned to clarifying the source types and assessment of total mercury emissions, as well as the options for reduction of mercury emissions [19]. Since there are no official data on mercury emissions in China, the estimates from different scholars differ [8, 9, 17, 20].

The purpose of this study is to analyze the trend of mercury emissions in China by comparing the statistics of different research. Assessment data comprise either those for East Asia or those for China, depending on the global mercury emission inventory used.

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Mercury emissions in China

The results are presented in three sections to provide insight into the status of mercury emission in China in recent years: mercury trends in China, mercury source composition, and mercury distribution. Because the relevant data come from Chinese domestic statistics as well as global statistics, selective aggregation is necessary to guarantee the objectivity and accuracy of the analysis [21]. Previous studies have tended to calculate mercury emissions in China based on each author's own theory [4, 14, 17, 18]. Here, we discuss the general pollution status and emission trends. This section discusses, in order, status and trends, source composition, and distribution in mercury emissions in China.

Mercury emissions status and trends in China

Pacyna et al. [22] provided the first systematic statistics on mercury emissions via a global mercury emissions inventory in 1995. Although some of the data are incomplete, the statistical methods and results have certain reference value. Generally, two approaches [23] are used to calculate mercury emissions: estimation by national emission experts, and calculation based on emission factors. In Pacyna's research, about 1900 t of mercury was emitted in total, of which China accounted for about 500 t in 1995.

Since 2002, a global mercury assessment [15] has been undertaken by UN Environment every 5 years, including data for China. The assessment shows that of global mercury emissions in 2010 of 1960 t, China accounted for about one-third, 650 t. In 2015, total mercury emissions increased to about 2220 t, of which China accounted for about 720 t.

In China, relevant research has also been undertaken. Wang et al. [24] calculated China's total mercury emissions in 2003 as 650 t. Cheng et al.'s [25] study of major heavy metal emissions in China concluded that mercury emissions were 842.22 t in 2010. Tian et al. [26] calculated an inventory of heavy metal emissions in China, placing mercury emissions in China at about 685.1 t in 2015. Data from the abovementioned literature are plotted in Fig. 1.

The average annual growth rate of mercury pollution from 1995 to 2005 is 5.14%. In this decade, mercury emissions rose from 500 to 825 t owing to rapid economic development and extensive environmental governance. During this period, artisanal and small-scale gold mining (ASGM) accounted for a large proportion of mercury emissions. Due to the adjustment of industrial structure, the strengthening of environmental governance, and the upgrading of production technology, mercury emissions

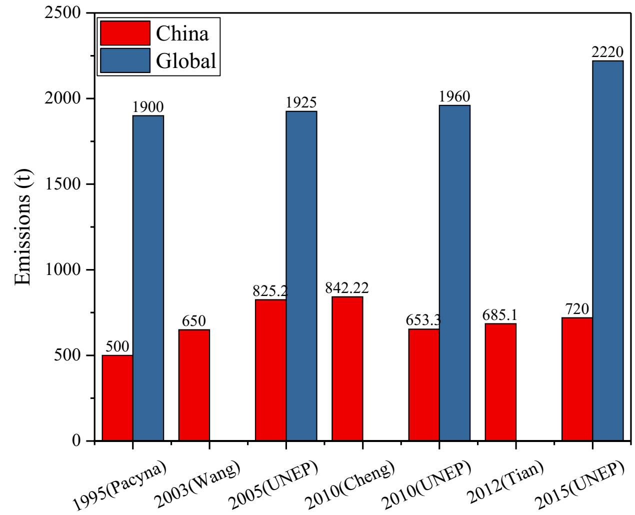


Fig. 1 Mercury emissions of China and the world

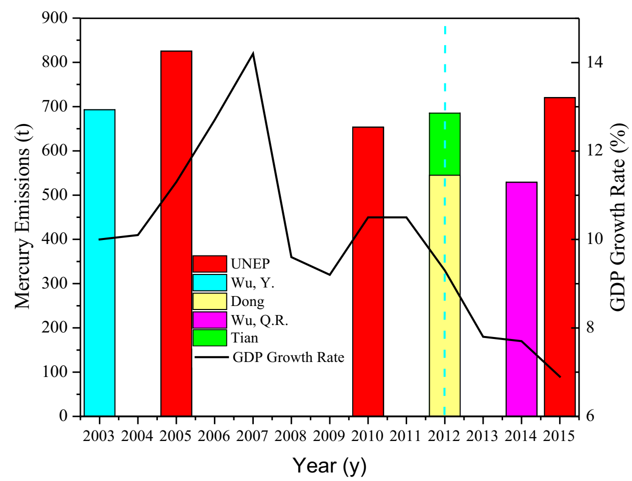


Fig. 2 Comparison of annual mercury emissions and GDP growth rate in China

were effectively controlled from 2005 to 2010. It is noteworthy that in 2010, Cheng's statistics for mercury emissions in China were on the high side compared to other works. Possible reasons are the higher estimates for primary mercury ore mining and the higher mercury content of Chinese coal and MSW. Although many emissions reduction measures were implemented continuously, mercury emissions in China slowly increased at an average annual growth rate of 1.96% from 2010 to 2015 [27]. In addition, it is important to note that China's share of global mercury emissions dropped from 42.8% in 2005 to 32.4% in 2015, which shows China's efforts in reducing emissions in recent years.

Depending on the specific mathematical model, the relationship between raw materials or products and mercury emissions can vary. In this way, the mercury emissions data over the years was tracked with GDP growth rates, as shown in Fig. 2.

Despite the lack of some data, mercury emissions are found to increase year by year before 2008, which is line with the trend of the GDP growth rate. In 2008, economic growth slowed due to the financial crisis, and mercury emissions also fell. In 2012, stricter emission standards for thermal power plants were issued, and more environmentally friendly technologies adopted, which is reflected in emissions reductions. Mercury emissions are also affected by volume of industry output and raw material consumption, which may be why mercury emissions have continued to rise in recent years even with more advanced technologies. It must be noted that the conclusions are highly uncertain owing to incomplete data and lack of official statistics.

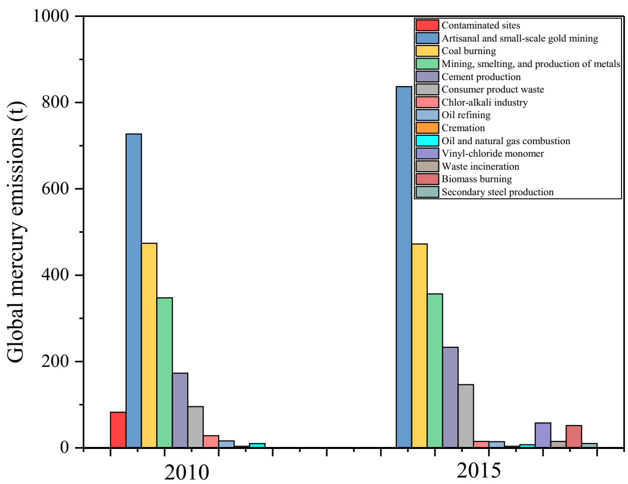


Fig. 3 Global mercury emissions statistics 2010 and 2015 from UNEP [2]

Source composition of mercury emissions in China

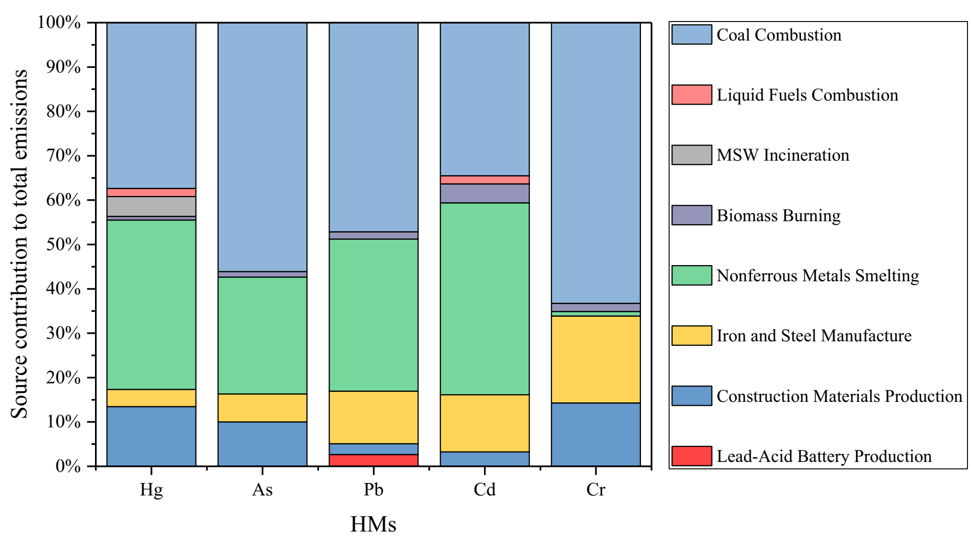
Atmospheric mercury pollution consists of many different anthropogenic sources. Figure 3 shows the sources of mercury emissions in global mercury emissions.

A breakdown of anthropogenic mercury emissions by industry is included in the 2015 UNEP global mercury assessment. The largest sources are artisanal and small-scale gold mining; coal burning [4, 27, 28]; mining, smelting, and production of metals [29]; and cement production. Moreover, mercury emissions from mercury-containing waste account for 5%, some of which flows into municipal solid waste streams and is discharged into the atmosphere by incineration [30].

The sources of mercury emissions inventory in China differ. The small-scale gold mining (ASGM) is illegal in China. Based on the estimation of the China Gold Association, mercury emissions from these illegal activities accounted for only 1%–3% of total mercury emissions in China in 2010 owing to an explicit order prohibiting the practice. In addition to its small contribution, owing to the uncertainty of its estimation, the small-scale gold mining (ASGM) is generally ignored in mercury emissions inventories in China. Because coal is the main fossil energy in China, the atmospheric mercury pollution caused by coal combustion accounts for a higher proportion. China's heavy metal emissions inventory is shown in Fig. 4.

Non-ferrous metals smelting, coal combustion, and construction materials production (including cement production) account for the largest proportion of mercury emissions by industry. It is noteworthy that other emissions, like vinyl-chloride monomer production [31], are not included in the calculation. Furthermore, with the improvement of metallurgical technology, mercury pollution caused by metallurgical technology needs to be re-evaluated.

Fig. 4 Emissions investigation of Hg, As, Pb, Cd, and Cr by source categories, China 2010 [25]



Based on data from UN Environment's global mercury assessment [15], we compare emissions from China, United States (US), and the European Union (EU), as shown in Fig. 5.

It should be noted that in the 2005 assessment, the emissions data of China, the US, and the EU are provided directly, while the data for 2010 and in 2015 are counted based on regional statistics, as reflected in Fig. 2. Thus, in 2010 and 2015, the actual emissions of China and the US are lower than those shown in Fig. 2. Moreover, the ASGM emissions data shown in the figures are calculated for the region of East and Southeast Asia [32, 33]. The proportion for China requires further analysis.

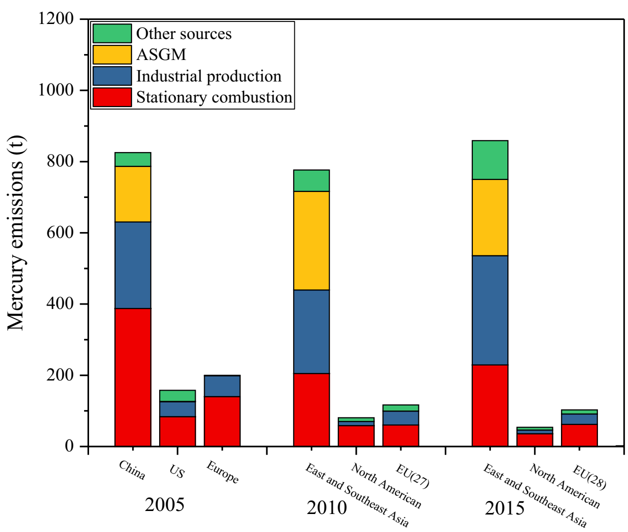


Fig. 5 Contrast of emission between China, US, and the EU [2, 6, 7]

However, in general, some useful information can be obtained from Fig. 5. The proportion of mercury pollution caused by stationary combustion in China has been significantly reduced, indicating that efforts to improve environmental regulation of stationary combustion have been successful. Emissions from industrial production and other sources, including mercury-containing by-products, are increasing. This indicates that industrial mercury removal may need more attention in the future. In terms of total mercury emissions, emissions in China far exceed those of the US and the EU, which requires more advanced control technology and stricter emissions standards.

Mercury geographic distribution in China

The emissions calculated in this work are shown in Fig. 6, with sub-regional spatial distributions from Wu et al. [12]. Figure 6a shows that mercury emissions in China in 2014 are mainly concentrated in Henan, Hebei, and Shandong, among other places, while the overall level of mercury emissions in the northern and western regions is relatively high. The changes in mercury emissions in different regions of China from 2003 to 2014 are shown in Fig. 6b. Variations in mercury emissions during this period are represented by corresponding colors. It can be seen that emissions in the western and eastern regions have increased significantly, while those in the northern regions have decreased accordingly [34]. This result shows that researchers should pay more attention to mercury-polluting industries in the western region.

These distribution data are calculated or estimated. Compared with other developed countries, China has only a few mercury detection points [35, 36], and it is impossible to obtain mercury emissions through measured data. Horowitz et al. [37] compared the monitored values of mercury

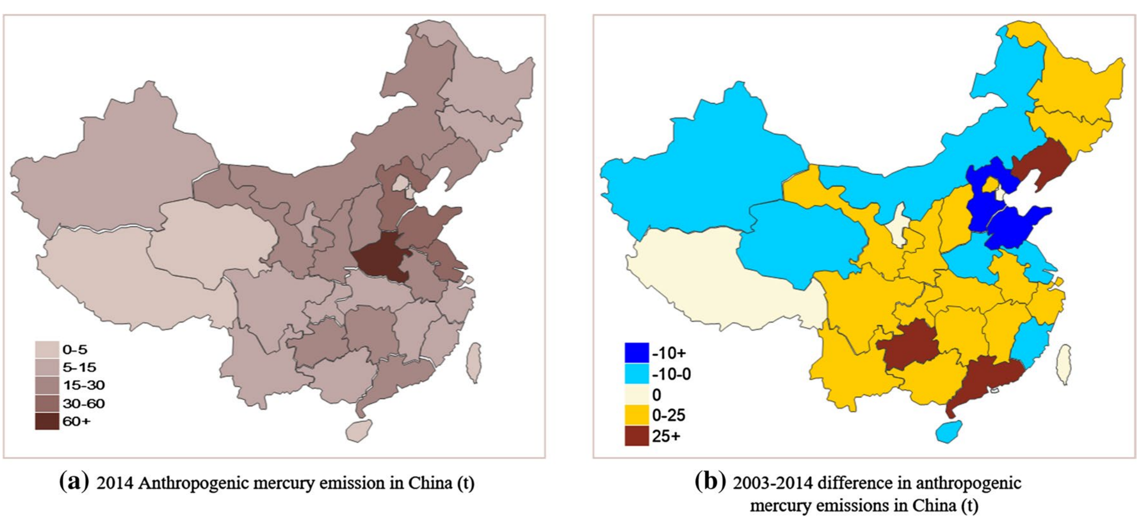


Fig. 6 Distribution of anthropogenic mercury emissions in China and the differences

emissions in North America, Europe, and China, as shown in Fig. 7.

From 2007 to 2013, observations are obtained from the Mercury Deposition Network (National Atmospheric Deposition Program, http://nadp.sws.uiuc.edu/mdn/) for North America (58 sites) [38], the European Monitoring and Evaluation Programme for Europe (20 sites), and data from Fu et al. [4, 39, 40] for China (9 sites).

Due to precipitation changes and sedimentation, the maximum mercury emissions in North America occur on the northwest coast, while the higher monitoring values along the Gulf of Mexico coast may be affected by deep convection scavenging upper-tropospheric air enriched in Hg^{2+} [41, 42]. The background concentration of mercury emissions in Europe is very low and uniformly distributed, and there is no obvious source of mercury emissions. This indicates that anthropogenic mercury emissions in Europe are well controlled. Meanwhile, the overall level of mercury monitoring in China is relatively high, and the distribution of mercury is uneven between urban and rural areas [43]. However, this result may be inaccurate owing to China's relatively fewer measuring points.

Conclusions

Because mercury pollution is a global problem, China, as the country with the largest anthropogenic source of mercury emissions in the world, has attracted wide attention. Specifically, it is necessary to define mercury emissions characteristics and regulations in China. This study collates the literature and provides an analysis of mercury emissions in China. Annual atmospheric mercury emissions in China are estimated to be 600–800 t over the past decade in related research and reports, which is in line with the calculated values but lower than the published values estimated by some surveys.

Unlike the long-term emission trends in EU and the US, the calculated results show that anthropogenic mercury emissions in China have increased slowly in recent years. Even though China has made considerable efforts to improve mercury emission technology and regulations, the reduction of mercury emissions has been offset to some extent by the use of coal combustion as the main energy source and the increase in mercury-polluting industrial capacity. This result shows that China makes a decisive impact on world mercury emissions. Because mercury emissions are affected by economic factors, future emission trends can be predicted from some data. In addition, policy, technology, and other factors should be considered comprehensively alongside emissions data.

It should be noted that although the UNEP report considers ASGM to account for a large proportion of total mercury emissions, this industry is seldom mentioned in domestic surveys in China. The Chinese industries with the largest mercury emissions are coal combustion, metal smelting, and cement production. Some mercury-polluting and waste incineration industries also need attention. Mercury emissions from all provinces over the years show that the emissions are concentrated in eastern China. Furthermore, the trend of increasing mercury emissions in south and southeast China shows that emission sources are moving westward gradually, which has important significance for guiding industrial structure and policy formulation.

Mercury concentration in rural areas of China is lower than that in the US, but the average mercury concentration is higher, which indicates that further studies are needed to understand the transmission and deposition of mercury in China, as well as to predict the impact of changes in mercury emissions in China on global mercury pollution.

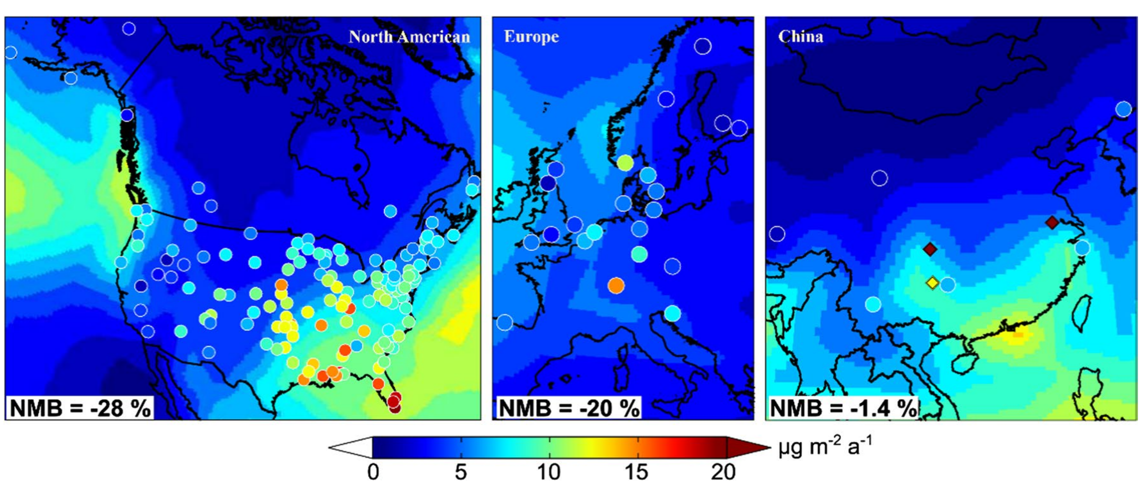


Fig. 7 Annual Hg wet deposition fluxes over North America, Europe, and China

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