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Spatial Distribution of $PM_{2.5}$-Related Premature Mortality in China

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Key Points:

- Based on an extended observational network in China, 1.55 million premature deaths attributed to $PM_{2.5}$ is estimated in 2016
- Higher premature mortality using the Global Exposure Mortality Model compared to the Integrated Exposure-Response model
- A positive spatial autocorrelation of the per capita premature mortality is found at the city levels

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Spatial Distribution of $PM_{2.5}$-Related Premature Mortality in China

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Abstract $PM_{2.5}$ is a major component of air pollution in China and has a serious threat to public health. It is very important to quantify spatial characteristics of the health effects caused by outdoor $PM_{2.5}$ exposure. This study analyzed the spatial distribution of $PM_{2.5}$ concentration (45.9 μg/m^3 national average in 2016) and premature mortality attributed to $PM_{2.5}$ in cities at the prefectural level and above in China in 2016. Using the Global Exposure Mortality Model (GEMM), the total premature mortality in China was estimated to be 1.55 million persons, and the per capita mortality was 11.2 per 10,000 persons in the year 2016, resulting in higher estimates compared to the integrated exposure-response model. We assessed the premature mortality attributed to $PM_{2.5}$ through common diseases, including ischemic heart disease (IHD), cerebrovascular disease (CEV), chronic obstructive pulmonary disease (COPD), lung cancer (LC), and lower respiratory infections (LRI). The premature mortality due to IHD and CEV accounted for 68.5% of the total mortality, and the per capita mortality (per 10,000 persons) for all ages due to IHD was 3.86, the highest among diseases. For the spatial distribution of disease-specific premature mortality, the top two highest absolute numbers of premature mortality associated with IHD, CEV, LC, and LRI, respectively, were found in Chongqing and Beijing. In 338 cities of China, we have found a significant positive spatial autocorrelation of per capita premature mortality, indicating the necessity of coordinated regional governance for an efficient control of $PM_{2.5}$.

Plain Language Summary Fine particulate matter ($PM_{2.5}$) concentrations have increased in general, in most developing countries in recent decades. In China, $PM_{2.5}$ pollution has become a major component of air pollution and has serious health impacts. To obtain a comprehensive understanding of the national health impacts of $PM_{2.5}$ in China, we have used the Global Exposure Mortality Model (GEMM) to estimate the premature mortality associated with $PM_{2.5}$ exposure in 338 cities in China at the prefectural level and above. In addition, we analyzed the spatial distribution of premature mortality attributed to $PM_{2.5}$ for five diseases, including ischemic heart disease (IHD), cerebrovascular disease (CEV), chronic obstructive pulmonary disease (COPD), lung cancer (LC), and lower respiratory infections (LRI). Our study finds that the total premature mortality associated with $PM_{2.5}$ exposure in China for 2016 was 1.55 million persons. The top two highest absolute numbers of premature mortality associated with IHD, CEV, LC, and LRI, respectively were found in Chongqing and Beijing. Furthermore, cities with high per capita premature mortality tended to be spatially connected with other cities with high per capita premature mortality, indicating the coordinated regional governance should be adopted to reduce the impact of $PM_{2.5}$ on human health.

1. Introduction

Fine particulate matter ($PM_{2.5}$) has a serious threat to public health. $PM_{2.5}$ concentrations have increased in most developing countries in recent decades (C. H. Lim et al., 2020). $PM_{2.5}$ sources include energy production, industry, transport, agriculture, desert dust, and residential solid fuel use (Kodros et al., 2018; Sarkar et al., 2018, 2019; Shaddick et al., 2020; Yun et al., 2020; Zhao et al., 2018). The increasing air pollution impacts visibility and contributes to long-term climate change, besides, threats to human health. The correlation between health issues and

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$PM_{2.5}$ has been pointed out by many studies (Balakrishnan et al., 2019; Burnett et al., 2018; Cropper et al., 2021; Dandona et al., 2017; Li et al., 2018; Liang et al., 2020; Mehta et al., 2021; Wu et al., 2019; X. Yang et al., 2020; Y. Yang et al., 2018). According to the comparative risk assessment of the global burden of disease (GBD) 2019 project of the Institute for Health Metrics and Evaluation (IHME), globally, about 6.67 million premature deaths are due to air pollution in the year 2019 (GBD 2019 Risk Factors Collaborators, 2020). The premature mortality caused by outdoor air pollution will be 6.6 million by 2050 if we do not take any step to curb the air pollution (Lelieveld et al., 2015), especially in Asia.

Efforts have been made in China to improve air quality, but the impact of $PM_{2.5}$ on human health must be taken seriously. In 2013, China issued the Air Pollution Prevention and Control Action Plan (APPCAP) that improved $PM_{2.5}$ concentration in China (Zhao et al., 2018; B. Zheng et al., 2018). In addition, due to the rapid urbanization and improved economic conditions, rural-to-urban migrants switched to cleaner fuel types, making a great contribution to the decline of $PM_{2.5}$ concentration in China. However, serving as the destinations of massive migrations, megacities such as Beijing and Shanghai experienced increases in $PM_{2.5}$ concentrations (Shen et al., 2017). Moreover, the population of Chinese mainland was 1.412 billion in 2020, increasing by 5.38% from 2010 to 2020. The GBD analysis found that ambient $PM_{2.5}$ pollution resulted in approximately 1.4 million premature deaths in the year 2019 in China (GBD 2019 Risk Factors Collaborators, 2020).

As cohort and time-series analysis has been extensively used in air pollution and human health research, several quantitative epidemiological studies were conducted in China and other countries showing a correlation between air particulate pollution and human health. Burnett et al. (2014) found that long-term exposure to $PM_{2.5}$ was closely related to premature deaths caused by ischemic heart disease (IHD), cerebrovascular disease (stroke, CEV), chronic obstructive pulmonary disease (COPD), lung cancer (LC), and lower respiratory infections (LRI). The GBD 2010 evaluated the health of people in severely polluted regions using an improved exposure-response relationship and quantified health loss caused by diseases, and risk factors (S. S. Lim et al., 2013). Epidemiological studies of chronic $PM_{2.5}$ exposure and cardiopulmonary disease in Asia have been carried out, and strong evidence for the adverse effect of $PM_{2.5}$ on mortality was provided (Ebenstein et al., 2017; Guan et al., 2016; Li et al., 2018; Vodonos et al., 2018). In China, efforts were made to analyze the quantitative relationship between exposure to $PM_{2.5}$ and human mortality rates (Cao et al., 2011; Huang et al., 2012; J. Liu et al., 2016), but these studies lack a detailed spatial analysis and concentration-response function analysis. Hu et al. (2017) found 1.30 million premature deaths attributed to $PM_{2.5}$ in China in 2013, which coincided with the estimation of 1.37 million by J. Liu et al. (2016) and 1.36 million by Lelieveld et al. (2015). According to the unchanged population scenario, Wang et al. (2019) estimated about 0.83 million premature deaths related to $PM_{2.5}$ exposure in 2020, and 0.74 million premature deaths in 2030. However, considering the increasing and aging population, about 1.04 million premature deaths in 2020, and 1.2 million premature deaths in 2030 were predicted. Air pollution and its health impacts show strong spatiotemporal variations. Although $PM_{2.5}$-related human health impacts have been evaluated in few cities and the whole country in China (Fang et al., 2016; Hu et al., 2017; Madaniyazi et al., 2015; Maji et al., 2018; S. Zheng et al., 2015), the spatial distribution analysis including spatial autocorrelation of health effects associated with $PM_{2.5}$ exposure in China is still lacking, in view of the large area and population distribution. In addition, for the estimation of premature deaths in China, the current studies (Hu et al., 2017; M. Liu et al., 2017; Tian et al., 2017; Yin et al., 2020) are mainly using the Integrated Exposure-Response (IER) (Burnett et al., 2014), and Log-linear (LL) models (Chen et al., 2017; Fang et al., 2016). The IER model is mainly based on cohort studies in Western Europe and North America, where the $PM_{2.5}$ exposure level is usually lower compared to China and other Asian countries. The Limitation of the IER model is the lack of cohort studies with high $PM_{2.5}$ exposure levels. Burnett et al. (2018) proposed an innovative Global Exposure Mortality Model (GEMM), which was initially applied globally (Bayat et al., 2019; Chowdhury et al., 2020; Lelieveld, Klingmüller, Pozzer, Burnett, et al., 2019; Lelieveld, Klingmüller, Pozzer, Pöschl, et al., 2019). Compared with the IER model, the GEMM assumes a logarithmic relationship between exposure and baseline hazard ratio and incorporates the results of the Chinese cohort study (Yin et al., 2017). Based on huge data from 41 cohorts in 16 countries, the GEMM takes higher air pollution into account. At present, there is a lack of detailed analysis on $PM_{2.5}$ exposure associated premature mortality in China using the GEMM method.

To obtain a comprehensive understanding of the national health impacts of $PM_{2.5}$ in China, we have computed $PM_{2.5}$ concentrations in 338 cities in China at the prefectural level and above based on an extended observational network, and estimated the premature mortality for different diseases (IHD, CEV, COPD, LC, and LRI) due

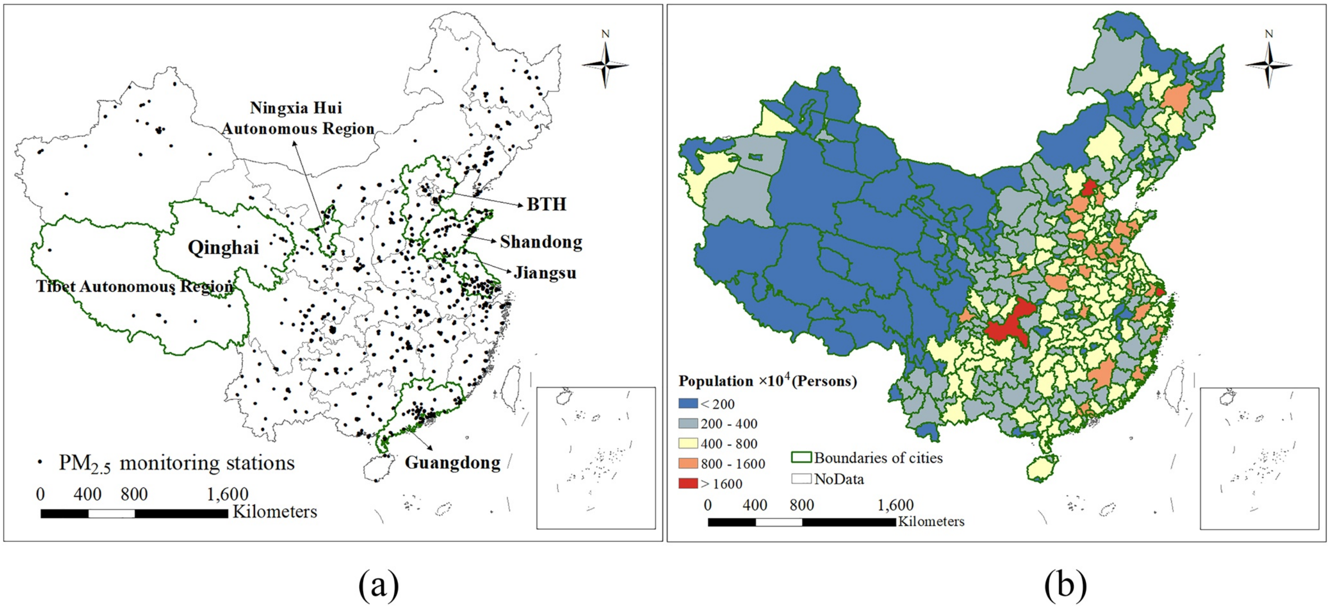


Figure 1. Spatial distribution of ground $PM_{2.5}$ monitoring sites and population in 2016, (a) refers to the $PM_{2.5}$ monitoring sites, (b) refers to the population in cities at the prefectural level and above in China.

to $PM_{2.5}$ using the GEMM, and analyzed the spatial characteristics of premature mortality in China at the city levels. Here we hypothesize that there is a significant spatial autocorrelation of premature mortality in 338 cities of China. Inadequate exposure-hazard relationships and spatial autocorrelation might have biased previous study results. The present spatially explicite analyses aims to improve these aspects.

2. Data and Methods

2.1. Data Sources

China announced the ambient air quality standards (GB 3095-2012) in 2012 which improved the validity of data statistics, and this regulation has been implemented nationwide since January 2016. Therefore, our study is focused on the year 2016.

Hourly concentrations of $PM_{2.5}$ data for the periods 1 January to 31 December 2016 were collected from 1,497 monitoring sites (Figure 1a) located in 338 cities at prefectural level and above in China, and data were taken from the China National Environmental Monitoring Center (CNEMC, http://www.cnemc.cn/). A prefectural level city is the second level of the administrative structure in China, which comprises both urban areas and surrounding rural areas (e.g., countries, towns, and villages).

The monitoring sites are concentrated in areas with a stronger socio-economic background, namely Beijing-Tianjin-Hebei (BTH) region and the eastern coastal provinces. Among the eastern coastal provinces, Shandong, Jiangsu, and Guangdong Provinces have the densest monitoring sites, accounting for 20% of the total number of stations, while monitoring stations are sparse in the western provinces such as Qinghai, Tibet Autonomous Region, and Ningxia Hui Autonomous Region, accounting for only 3% (Figure 1a).

Population data were obtained from the National Bureau of Statistics of China (http://www.stats.gov.cn/), and provincial statistical yearbooks (Figure 1b). Population numbers are highest in Chongqing (30.48 million), followed by Shanghai (24.20 million), and Beijing (21.73 million).

Table 1
GEMM Parameter Estimates for the Population Above 25 years by Cause of Death (Burnett et al., 2018)

Cause of death	θ	Standard error θ	α	μ	ν
IHD	0.2969	0.01787	1.9	12	40.2
CEV	0.2720	0.07697	6.2	16.7	23.7
COPD	0.2510	0.06762	6.5	2.5	32
LC	0.2942	0.06147	6.2	9.3	29.8
LRI	0.4468	0.11735	6.4	5.7	8.4

2.2. Methods

2.2.1. Concentration-Response Functions

The Log-Linear (LL) model is commonly used to estimate premature deaths due to $PM_{2.5}$ exposure (US Environmental Protection Agency, 2015). Motivated by the LL model, Burnett et al. (2018) developed the GEMM for the association between $PM_{2.5}$ and premature mortality, and constructed GEMMs for five specific diseases (IHD, CEV, COPD, LC, and LRI). The relationship between $PM_{2.5}$ concentrations and mortality is described by the following hazard ratio (HR) function:

$$HR(z) = \exp\{\theta T(z)\} \tag{1}$$

where θ is the concentration-response model coefficient, $z = \max$ (0, $PM_{2.5}$–2.4 μg/m^3), $T(z) = f(z)\omega(z)$, with $f(z) = \log(1 + z/\alpha)$, $\omega(z) = 1/(1 + \exp\{-(z-\mu)/(\nu)\})$. α, μ, and ν determine the curved form of the hazard ratio function. Overall, through specifying the parameters (α, μ, ν) in Table 1, we can calculate $HR(z)$ (Burnett et al., 2018).

2.3. Mortality Estimation

The premature mortality for five different diseases (IHD, CEV, COPD, LC, and LRI) associated with $PM_{2.5}$ was calculated and analyzed using the health impact function (Lelieveld et al., 2013, 2015; Pozzer et al., 2019; S. Zheng et al., 2015) based on the annual average $PM_{2.5}$ concentration in each city.

$$\Delta\text{Mort} = y_0 \times \text{Pop} \times \left(\frac{\text{HR} - 1}{\text{HR}}\right) \tag{2}$$

where ΔMort is the change in annual mortality due to $PM_{2.5}$. y_0 refers to the baseline mortality rate (BMR) for a given population and a specific disease. The BMR attributed to each disease in China was obtained at the provincial scale available by Zhou et al. (2016). However, Zhou et al. (2016) only provided BMR data for the year 2013. We have estimated the premature mortality based on the hypothesis of unchanged BMR values for each province for the years 2013 and 2016. In this study, we have considered GEMM parameters for the population above 25 years and below 5 years of age. Pop represents the adult population (above 25 years of age) and infants (below 5 years of age) exposed to $PM_{2.5}$ in a certain area.

Based on the population data and baseline mortality rate, the number of premature deaths from the five diseases attributable to $PM_{2.5}$ at the city levels was calculated using the health impact function. For the population above 25 years, we used the corresponding population data and GEMM parameters (Table 1) to calculate the premature mortality due to the five diseases. For the infants below 5 years, we used the corresponding population data (below 5 years) and GEMM parameters to calculate the premature mortality due to LRI. Finally, the total premature mortality was the sum of the premature mortality at these two age groups. Uncertainty ranges were expressed as the 95% confidence interval (95% CI) (Burnett et al., 2018).

2.3.1. Spatial Autocorrelation Analysis

We considered the spatial autocorrelation analysis to determine whether there is a spatial correlation pattern (convergence or heterogeneity) between premature deaths attributed to $PM_{2.5}$ in each city of neighboring cities. A global spatial autocorrelation analysis is performed to determine the spatial characteristics of the premature deaths in the entire region. A local spatial autocorrelation analysis is conducted to determine the spatial heterogeneity of the premature deaths.

The indicators and methods for measuring global spatial autocorrelation mainly include global Moran's I and Geary's C. Since Moran's I is the most widely used, this study used this indicator to test the spatial agglomeration, and it is calculated as follows.

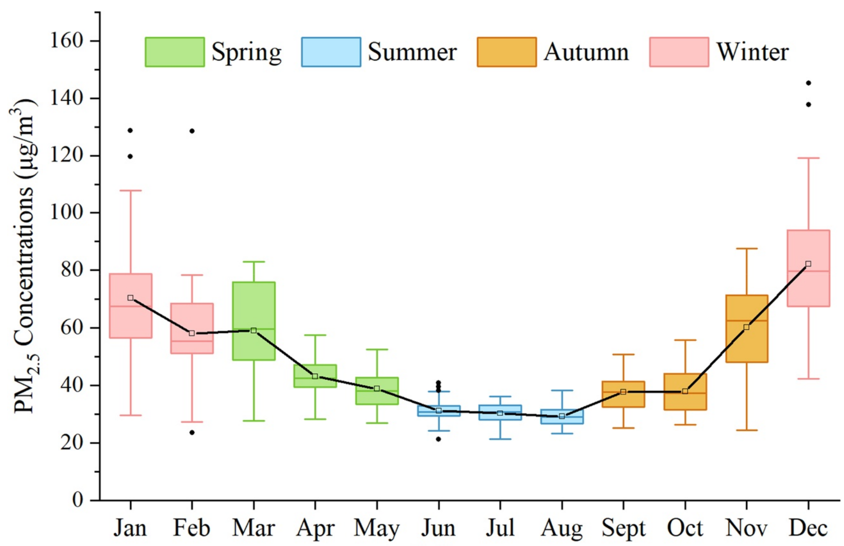


Figure 2. Boxplot (median and interquartile range) of monthly $PM_{2.5}$ concentrations in China in the year 2016. The black line represents the mean of monthly $PM_{2.5}$ concentrations.

$$I = \frac{n \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} W_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} W_{ij}} \tag{3}$$

where I means the Moran's I index. n refers to the number of spatial units. x_i and x_j represent the premature deaths of adjacent spatial units. $\bar{x}$ is the average of the total premature mortality in all spatial units. W_{ij} means the spatial weight matrix (determined by queen contiguity in this study) and is used to express the proximity of the spatial units. The value of Moran's I ranges from −1 to 1. Positive values of Moran's I suggest a positive spatial autocorrelation among premature mortality of different spatial units, and negative values represent a negative spatial autocorrelation among premature mortality of different spatial units. A zero value of Moran's I indicates the random spatial pattern among premature mortality of different spatial units.

The local spatial correlation and difference between each spatial unit (city in this study) and its surrounding spatial unit can be assessed by the local spatial autocorrelation analysis. The methods for measuring local spatial autocorrelation mainly include G_i statistics, Moran scatter plot, and local indicator spatial autocorrelation (LISA) (Anselin, 2019; Anselin & Li, 2019). LISA maps could provide a statistic for each spatial unit with an assessment of significance. The degree of concentration of similar values around a spatial unit could be well presented in LISA maps. This study used the indicator of LISA to analyze the local spatial correlation, and it is calculated as:

$$I_i = z_i \sum_{j \neq i}^{n} W_{ij} z_j \tag{4}$$

where z_i and z_j are the standardized form of the premature mortality in the corresponding spatial unit. W_{ij} is the spatial weight matrix (determined by queen contiguity in this study).

3. Results and Discussion

3.1. Spatiotemporal Characteristics of $PM_{2.5}$

The average $PM_{2.5}$ concentration of all stations in 338 cities in the year 2016 was 45.9 μg/m^3. It was highest during winter (December-February, 70.7 μg/m^3), followed by spring (March–May, 47.1 μg/m^3), autumn (September–November, 45.4 μg/m^3), and summer (June–August, 30.2 μg/m^3) seasons. The mean of monthly $PM_{2.5}$ (shown in Figure 2) shows low $PM_{2.5}$ pollution during summer and high $PM_{2.5}$ pollution during winter season. In summer, late spring, and early autumn seasons, $PM_{2.5}$ pollution was low, 38.9, 31.3, 30.3, 29.2, 37.9, 38.0 μg/m^3 in the months of May, June, July, August, September, and October, respectively. In winter season, the $PM_{2.5}$

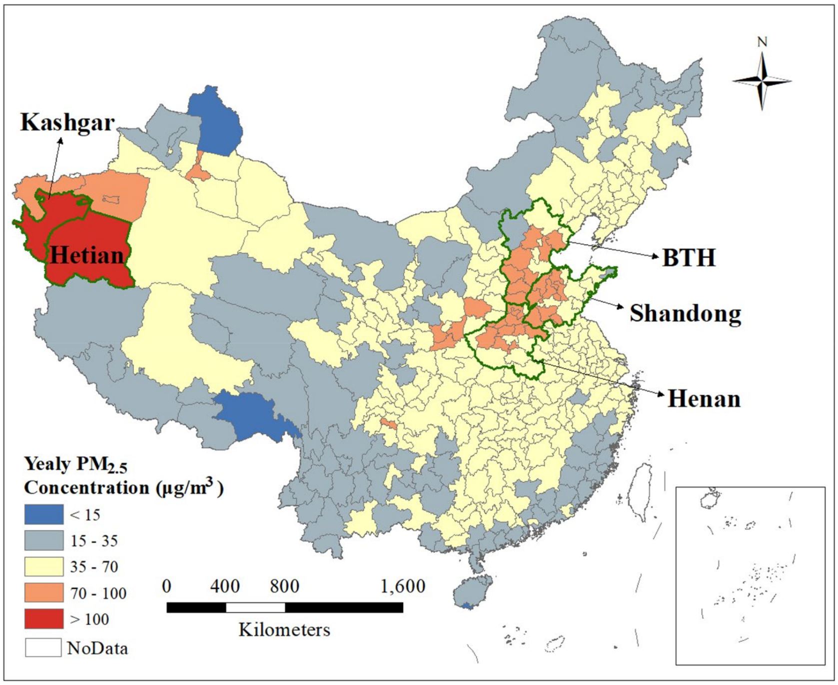


Figure 3. Spatial distribution of the annual $PM_{2.5}$ concentration across China in 2016.

pollution was very high, highest in the month of December. The monthly average of $PM_{2.5}$ concentration was 82.8 μg/m^3 in the month of December, 2.8 times compared to the month of August, which had the lowest monthly average of $PM_{2.5}$ concentration.

The annual average of $PM_{2.5}$ is the average of $PM_{2.5}$ concentration in all stations in each city. Figure 3 shows the spatial distribution of the annual average of $PM_{2.5}$ concentration in 338 cities in 2016, ranging 10–157 μg/m^3. China announced the ambient air quality standards (GB 3095-2012) in the month of February 2012. The threshold values of the annual average of $PM_{2.5}$ concentration were set in this standard, with 15 μg/m^3 as the first concentration threshold (i.e., annual Grade I standard), and 35 μg/m^3 as the second concentration threshold (i.e., annual Grade II standard). Among the 338 cities, there were 70% cities with the annual mean concentration of $PM_{2.5}$ above 35 μg/m^3, namely exceeded the second concentration threshold. The annual mean $PM_{2.5}$ in each city was mainly in the range of 35–70 μg/m^3, accounting for 59%. The cities where annual $PM_{2.5}$ concentration above 70 μg/m^3 accounting for 11%, were mainly located in the southwest of BTH region, north of Henan Province, west of Shandong Province, Hetian, Kashgar, Aksu, and Kizilsu Kirghiz Autonomous Prefecture in west of Xinjiang Uygur Autonomous Region.

3.2. Premature Mortality Associated With the $PM_{2.5}$ Exposure

3.2.1. Total Premature Mortality Analysis

With the health impact function of Equation 2, the $PM_{2.5}$ exposure associated premature mortality was estimated. In 2016, the total premature mortality due to the five diseases was 1,546,492 persons (95% CI: 1,036,657–1,944,566) in 338 cities of China, and the per capita mortality for all ages was 11.2 per 10,000 persons (95% CI: 7.5–14.1). We found that our assessment of 1.55 million premature deaths due to $PM_{2.5}$ in 2016 was higher than the results of earlier studies (Table 2). From Equations 1 and 2, the premature mortality due to $PM_{2.5}$ is influenced by the hazard ratio function, population, and baseline mortality rate. We considered the year 2016 and obtained the hourly concentrations of $PM_{2.5}$ data from the CNEMC and population from the National Bureau of Statistics of China as the study carried out by Maji et al. (2018). The main difference is the hazard ratio function. Our estimation was 60% higher compared to the estimation (0.964 million) by Maji et al. (2018) for the year 2016. This was because we considered the GEMM developed by Burnett et al. (2018) to estimate premature mortality associated with long-term exposure to $PM_{2.5}$, while earlier studies (Hu et al., 2017; J. Liu et al., 2016; Maji et al., 2018)

Table 2
Earlier Estimations of Premature Mortality Due to $PM_{2.5}$ by the IER Model in China

Studies	Year	Disease-specific premature mortality
Lelieveld et al. (2015)	2010	1,357,000 persons due to CEV, COPD, IHD, LC, and acute LRI
Xie et al. (2016)	2010	1,255,400 persons due to CEV, COPD, IHD, and LC
Hu et al. (2017)	2013	1,300,000 persons due to CEV, COPD, IHD, and LC
J. Liu et al. (2016)	2013	1,367,300 persons due to CEV, COPD, IHD, and LC
Maji et al. (2018)	2016	964,000 persons due to CEV, COPD, IHD, and LC

used the IER model. Comparing with the IER model, the GEMM provides the hazard ratio based on a larger data set from 41 cohort studies in 16 countries, which includes the cohort study in China with exposure to much larger $PM_{2.5}$ concentrations (Yin et al., 2017), thus, greatly extending the range of experimentally derived $PM_{2.5}$ exposure. For the GBD 2015 version of the IER model, the available $PM_{2.5}$ observations from outdoor air pollution were limited to about 35 μg/m^3. The epidemiological studies were augmented by using data from second-hand and active smoking studies, although it is not fully clear if this would lead to a correct estimation of the hazard ratios at high concentrations (Burnett & Cohen, 2020). The $PM_{2.5}$ exposure observations in the GEMM can be as high as 84 μg/m^3 by including cohort data from China (Burnett et al., 2018). Furthermore, Xue et al. (2019) found that the $PM_{2.5}$-related deaths from census-based epidemiology were in better agreement with the GEMM estimates compared to the IER model estimates. Globally, The GEMM estimated 6.9 million premature deaths in 2015 due to specific causes (LRI, CEV, COPD, LC, and IHD), 73% higher than the estimation by IER (4.0 million premature deaths). In China, GEMM estimated 1.946 million premature deaths in 2015, 75% higher than the estimation by IER (1.110 million premature deaths) (Burnett et al., 2018). In addition, Lelieveld, Klingmüller, Pozzer, Burnett, et al. (2019) estimated 2.201 million premature deaths due to the five specific causes in China in 2015. Comparing with the results of Burnett et al. (2018) and Lelieveld, Klingmüller, Pozzer, Burnett, et al. (2019), our assessment of 1.55 million premature deaths in 2016 is lower. This is caused by different study years, different population and $PM_{2.5}$ data sources, and different statistical units (the population and $PM_{2.5}$ data are statistically analyzed at the city levels in this study). The present study estimated premature deaths in China using the GEMM, suggesting that $PM_{2.5}$ exposure has much more serious health effects compared to earlier studies using the IER model.

High absolute numbers of premature mortality were found in the north, east, and southwest of China. The cities with the top 10 numbers of premature mortality were given in Table 3. The five cities with the highest numbers of total premature mortality were Chongqing (36,593 persons), Beijing (26,945 persons), Chengdu (21,231

Table 3
The Ten Cites With the Highest Number of Total Premature Mortality

City	$PM_{2.5}$ concentration (μg/m^3)	Premature mortality	Uncertainty ranges of the premature mortality (95% CI)		Population (10,000 persons)	Per capita mortality for all ages (per 10,000 persons)
			Lower bound	Upper bound		
Chongqing	53.0	36,593	23,234	46,980	3048.43	12
Beijing	72.0	26,945	19,357	32,508	2172.9	12.4
Chengdu	61.9	21,231	13,344	27,144	1591.76	13.34
Tianjin	70.1	20,040	14,470	24,127	1562.12	12.83
Baoding	92.3	19,260	13,519	23,264	1163.45	16.55
Shijiazhuang	95.0	18,023	12,667	21,738	1078.46	16.71
Harbin	50.3	16,583	11,777	20,391	1066.5	15.55
Shanghai	45.6	16,153	10,418	20,762	2419.7	6.68
Linyi	67.5	15,278	10,628	18,751	1044.3	14.63
Handan	81.5	15,024	10,484	18,267	949.28	15.83

Table 4
The Premature Mortality Attributed to $PM_{2.5}$ by Disease Category and the Corresponding Per Capita Mortality (IHD, CEV, COPD, and LC for People >25 years and LRI for People >25 years and Infants <5 years) in China in the Year 2016

Disease	Premature mortality (million)	Percent (%)	Per capita mortality for all ages (per 10,000 persons)	Uncertainty ranges of the premature mortality (95% CI, million)	
				Lower bound	Upper bound
IHD	0.534	34.5	3.86	0.489	0.575
CEV	0.525	34	3.8	0.266	0.724
COPD	0.242	15.6	1.75	0.127	0.333
LC	0.142	9.2	1.03	0.093	0.182
LRI	0.103	6.7	0.75	0.062	0.13

persons), Tianjin (20,040 persons), and Baoding (19,260 persons). The corresponding per capita mortality (per 10,000 persons) for all ages was 12 in Chongqing, 12.4 in Beijing, 13.34 in Chengdu, 12.83 in Tianjin, and 16.55 in Baoding. Considering the population differences among cities, the five cities with the highest per capita mortality were Kashi (20.28 per 10,000 persons), Hetian (18.65 per 10,000 persons), Aksu (17.66 per 10,000 persons), Shijiazhuang (16.71 per 10,000 persons), and Urumqi (16.64 per 10,000 persons).

3.2.2. Disease-Specific Premature Mortality Analysis

Table 4 shows the disease-specific premature mortality in 2016 in China. The premature mortality due to IHD was highest (0.534 million persons), and accounted for 34.5% of the total premature mortality, followed by CEV, of 0.525 million persons, and the corresponding ratio was 34%. The premature mortality due to LRI was the lowest (0.103 million) and accounted for only 6.7% of the total premature mortality. The per capita mortality (per 10,000 persons) for all ages due to IHD, CEV, COPD, LC, and LRI was 3.86, 3.8, 1.75, 1.03, and 0.75, respectively. Our findings show that in China, the premature mortality due to $PM_{2.5}$ was mainly from IHD and CEV, accounting for 68.5% in total, while LRI had the lowest portion.

The spatial distribution of premature mortality due to the five diseases associated with $PM_{2.5}$ in 338 cities of China is shown in Figure 4. The five cities with the highest premature mortality due to IHD were Beijing (11,671 persons), Chongqing (8,959 persons), Tianjin (8,782 persons), Harbin (7,508 persons), and Baoding (7,373 persons). The five cities with the highest premature mortality due to CEV were Chongqing (11,037 persons), Beijing (8,600 persons), Baoding (8,104 persons), Shijiazhuang (7,588 persons), and Chengdu (6,610 persons). The five cities with the highest premature mortality due to COPD were Chongqing (10,248 persons), Chengdu (6,190 persons), Shanghai (3,015 persons), Nanchong (2,327 persons), and Wuhan (2,186 persons). The five cities with the highest premature mortality due to LC were Chongqing (4,213 persons), Beijing (2,851 persons), Shanghai (2,390 persons), Chengdu (2,285 persons), and Tianjin (2,224 persons). Regarding the premature mortality due to LRI, Chongqing, Beijing, Tianjin, Chengdu, and Zunyi had the highest premature mortality, and they were 2,135, 1,764, 1,718, 1,681, and 1,099 persons, respectively. Overall, the top two highest premature mortality due to IHD, CEV, LC, and LRI, respectively were found in Chongqing and Beijing. Chengdu had the top five highest premature mortality due to CEV, COPD, LC, and LRI, respectively.

For the per capita mortality due to each disease, the top five cities with the highest per capita mortality due to IHD were Kashi (8.21 per 10,000 persons), Hetian (7.6 per 10,000 persons), Aksu (7.21 per 10,000 persons), Harbin (7.04 per 10,000 persons), and Urumqi (6.82 per 10,000 persons). Table 5 presents the top five cities with the highest per capita mortality due to each disease. Shijiazhuang (7.04 per 10,000 persons) in Hebei Province has the highest per capita mortality due to CEV. Zigong (4.24 per 10,000 persons) in Sichuan Province has the highest per capita mortality due to COPD.

3.2.3. Spatial Autocorrelation of Per Capita Mortality

A spatial autocorrelation analysis was applied to find spatial correlation patterns between the per capita mortality due to the five diseases in each city. Using Equation 3, the value of global spatial autocorrelation coefficient, that is, global Moran's I of the per capita premature mortality caused by $PM_{2.5}$ in 338 cities was estimated to be 0.74 ($p < 0.01$). This means that the per capita premature mortality caused by $PM_{2.5}$ in 338 cities in China is not randomly distributed, but there is a significant positive spatial autocorrelation, that is, a clustering of similar values.

In order to identify the cluster pattern of per capita premature mortality due to $PM_{2.5}$ in local space, this study used Equation 4 to calculate the local spatial autocorrelation coefficient, that is, LISA of each city in China, and further used the local Moran's I scatter plot (Figure 5) and LISA map (Figure 6) to characterize the local spatial correlation. In the Moran's I scatter plot (Figure 5), the first and third quadrant represents High-High and Low-Low areas, respectively, indicating that one high value (high per capita premature mortality in this study) is surrounded by another high value, or that one low value (low per capita premature mortality in this study) is surrounded by another low value, meaning that there is a strong positive spatial autocorrelation, that is, spatial homogeneity. In

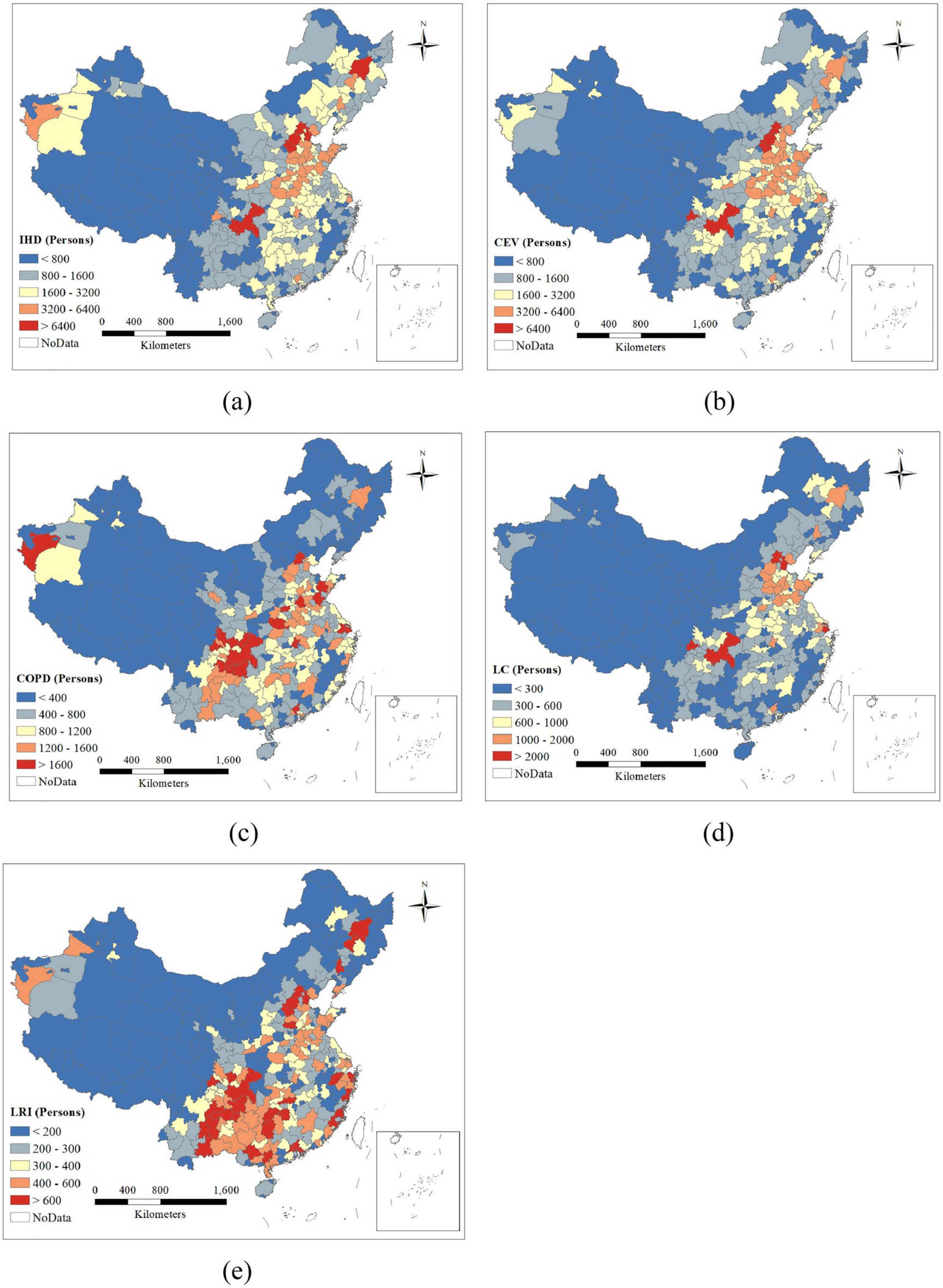


Figure 4. Spatial distribution of the premature mortality associated with (a) IHD, (b) CEV, (c) COPD, (d) LC, (e) LRI across China in the year 2016.

Table 5
The Top Five Cities With the Highest Per Capita Mortality (Per 10,000 Persons) Due to Each Disease

IHD		CEV		COPD		LC		LRI	
City	Per capita mortality	City	Per capita mortality	City	Per capita mortality	City	Per capita mortality	City	Per capita mortality
Kashi	8.21	Shijiazhuang	7.04	Zigong	4.24	Jinzhou	1.77	Naqu	1.87
Hetian	7.6	Baoding	6.97	Luzhou	3.98	Liaocheng	1.75	Zunyi	1.76
Aksu	7.21	Hengshui	6.83	Chengdu	3.89	Shenyang	1.74	Liupanshui	1.70
Harbin	7.04	Xingtai	6.82	Meishan	3.78	Anshan	1.73	Guiyang	1.63
Urumqi	6.82	Handan	6.64	Kashi	3.73	Dezhou	1.73	Qiandongnan	1.54

addition, the second and fourth quadrants represent Low-High and High-Low areas, respectively, where a strong spatial negative autocorrelation exists, that is, the spatial unit (cities in this study) is heterogeneous.

The number of cities in the High-High and Low-Low quadrants accounted for 142/338 and 142/338 of the total, respectively. This means that the per capita premature mortality was spatially related, and cities with high per capita premature mortality tended to have a spatially connected and neighboring relationship with other cities with high per capita premature mortality.

Figure 6 shows the LISA cluster map and LISA significance map of the per capita premature mortality in 338 cities. The High-High agglomeration cities were mainly distributed in the west of Xinjiang Uygur Autonomous Region, southeast of Shanxi Province, south of Hebei Province, Shandong Province, Henan Province, Liaoning Province, and Jilin Province. According to the hazard ratio function and mortality estimation equation, the per capita premature mortality is largely influenced by $PM_{2.5}$ concentrations. In the High-High agglomeration cities (66 cities in total), the spearman's rank correlation coefficient between $PM_{2.5}$ concentration and per capita premature mortality is 0.829, with statistical significance p-value <0.0001. Industrial emissions have a significant impact on the $PM_{2.5}$ concentration, and influence the cluster pattern of per capita premature mortality. For example, Shanxi is the main production and consumption area of raw coal in China (He et al., 2017). Hebei, Shandong, and Henan are the main concentration areas of coal-based industries in China (Luo et al., 2017). Therefore, high $PM_{2.5}$ concentrations led to the formation of High-High agglomeration areas. In addition, meteorological conditions are also key factors affecting the regional $PM_{2.5}$ concentrations. In Xinjiang Uygur Autonomous Region, high $PM_{2.5}$ concentrations also occur due to the prevalence of sandy and dusty weather (J. Liu et al., 2021). A consequence of High-High agglomeration cities is that $PM_{2.5}$ pollution demands for regional control and governance. The Low-Low agglomeration cities were mainly distributed in Zhejiang, Fujian, Guangdong, Hainan, Yunnan Provinces. The Low-High agglomeration cities of statistical significance was in Xuzhou city of Jiangsu Province, and Yanbian Korean Autonomous Prefecture in Jilin Province. The per capita premature mortality in Xuzhou was 10.1 per 10,000 persons, much lower than that in its surrounding areas of Zaozhuang (15.54 per 10,000 persons), Linyi (14.63 per 10,000 persons), Jining (14.88 per 10,000 persons), and Heze (15.84 per 10,000 persons). The per capita premature mortality in Yanbian Korean Autonomous Prefecture was 10.86 per 10,000 persons, much lower than that in its surrounding areas of Jilin (12.77 per 10,000 persons), Mudanjiang (12.9 per 10,000 persons), and Baishan (14.39 per 10,000 persons).

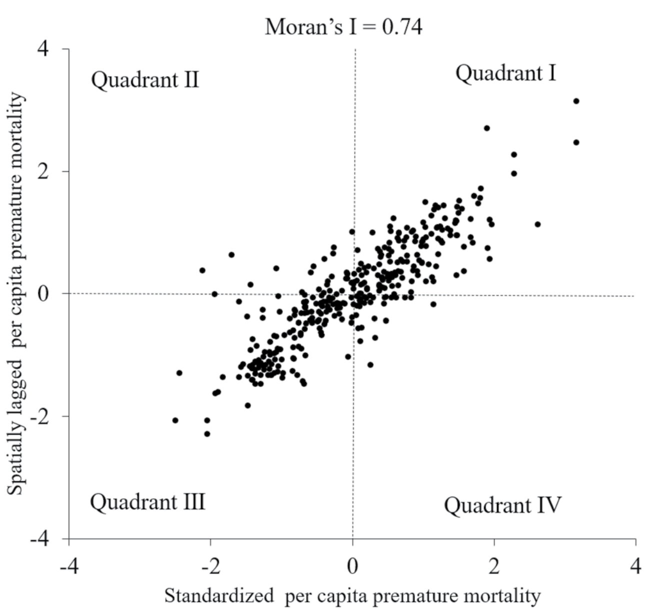
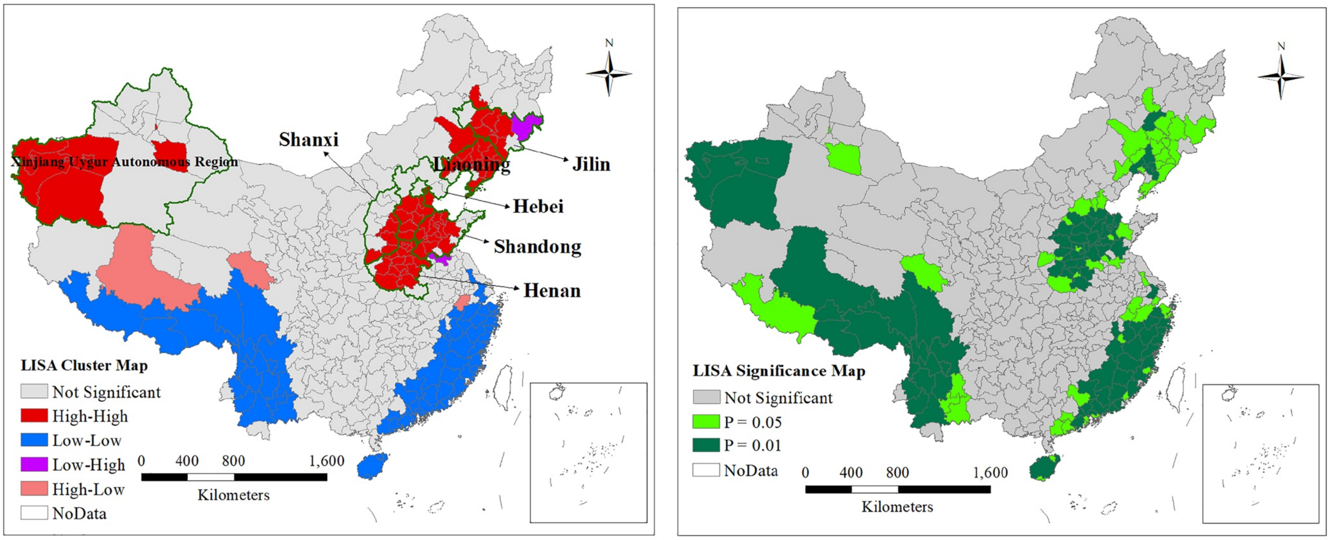


Figure 5. Moran's I scatter plot of the per capita premature mortality in 338 cities.

4. Conclusion

We have studied the spatiotemporal characteristics of $PM_{2.5}$, and the spatial distribution of premature mortality associated with $PM_{2.5}$ in 338 cities of China in the year 2016. High $PM_{2.5}$ concentrations (poor air quality) were observed during winter season, while low $PM_{2.5}$ concentrations during summer.



(a) (b)

Figure 6. The local spatial autocorrelation of the per capita premature mortality due to $PM_{2.5}$ in China in 2016, (a) the local indicator spatial autocorrelation (LISA) cluster map, and (b) LISA significance map.

The cities where annual $PM_{2.5}$ concentration above 70 μg/m^3 were mainly located in BTH region, Henan, Shandong, and Xinjiang Uygur Autonomous Region. In 2016, the total premature mortality due to the five diseases was around 1.55 million persons, and the per capita mortality for all ages was 11.2 per 10,000 persons. The estimated premature deaths were higher than other earlier studies due to the application of GEMM which extends the range of $PM_{2.5}$ exposure. High absolute numbers of premature mortality were found in the north, east, and southwest of China. For the disease-specific premature mortality in 2016 in China, the premature mortality due to IHD was highest, accounting for 34.5% of the total premature mortality, while the premature mortality due to LRI was lowest, accounting for only 6.7%. The per capita mortality (per 10,000 persons) for all ages due to IHD, CEV, COPD, LC, and LRI was 3.86, 3.8, 1.75, 1.03, and 0.75, respectively. For the spatial distribution of disease-specific premature mortality, Chongqing and Beijing were the top two cities with the highest premature mortality due to IHD, CEV, LC, and LRI, respectively. Through the spatial autocorrelation analysis, we found a significant positive spatial autocorrelation between the per capita premature mortality caused by $PM_{2.5}$ in 338 cities of China. Cities with high per capita premature mortality tended to be spatially connected with other cities with high per capita premature mortality. The High-High agglomeration cities were mainly distributed in the west of Xinjiang Uygur Autonomous Region, southeast of Shanxi Province, south of Hebei Province, Shandong Province, Henan Province, Liaoning Province, and Jilin Province, indicating the coordinated regional governance should be adopted to reduce $PM_{2.5}$ concentration and its health impacts. The finding of this study is crucial for quantitative analysis and evaluation of China's air pollution impacts on human health, and helpful to make strategies to reduce the health hazards due to $PM_{2.5}$.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The authors are grateful to the China National Environmental Monitoring Centre (CNEMC, http://www.cnemc.cn/) for making $PM_{2.5}$ data for 2016 available. The authors are grateful to the two anonymous Referees and to the Editor for providing us very thoughtful comments/suggestions which have helped us to improve earlier version of the manuscript.

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