



# Estimating mortality burden attributable to short-term PM<sub>2.5</sub> exposure: A national observational study in China

Tiantian Li<sup>a,1</sup>, Yuming Guo<sup>b,1</sup>, Yang Liu<sup>c,1</sup>, Jiaonan Wang<sup>a</sup>, Qing Wang<sup>a</sup>, Zhiying Sun<sup>a</sup>, Mike Z. He<sup>d</sup>, Xiaoming Shi<sup>a,\*</sup>

<sup>a</sup> National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, Beijing, China

<sup>b</sup> Department of Epidemiology and Preventive Medicine, School of Public Health and Preventive Medicine, Monash University, Melbourne, Australia

<sup>c</sup> Department of Environmental Health, Rollins School of Public Health, Emory University, Atlanta, USA

<sup>d</sup> Department of Environmental Health Sciences, Columbia University Mailman School of Public Health, New York, USA

## ARTICLE INFO

Handling Editor: Xavier Querol

Keywords:

PM<sub>2.5</sub>

Short-term

Mortality burden

Non-linear

## ABSTRACT

Studies worldwide have estimated the number of deaths attributable to long-term exposure to fine airborne particles (PM<sub>2.5</sub>), but limited information is available on short-term exposure, particularly in China. In addition, most existing studies have assumed that short-term PM<sub>2.5</sub>-mortality associations were linear. For this reason, the use of linear exposure-response functions for calculating disease burden of short-term exposure to PM<sub>2.5</sub> in China may not be appropriate. There is an urgent need for a comprehensive, evidence-based assessment of the disease burden related to short-term PM<sub>2.5</sub> exposure in China. Here, we explored the non-linear association between short-term PM<sub>2.5</sub> exposure and all-cause mortality in 104 counties in China; estimated county-specific mortality burdens attributable to short-term PM<sub>2.5</sub> exposure for all counties in the country and analyzed spatial characteristics of the mortality burden due to short-term PM<sub>2.5</sub> exposure in China. The pooled PM<sub>2.5</sub>-mortality association was non-linear, with a reversed J-shape. We found an approximately linear increased risk of mortality from 0 to 62 µg/m<sup>3</sup> and decreased risk from 62 to 250 µg/m<sup>3</sup>. We estimated a total of 169,862 additional deaths from short-term PM<sub>2.5</sub> exposure throughout China in 2015. Models using linear exposure-response functions for the PM<sub>2.5</sub>-mortality association estimated 32,186 deaths attributable to PM<sub>2.5</sub> exposure, which is 5.3 times lower than estimates from the non-linear effect model. Short-term PM<sub>2.5</sub> exposure contributed greatly to the death burden in China, approximately one seventh of the estimates from the chronic effect. It is essential and crucial to incorporate short-term PM<sub>2.5</sub>-related mortality estimations when considering the disease burden attributable to PM<sub>2.5</sub> in developing countries such as China. Traditional linear effect models likely underestimated the mortality burden due to short-term exposure to PM<sub>2.5</sub>.

## 1. Introduction

Fine particulate matter (particles  $\leq 2.5\mu\text{m}$  in aerodynamic diameter; PM<sub>2.5</sub>) has been a major public health concern in China over the past few decades, ranking fifth among risk factors for disease burden in China in 2010 (Forouzanfar et al., 2016). According to the most recent Global Burden of Disease (GBD) study, exposure to ambient PM<sub>2.5</sub> caused 4.2 million deaths globally in 2015 (Cohen et al., 2017). China leads the world in disease burden attributable to PM<sub>2.5</sub>, which accounted for more than one-quarter of total PM<sub>2.5</sub>-attributable deaths in the world in 2015 (Cohen et al., 2017). Many studies performed using the GBD methodology have confirmed that over one million deaths are

attributable to PM<sub>2.5</sub> exposure in China (Wang et al., 2018; Lelieveld et al., 2015; Lim et al., 2012; J. Liu et al., 2016; M. Liu et al., 2016). Notably, all of these results from previous studies have focused on the estimations of deaths attributable to the chronic effects of PM<sub>2.5</sub>.

Many studies have shown that short-term exposure to PM<sub>2.5</sub> is related to increased risks of mortality (Atkinson et al., 2014; Chen et al., 2018; Chen et al., 2017). Thus, the mortality burden due to short-term exposure to PM<sub>2.5</sub> may also be serious in China because of the combined impact of the high magnitude of PM<sub>2.5</sub> exposure and the large population. A quantitative estimate of the disease burden related to short-term PM<sub>2.5</sub> exposure is urgently needed in China to develop better emission control, disease control, and health policies.

\* Corresponding author at: National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, No. 7, Panjiayuan Nanli, Chaoyang District, Beijing 10021, China.

E-mail address: [shixm@chinacdc.cn](mailto:shixm@chinacdc.cn) (X. Shi).

<sup>1</sup> Tiantian Li, Yuming Guo and Yang Liu are co-first authors.

<https://doi.org/10.1016/j.envint.2019.01.073>

Received 17 November 2018; Received in revised form 28 January 2019; Accepted 28 January 2019

0160-4120/© 2019 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Although a large number of air pollution epidemiologic studies have shown that short-term exposure to PM<sub>2.5</sub> is associated with mortality, the assumption for the exposure-response relationship is critical for calculating the burden of disease. Generally, a linear exposure-response function is used to calculate the burden of disease due to short-term PM<sub>2.5</sub> exposure (Atkinson et al., 2014). However, recently, little evidence has suggested that the association between short-term PM<sub>2.5</sub> exposure and mortality is non-linear in China (Chen et al., 2017; Chen et al., 2011), which has not been found in previous studies in developed countries with low exposure levels (Daniels et al., 2000; Schwartz and Zanobetti, 2000; Schwartz et al., 2002). As such, the use of linear exposure-response functions for calculating disease burden of short-term exposure to PM<sub>2.5</sub> in China may not be appropriate.

To address the limitations listed above, this study investigated the national level mortality burden attributable to short-term exposure of PM<sub>2.5</sub> in China. Our objectives are as follows: (1) to explore the non-linear association between short-term PM<sub>2.5</sub> exposure and all-cause mortality in 104 counties in China; (2) to estimate county-specific mortality burdens attributable to short-term PM<sub>2.5</sub> exposure for all counties in the country; and (3) to analyze spatial characteristics of the mortality burden due to short-term PM<sub>2.5</sub> exposure in China.

## 2. Methods

### 2.1. Data

We collected daily county level (a key unit for administration and policy making in China) mortality, PM<sub>2.5</sub> and meteorological data from 2013 to 2015 in 104 counties in China from SHEAP dataset (SHEAP data is from the project of short-term health effect of air pollution in China). The locations of the counties are shown in Fig. 1. Daily county-specific all-cause mortality data were collected from the Chinese Center for Disease Control and Prevention. Daily county-specific mean temperature and relative humidity were collected from the China Meteorological Data Sharing Service System. Daily county-specific PM<sub>2.5</sub> data were estimated from Moderate Resolution Imaging Spectroradiometer (MODIS) collection 6 level 2 aerosol optical depth (AOD) at 10 km resolution. We used multiple imputation to fill in missing satellite data and then divided the study domain into seven clusters to control for unobserved spatial heterogeneity. We trained a cluster-based random forest model with daily convolution layer of PM<sub>2.5</sub> constructed from ground PM<sub>2.5</sub> measurements as an input to account for the spatial autocorrelation of PM<sub>2.5</sub>. The centroid of each 10 km grid was spatially joined with the selected 104 counties. An unweighted average of PM<sub>2.5</sub> concentrations was calculated when a county contained more than one PM<sub>2.5</sub> grid. If no PM<sub>2.5</sub> grids fell within the county, then the closest grid was assigned as the PM<sub>2.5</sub> concentration for that county.

Fig. S1 shows the workflow of PM<sub>2.5</sub> modeling. First, we filled missing satellite data by multiple imputation including the Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depth (AOD) from Aqua and Terra satellites, the MODIS cloud fraction (Platnick et al., 2003), the Community Multi-scale Air Quality (CMAQ) AOD simulations (Appel et al., 2012), and elevation data (Xiao et al., 2017). After gap-filling, the coverage of satellite retrieval increased to 100% in space and time. Second, the modeling domain was divided into seven clusters using geographically weighted regression (GWR), the K-means algorithm, and GIS methods. Dividing a large modeling domain into sub-regions controlled unobserved spatial heterogeneity and improved model performance. This cluster pattern was stable in time. Random forest models were trained in each region separately. Finally, we used the fitted random forest models to estimate daily PM<sub>2.5</sub> concentrations at grid cells without monitor. To evaluate model performance, the ten-fold cross validation results are shown in Fig. S2. The random forest model predictions were closely consistent with ground measurements, with R<sup>2</sup> larger than 0.90 and slope close to 1.0.

To estimate the additional deaths attributable to PM<sub>2.5</sub> in China in

2015, we also extracted county-specific population and total mortality rate data for all of the counties in China from the sixth nationwide population census (National Bureau of Statistics of China, 2015). The county-specific daily PM<sub>2.5</sub> of all 2851 counties in China in 2015 was also modeled using the method mentioned above.

### 2.2. Statistical analysis

#### 2.2.1. Non-linear effect model

A three-stage analysis was performed in this study. In the first stage, we estimated the county-specific non-linear PM<sub>2.5</sub>-mortality relationships in 104 counties in China. During the second stage, we pooled the estimated county-specific exposure-response functions using a meta-regression model. In the third stage, we estimated the additional deaths due to short-term exposure to PM<sub>2.5</sub> in China in 2015 by combining the pooled PM<sub>2.5</sub>-mortality association and county-level daily PM<sub>2.5</sub> exposure.

**2.2.1.1. First stage analysis.** We implemented a standard time series quasi-Poisson regression for each county to evaluate the effect of same-day PM<sub>2.5</sub> on all-cause mortality. We modeled the exposure-response curve with natural cubic splines with two internal knots at 35 µg/m<sup>3</sup> and 75 µg/m<sup>3</sup> of PM<sub>2.5</sub> concentrations for the main analysis. We applied a county-specific 95% percentile of PM<sub>2.5</sub> concentration as the cut-off point for PM<sub>2.5</sub> values to avoid extremely high values which affected the model performance. We controlled for day of the week as a categorical variable, daily mean temperature and relative humidity using a natural cubic spline with 3 degrees of freedom (df) respectively, and seasonal and long-term trends with a natural cubic spline with 5 df per year. We then predicted the county-specific log relative risk (RR) and standard error (SE) for daily PM<sub>2.5</sub> exposure.

**2.2.1.2. Second stage analysis.** In the second stage, we pooled the associations between PM<sub>2.5</sub> and mortality for 104 counties using a random-effect meta-regression with restricted maximum likelihood (REML) estimation.

The main model above is defined as Model 1. We conducted several sensitivity analyses to check the non-linear association. We used a linear model to examine the linear association between PM<sub>2.5</sub> and mortality (Model 2). We set natural cubic splines with three knots at 35 µg/m<sup>3</sup>, 50 µg/m<sup>3</sup>, and 75 µg/m<sup>3</sup> (Model 3), and with four knots at 35 µg/m<sup>3</sup>, 50 µg/m<sup>3</sup>, 75 µg/m<sup>3</sup>, and 125 µg/m<sup>3</sup> (Model 4). The knots were also changed in the first stage analysis for Model 3 and Model 4. We used I<sup>2</sup> statistics to quantify the heterogeneity among models (Supplementary Table S3), and we selected model 1, which provided the lowest I<sup>2</sup> value in the main analysis. We used 0 µg/m<sup>3</sup> as the centering value and the reference PM<sub>2.5</sub> concentration to calculate the relative risks.

**2.2.1.3. Third stage analysis.** We finally applied model 1 to predict PM<sub>2.5</sub> and all-cause mortality associations in all 2851 counties in China to calculate the additional short-term all-cause deaths related to PM<sub>2.5</sub> in 2015 by incorporating county-specific modeled daily PM<sub>2.5</sub> concentrations, county-specific populations, and mortality rates from the sixth nationwide population census.

Daily additional deaths attributable to PM<sub>2.5</sub> for county *i* were calculated as follows:

$$\Delta Mortality_i = Y_i \times ERC_i \times POP_i \quad (1)$$

Here,  $\Delta Mortality_i$  is the daily PM<sub>2.5</sub>-related additional deaths in county *i*,  $Y_i$  represents the baseline daily mortality rate in county *i*,  $POP_i$  is the population in county *i*.  $ERC_i$  is the attributable percentage variation in mortality for a specified variation in PM<sub>2.5</sub>, derived from the calculated relative risk at each PM<sub>2.5</sub> concentration from the meta-regression model in the second stage of analysis.

We calculated the daily death attributable to PM<sub>2.5</sub> by this method

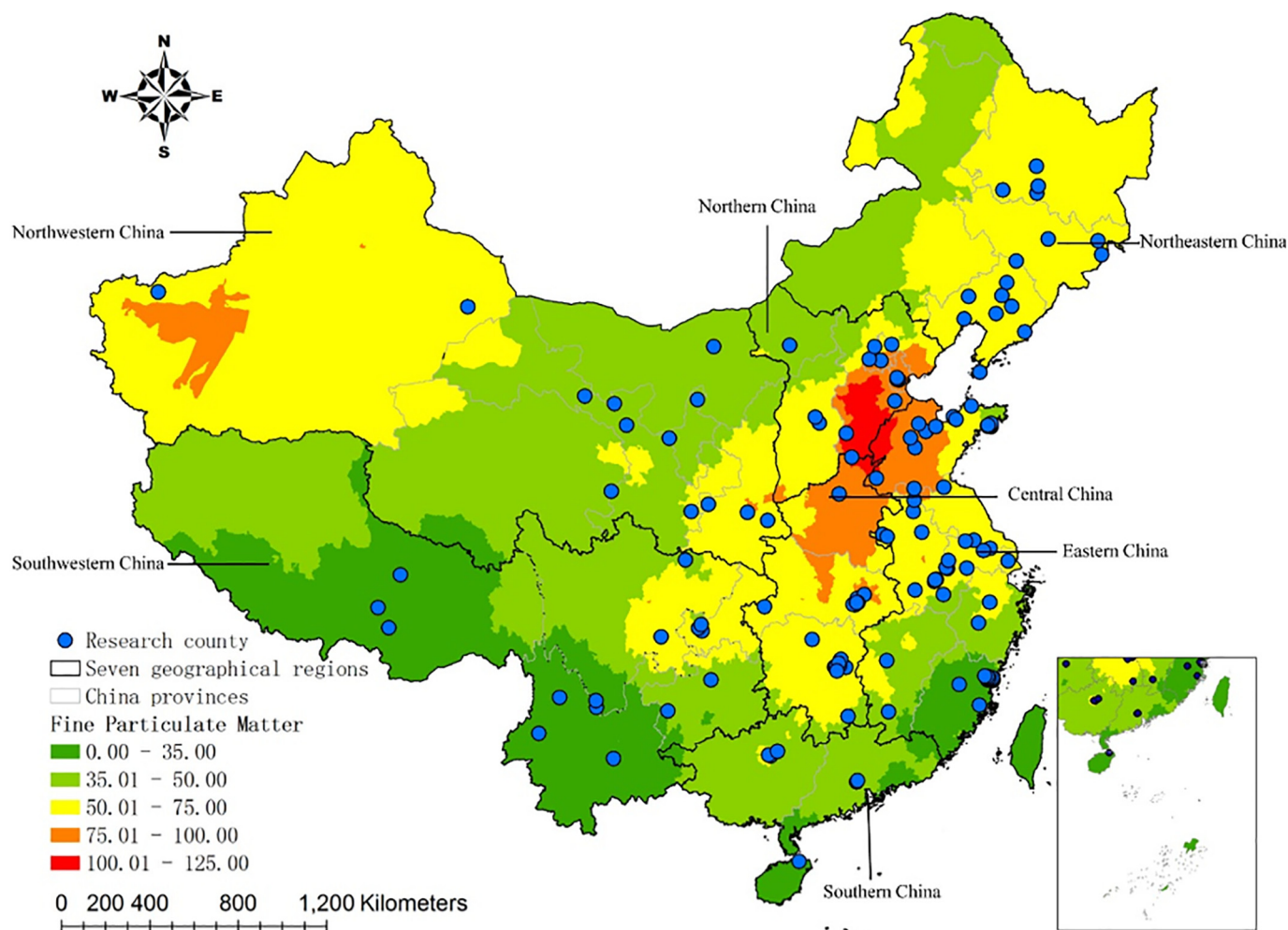


Fig. 1. Map of  $PM_{2.5}$  concentration during the study period (2013–2015). Blue points indicate the geographic centers of 104 counties. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for all 365 days in 2015 in each county. We then calculated the sum of  $PM_{2.5}$ -related deaths in all counties in China in 2015.

### 2.2.2. Linear effect model

We also conducted the same analysis using a linear effect model for the  $PM_{2.5}$ -mortality association and mortality burden estimation for comparison with the non-linear effect models. A three-stage analysis was used to investigate the relationship of the  $PM_{2.5}$  and mortality and the mortality burden of  $PM_{2.5}$ .

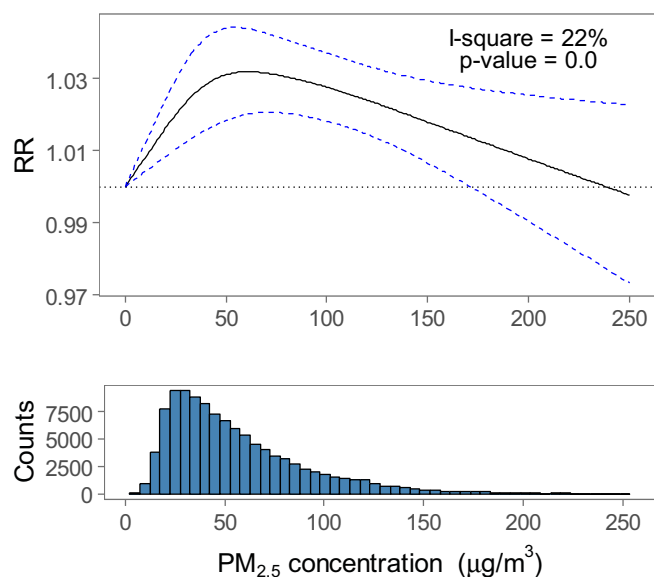
In the first stage, generalized linear models assuming a quasi-Poisson distribution were used to generate county-specific  $PM_{2.5}$ -mortality associations. Same-day  $PM_{2.5}$  concentrations were used in the main analysis (Table S2). We controlled for daily average temperature, relative humidity, day of the week, and calendar date in the model. The covariates were adjusted according to the following: a natural cubic spline with 3 degrees of freedom (df) for daily mean temperature and daily mean relative humidity, a natural cubic spline with 5 df per year for the long-term trend and day of the week. Sensitivity analyses were also conducted to check the robustness of the results in the main analysis (Table S1). In the second stage, we pooled the county-specific associations to generate an overall association between  $PM_{2.5}$  and mortality by conducting a random-effect meta-analysis. In the third stage, we used the association from the second stage to calculate the additional short-term all-cause deaths related to  $PM_{2.5}$  in 2015 by incorporating the county-specific modeled daily  $PM_{2.5}$  concentrations, county-specific populations, and mortality rates from the sixth

national population census. We calculated the daily death attributable to  $PM_{2.5}$  by this method for all 365 days in 2015 in each county. We then calculated the sum of  $PM_{2.5}$ -related deaths in all of the counties in China in 2015.

All of the analyses were performed using the R statistical software (version 3.3.1, 64-bit, Foundation for Statistical Computing, Vienna, Austria). The “mvmeta” and “dlnm” package in R software was used in this study.

## 3. Results

Fig. 1 presents  $PM_{2.5}$  concentrations during the study period (2013–2015). The blue points show centroids of the 104 counties used in the first stage of analysis. The 104 counties cover all seven geographical regions in China (Eastern, Northern, Central, Southern, Southwestern, Northwestern, and Northeastern) and 31 provinces (except Hong Kong, Macao, and Taiwan). The highest  $PM_{2.5}$  concentrations were observed in the Beijing-Tianjin-Hebei region, with annual mean concentrations above  $100 \mu\text{g}/\text{m}^3$ . Table S2 shows the descriptive statistics for mortality,  $PM_{2.5}$ , and meteorological data for the 104 counties. The dataset included 1,069,911 deaths. Approximately 9 all-cause deaths per day on average occurred during the study period, with the highest number of daily average, 28 deaths per day, recorded in Yongqiao County in Anhui Province. The overall mean daily concentrations of  $PM_{2.5}$  were  $61.6 \mu\text{g}/\text{m}^3$  in these 104 counties. The highest county-specific daily mean concentration of  $PM_{2.5}$  is  $106.7 \mu\text{g}/\text{m}^3$ ,



**Fig. 2.** Association between daily  $PM_{2.5}$  concentration and relative risk of total mortality using random-effect meta-regression with a natural cubic spline model for  $PM_{2.5}$  with 2 knots (Model 1).

which was recorded in Xingtai County in Hebei Province. The lowest county-specific daily mean concentration of  $PM_{2.5}$  was  $23.2 \mu\text{g}/\text{m}^3$ , which was recorded in Meilan County in Hainan Province.

The association between daily  $PM_{2.5}$  concentration and relative risk of total mortality from model 1 is shown in Fig. 2. The association was non-linear, with approximately linear increasing mortality risk from 0 to  $62 \mu\text{g}/\text{m}^3$ . From  $62$  to  $250 \mu\text{g}/\text{m}^3$ , the risk decreases gradually. The RRs are 1.026 (95% CI: 1.014–1.038) and 1.031 (95% CI: 1.021–1.042) for  $PM_{2.5}$  concentration of  $35 \mu\text{g}/\text{m}^3$  and  $75 \mu\text{g}/\text{m}^3$  versus  $0 \mu\text{g}/\text{m}^3$ , respectively. The  $I^2$  of model 1 is 22%, which accounts for the minimum heterogeneity among all the models. The  $I^2$  statistics of all models is shown in Table S3, and model 2 (linear effect model) showed the most heterogeneity. The associations between  $PM_{2.5}$  and mortality estimated by model 2, model 3, and model 4 are shown in Figs. S3, S4, and S5, respectively.

Regional statistics of county level population, mortality rate, and annual  $PM_{2.5}$  concentration are shown in Table S4. The predicted number of additional deaths attributable to  $PM_{2.5}$  and the corresponding additional death rate in the seven regions of China in 2015 are shown in Table 1. The number of predicted additional deaths attributable to short-term  $PM_{2.5}$  exposure was 169,862 (95% CI: 97,994, 240,967), and the additional death rate was 13.78 (95% CI: 7.95–19.55) per 100,000 people throughout China in 2015. The highest additional death was observed in Eastern China, with 52,502 (95% CI: 30,505–74,266) deaths. The population of Eastern China is 358,863,351, and the average mortality rate is 6.0‰ with a mean annual  $PM_{2.5}$  concentration of  $49.5 \mu\text{g}/\text{m}^3$ . The highest additional death

rate was 15.03 (95% CI: 8.51–21.49) per 100,000 people in Southwestern China, which has a population of 185,917,082, an average mortality rate of 6.5‰, and a mean annual  $PM_{2.5}$  concentration of  $35.1 \mu\text{g}/\text{m}^3$ . The mortality burden of  $PM_{2.5}$  estimated from linear effect model was 32,186 (95%CI: 10,705–53,631) in China, which is much lower than the estimation from the non-linear effect model.

We estimated and mapped county-specific additional deaths associated with short-term exposure to  $PM_{2.5}$ , as well as additional deaths rate (1/100,000) and additional deaths per  $100 \text{ km}^2$  (Figs. 3, 4, and S6). Regions of high additional deaths included the Beijing-Tianjin-Hebei area in Northern China, the Yangtze River Delta in Eastern China, the Changsha-Zhuzhou-Xiangtan and Wuhan area in Central China, the Sichuan Basin in Southwestern China, and the southwest coast of Guangdong Province in Southern China. The spatial pattern of the increase in death rates showed little difference than those for additional deaths. Aside from the Beijing-Tianjin-Hebei area in Northern China, the Yangtze River Delta in Eastern China and Sichuan Basin in Southwestern China, the North Tibet area in Southwestern China, the South Sinkiang area in Northwestern China and Liaoning Province in Northeastern China also exhibited high additional death rates. The spatial pattern of additional deaths per  $100 \text{ km}^2$  was similar to that of additional deaths except for southwest region.

#### 4. Discussion

To the best of our knowledge, this is the first study to evaluate county-specific additional deaths due to short-term  $PM_{2.5}$  exposure in China using a non-linear effect model. The impacts of short-term exposure to  $PM_{2.5}$  on mortality were linearly positive from 0 to  $62 \mu\text{g}/\text{m}^3$ , and then decreasing RR from 62 to  $250 \mu\text{g}/\text{m}^3$ . We estimated the number of deaths related to short-term exposure of  $PM_{2.5}$  from the non-linear model to be 169,862 (95% CI: 97,994 and 240,967) for the entire country in 2015. However, the linear effect model estimated only 32,186 deaths for the entire country in 2015.

Our findings suggest that in developing countries like China, often with a wide range of  $PM_{2.5}$  concentrations, the relationship between  $PM_{2.5}$  and mortality is non-linear. This study delivers the first insight into the burden of disease associated with short-term exposure to  $PM_{2.5}$  in areas with high exposure to  $PM_{2.5}$ , which may provide a scientific foundation for implementing public health intervention policies. The use of a linear function may greatly underestimate the mortality burden attributable to short-term  $PM_{2.5}$  exposure in China.

Although a large number of previous studies have assumed a linear relationship (Atkinson et al., 2014; Lu et al., 2015; Franklin et al., 2007) between  $PM_{2.5}$  and mortality, some studies have provided clues suggesting that the shape of the  $PM_{2.5}$ -mortality exposure-response relationship is non-linear (Chen et al., 2017; Daniels et al., 2000; Schwartz and Zanobetti, 2000; Schwartz et al., 2002). Some US studies have investigated the shape of the relationship between short-term particulate matter and mortality. These studies focused on the evidence of a threshold at low concentrations. However, these studies found that the exposure-response relationship to be nearly linear, with no evidence

**Table 1**

Predicted  $PM_{2.5}$ -related additional deaths and increase in death rates in different regions of China in 2015, with non-linear  $PM_{2.5}$ -mortality association estimated using Model 1.

| Region             | Additional deaths               | Increase in death rate (1/100,000) |
|--------------------|---------------------------------|------------------------------------|
| Eastern China      | 52,502 (95%CI: 30,505–74,266)   | 14.63 (95%CI: 8.50–20.69)          |
| Northern China     | 18,032 (95%CI: 10,396–25,580)   | 13.67 (95%CI: 7.88–19.39)          |
| Central China      | 29,899 (95%CI: 17,669–41,992)   | 14.59 (95%CI: 8.62–20.49)          |
| Southern China     | 15,263 (95%CI: 8622–21,851)     | 10.41 (95%CI: 5.88–14.91)          |
| Southwestern China | 27,945 (95%CI: 15,823–39,948)   | 15.03 (95%CI: 8.51–21.49)          |
| Northwestern China | 11,944 (95%CI: 6842–16,984)     | 12.60 (95%CI: 7.22–17.92)          |
| Northeastern China | 14,277 (95%CI: 8137–20,346)     | 13.00 (95%CI: 7.41–18.52)          |
| China              | 169,862 (95%CI: 97,994–240,967) | 13.78 (95%CI: 7.95–19.55)          |

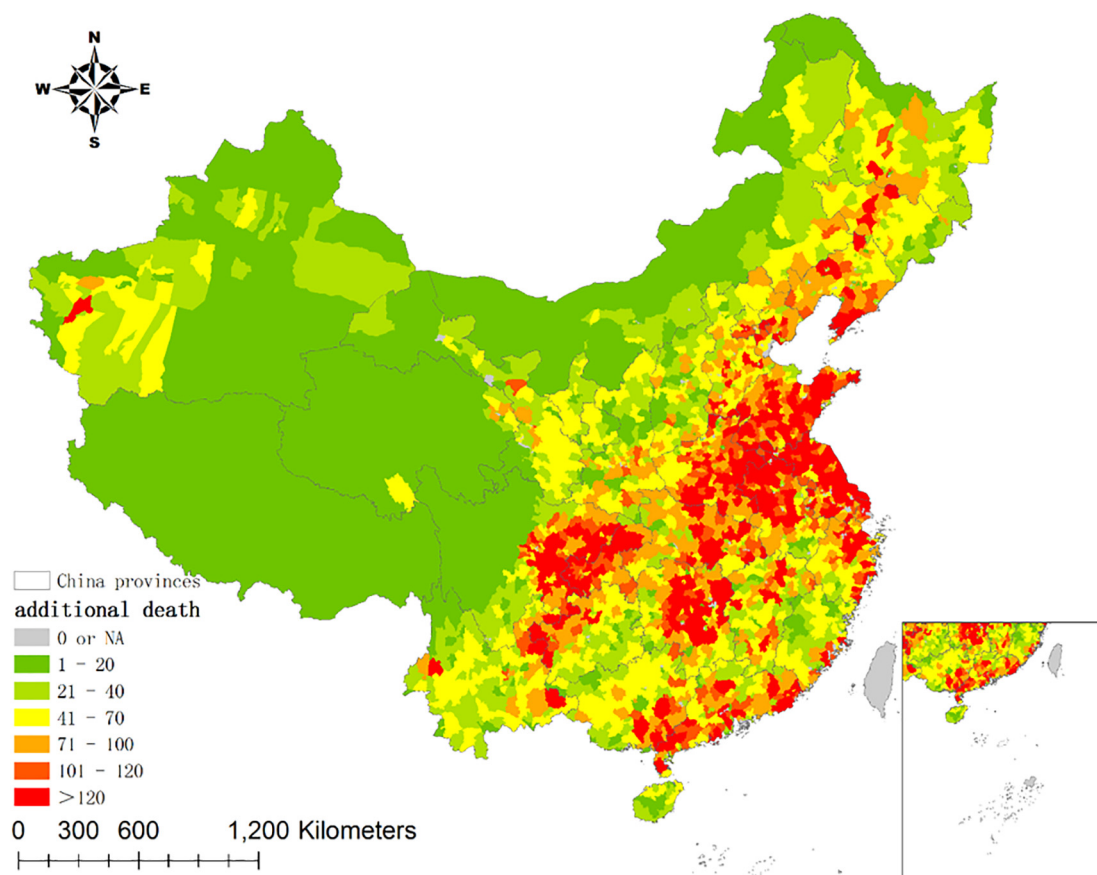


Fig. 3. Predicted short-term  $PM_{2.5}$ -related additional deaths in China in 2015 as indicated by Model 1.

of the presence of a threshold at low concentrations (Daniels et al., 2000; Schwartz and Zanobetti, 2000; Schwartz et al., 2002). The concentrations of  $PM_{2.5}$  in these US studies were very low, normally daily  $PM_{2.5}$  concentrations below  $35 \mu\text{g}/\text{m}^3$  (Franklin et al., 2007). However, the  $PM_{2.5}$  exposure in China has an extensive range of concentrations, the daily concentration of  $PM_{2.5}$  normally ranged from a few to many hundreds. A recent short-term  $PM_{2.5}$  and mortality study in 272 Chinese cities showed that the shape of  $PM_{2.5}$  and mortality relationship is non-linear, with the effect that magnitude tended to be lower at higher concentrations (Chen et al., 2017), which is very similar to our results in this study. We found that the non-linear model accounts for smaller heterogeneity than the linear model in China. In model 1, two knots showed very low heterogeneity with an  $I^2$  of 22%, which means that this non-linear model may explain the majority of the heterogeneity among effects under different exposure levels. Our study and previous evidence from Chinese studies confirmed that the shape of the association between  $PM_{2.5}$  and mortality could be a non-linear curve in China, where the concentration of  $PM_{2.5}$  can range from very low to extremely high. At low  $PM_{2.5}$  exposure levels, our study found an approximately linear relationship between  $PM_{2.5}$  and mortality, which is consistent with previous US studies. At the middle and high levels of  $PM_{2.5}$ , we found the magnitude of the effect to decrease as the concentration of  $PM_{2.5}$  increased. The number of days during which  $PM_{2.5}$  concentration was below  $62 \mu\text{g}/\text{m}^3$  is quite high (about 68%). This phenomenon may be attributable to the “harvesting effect,” which means the most sensitive individuals among the population may have already died at lower levels of exposure (Costa et al., 2016).

Most studies have focused on estimation of the disease burden due to long-term exposure to  $PM_{2.5}$  (Wang et al., 2018; Lelieveld et al., 2015; Lim et al., 2012; J. Liu et al., 2016; M. Liu et al., 2016). Earlier studies used exposure-response functions from Western countries with

lower levels of  $PM_{2.5}$  exposure to estimate the global burden of disease from long-term exposure to  $PM_{2.5}$  (Cohen et al., 2005). In a country like China with high levels of exposure to  $PM_{2.5}$ , using a linear exposure-response relationship derived from the cohort studies performed in Western countries may overestimate the magnitude of the health effects. More and more studies have revealed that the association between long-term  $PM_{2.5}$  exposure and mortality is non-linear (Yin et al., 2017; Burnett et al., 2014). In order to address this limitation, a GBD study developed the integrated exposure-response (IER) curve to estimate the long-term  $PM_{2.5}$  exposure-response association from low exposure level to concentration as high as  $1000 \mu\text{g}/\text{m}^3$  (Burnett et al., 2014). Many studies have used the IER model to estimate the number of long-term  $PM_{2.5}$ -related deaths in China (Wang et al., 2018). GBD 2010 studies reported 1.23 million additional deaths (Lim et al., 2012), while other studies reported additional deaths ranging from 1.23 to 1.37 million (Wang et al., 2018; Lelieveld et al., 2015; Lim et al., 2012; J. Liu et al., 2016; M. Liu et al., 2016).

While many studies already estimate deaths attributable to long-term  $PM_{2.5}$  exposure, there are almost no studies that focus on the estimation of the number of additional deaths attributable to short-term  $PM_{2.5}$  at the global and country levels. In China, no study has reported the short-term  $PM_{2.5}$ -related additional deaths throughout the entire country. One possible reason for this is that the health effects of acute  $PM_{2.5}$  are far less pronounced than those of chronic exposure (Atkinson et al., 2014; Chen et al., 2017; Yin et al., 2017; Di et al., 2017), which may explain the very small burden of disease in developed countries with low levels of exposure and relatively small populations. In developing countries, however, the situation is completely different. Even with the relative small acute health effect, the burden of disease from short-term  $PM_{2.5}$  exposure should not be disregarded with high levels of  $PM_{2.5}$  exposure and a huge population, especially in China. We found

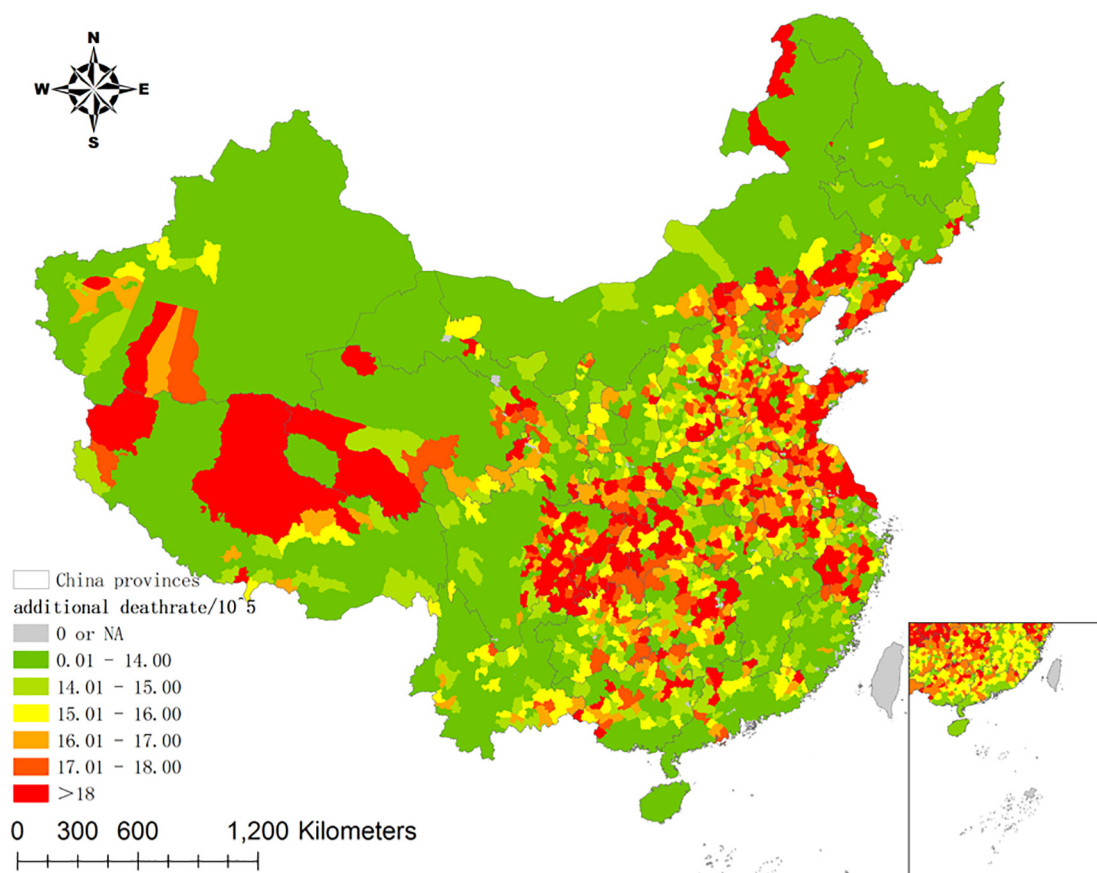


Fig. 4. Predicted short-term PM<sub>2.5</sub>-related increase in the death rate (1/100,000) in China in 2015 as indicated by Model 1.

approximately 0.17 million short-term PM<sub>2.5</sub>-related additional deaths in China, which is about one seventh the size attributable to chronic effects. It is essential to include short-term PM<sub>2.5</sub>-related mortality when considering the overall PM<sub>2.5</sub>-related disease burden in China. For the most part, the linear exposure-response association was expected in few short-term PM<sub>2.5</sub>-related health impact studies (Chen et al., 2017; Zhao et al., 2017; Lin et al., 2017). However, using the linear PM<sub>2.5</sub> and mortality associations rather than a non-linear relationship could substantially change the estimation of disease burden (Roberts and Martin, 2006). Previously, limited health impact estimation studies in China had considerable uncertainty because these studies did not use a non-linear association between PM<sub>2.5</sub> and mortality (Chen et al., 2017; Zhao et al., 2017; Lin et al., 2017). In our study, we reported the 95% confidence interval for additional deaths attributable to short-term exposure to PM<sub>2.5</sub>. Our work also showed a fairly wide range of estimated values, but it nonetheless provides more accurate results than most previous studies, which only reported estimates without acknowledging uncertainty.

The spatial distribution of PM<sub>2.5</sub> concentration, additional deaths, and death rate were somewhat different, mainly because the exposure-response differed across different PM<sub>2.5</sub> exposure concentration for a given population density in different counties. The spatial distribution of high levels of mortality related to short-term PM<sub>2.5</sub> exposure is consistent with previous estimations of the health impact of the effects of chronic exposure to PM<sub>2.5</sub> (Wang et al., 2018). The Chinese government has released a series of air pollution prevention measures, such as those in the Air Pollution Prevention and Control Action Plan and the Three-year Plan on Defending the Blue Sky (2018–2020) (The State Council, 2017) and has already taken measures to correct these problems over the past several years, especially in the three key areas and 10 urban agglomerations identified in the action plan. These areas are

essentially the same as those recognized as the high disease burden area in our study (State Department of People's Republic of China, 2013). By population, China is the largest country in the world (Cohen et al., 2017). In 2015, the Chinese government announced a two-child policy to address the country's accelerating aging problem (The 18th CPC central committee, 2015). For this reason, the disease burden attributable to PM<sub>2.5</sub> in China may remain high even as air quality improves because of the increasing size and age of the population. Although air pollution control measures have played a part in the government's efforts, our findings and the future demographic trends indicate that prompt action to improve the air quality in China is urgently needed, which could rapidly reduce the acute health impacts from short-term PM<sub>2.5</sub> and also mitigate the disease burden in China attributable to long-term PM<sub>2.5</sub> exposure.

Our work has some limitations. The census data of county-level population and mortality rate in 2010 were used in this study to calculate the burden of disease in 2015. These are the latest and only available county-level statistical data in China from the nationwide extensive demographic census every 10 years. Our study provided only short-term PM<sub>2.5</sub>-related all-cause mortality burden and does not address the disease burden of cause of death because of the lack of cause-specific mortality data. Finally, we used modeled PM<sub>2.5</sub> concentration in this study because China's PM<sub>2.5</sub> monitoring system cannot cover the entire country and PM<sub>2.5</sub> was the sole pollutant included. However, previous studies in China either used PM<sub>2.5</sub> alone to analyze the acute mortality effect (Chen et al., 2017) or showed that the acute mortality effect of PM<sub>2.5</sub> remained robust regardless of whether adding other pollutants (Chen et al., 2018).

Overall, this study adds significant new evidence on the short-term PM<sub>2.5</sub> exposure and mortality association across a broad PM<sub>2.5</sub> exposure range. Our estimates of disease burden attributable to short-term PM<sub>2.5</sub>

exposure may inform future studies in developing countries that have high concentrations of PM<sub>2.5</sub>.

## Acknowledgements

This work was supported by grants from the National Key Research and Development Program of China (Grant No. 2016YFC0206500), the National Natural Science Foundation of China (Grant Nos. 81573247, 91543111), the National High-Level Talents Special Support Plan of China for Young Talents.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envint.2019.01.073>.

## References

- Appel, K.W., et al., 2012. Examination of the Community Multiscale Air Quality (CMAQ) model performance over the North American and European domains. *Atmos. Environ.* 53, 142–155.
- Atkinson, R.W., Kang, S., Anderson, H.R., Mills, I.C., Walton, H.A., 2014. Epidemiological time series studies of PM<sub>2.5</sub> and daily mortality and hospital admissions: a systematic review and meta-analysis. *Thorax*. <https://doi.org/10.1136/thoraxjnl-2013-204492>.
- Burnett, R.T., et al., 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ. Health Perspect.* <https://doi.org/10.1289/ehp.1307049>.
- Chen, R., et al., 2011. Coarse particles and mortality in three Chinese cities: the China Air Pollution and Health Effects Study (CAPES). *Sci. Total Environ.* 409, 4934–4938.
- Chen, R., et al., 2017. Fine particulate air pollution and daily mortality. A nationwide analysis in 272 Chinese cities. *Am. J. Respir. Crit. Care Med.* 196, 73–81.
- Chen, C., et al., 2018. Short-term exposures to PM<sub>2.5</sub> and cause-specific mortality of cardiovascular health in China. *Environ. Res.* 161, 188–194.
- Cohen, A.J., et al., 2005. The global burden of disease due to outdoor air pollution. *J. Toxicol. Environ. Health A* 68, 1301–1307.
- Cohen, A.J., et al., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *Lancet* 389, 1907–1918 Lond. Engl.
- Costa, A.F., Hoek, G., Brunekreef, B., Ponce de Leon, A.C.M., 2016. Air pollution and deaths among elderly residents of São Paulo, Brazil: an analysis of mortality displacement. *Environ. Health Perspect.* 125.
- Daniels, M.J., Dominici, F., Samet, J.M., Zeger, S.L., 2000. Estimating particulate matter-mortality dose-response curves and threshold levels: an analysis of daily time-series for the 20 largest US cities. *Am. J. Epidemiol.* 152.
- Di, Q., et al., 2017. Air pollution and mortality in the medicare population. *N. Engl. J. Med.* 376, 2513–2522.
- Forouzanfar, M.H., et al., 2016. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. *Lancet* 388, 1659–1724.
- Franklin, M., Zeka, A., Schwartz, J., 2007. Association between PM<sub>2.5</sub> and all-cause and specific-cause mortality in 27 US communities. *J. Expo. Sci. Environ. Epidemiol.* 17, 279–287.
- Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* 525, 367–371.
- Lim, S.S., et al., 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet* 380, 2224–2260.
- Lin, H., et al., 2017. Using daily excessive concentration hours to explore the short-term mortality effects of ambient PM 2.5 in Hong Kong. *Environ. Pollut.* 229, 896–901.
- Liu, J., Han, Y., Tang, X., Zhu, J., Zhu, T., 2016. Estimating adult mortality attributable to PM<sub>2.5</sub> exposure in China with assimilated PM<sub>2.5</sub> concentrations based on a ground monitoring network. *Sci. Total Environ.* <https://doi.org/10.1016/j.scitotenv.2016.05.165>.
- Liu, M., et al., 2016. Spatial and temporal trends in the mortality burden of air pollution in China: 2004–2012. *Environ. Int.* <https://doi.org/10.1016/j.envint.2016.10.003>.
- Lu, F., et al., 2015. Systematic review and meta-analysis of the adverse health effects of ambient PM<sub>2.5</sub> and PM<sub>10</sub> pollution in the Chinese population. *Environ. Res.* 136, 196–204.
- National Bureau of Statistics of China, 2015. Total population in China. Available at: <http://data.stats.gov.cn/easyquery.htm?cn=C01&zb=A0301&sj=2015>.
- Platnick, S., et al., 2003. The MODIS cloud products: algorithms and examples from Terra. *IEEE Trans. Geosci. Remote Sens.* 41, 459–473.
- Roberts, S., Martin, M.A., 2006. The question of nonlinearity in the dose-response relation between particulate matter air pollution and mortality: can Akaike's information criterion be trusted to take the right turn? *Am. J. Epidemiol.* 164, 1242–1250.
- Schwartz, J., Zanobetti, A., 2000. Using meta-smoothing to estimate dose-response trends across multiple studies, with application to air pollution and daily death. *Epidemiology* 11, 666–672.
- Schwartz, J., Laden, F., Zanobetti, A., 2002. The concentration-response relation between PM<sub>2.5</sub> and daily deaths. *Environ. Health Perspect.* 110, 1025–1029.
- State Department of People's Republic of China, 2013. Air Pollution Control Action Plan. The 18th CPC central committee, 2015. Official Report of the Fifth Plenary Session of the 18th CPC Central Committee.
- The State Council, 2017. Three-year Plan on Defending the Blue Sky (2018–2020).
- Wang, Q., Wang, J., He, M.Z., Kinney, P.L., Li, T.A., 2018. County-level estimate of PM<sub>2.5</sub> related chronic mortality risk in China based on multi-model exposure data. *Environ. Int.* 110, 105–112.
- Xiao, Q., et al., 2017. Full-coverage high-resolution daily PM 2.5 estimation using MAIAC AOD in the Yangtze River Delta of China. *Remote Sens. Environ.* 199, 437–446.
- Yin, P., et al., 2017. Long-term fine particulate matter exposure and nonaccidental and cause-specific mortality in a large national cohort of Chinese men. *Environ. Health Perspect.* 125.
- Zhao, Y., et al., 2017. Ambient fine and coarse particulate matter pollution and respiratory morbidity in Dongguan, China. *Environ. Pollut.* 222, 126–131.