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High-resolution mapping of premature mortality induced by atmospheric particulate matter in China

Sheng Zheng^{1,2,5}  · Xue Wu¹ · Eric Lichtfouse^{3,4} · Jing Wang^{5,6}

Abstract

Air pollution, measured by the concentration of airborne particulate matter with diameter below 2.5 μm ($\text{PM}_{2.5}$), is known to cause globally adverse health effects leading to premature mortality, yet high-resolution spatial distribution of premature deaths is lacking due to the absence of detailed data for the calculation of premature mortality. Here, we mapped the impact of $\text{PM}_{2.5}$ on premature mortality at high resolution in 2018 using the global exposure mortality model, then we carried out statistical analysis in provincial-level administrative divisions. Results show that the $\text{PM}_{2.5}$ threshold of 35 $\mu\text{g}/\text{m}^3$ is exceeded in the Xinjiang Uygur Autonomous Region, and in mideastern, highly urbanized and industrial regions of Tianjin, Hebei, Shandong, Henan, Jiangsu, Hubei, Anhui, and Shanghai. Premature deaths due to $\text{PM}_{2.5}$ exposure in China amounted to 1.44 million, including 510,847 from ischemic heart disease, 471,487 from cerebrovascular disease, 220,837 from chronic obstructive pulmonary disease, 131,321 from lung cancer, and 103,658 from lower respiratory infection. Premature mortality was higher in men, of 879,521 persons accounting for 61%, than women, of 558,629 persons. In provincial-level administrative divisions, high premature deaths were mainly concentrated in the North China Plain, with the highest per capita premature mortality in the Xinjiang Uygur Autonomous Region, Henan, Hebei, and Shandong. Our finer resolution data, together with the age- and sex-specific population data, have improved the estimation of health impacts of $\text{PM}_{2.5}$ exposure.

Keywords Premature mortality · $\text{PM}_{2.5}$ · Age- and sex-specific population data · Spatial distribution

Introduction

Coal power plants are common in Asian countries such as China and India (Prasad et al. 2006; 2012). The emissions from these power plants are one of causes of poor air quality and atmospheric pollution, which have adverse impacts on health, radiative forcing, and climate change (Gao et al. 2018). In the last decade, airborne particulate matter with diameter below 2.5 μm ($\text{PM}_{2.5}$) has consistently been considered as the major air pollutant in China (Cheng et al. 2017). $\text{PM}_{2.5}$ pollution has been closely linked to premature mortality due to ischemic heart disease, chronic obstructive pulmonary disease, lung cancer, cerebrovascular disease, and lower respiratory infection (Burnett et al. 2014; 2018). About 6.67 million people died prematurely due to air pollution globally in 2019, of which about 1.4 million deaths were caused by $\text{PM}_{2.5}$ pollution in China (GBD 2019 Risk Factors Collaborators 2020).

The premature mortality caused by $\text{PM}_{2.5}$ pollution is typically assessed based on different exposure-response functions such as linear and log-linear models (Cohen

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et al. 2004), integrated exposure–response (IER, Burnett et al. 2014; Li et al. 2020), and the global exposure mortality model (GEMM, Burnett et al. 2018; Tarín-Carrasco et al. 2021). According to the integrated exposure–response model, the PM_{2.5} exposure-induced premature deaths in China increased from 1.26 million in 2010 to 2.19 million in 2013, decreased to 1.94 million in 2014, 1.65 million in 2015, 0.96 million in 2016, then slightly increased to 1.05 million in 2017 (Xie et al. 2016; Li et al. 2018; Maji et al. 2018; Zou et al. 2019). Later studies showed that the GEMM model, proposed by Burnett et al. (2018), gives better estimates because this model considers a large range of PM_{2.5} concentrations, up to 84 µg/m³, and is thus particularly adapted for exposure–response investigations in high PM_{2.5} pollution areas (Bayat et al. 2019; Lelieveld et al. 2020). Indeed, an epidemiological study of PM_{2.5} in China showed better estimates with the GEMM model rather than the integrated exposure–response model (Xue et al. 2019).

The estimation of PM_{2.5}-induced premature mortality depends on exposure–response functions and data sources such as PM_{2.5}, population, and baseline mortality rate. In particular, estimates may vary widely depending on the spatial resolution of the data, notably in urban and suburban areas where population is not evenly distributed. A previous study in China reported PM_{2.5} with a rather coarse spatial resolution of 10 km, and population data lacked the use of raster data and were not gender-specified (Li et al. 2019). Previous investigations of health effects in China are mainly based on statistical studies of whole regions, and lack high spatial resolution of the data (Wang et al. 2018; Chowdhury et al. 2020; Zheng et al. 2021). It has been shown that the coarse-level mortality statistics would bias the results while the finer resolution of the data opens up the possibility to improve the estimation of PM_{2.5}-induced health impacts (Goto et al. 2016; Liu et al. 2019). Therefore, we studied the spatial distribution of the premature mortality attributable to PM_{2.5} pollution using the GEMM model with high-resolution gridded PM_{2.5}, population data, and provincial baseline mortality rates.

Experimental

Data sources

Gridded population in 2018 is from WorldPop (www.worldpop.org), with a spatial resolution of 30 arc seconds: 0.00833°, nearly 1 km at the equator. Demographic data from WorldPop were generated by combining high-resolution satellite remote sensing imagery and census data, and grouped by sex (male, female) and age, including 0–1 and by 5-year up to 80+. The mapping strategy was sourced from Pezzulo et al. (2017).

Concentrations of surface airborne particulate matter with diameter below 2.5 µm (PM_{2.5}) concentrations in China were from the Atmospheric Composition Analysis Group with a spatial resolution of 0.01° × 0.01° (<https://sites.wustl.edu/acag/datasets/surface-pm2-5/#V4.CH.03>; van Donkelaar et al. 2019; Hammer et al. 2020). The dataset contains ground-based observations of total PM_{2.5} concentrations from a network of observatories in China in 2018 and provides combined geophysical–statistical estimates of PM_{2.5} concentrations for the national region (Hammer et al. 2020; van Donkelaar et al. 2019).

The baseline mortality rates (BMR) due to five diseases associated with PM_{2.5} exposure are from Zhou et al. (2016), a dataset that included the number of premature deaths for leading causes in provincial-level administrative divisions (PLADs) in China. The baseline mortality rates for the Taiwan Province were obtained from the Global Burden of Disease (GBD)’s age-standardized data (<http://ghdx.healthdata.org/gbd-results-tool>).

Global exposure mortality model

The global exposure mortality model (GEMM) was applied to estimate age-related hazard ratios for the five diseases in adults (> 25 years) and lower respiratory infection (LRI) in children under 5 years of age. GEMM revealed the exposure–mortality association and used a large range of concentration intervals (2.4–84.0 µg/m³) (Burnett et al. 2018). The hazard ratio (HR) has been calculated using:

$$HR = \exp \{ \beta \log (z/\alpha + 1) / (1 + \exp \{ -(z - \mu)/\nu \}) \} \quad (1)$$

where HR is the hazard ratio of premature mortality attributable to PM_{2.5} pollution; β is the exposure–response model coefficient; z is max (0, PM_{2.5}–2.4 µg/m³), 2.4 µg/m³ represents the theoretical lowest exposure concentration; and the set of parameters (α, μ, ν) controls the curve form of the mortality–PM_{2.5} relationship (Burnett et al. 2018).

Estimation of premature mortality

The formula for calculating the PM_{2.5}-attributable premature mortality is:

$$\Delta \text{Mort} = B \times P \times \left(\frac{HR - 1}{HR} \right) \quad (2)$$

where ΔMort is the PM_{2.5} exposure-induced premature mortality; B is the baseline mortality rates of five specific diseases related to PM_{2.5}, including ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), lung cancer (LC), cerebrovascular disease (CEV), and lower respiratory infection (LRI); P refers to the exposed population; and HR is the estimated hazard ratios of the five diseases

using Eq. 1. Baseline mortality rates at the provincial level in 2013 are from Zhou et al. (2016). We established estimates according to the hypothesis of unchanged baseline mortality between 2013 and 2018.

Guidelines on PM_{2.5} exposure and risk

The WHO air quality guidelines have set four decreasing thresholds of annual average PM_{2.5} concentrations 35 µg/m³ for interim target 1, 25 µg/m³ for interim target 2, 15 µg/m³ for interim target 3, and 10 µg/m³ for interim target 4 (WHO, 2021). Those thresholds are defined as the lowest exposure level of an air pollutant above which adverse health effects would increase. Interim targets refer to incremental steps in reducing air pollution for a specific decrease in health risk. The Chinese guidelines, named ambient air quality standards (AAQS) (MEP, 2012) set the grade I threshold at 15 µg/m³ and the grade II threshold at 35 µg/m³.

Results and discussion

Spatial distribution of airborne particulate matter

Figure 1 shows the spatial distribution of airborne particulate matter with diameter below 2.5 µm (PM_{2.5}) concentration in 2018 at the provincial level in China. Areas that exceed the standard of 35 µg/m³ are mainly concentrated in

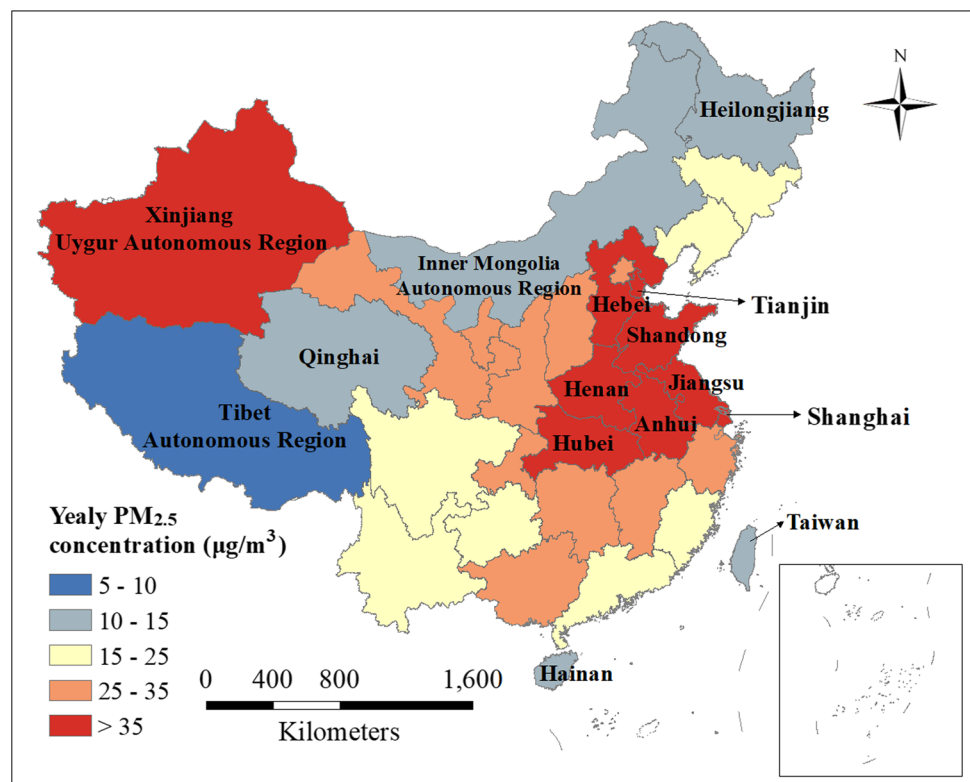
the Xinjiang Uygur Autonomous Region, named 'Xinjiang' for short in the text below, and mideastern areas of Tianjin, Hebei, Shandong, Henan, Jiangsu, Hubei, Anhui, and Shanghai. The main sources of PM_{2.5} pollution in the Tianjin-Hebei region, the Yangtze River Delta, and the Shandong Peninsula are traffic emissions, industrial emissions, and construction dust (Shan et al. 2020; Chen et al. 2019).

The highest PM_{2.5} concentration were found in Henan, of 51.3 µg/m³, and Tianjin, of 48.3 µg/m³. Beijing, Hunan, and Shanxi also had high PM_{2.5} concentrations. The less polluted region is the Tibet Autonomous Region with 5.3 µg/m³, which is below the fourth WHO target threshold of 10 µg/m³. Other less polluted provincial-level administrative divisions include Taiwan, of 11.6 µg/m³, Qinghai, of 12.3 µg/m³, Heilongjiang, of 14.2 µg/m³, Hainan, of 14.2 µg/m³, and Inner Mongolia Autonomous Region, of 15.0 µg/m³. These regions are mainly located at borders or in sparsely populated areas. These findings are in agreement with previous reports (Wang et al. 2018; Huang et al. 2018). Overall, we found the highest PM_{2.5} pollution in the Xinjiang and mideastern areas, and the lowest in less-populated Tibet Autonomous Region.

Premature mortality induced by airborne particulate matter

At the country level, our calculations indicate that the mean total premature mortality caused by PM_{2.5} pollution in China

Fig. 1 Annual average of pollution by airborne particulate matter with diameter below 2.5 µm (PM_{2.5}) in China in 2018. The highest pollution levels are observed for the Xinjiang Uygur Autonomous Region and mideastern provincial-level administrative divisions



in 2018 was 1.44 million, ranging from 0.96 to 1.83 million with 95% confidence. The $PM_{2.5}$ exposure-induced premature deaths were:

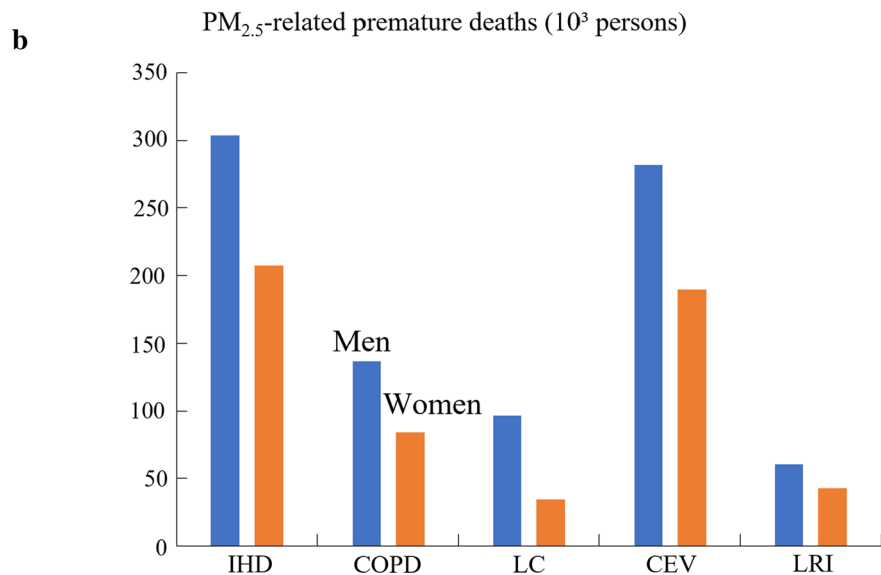
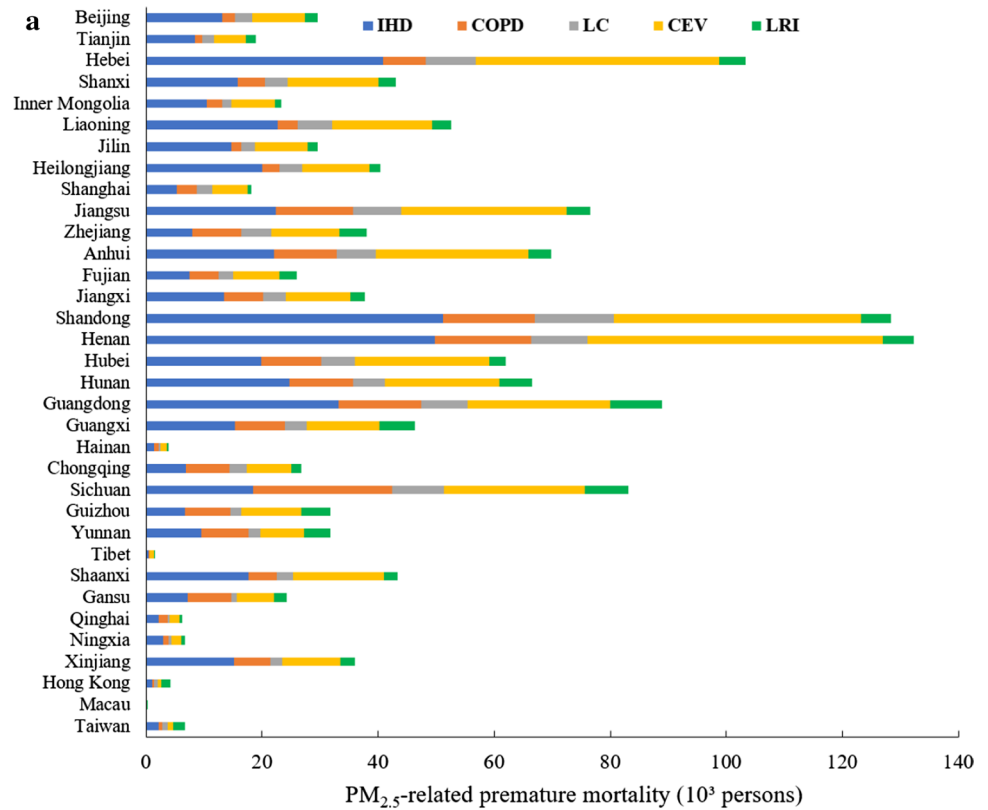
- 510,847 (465,290–553,327) for ischemic heart diseases
- 471,487 (233,441–662,819) for cerebrovascular diseases
- 220,837 (114,070–309,452) for chronic obstructive pulmonary diseases
- 131,321 (84,158–171,076) for lung cancers

- 103,658 (60,588–133,134) for lower respiratory infections

Ischemic heart and cerebrovascular diseases thus accounted for 68.3% of $PM_{2.5}$ pollution deaths.

The distribution of the causes of premature mortality is given in Fig. 2a for the 34 Chinese provincial-level administrative divisions. Ischemic heart diseases and lung cancers were the highest causes in the Shandong province reaching

Fig. 2 a Disease-specific premature mortality caused by pollution by airborne particulate matter with diameter below $2.5 \mu m$ ($PM_{2.5}$) in the 34 provincial-level administrative divisions in China in 2018. **b** Gender impact of premature mortality. The blue bars represent men and the orange bars represent women. IHD: ischemic heart disease, COPD: chronic obstructive pulmonary disease, LC: lung cancer, CEV: cerebrovascular disease, LRI: lower respiratory infection. $PM_{2.5}$: airborne particulate matter with diameter below $2.5 \mu m$



51,194 and 13,596 deaths, respectively. Henan showed the highest cerebrovascular diseases premature mortality of 50,918. Premature mortality from chronic obstructive pulmonary diseases and lower respiratory infections peaked at 23,991 in Sichuan and 8858 in Guangdong, respectively. This is because among the 34 provincial-level administrative divisions:

- Guangdong, Shandong, and Henan provinces had the top three highest population
- Henan and Shandong provinces had the top four highest PM_{2.5} concentration
- Shandong had the eighth highest baseline mortality rate for ischemic heart disease in men, twelfth highest baseline mortality rate for ischemic heart disease in women, third highest baseline mortality rate for lung cancer in men, and seventh highest baseline mortality rate for lung cancer in women
- Henan had the eighth highest baseline mortality rate for cerebrovascular disease in men, and second highest baseline mortality rate for cerebrovascular disease in women
- Sichuan had the fourth highest baseline mortality rate for chronic obstructive pulmonary disease in men, and fourth highest baseline mortality rate for chronic obstructive pulmonary disease in women
- Guangdong had the thirteenth highest baseline mortality rate for lower respiratory infection in men, and fourteenth highest baseline mortality rate for lower respiratory infection in women

In terms of gender, premature mortality for all diseases was higher in men (879,521) than women (558,629), especially for lung cancers, where the premature mortality in men was about 2.8 times that in women (Fig. 2b). The PM_{2.5} exposure-induced premature deaths in terms of gender were:

- 303,461 in men and 207,386 in women for ischemic heart diseases
- 281,953 in men and 189,534 in women for cerebrovascular diseases
- 136,924 in men and 83,913 in women for chronic obstructive pulmonary diseases
- 96,576 in men and 34,745 in women for lung cancers
- 60,606 in men and 43,052 in women for lower respiratory infections

We compared our results of premature mortality caused by PM_{2.5} pollution, of 1.44 million, with previous reports (Table S1). Previous studies found premature mortality caused by PM_{2.5} pollution ranging from 0.91 million to 1.83 million. Our result of 1.44 million is very close to the data of 1.43 million by Maji et al. (2020), which is based on the city-level populations and PM_{2.5} concentrations. Our result is also

very close to the data of 1.42 million by Giani et al. (2020), despite the fact that these authors did not take the deaths from lower respiratory infection into account. Their data had a 8 km resolution for PM_{2.5} concentration, which is a coarser resolution than our resolution, of 0.01° (nearly 1 km). The lowest estimates of 0.91 million by Maji et al. (2020) are explained because the integrated exposure–response calculations involve a much lower risk ratio (Burnett et al. 2018). The highest estimates of 1.83 million by Ma et al. (2021) are mainly attributed to different data sources for population and baseline mortality rates. We used the same spatial resolution of 1 km for PM_{2.5} concentration as Ma et al. (2021). Nonetheless, they used all-age population density data, whereas we used different age ranges. Overall, if we take into account the differences in calculations and data, and the elevated confidence intervals, our results are in agreement with previous work, and show a rather elevated number of premature deaths caused by PM_{2.5} pollution.

Spatial distribution of premature mortality

The map of grid-level premature deaths at 1 km resolution shows that the highest mortalities are located in eastern areas, mainly in the urbanized agglomerations downstream of the Yellow River, the eastern part of the Sichuan-Chongqing region, middle reach of the Yangtze River, the eastern coastal region, the central part of Shaanxi and Shanxi, and the western coastal region of Taiwan (Fig. 3a). In terms of specific raster values, the vast majority of grids had less than 5 cases per grid, whereas there were 332 grids (2.41×10^{-5} of all grids) with more than 50 cases, which mainly located in Tianjin, Shaanxi, Liaoning, Guangdong, Henan, Xinjiang (> 20 grids each). Our findings are roughly in accordance with previous studies (Xie et al. 2016; Wang et al. 2018), but the data in this study had finer spatial resolution and were sorted by age groups and gender. The finer spatial resolution could take tiny spatial differences in exposure or mortalities into account and reduce bias in the estimation (Vodonas et al. 2021).

The grid-level map provides a high-resolution distribution of premature deaths based on detailed parameters (Table S1). However, provincial-level administrative divisions are the first-level administrative divisions in China, and air pollution intervention policies in China are based on provincial scales; we have conducted statistical analysis at the provincial scale. The map of premature deaths in provincial-level administrative divisions shows that high premature mortalities are located mainly in the North China Plain, and amount to 132,360 in Henan, 128,461 in Shandong, 103,337 in Hebei, 76,479 in Jiangsu, and 69,874 in Anhui (Fig. 3b). The premature deaths are also high (red legend in Fig. 3b) in Guangdong (88,904) and Sichuan (83,115). The cases in

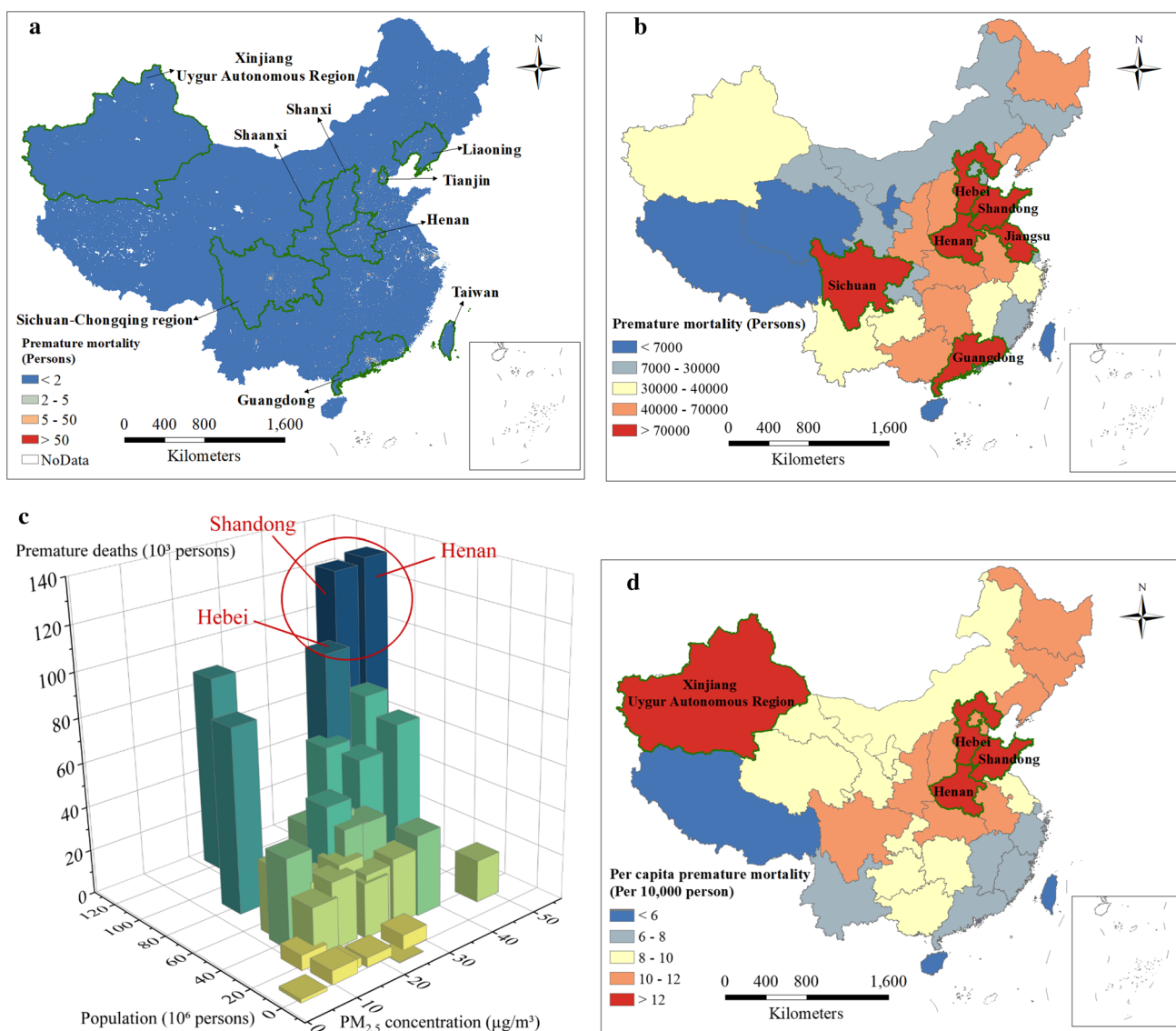


Fig. 3 Spatial distribution of premature mortality in 2018 in China at the grid scale (a) and scale of provincial-level administrative divisions (b). c $PM_{2.5}$ exposure-induced premature mortality by population and $PM_{2.5}$ concentration in 34 provincial-level administrative

divisions. The red circle indicates the regions with high total premature deaths were concentrated in highly polluted and high population regions. d Spatial distribution of per capita premature mortality. $PM_{2.5}$: airborne particulate matter with diameter below $2.5 \mu m$

these provincial-level administrative divisions represent 47% of Chinese cases.

The number of premature deaths roughly increases with population and $PM_{2.5}$ concentrations (Fig. 3c). The top three provincial-level administrative divisions, Henan, Shandong, and Hebei, with the largest number of deaths had annual average $PM_{2.5}$ concentrations over $35 \mu g/m^3$, with Henan and Shandong both exceeding $45 \mu g/m^3$. This spatial characteristic is also reflected in existing air pollution control policies. In October 2021, Ministry of Ecology and Environment of the People's Republic of China issued 2021–2022 Autumn and Winter Action Plan for Air Pollution Management, involving Henan, Shandong, Hebei and surrounding areas.

The large population also accounted for the high premature mortality. For example, yearly $PM_{2.5}$ concentration was relatively low in Guangdong ($23.8 \mu g/m^3$), but was considerable premature mortality (88,904) due to its high population. In comparison, Macau, Tibet Autonomous Region, Hainan, Hong Kong, Qinghai, Ningxia Hui Autonomous Region, and Taiwan, which were mainly concentrated in Western China and Southern China, had fairly low case numbers, below 70,000. In order to quantify the relationship among premature deaths, population, and $PM_{2.5}$ concentrations, we constructed the multiple regression model for the number of premature deaths using population and $PM_{2.5}$ concentrations in 34 provincial-level administrative divisions. The

value of the coefficient of determination (R^2) is 0.892 (p value < 0.001), which means that 89.2% of the number of premature deaths can be attributed to population and $PM_{2.5}$ concentrations. Specifically, population has a more significant effect on the number of deaths than $PM_{2.5}$, with standardized coefficients of 0.824 (p value < 0.001) and 0.221 (p value < 0.01), respectively.

Since population has an impact on the calculation of premature deaths, in order to eliminate the influence of population, the per capita premature mortality in provincial-level administrative divisions was estimated. The per capita premature mortality was a more direct indicator of $PM_{2.5}$ pollution than the total number of deaths, because the correlation between $PM_{2.5}$ concentration and per capita premature mortality was greater than that between $PM_{2.5}$ concentration and the number of deaths, with the spearman's rank correlation coefficient of 0.64 (p value < 0.0001), and 0.51 (p value < 0.01), respectively. The areas with the highest per capita premature mortality included Xinjiang, Henan, Hebei, and Shandong (14.3, 13.7, 13.6, and 12.8 per 10,000 persons, respectively) (Fig. 3d), which was consistent with the distribution of provincial-level administrative divisions with the highest $PM_{2.5}$ concentrations.

Tianjin, Anhui, and Liaoning also had high per capita premature mortality, although they were relatively lower than the above-mentioned areas. In some provincial-level administrative divisions, the per capita premature mortality was relatively low, despite severe $PM_{2.5}$ pollution. For example, Shanghai and Jiangsu had a per capita premature mortality of 6 and 9.2 per 10,000 persons, respectively, but they both had $PM_{2.5}$ concentrations above $35 \mu\text{g}/\text{m}^3$ (Fig. 4). The phenomenon could be attributed to the relatively low baseline mortality rates of these provincial-level administrative divisions. Specifically, ischemic heart and

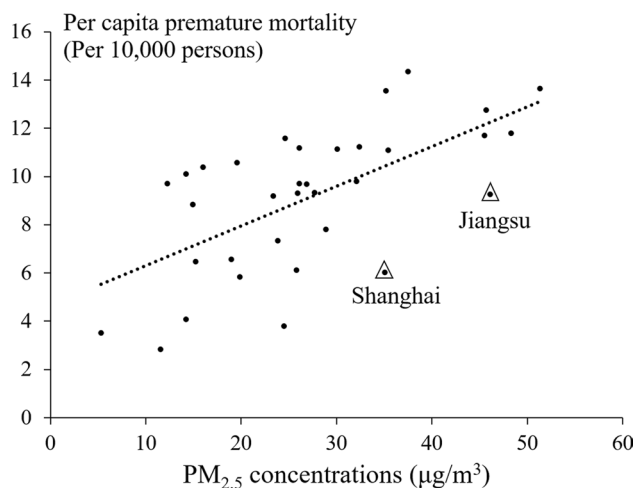


Fig. 4 Relationship between per capita premature mortality and concentrations of airborne particulate matter with diameter below $2.5 \mu\text{m}$ ($PM_{2.5}$)

cerebrovascular diseases accounted for 68.3% of all premature deaths. The baseline mortality rates for the two diseases were relatively low in Shanghai and Jiangsu. In men, for example, the baseline mortality rate for ischemic heart disease was the third and seventh lowest in Shanghai and Jiangsu, respectively, and the baseline mortality rate for cerebrovascular disease was the fourth and tenth lowest in Shanghai and Jiangsu, respectively (Zhou et al. 2016).

Conclusion

We spatially quantified the effects of $PM_{2.5}$ on human health based on gridded population and $PM_{2.5}$ data. Compared to previous provincial or municipal population data, the data in this study not only had more refined age segmentation but also were sorted by gender. In addition, since the BMR values were based on provincial-level administrative divisions, our overall results were more detailed at the pixel level. Our results show that areas of China with high $PM_{2.5}$ concentrations were mainly distributed in the Xinjiang and mideastern regions. With respect to specific causes, ischemic heart disease and cerebrovascular disease were responsible for the majority of $PM_{2.5}$ exposure-induced premature mortality. The number of total premature mortalities was about 1.44 million and mortality in all five specific causes was higher in men than women. Moreover, in provincial-level administrative divisions, high premature deaths were mainly concentrated in the North China Plain. Per capita premature mortality was a more direct indicator of $PM_{2.5}$ pollution than the total number of deaths. The areas with the highest per capita premature mortality included Xinjiang, Henan, Hebei, and Shandong. These findings require the government to implement more stringent and efficient air quality improvement measures.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10311-022-01445-6>.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest in this work.

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Supplementary Material

Table S1. Premature deaths caused by PM_{2.5} pollution in China in 2018. PM_{2.5}: airborne particulate matter with diameter below 2.5 μm, GEMM: global exposure mortality model, IER: integrated exposure-response, IHD: ischemic heart disease, COPD: chronic obstructive pulmonary disease, LC: lung cancer, CEV: cerebrovascular disease, LRI: lower respiratory infection.

Premature mortality (million)	0.91 (0.41-1.30)	1.42 (1.20-1.68)	1.43 (0.98-1.80)	1.44 (0.96-1.83)	1.83
Exposure-response model	IER	GEMM	GEMM	GEMM	GEMM
PM _{2.5} exposure-induced diseases	IHD, CEV, COPD, LC, LRI	IHD, CEV, COPD, LC	IHD, CEV, COPD, LC, LRI	IHD, CEV, COPD, LC, LRI	IHD, CEV, COPD, LC, LRI
PM _{2.5} resolution	City-level	8 km	City-level	1 km	1 km
Population resolution and age factors	City-level, age-specific	1 km, age-specific	City-level, age-specific	1 km, age- and sex-specific	1 km, all-age
Baseline mortality rates	Country-level	Country-level	Country-level	Province-level and sex-specific	Province-level
References	Maji et al. 2020	Giani et al. 2020	Maji et al. 2020	This study	Ma et al. 2021