A county-level estimate of PM$_{2.5}$ related chronic mortality risk in China based on multi-model exposure data

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Abstract

Background—Ambient fine particulate matter (PM$_{2.5}$) pollution is currently a serious environmental problem in China, but evidence of health effects with higher resolution and spatial coverage is insufficient.

Objective—This study aims to provide a better overall understanding of long-term mortality effects of PM$_{2.5}$ pollution in China and a county-level spatial map for estimating PM$_{2.5}$ related premature deaths of the entire country.

Method—Using four sets of satellite-derived PM$_{2.5}$ concentration data and the integrated exposure-response model which has been employed by the Global Burden of Disease (GBD) to estimate global mortality of ambient and household air pollution in 2010, we estimated PM$_{2.5}$ related premature mortality for five endpoints across China in 2010.

Result—Premature deaths attributed to PM$_{2.5}$ nationwide amounted to 1.27 million in total, and 119,167, 83,976, 390,266, 670,906 for adult chronic obstructive pulmonary disease, lung cancer, ischemic heart disease, and stroke, respectively; 3995 deaths for acute lower respiratory infections were estimated in children under the age of 5. About half of the premature deaths were from counties with annual average PM$_{2.5}$ concentrations above 63.61 μg/m^3, which cover 16.97% of the Chinese territory. These counties were largely located in the Beijing-Tianjin-Hebei region and the North China Plain. High population density and high pollution areas exhibited the highest health risks attributed to air pollution. On a per capita basis, the highest values were mostly located in heavily polluted industrial regions.

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Conclusion—PM$_{2.5}$-attributable health risk is closely associated with high population density and high levels of pollution in China. Further estimates using long-term historical exposure data and concentration-response (C-R) relationships should be completed in the future to investigate longer-term trends in the effects of PM$_{2.5}$.

Keywords

Multi-model PM$_{2.5}$; Chronic mortality effect; Spatial; County-level; China

1. Introduction

Fine particulate matter (particles 2.5 μm in aerodynamic diameter; PM$_{2.5}$) is a major concern for public health. PM$_{2.5}$ has been found to be associated with both short-term and long-term adverse health effects (Dockery et al., 1993; Schwartz, 2000; Laden et al., 2000; Kunzli et al., 2001; Boldo et al., 2006; Chow et al., 2006; Pope and Dockery, 2013; Lu et al., 2015). According to the Global Burden of Disease (GBD) 2010 assessment, 3.2 million premature deaths per year were attributable to ambient PM2.5 exposure, and PM2.5 is one of the leading risk factors for premature mortality (Cohen et al., 2012). For China, ambient PM pollution ranked fourth in leading risk factors and was associated with 1.2 million premature deaths per year (Lim et al., 2012; Yang et al., 2013). Haze and smog (characterized by high concentrations of PM$_{2.5}$) has been a critical social issue in China. An accurate assessment of the health effects related to PM$_{2.5}$ exposure is needed for evidence-based priority setting at the local level in China.

The short-term effects of PM$_{2.5}$ in China have been well studied in recent years (Guo et al., 2010; Chen et al., 2012; Lu et al., 2015), which has served as the corner stone of countermeasures and policy making. However, to-date, there has been little epidemiologic work on the chronic effects of PM$_{2.5}$ in China, due in part to the lack of long-term air monitoring data and the lack of scientific exposure-response relationship for regions with high PM$_{2.5}$ concentration. Techniques for deriving PM$_{2.5}$ from remote sensing data based on ground monitoring data and land-use information have been evolving, and PM$_{2.5}$ can now be determined with relatively high accuracy. Some models have been de-veloped to estimate long-term historical PM$_{2.5}$ exposure, including satellite-based aerosol optical depth (AOD) models, land-use regression models, chemical transport model (CTM) simulations and other integrated models (Kloog et al., 2014; Brauer et al., 2016; Di et al., 2016; Ma et al., 2016; Van Donkelaar et al., 2016). These techniques have also been used to estimate the global and regional mortality associated with PM$_{2.5}$ (Evans et al., 2013; Lim et al., 2012). However, previous studies are mostly based on single model for the PM$_{2.5}$ exposure estimate, which bring much uncertainty. To better express modeling estimate uncertainty, the multi-model method has been applied in several studies especially studies on climate and health, which can be applied in the PM$_{2.5}$ exposure estimates (Kinney et al., 2008; Jerrett et al., 2017; Silva et al., 2017).

To achieve a better exposure-response curve in more polluted regions, Burnett et al. (2014), building on Pope et al. (2009, 2011), developed integrated exposure-response functions (IERs) that constrain the shape of the concentration-response (C-R) relationship using

epidemiologic data derived from higher exposure concentrations (e.g., household air pollution from the use of solid fuels, secondhand tobacco smoke, active tobacco smoking). Following GBD 2010, Apte et al. (2015) employed those IERs to estimate relative risks attributable to $PM_{2.5}$ exposure for five major endpoints (for adults: ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), lung cancer (LNC), and stroke; for children under the age of 5: acute lower respiratory infections (ALRI)) and estimated that 3.24 million premature deaths were attributable to $PM_{2.5}$ worldwide in 2010, and this result is in accordance with the estimates of GBD 2010.

Following these achievements in estimating long-term exposure and attributive relative risk (RR) of $PM_{2.5}$ for higher exposure concentrations, a few studies have attempted to estimate the long-term chronic effects of $PM_{2.5}$ in China (Xie et al., 2016; J. Liu et al., 2016a; M. Liu et al., 2016b), using these satellite-derived $PM_{2.5}$ data and similar methods to those employed by the GBD 2010 assessment and Apte et al. (2015). However, there are variations among these studies due to differentiations of data sources and modeling methods. The estimated $PM_{2.5}$ exposure from each individual model also requires further verification and comparison. Furthermore, these previous studies are all based on city-level or grid data of populations at all ages, and failed to take into consideration multi-model $PM_{2.5}$ data and the differences among age groups. In fact, the attributive relative risk (RR) varies greatly among different age groups and different counties within a city/province. China has > 2850 counties, and the county is a key unit for administration and policy making in China.

Therefore, to address the above problems, this study uses multi-model $PM_{2.5}$ concentration data, county-level population data, and C-R relationships for the full range of $PM_{2.5}$ concentrations to estimate the $PM_{2.5}$ related health effects for each county in China, and analyzes the spatial patterns and regional characteristics of these estimates for the entire country.

2. Materials and methods

The key elements of the $PM_{2.5}$ risk assessment include an exposure assessment, population in the study area, baseline health incidence information, and the $PM_{2.5}$C-R function from epidemiological studies.

2.1. PM$_{2.5}$ concentration data

We used the annual mean $PM_{2.5}$ concentration in 2010 as the exposure in our model. The multi-source $PM_{2.5}$ concentration estimates were based on four different satellite-derived models (Supplemental Table S1). We estimated annual mean $PM_{2.5}$ concentration for each county using zonal statistic tools (Supplemental Fig. S1).

2.2. Demographic data

The county-level age-specific demographic data in this study are from the sixth demographic census of China in 2010. This dataset includes information on populations for each age group from 0 to 84 years old in 5-year intervals, and the group for 85 years of age or older. There were about 2860 counties in China in 2010, but we include 2826 counties in our

model, and a total population of 1.325 billion, since demographic data for a few counties were missing or could not be matched with the county map (to join with the $PM_{2.5}$ data).

2.3. Baseline mortality data

Ideally, the county-level estimates should use county-level baseline mortality data, but because these data are not available in China, we instead use provincial-level data. The age-specific mortality rate for each disease was obtained from Zhou et al. (2015) and the results of GBD 2013 studies (Naghavi et al., 2015). The data table is provided in the Supplementary Materials (Table S2 and Supplementary Materials-2).

2.4. The C-R function

A C-R function is a mathematical equation that describes the relationship between exposure (long-term exposure to $PM_{2.5}$) and the risk of a health outcome (mortality of each endpoint). The C-R function expresses the relative risk of mortality associated with an incremental change in $PM_{2.5}$ concentration. In this study, the C-R functions and relative risk (Eq. (1)) were based on the integrated exposure-response functions (IERs) GBD 2010 (Burnett et al., 2014) and Apte et al. (2015), across the full range of $PM_{2.5}$ concentrations.

$$PR_{IER}(z) = \begin{cases} 1, & z < z_{ef} \\ 1 + \alpha \left\{ 1 - \exp[-\gamma(z - z_{cf})^{\delta}] \right\}, & z \geq z_{ef} \end{cases} \quad (1)$$

$RR_{IER}(z)$ represents the relative risk in the $PM_{2.5}$ exposure concentration of z (in micrograms per meter cubed); z_{cf} is the counterfactual concentration below which we assumed there is no additional risk. For very large z, RR_{IER} approximates $1 + \alpha$. A power of $PM_{2.5}$, δ, was included here to predict risk over a very large range of concentrations (Burnett et al., 2014).

2.5. Modeling

We adapted a calculation approach developed for GBD 2010 to estimate $PM_{2.5}$-related premature mortality in each county, and the following five endpoints are included in our estimation: IHD, COPD, LNC, and stroke in adults, and ALRI in children under 5-years-old. For IHD and stroke, the RR is different between age strata, and for COPD and LNC, the RR in the same exposure concentration is the same for the entire group of adults (aged 25 or more) (Apte et al., 2015). We estimated the premature mortality M_{ij} of each county (and of each age stratum for IHD and stroke) and disease endpoint j attributable to ambient $PM_{2.5}$ for county i located in region k.

$$M_{i,j} = P_i \times \hat{I}_{j,k} \times (RR_j(C_i) - 1) \text{ where: } \hat{I}_{j,k} = \frac{I_{j,k}}{RR_{j,k}} \quad (2)$$

$\hat{I}_{j,k}$ represents the hypothetical "underlying incidence" (i.e., cause-specific mortality rate) that would remain for region k if $PM_{2.5}$ concentrations were reduced to the theoretical minimum risk concentration throughout that region.

Here, P_i is the population of county i, $I_{j,k}$ is the reported regional average annual disease incidence (mortality) rate for endpoint j in region k, C_i represents the annual-average PM$_{2.5}$ concentration in county i, $RR_j(C_i)$ is the relative risk for end point j at concentration C_i, and $\overline{RR}_{j,k}$, as defined below, represents the average population-weighted relative risk for end point j within region k:

$$\overline{RR}_{j,k} = \frac{\sum_{i=1}^{N} P_i \times RR_j(C_i)}{\sum_{i=1}^{N} P_i} \tag{3}$$

In addition to the absolute number of premature deaths associated with PM$_{2.5}$, we also computed per-capita impacts. Per-capita mortality eliminates the influence of population density when examining spatial patterns of the effects of PM$_{2.5}$. Furthermore, the territorial area differs significantly among different counties; a county with a large number of PM$_{2.5}$ related deaths may still have a low per-unit-area mortality due to its large territorial area. To resolve this problem, an indicator of 'per-unit-area mortality' was applied to see the spatial patterns of PM$_{2.5}$ related premature mortality. Therefore, the per-capita and per-unit-area mortality for each county were calculated, and maps were made to see the spatial variations in impacts independent of population density. Provincial-level statistics were also explored to see the variations among different provinces.

3. Results

3.1. Total attributive deaths for different diseases

For each of the 2826 counties, PM$_{2.5}$-related deaths in 2010 by specific causes (stroke, COPD, LNC, IHD and ALRI) were evaluated. For the four types of PM$_{2.5}$ exposure data and two types of cause-specific baseline mortality data, we obtained eight groups of estimates. The total number of premature deaths from stroke, COPD, LNC, IHD and ALRI attributable to ambient PM$_{2.5}$ in 2010 ranges from 1.18 million to 1.38 million based on different model-inputs, and the PM$_{2.5}$-related premature mortality was 95.72/10^5 persons (Table 1). The average number of premature deaths from the eight model estimates (1.27 million) is close to that of the results of GBD 2010 and is in accordance with previous studies (Fig. 1).

We compared our estimates with those of other recent studies in China and worldwide (Table S3), including the studies that adopted the IER model (Lim et al., 2012; Lelieveld et al., 2015; Rohde and Muller, 2015; J. Liu et al., 2016a; M. Liu et al., 2016b; Xie et al., 2016) (Fig. 1), and found that our 1.27 million estimate of national premature deaths attributed to PM$_{2.5}$ in 2010 was close to the results of the following studies: 1.23 million of the GBD 2010 study (Lim et al., 2012), the 1.25 million by M. Liu et al. (2016b) (in 2012, including stroke, IHD and LNC) and the 1.25 million Xie et al. (in 2010, not including ALRI for children). M. Liu et al. (2016b) also used the IER models and a satellite-derived PM$_{2.5}$ dataset (10 km resolution), and all-age population maps at 1 km resolution in 2010; the endpoint ALRI and COPD death was not included in their study. Xie et al. (2016) explored the long-term trend and spatial pattern of PM$_{2.5}$ induced premature mortality in China between 2000 and 2010, based on the same 1 km × 1 km grid population density map of

China and satellite retrieved $PM_{2.5}$ concentrations and provincial health data. Our results were lower than the 1.36 million by Lelieveld et al. (2015), the 1.37 million by J. Liu et al. (2016a), and the 1.60 million reported by Rohde and Muller (2015). These differences in $PM_{2.5}$ related mortality may be due to the use of different data sources for $PM_{2.5}$ exposure data, the modeling scale, the population data, and the annual incidence rate of mortality for the five diseases. For example, Lelieveld et al. (2015) estimated the global premature deaths related to $PM_{2.5}$ and O_3 based on the method of the GBD 2010, but with an atmospheric chemistry–general circulation model to compute global air quality, combined with country-level population data and health statistics. J. Liu et al. (2016a) estimated the adult mortality attributable to $PM_{2.5}$ exposure in China at a 45 km × 45 km resolution, using the IERs model but based on $PM_{2.5}$ measurements from monitoring sites and a regional air quality model; the population data of their study was 1 km × 1 km grid data in 2010, which was not age-specified, and was projected to 2013 based on the provincial population from the China Statistical Yearbook; and they not include ALRI for children, and some north and northwest regions were out of consideration. Rohde and Muller (2015) carried out another study using the IERs, and obtained a $PM_{2.5}$-attributable mortality of 1.6 million in China. Their population data and pollution data were prefecture city level and the incidence data were based of national average death rates.

Among the $PM_{2.5}$-related premature deaths, the contribution of stroke is the largest (52.90%), followed by IHD (30.77%); COPD and LC in adults accounted for 9.40% and 6.62%, respectively, and the proportion of ALRI in children was the lowest at around 0.32% (Fig. 2 and Fig. 3; for each of the eight estimates, see Fig. S4). Adult IHD and stroke accounted for > 80% of combined $PM_{2.5}$-attributable mortality for all five causes, which is higher than the ~70% of the previous global concentration-mortality relationships (Apte et al., 2015), and the 72% from GBD 2010.

3.2. Total attributive deaths for different diseases

> 58% of the premature deaths were from the elderly group (aged 65 or more); 33.66% in the age group 65–79 and 24.73% in the age group of 80 years old and up (Fig. S5). $PM_{2.5}$-related premature mortality varies greatly among different age groups (Fig. S6) and increases with age. The oldest group (aged 80 or more) has the highest $PM_{2.5}$-related premature mortality at 1497 premature deaths/10^5 persons; the youngest group (aged 5 or less) has the lowest, 5 deaths/10^5 persons. This indicated the $PM_{2.5}$-related disease burden among the aged population is much higher than that in the younger.

3.3. The regional patterns in mortality from $PM_{2.5}$

A map of county-level $PM_{2.5}$ concentration and the total attributable deaths is shown in Fig. 4 (For specific causes, see Supplementary Information Fig. S2). We can see that the spatial pattern of $PM_{2.5}$ related deaths follows the pattern of population density. The Beijing-Tianjin-Hebei Region and the North China Plain were the "center" regions with high $PM_{2.5}$ concentration (Fig. 4-a) and attributable mortality (Fig. 4-b). The Yangtze River Delta Region, the Sichuan Basin (east of Sichuan Province), the central region of the Northeast Plain, the Wuhan Metropolitan Region, and the Changsha - Zhuzhou - Xiangtan Region were 'sub-centers' with high attributive mortality next to the above regions. According to the

Twelfth Five-year Plan for Air Pollution Control of the Key Areas in China, these above regions are among the most polluted and fastest-developing regions of the 'Three Districts and Ten Metropolitan Groups' (The State Council of the People's Republic of China, 2012). In comparison, the western, northwestern and southern parts of China had lower $PM_{2.5}$ concentrations and lower disease burdens, especially in the counties with lower population densities. Counties with high levels of pollution and population density, such as Chaoyang and Haidian in Beijing and Nanyang and Luoyang in the North China Plain had the largest number of deaths related to $PM_{2.5}$, while the highest per capita attributable deaths are all located in heavy-pollution industrial regions such as Anshan and Fushun in Liaoning Province, Tangshan and Hengshui in Hebei province and Kaifeng and Luohe in Henan Province. This regional pattern is generally consistent with previous estimates (J. Liu et al., 2016a; M. Liu et al., 2016b; Xie et al., 2016; Rohde and Muller, 2015; Fang et al., 2016), although there were some variations for different indices. Among the top 20 counties with the largest number of $PM_{2.5}$ related premature deaths, five were located in Henan Province, three in Beijing and three in Shandong Province; the top three counties were Chaoyang in Beijing, Pudong in Shanghai and Dongguan in Guangdong Province, all highly populated regions. Among the top 20 counties with the highest per unit area deaths, Liaoning province had 5 and Tianjin had 4, and the top 3 counties were Shenhe and Heping in Shenyang, Liaoning Province, and Wuhua in Kunming, Yunnan Province. (For detailed information, please see Supplementary Information Table S4–S6).

With respect to per-capita mortality (Fig. 4-c), vast regions of the North China Plain, including Henan, Shandong, and the southern part of Hebei Province had the highest values. Among the top 20 counties with the highest per capita premature deaths, seven were in Liaoning Province, five were in Hebei Province and five in Henan Province, and the top three counties were Lishan in Anshan, Liaoning Province, Guye district in Tangshan, Hebei Province, and Gulou District in Kaifeng, Henan Province. In highly populated regions such as the Beijing-Tianjin-Hebei region, the Pearl River Delta region, and the Yangtze River Delta region, the per-capita mortality is relatively low despite the high $PM_{2.5}$ concentration and the large number of attributive deaths. Per-capita mortality in areas of central China such as Hunan, Hubei and Guizhou province were also high, albeit relatively lower than the above-mentioned regions.

The spatial pattern of 'per-unit-area mortality' is similar to those for total deaths and per-capita deaths, but still has some differences (Fig. 4-d). Counties in the Yangtze River Delta region and in some metropolitan areas such as Shanghai, Beijing and Tianjin had high 'per-unit-area mortality' for both the high levels of pollution and population density. The Pearl River Delta region, where the $PM_{2.5}$ concentration is relatively low, had high 'per-unit-area mortality' mainly resulting from the high population density.

3.4. The cumulative mortality from $PM_{2.5}$

About one half of the total 1.27 million attributive deaths were under/above the annual average concentration of 63.61 μg/m^3, about 0.45 million (35.51% of total deaths) deaths were from counties with annual average $PM_{2.5}$ concentrations of higher than 75.00 μg/m^3, and 0.14 million (10.95%) from counties lower than 35.00 μg/m^3 (Fig. 5). For the entire

country, there were about 373.2 million people (28.16% of Chinese population) living in areas where the annual average concentration of ambient $PM_{2.5}$ was above 75.00 μg/m^3, and only 227.5 million people (17.17%) were living in areas where the annual concentration was under 35 μg/m^3 (China national standard) in 2010 (Fig. S3). This finding documents the very high levels of $PM_{2.5}$ exposures in China, especially in densely populated regions. The results also indicate that the $PM_{2.5}$ related mortality rate is $61.0/10^5$ in the cleanest areas (annual average $PM_{2.5}$ concentrations lower than 35.00 μg/m^3) and $120.7/10^5$ in the most polluted areas (annual average $PM_{2.5}$ concentrations higher than 75.00 μg/m^3). This difference is mainly related to the different RRs which resulted from different exposure levels. According to our comparison (Fig. S8, S9), the RRs of all age groups for all end points in the most polluted areas are significantly higher than those in the cleanest areas. For baseline incidence however, there are no significant differences between the cleanest areas and the most polluted areas.

3.5. Provincial-level comparison

At the provincial level, the top four provinces with the highest $PM_{2.5}$-related deaths were Shandong, Henan, Hebei, and Sichuan, and these regions also had high level of air pollution and population density. The provinces in northern China such as Liaoning, Hebei, Shandong and Henan province had the highest per-capita attributed mortality from $PM_{2.5}$, and Tibet, Yunnan and Hainan had the lowest. Shanghai, Beijing, Tianjin and Shandong were the top four provinces/cities which had the highest per-unit-area mortality, and Tibet, Xinjiang, Qinghai and Inner Mongolia, were the lowest four (see Fig. 6).

4. Discussion

We applied a range of state of the art exposure databases to generate new findings on spatial patterns of mortality related to $PM_{2.5}$ in China. There are several important differences in our analysis compared to previous studies. First, this study was conducted using multi-model $PM_{2.5}$ exposures and a spatial scale at the county-level that covers all of China. The multi-model $PM_{2.5}$ data better expresses the uncertainties related to exposure estimates in assessing disease burden. Second, previous studies based their estimates on gridded all-age population and did not fully cover all of China for missing values. In contrast, we used higher and more relevant "age-specified, county-level population", which captures more detailed demographic information. Third, all of our modeling processes were carried out at the county level, which is a significant advancement compared to the grid, city, or provincial levels. In addition, our study covered 99% of the 2860 counties in China, and our results not only confirmed and improved the results found in previous studies but also added additional spatial richness.

In comparison to surface station measurements, satellite-derived $PM_{2.5}$ concentrations have advantages in terms of spatial coverage, particularly in the vast rural regions not covered by monitoring networks. Different kinds of models have been developed to estimate the exposure of $PM_{2.5}$ concentration from satellite images. After comparing several sources of satellite-derived $PM_{2.5}$ concentrations, we found that the general spatial patterns of these estimates among different models coincided with each other in the large spatial scale, but

many differences were found in smaller scales (Fig. S1). Therefore, to better express the uncertainties introduced by alternative exposure methods, we applied multi-model concentration estimates to obtain more reliable exposure inputs.

Previous estimates of the long-term health effects of $PM_{2.5}$ in China mainly used gridded, provincial, or city-level all-age population data, which are larger scale geographical units compared to counties. By using counties, we were better able to account for differences in demographic and social conditions that vary on fine spatial scales. For example, the aging phenomenon and the urbanization in China has led to great variation of the population age-structure between counties (National Bureau of Statistics of China, 2011; Chen and Hao, 2014). Health status, immunity, and mortality rates differ greatly among different counties and age groups. More detailed modeling using high resolution (county-level and age-specified) population data can better account for these factors in estimating $PM_{2.5}$-related health effects.

Cardiovascular and cerebrovascular disease (IHD and stroke) accounted for the majority of the premature deaths related to $PM_{2.5}$ pollution, and the elderly accounted for the majority of the premature deaths from these two endpoints. The incidence and mortality of these two diseases are higher than the other three diseases in China (National Health and Family Planning Commission of the PRC, 2015; Sui et al., 2016). Our study found the proportion of $PM_{2.5}$-attributable mortality for IHD and stroke account for ~80% of the total number of all five causes combined. This is somewhat higher than the ~70% reported by the GBD study for the entire world. The comparison among age groups and different endpoints indicates that the elderly population groups and theses with cardiovascular and cerebrovascular disease are more vulnerable and sensitive to $PM_{2.5}$ pollution, and should pay more attention to protect them from $PM_{2.5}$ exposure.

The counties with high $PM_{2.5}$-related-mortality are mainly located in the heavily polluted and densely populated regions like Beijing-Tianjin-Hebei region and the North China Plain. This highlights the urgency for China to control air pollution in these regions. Still, a considerable number of premature deaths were seen in other regions with lower average concentration of the air $PM_{2.5}$. For example, some counties with relatively low $PM_{2.5}$ concentration but high population density in Shanghai and Guangdong had large numbers of premature deaths (Fig. S7). Also, the Pearl River Delta region, where the $PM_{2.5}$ concentration is relatively low, had a high 'per-unit-area mortality' resulting from the high population density. These information is important for making priority emission-reducing policies for different regions. For the highly-populated regions, policies and air quality standards may need to be stricter to avoid more $PM_{2.5}$ related premature deaths.

In recent years, the Chinese government has taken measures to control the pollution. According to the 13th Five-Year Plan of National Environmental Protection of China (Zhao, 2014), by the year 2030, all counties in China will reach the national standard. The disease burden of $PM_{2.5}$ will likely decline if the emission reduction targets are reached. Nevertheless, Combined with the acceleration of aging (National Bureau of Statistics of China, 2011; Wang and Chen, 2014), the disease burden from air pollution is likely to remain heavy in spite of the planned improvement of air quality. To reduce the health effects

of $PM_{2.5}$, China needs continuous efforts in pollution reduction. Measures and improvement should be step by step, under the guidance of scientific evidence.

Our study has the advantage in the spatial resolution and reliability for both $PM_{2.5}$ exposure and population data. These new results add useful spatial dimensions to previous health burden estimates for China. However, it is important to keep in mind that this is an ecological study of the impact of $PM_{2.5}$ on deaths at the county-level of China. It is known that analysis of health impacts of air pollution can be subject to large uncertainties (Kinney et al., 2010; Roman et al., 2008). First, we did not take all age groups into consideration. The '5–24' age group was not considered in our model, which may lead to some underestimation of the health burden. However, people of this age group are young and relatively healthier than those of other age groups, and might have better resistance to air pollution related premature deaths. Secondly, baseline mortality data for each disease was available at the provincial level. Optimally, county-level estimates should use county-level base-line mortality data, but these data were not available. Therefore, we adopted provincial baseline mortality data, and an implicit assumption in our approach is that the underlying disease incidence is spatially invariant within each province. To support more accurate studies in the future, China should systematically collect and make available statistics for county-level disease-specific baseline mortality. Another uncertainty could come from the IER model applied in this study. To consider a wide range of exposures, Burnett et al. (2014) developed the IER model to estimate the $PM_{2.5}$-related deaths. The RRs from secondhand smoking, active smoking, and household air pollution were integrated to form the IER model. A comparison done between the RRs observed in China and those evaluated by the IER model suggests that the IER model can yield sensible results in the risk analysis over the range of concentrations that prevail in China (Burnett et al., 2014). However, the 95% confidence interval (CI) of the RRs developed from the IERs was somewhat wide, and more information should be collected from epidemiologic studies in China to obtain better RRs. In addition, the adverse effect of $PM_{2.5}$ exposure could be accumulated for longer time periods, so it is also necessary to estimate the long-term cumulative effects of $PM_{2.5}$.

5. Conclusion

Following the methods of the GBD 2010 and the study of Apte et al. (2015), using four sources of satellite-derived $PM_{2.5}$ concentration data and county-level age-specified population data across China in 2010, we estimated the $PM_{2.5}$ related mortality for each county in China and observed significant spatial variations. This study provides a refined estimation of historical health effects attributable to outdoor $PM_{2.5}$ in China at the county-level in 2010. To our knowledge, this is the first study to quantify the health consequences of China's $PM_{2.5}$ pollution at the county-level. Although some limitations exist, this work contributes valuable insights into the strong spatial variations of $PM_{2.5}$ related health burdens in China. The findings of this study provide important implications for urban planners and policy makers regarding priority areas of national joint air pollution prevention and control in China. Moreover, open publication of our county-level health effects datasets also makes it possible to further explore the determinants of these health impacts.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2017.10.015.

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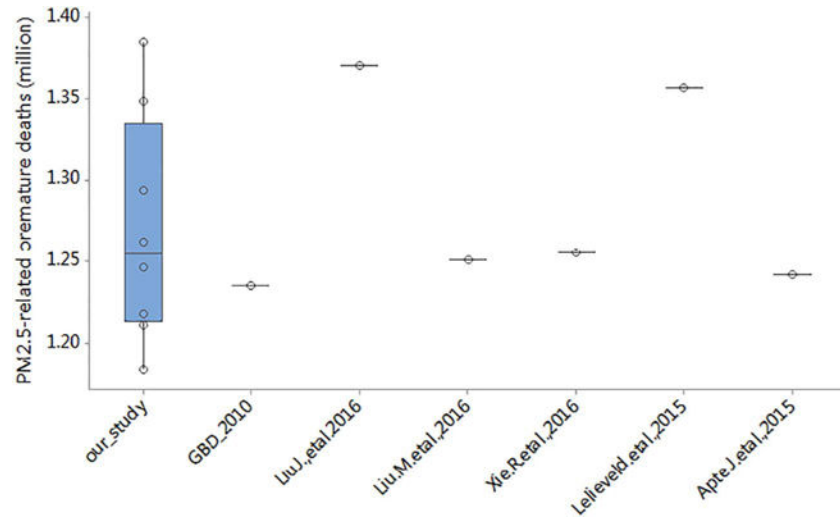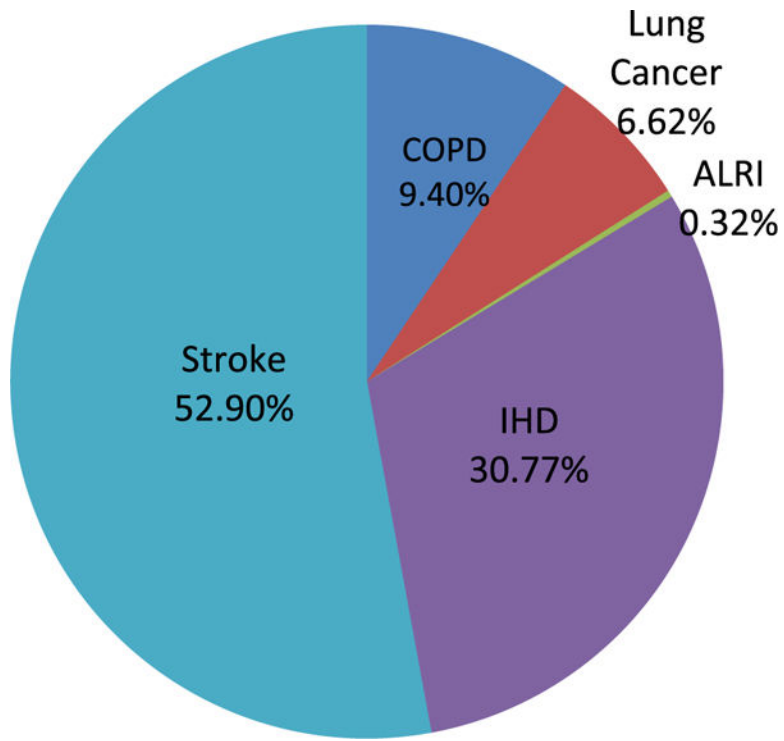
Fig. 1.
PM$_{2.5}$-related premature deaths of our study and previous studies.

Fig. 2.
Proportions of $PM_{2.5}$-related premature deaths for each endpoint.
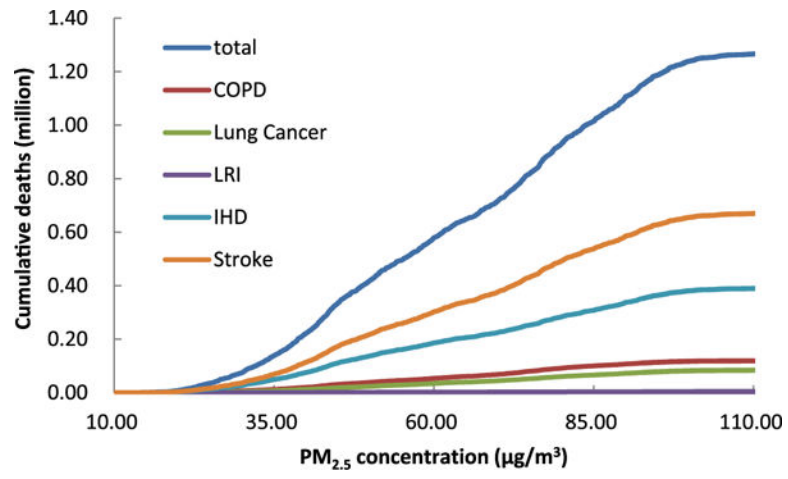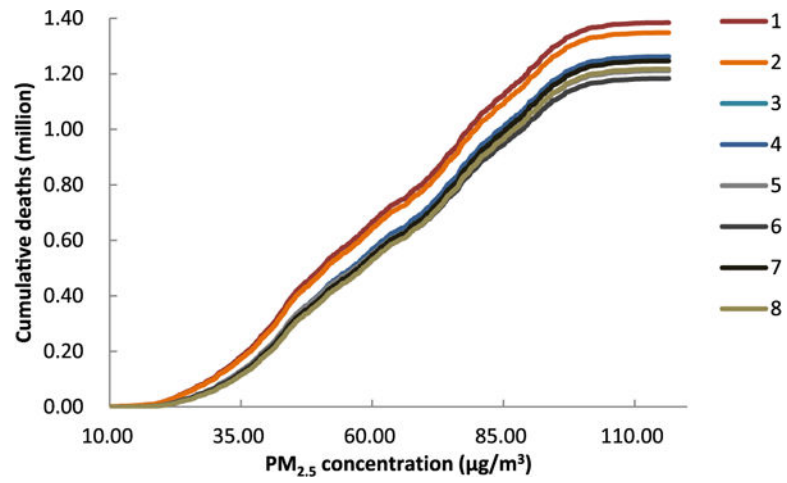
Fig. 3.
Cumulative numbers of PM$_{2.5}$-related deaths for each endpoint.
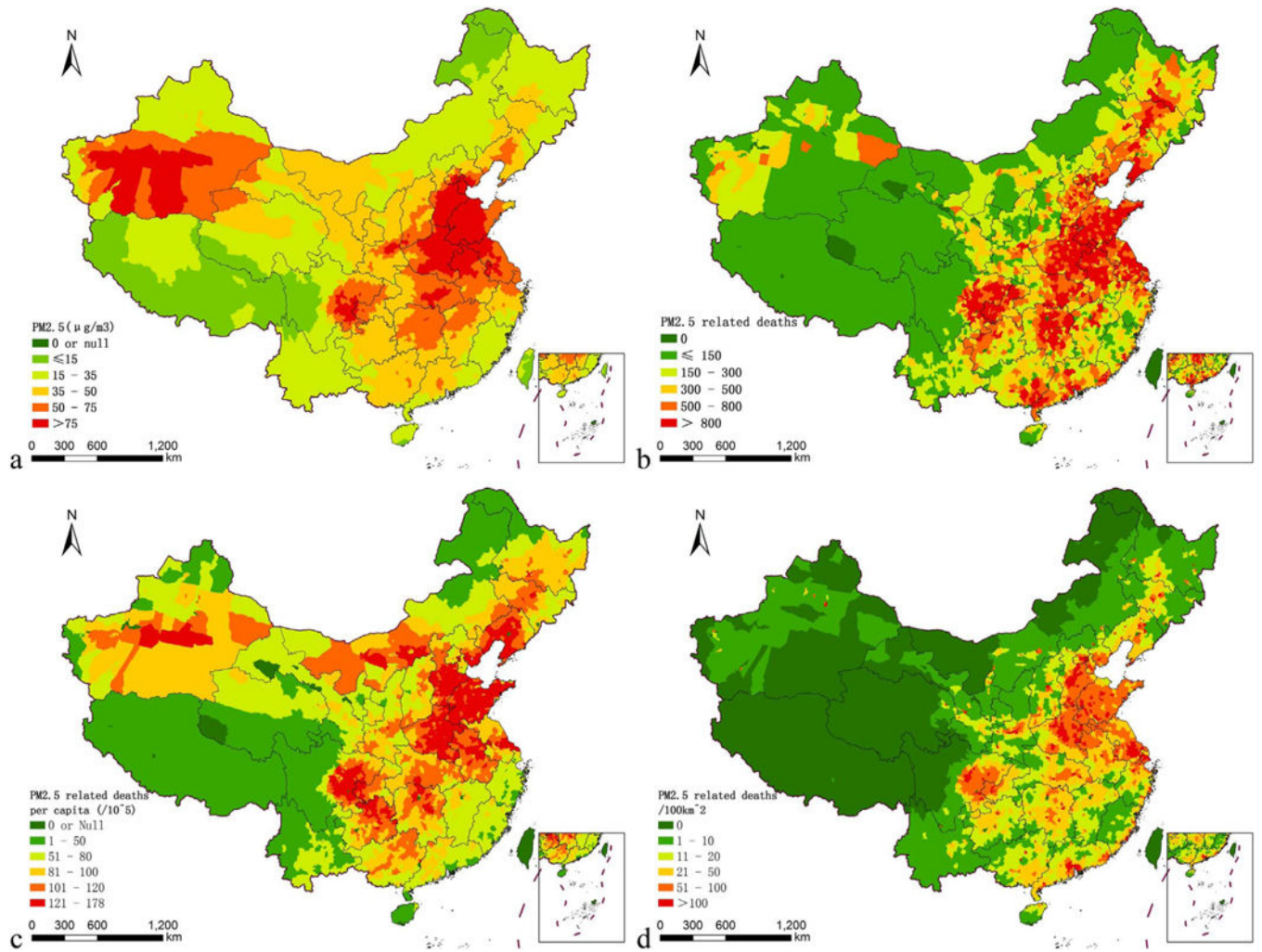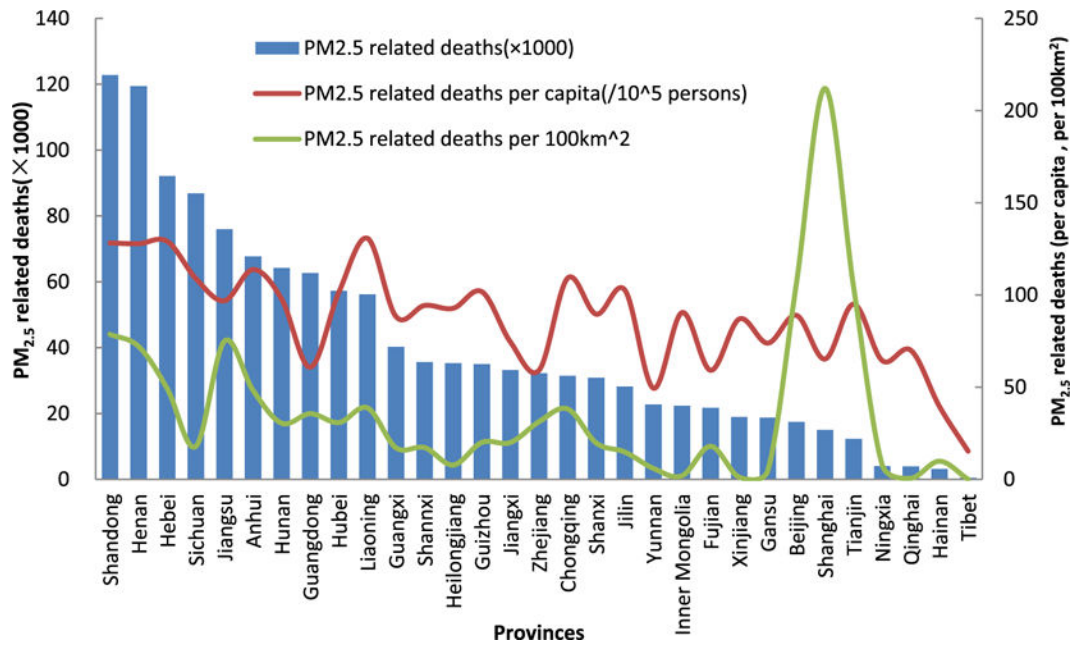
Fig. 4.
PM$_{2.5}$ concentration (an average of the four models) and related deaths of China.

Fig. 5.
Cumulative numbers of PM$_{2.5}$-related deaths (Note: Number 1–8 represents eight estimates based on eight sets of data sources, as listed in Table 1).

Fig. 6.

The regional patterns in premature mortality from PM$_{2.5}$ in China (The main vertical axes indicate the number of PM$_{2.5}$ related premature deaths, and the secondary vertical axes indicate the per-capita deaths and per-unit-area mortality attributed to PM$_{2.5}$).

Table 1

PM$_{2.5}$-related premature deaths in China in 2010 (×1000 deaths).

No.	PM$_{2.5}$ data set	Mortality data set	COPD	LNC	ALRI	IHD	Stroke	Total	Per capita deaths/10^5	/100 km^2
1	Satellite-Ma et al., 2016	Zhou's + GBD	148.82	98.17	5.26	412.41	719.66	1384.31	104.47	14.55
2	Satellite-Ma et al., 2016	GBD	121.34	90.69	4.07	412.41	719.66	1348.16	101.74	14.17
3	GBD 2010	Zhou's + GBD	133.62	88.79	4.61	392.12	674.68	1293.81	97.64	13.60
4	GBD 2010	GBD	109.39	82.06	3.57	392.12	674.68	1261.82	95.23	13.26
5	ACAG-dust	Zhou's + GBD	116.35	78.01	3.87	374.98	638.08	1211.28	91.41	12.73
6	ACAG-dust	GBD	94.97	72.14	2.99	374.98	638.08	1183.16	89.29	12.44
7	NASA	Zhou's + GBD	125.45	84.01	4.27	381.57	651.21	1246.51	94.07	13.10
8	NASA	GBD	103.40	77.93	3.32	381.57	651.21	1217.42	91.88	12.80
9	Average		119.17	83.98	4.00	390.27	670.91	1268.31	95.72	13.33

Note: the left three column means the eight estimating scenarios based on the two kinds of cause-specific mortality data and four types of PM2.5 exposure data. The line No. 9 represents the average of the eight model estimates.