Fine Particulate Air Pollution and Daily Mortality: A Nationwide Analysis in 272 Chinese Cities

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AT A GLANCE COMMENTARY:

Scientific Knowledge on the Subject: Fine particulate matter ($PM_{2.5}$) air pollution constitutes a considerable public concern worldwide, especially in developing countries (such as China) which have severe air pollution problems. A recent systemic review and meta-analysis showed that the existing evidence about acute health effects of $PM_{2.5}$ was mainly obtained from Europe and North America where air pollution levels are very low.

What This Study Adds to the Field: This nationwide analysis in 272 representative Chinese cities found that the coefficient of exposure-response relationship in China was lower than in Europe and North America and there was a leveling-off in the exposure-response curves at high concentrations in most, but not all, Chinese regions. Furthermore, the associations were stronger in cities with lower $PM_{2.5}$ levels or higher temperatures, as well as in subpopulations with elder age or less education.

This article has an online data supplement, which is accessible from this issue's table of content online at www.atsjournals.org.

Abstract:

Rationale: Evidence concerning the acute health effects of fine particulate ($PM_{2.5}$) air pollution in developing countries is quite limited.

Objectives: To evaluate short-term associations between $PM_{2.5}$ and daily cause-specific mortality in China.

Methods: A nationwide time-series analysis was performed in 272 representative Chinese cities from 2013 to 2015. Two-stage Bayesian hierarchical models were applied to estimate regional- and national-average associations between $PM_{2.5}$ concentrations and daily cause-specific mortality. City-specific effects of $PM_{2.5}$ were estimated using the overdispersed generalized additive models after adjusting for time trends, day of the week and weather conditions. Exposure-response relationship curves and potential effect modifiers were also evaluated.

Measurement and Main Results: The average of annual-mean $PM_{2.5}$ concentrations in each city was 56 $\mu g/m^3$ (18 to 127 $\mu g/m^3$). Each 10 $\mu g/m^3$ increase in daily $PM_{2.5}$ concentrations (lag 01) was significantly associated with increments of 0.22% in mortality from total non-accidental causes, 0.27% from cardiovascular diseases, 0.39% from hypertension, 0.30% from coronary heart diseases, 0.23% from stroke, 0.29% from respiratory diseases and 0.38% from chronic obstructive pulmonary disease. There was a leveling-off in the exposure-response curves at high concentrations in most, but not all, regions. The associations were stronger in cities with lower $PM_{2.5}$ levels or higher temperatures, as well as in subpopulations with elder age or less education.

Conclusions: This nationwide investigation provided robust evidence of the associations between short-term exposure to $PM_{2.5}$ and increased mortality from various cardiopulmonary diseases in China. The magnitude of associations was lower than those reported in Europe and North America.

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Keywords: Fine particulates; air pollution; mortality; time-series; China

Over the last two decades, a growing body of epidemiological and clinical literatures has documented the hazardous effects of ambient air pollution on human health (1-5). Among various air pollutants, fine particulate matter ($PM_{2.5}$, particulate matter with an aerodynamic diameter less than or equal to 2.5 μm) was widely considered as the predominant pollutant in the air. $PM_{2.5}$ constitutes a considerable public concern worldwide, especially in developing countries. For example, in China, ambient $PM_{2.5}$ was ranked the 4th risk factor for disease burden, leading to more than 0.90 million premature deaths annually (6).

Evidence from epidemiological studies of air pollution has played a pivotal role in regulatory policy making and standards setting (7). Up to date, air quality health impact assessment and standard revision in developing countries has mainly relied on the extrapolation of results from epidemiological studies obtained from Europe and North America (8). The health effects of particulate matter have been less investigated in developing countries, despite the fact that these countries typically have much higher levels of exposure (3). This has raised a number of uncertainties in policy making and standards setting due to large differences in levels and nature of air pollution mixture, indoor air pollution, socioeconomic characteristics, and population susceptibilities across different geographic regions. Disagreement remained about whether the coefficients of exposure-response (E-R) relationships varied in different levels of air pollution (9-11).To date, the evidence was still scarce about the association between $PM_{2.5}$ and daily mortality in developing countries due to the limitations of air quality monitoring network and death registry system.

Since January 2013, China has gradually introduced $PM_{2.5}$ in the national air quality monitoring network and up to 366 Chinese cities have publicized real-time monitoring data on $PM_{2.5}$ by the end of 2015. We therefore conducted a nationwide time-series study from January 2013 to December 2015 to evaluate the short-term associations between $PM_{2.5}$ and daily mortality in China. We evaluated mortality from both total non-accidental causes and various cardiopulmonary diseases. City-level and individual-level potential effect modifiers were also evaluated. Some of the results of these studies have been previously reported in the form of an abstract in this journal (12).

METHODS

Mortality data

The daily mortality data during the period from January 2013 to December 2015 were obtained from the China's Disease Surveillance Points system (DSPS), which is administrated by the Chinese Center for Disease Control and Prevention (China CDC). The detailed descriptions of the sampling and development of the DSPS were published elsewhere (13, 14). From 2013, this system is comprised of 605 communities from 322 cities and covers a population of 323.8 million (24.3% of the total population in China). All communities were subject to strict quality control procedures administered by CDC network at county/district, prefecture, province and national levels, for accuracy and completeness of the death data. The current DSPS has been proved to be representative at both national and provincial level and data from this system have been extensively used to assess the burden of disease both regionally and nationally in China and globally (14-16).

We extracted daily cause-specific mortality from the database in the DSPS based on the underlying cause of death defined by International Classification of Disease, 10th revision. We focused on total non-accidental causes (briefed as total, codes: A00-R99), cardiovascular diseases (briefed as CVD, codes: I00-I99), hypertension (codes: I10-I15), coronary heart disease (briefed as CHD, codes: I20-I25), stroke (codes: I60-I69), respiratory diseases (codes: J00-J98), and chronic obstructive pulmonary disease (briefed as COPD, codes: J41-J44). In order to ensure enough statistical power when fitting time-series data, we excluded cities with less than 3 total deaths on average per day. Finally, we divided daily total deaths into several strata by gender, age ranges (5–64 years, 65–74 years and 75 years or older) and educational attainment (low: less than or equal to 9 years of education; high: more than 9 years of education). Deaths under age 5 were too few and therefore were excluded from our analysis. Daily deaths from all communities in a city were aggregated. Then, these cities were clustered into 6 geographical regions, i.e., Northeast, North, East, Middle-south, Southwest and Northwest, as shown in Figure E1 in the online supplement.

Ethical approval

The Institutional Review Board at the School of Public Health, Fudan University, approved the study protocol (NO. 2014-07-0523) with a waiver of informed consent. Data were analyzed at aggregate level and no participants were contacted.

Environmental data

Daily $PM_{2.5}$ data were obtained from the National Urban Air Quality Real-time Publishing Platform (http://106.37.208.233:20035/). The platform is administrated by the China's Ministry of Environmental Protection and displays real-time concentrations of criteria air pollutants in all state-controlled monitoring sites. The methods based on the tapered elementoscillating microbalance were used for measuring $PM_{2.5}$. The 24-h mean concentrations for $PM_{2.5}$ were simply averaged from all valid monitoring sites in a city. This platform was put in operation beginning January 2013, and then cities were added to the platform in a staged manner. In 2015, it has covered all cities at prefecture level or above.

To allow for the adjustment of weather conditions, we obtained daily mean temperature and mean relative humidity in each city from the China Meteorological Data Sharing Service System (http://data.cma.cn/).

Statistical analysis

In the first stage, we estimated the city-specific associations using the generalized additive models with *quasi*-Poisson regression. Several confounders were introduced in the models: (1) a natural cubic spline smooth function of calendar day with 7 degrees of freedom (*df*) per year to exclude unmeasured time trends longer than 2 months in mortality; (2) an indicator variable for "day of week" to account for possible variations in a week; (3) natural smooth functions with 6 *df* for 3-day moving average temperature and 3 *df* for 3-day moving average relative humidity to exclude potential nonlinear and lagged confounding effects of weather conditions. We did not use separate terms of the current day's weather parameters and the mean of the previous 3 days' parameters as done in some previous studies (17, 18), because they were highly correlated with Pearson *r* typically > 0.95. We used 2-day moving average of current- and previous-day concentrations of $PM_{2.5}$ (lag 01) in our main analyses, because it often produced the largest effect estimate in previous studies (10, 11). We still used single lags of 0, 1, 2 days to explore the lag pattern in the effects.

In the second stage, we used Bayesian hierarchical models to obtain regional-average and national-average estimates on the associations between $PM_{2.5}$ and cause-specific mortality (17). This approach has been widely used in multisite epidemiological studies to combine risk estimates across sites accounting for within-site statistical error and for between-site variability of the "true" risk (also called "heterogeneity"). The model calculated the posterior probability that the average effect is positive and values greater than 0.95 are considered significant (18). We then reported the percentage change, including the posterior mean and 95% posterior interval (PI), in daily mortality per 10 μg/m^3 increase of $PM_{2.5}$ concentrations.

In addition, we combined the E-R relationship curves at the national and regional level using the same approach as in the “Air Pollution and Health - A European Approach” (APHEA) project and in the “China Air Pollution and Health Effects Study” to get an overall shape of $PM_{2.5}$-mortality association at both the national level and regional level (19, 20).

We conducted stratification analyses by age, sex and education for exploring the potential individual-level effect modifiers of $PM_{2.5}$ using the above models. We tested the statistical significance of differences in effect estimates between the strata using a formula described previously (10, 21). Potential city-level effect modifiers were also investigated by establishing a meta-regression model with city-specific effect estimates, annual-average $PM_{2.5}$ concentrations and annual-average temperatures in each city during the study periods.

Furthermore, in order to roughly evaluate the potential public health impact of our estimates, we calculated the annual reduction (H) in cause-specific mortality attributable to a 10-μg/m^3 reduction in the daily $PM_{2.5}$ level (17). H is defined as $H=(\exp(\beta\times\Delta x)-1) \times N$, where β is the national-average mortality estimate for a 1 μg/m^3 change in $PM_{2.5}$ in main analyses, Δx is 10 μg/m^3, and N is the total number of cause-specific deaths in China in 2014, which were calculated by multiplying the total population size (1.3 billion) and national-average mortality of each cause in China.

We conducted three sensitivity analyses with regard to 1) the use of different subsets of cities with 1-, 2- and 3- year data; 2) the alternative adjustment of weather conditions: temperatures at lag 0 and 1 day, using 6 *df* in natural smooth functions (22); and 3) the *df* in the smoothness of calendar day (6~10 per year).

The first- and second-stage analyses were conducted in the R software, version 3.1.1 (R Foundation for Statistical Computing, Vienna, Austria) using the *mgcv* and *tlnise* packages, respectively.

RESULTS

Descriptive statistics

Considering all available data on daily mortality, air quality and weather conditions, a total of 272 cities (69 cities with 3-year data, 74 cities with 2-year data and 129 cities with 1-year data) were included in this national analysis. The region-specific statistics on daily-average total deaths, population size, and age structure were summarized in Table E1 and Table E2 in the online supplement. On average, cities in east, southwest and north of China have higher daily deaths. There are higher proportions of elders aged 65 or above in southeast, east and northeast regions.

Table 1 summarizes the descriptive statistics in this analysis. The average of annual-mean $PM_{2.5}$ concentrations in 272 cities was 56 μg/m^3 (ranging from 18 to 127 μg/m^3), far beyond the air quality guidelines of World Health Organization (annual mean for $PM_{2.5}$: 10 μg/m^3). There were drastic differences in climatic conditions in these cities. On average, we recorded a daily average of 16 deaths for total causes, 8 for CVD, 1 for hypertension, 3 for CHD, 4 for stroke, 2 for respiratory diseases, and 2 for COPD.

Regression results

Figure 1 presents the national-average mortality estimates for lag 01 and single lags of 0, 1, and 2 days per 10 μg/m^3 increase of $PM_{2.5}$ concentrations. For all outcomes other than hypertension, the single-lag models estimated significant associations on lag 0 and 1 days, and marginally significant or insignificant associations on lag 2 days. For hypertension, there was an association only on lag 0 day. The lag 01 day estimated appreciably stronger associations than all single lags examined. The effects of exposure on cardiopulmonary mortality were all larger than on total mortality (Figure 1 and Table 2). Each 10 μg/m^3 increase of $PM_{2.5}$ concentrations at lag 01 day was associated with increments of 0.22% (95%PI: 0.15, 0.28) in mortality from total causes, 0.27% (95%PI: 0.18, 0.36) from CVD, 0.39% (95%PI: 0.13, 0.65) from hypertension, 0.30% (95%PI: 0.19, 0.40) from CHD, 0.23% (95%PI: 0.13, 0.34) from stroke, 0.29% (95%PI: 0.17, 0.42) from respiratory diseases and 0.38% (95%PI: 0.23, 0.53) from COPD. As shown in Figure 2, the national-average E-R curve for $PM_{2.5}$ (lag 01) and total mortality was slightly nonlinear with a sharp slope at < 70 μg/m^3, a moderate slope at 70~200 μg/m^3 and a leveling with much wider confidence intervals at > 200 μg/m^3..

The PM$_{2.5}$-mortality associations showed a significant heterogeneity across different regions of China (Figure 3). Generally, we found weak or non-significant effects on mortality due to various diseases in the Northeast and Northwest regions (except for respiratory diseases). The effects on cardiovascular mortality were more evident in Southwest, Middle-south and East regions, whereas the effects on respiratory mortality were stronger in Northwest, Middle-south and North regions. The shape of regional-average curves varied appreciably (*see* Figure 4). For instance, there were no discernible slopes in the Northeast and Northwest regions and no leveling at high concentrations of PM$_{2.5}$ in Eastern China.

The associations between PM$_{2.5}$ and mortality (lag 01) varied by age, sex and educational attainment (Figure 5). For age groups, the effects on total mortality were much higher among people aged 75 years and above than among people aged 5~64 years (*P*=0.02), whereas the effects on respiratory mortality were similar across the three age groups. We consistently found a slightly stronger effect in females than in males for total, CVD and respiratory mortality, but the differences were not statistically significant. The effect estimates in people with lower educational attainment were much stronger than in those with higher educational attainment (*P*=0.03 for total mortality).

For the city-level modifiers, there were larger effect estimates of PM$_{2.5}$ on daily total mortality associated with lower annual average levels of $PM_{2.5}$ (posterior probability = 0.998) and higher annual average temperature (posterior probability = 0.996). For each 10 μg/m^3 increment of $PM_{2.5}$ on lag 01 day, a city with 10 μg/m^3 lower $PM_{2.5}$ concentrations and 1℃ higher temperature on a yearly basis with respect to another city was estimated to have an additional 0.048% (95%PI: 0.017%, 0.079%) and 0.023% (95%PI: 0.007%, 0.038%) increase in daily total mortality, respectively.

Table 2 provided the estimated annual reduction in cause-specific deaths attributable to a 10 μg/m^3 decrease in the daily $PM_{2.5}$. For example, a 10 μg/m^3 reduction in $PM_{2.5}$ would reduce total deaths by 17.55 (95%PI: 12.25, 22.86) thousand nationwide in 2014, 84.79% of which are attributable to cardiopulmonary diseases.

In sensitivity analyses, we estimated similar effects of $PM_{2.5}$ when only analyzing the 1-year data, 2-year data and 3-year data. The percentage increase in total mortality per a 10 μg/m^3 increase of 2-day average $PM_{2.5}$ concentrations was 0.22%in all cities, 0.36% in cities with 1-year data, 0.16% in cities with 2-year data, and 0.23% in cities with 3-year data. With the adjustment of temperatures at lag 0 and 1 day, we obtained very similar effect estimates per 10 μg/m^3 increase of 2-day average $PM_{2.5}$ concentrations: 0.21% for total mortality, 0.28% for CVD mortality and 0.26% for respiratory mortality. Within the range of 6–10, the change of *df* per year for time trend control did not substantially affect the results (data not shown).

DISCUSSION

This multisite study in 272 representative Chinese cities had the strength of analyzing the national data by the same protocol and avoiding the potential for publication bias that were common in single-city studies. We found a stronger association of $PM_{2.5}$ with cardiopulmonary mortality than with total mortality. There was a leveling-off in the exposure-response curves at high concentrations in most, but not all, regions. Furthermore, the associations varied in cities with different annual-mean $PM_{2.5}$ concentrations or temperatures, as well as in people with different ages or educational levels.

Overall, we found significant associations between short-term exposure to $PM_{2.5}$ and all mortality outcomes on a national scale, but the coefficients for the associations were smaller than most previously-reported estimates. For a 10 $\mu g/m^3$ increase of $PM_{2.5}$ concentrations, we estimated a 0.22% increase for total mortality, which was slightly below a recent multicity study in 150 U.S. cities (23), but appreciably smaller than other multicity studies in the Europe and North America (24-27). Noteworthy was that our estimate was well below a pooled estimate (0.94 %) in North America and another estimate of 1.23% in Europe per 10 $\mu g/m^3$ increase of $PM_{2.5}$ according to a worldwide meta-analysis (27). However, our estimate is also slightly lower than that obtained in 11 East Asian cities (0.38%) (11). In addition, Chen et al estimated a 0.46% increment in total mortality per 10 $\mu g/m^3$ increase of $PM_{2.5}$ (lag 01) in three Chinese cities

(9).

The weaker effects of $PM_{2.5}$ in our analysis than in Europe and North America might be attributable to the distinct characteristics of China. Firstly, as shown in our E-R relationship curves and a previous APHEA study (28), there was an apparent plateauing trend at high levels of $PM_{2.5}$ that are ubiquitous in Chinese cities. This saturation effect may also be supported by smaller effects of daily $PM_{2.5}$ concentration changes in cities with higher long-term level of $PM_{2.5}$, as shown in the meta-regression analyses. Furthermore, the observed leveling-off at higher concentrations may be virtually a consequence of “harvesting effect” in that susceptible people might have died before air pollutant concentrations reached a reasonably high level (29). Nonetheless, it does not denote that these higher levels have negligible health effects, but that the effects of acute exposure examined in such a study are much lower than of cumulative exposure, which would require a cohort study conducted over years of follow-up to be determined. Secondly, $PM_{2.5}$ in China has high content of crustal materials due to transported dust from desert and arid loess-land and locally-induced dust in relation to lower vegetation coverage and intensive urban construction (30). Crustal components or dust may have relatively lower toxicity than those mainly originated from fossil combustion (31-33), but there may still some independent effects of dust and particles from biomass burning (34). Thirdly, compared to the developed countries, China has a younger age structure, making it less sensitive to exposure to air pollutants.

We found strong evidence for spatial heterogeneity in the effects of $PM_{2.5}$ on daily mortality in China. The underlying reasons were difficult to be determined but were still somewhat plausible in terms of the toxicity or hazards of various particle constituents and sources, long-term $PM_{2.5}$ levels, climatic characteristics and age structure. First, the weak or non-significant effects in the Northeast and Northwest regions might be because $PM_{2.5}$ in the two regions were not hazardous as in other regions due to higher proportions of crustal materials and elements relevant to biomass burning (30-33), although there were still some studies pointing to their independent health effects (34-36). However, the insufficient data on the composition and sources of $PM_{2.5}$ in each city as well as their relative toxicity limited our ability to further investigate the between-city heterogeneity of its health effects. Second, we observed a downward trend for the effects of daily $PM_{2.5}$ in cities with higher annual levels of $PM_{2.5}$. It may be caused by larger exposure misclassification due to reinforced public health policies, as well as behavioral and small-scale interventions to lower exposures (such as staying at home, wearing masks and using air purifiers). Third, as shown in a previous nationwide analysis in the USA (17), we reported a positive effect modification of annual average temperatures. Cold climate may result in restricted outdoor activities and less efficient penetration of $PM_{2.5}$ from outdoors to indoors, thus leading to larger measurement errors in colder regions than in warmer regions when utilizing the outdoor fixed-site monitoring data (37). Fourth, because the effects of

$PM_{2.5}$ were restricted in the elderly (Figure 5), the somewhat older age structure in southern regions than in northern regions (*see* Table E2) added the susceptibility to $PM_{2.5}$ (Figure 3). Fifth, unlike other parts of China, the east region did not see a discerned leveling-off in the E-R curve at high concentrations. It might occur by chance, or by higher toxicity of $PM_{2.5}$ on severe haze days relevant to region-specific emission sources, climatic conditions and socioeconomic characteristics that remain to be addressed in further studies.

Our results on individual-level modifiers had certain public health significance. Consistent with previous studies (10, 21, 24), we reported much higher vulnerability to $PM_{2.5}$ among the elderly and persons with low educational attainment. The larger risk estimates in less-educated populations may result from the issue of environmental health inequalities and inequities associated with socioeconomic status (SES) (38). Low SES may modify the health effects of outdoor air pollution by virtue of higher prevalence of preexisting diseases, less affordable health care resources, disadvantaged living conditions, smaller exposure measurement errors, higher exposure or co-exposure (with household and occupational sources) levels, and limited access to air conditioning (39). Given the distinction in the population susceptibility to $PM_{2.5}$, public health prevention strategies can be efficiently developed to reduce the disease burden.

Our study had some limitations. Firstly, as in most previous time-series studies, exposure measurement errors were inevitable because we simply averaged the monitoring results across various stations as the proxy for true population exposures. However, this kind of non-differential error may lead to an underestimate on the effects of $PM_{2.5}$ (25). Secondly, as in all studies using registry-based mortality data, diagnosis coding errors may occur, especially in a national analysis. Thirdly, this study was inherently an ecologic analysis, thus potential confounding from individual-level risk factors could not be fully excluded. Overall, our results should be interpreted with caution because we only evaluated day-to-day effects of $PM_{2.5}$ and did not include its cumulative effects over years.

In summary, as the largest epidemiological study in developing world, this investigation provided robust evidence of the associations between short-term exposure to $PM_{2.5}$ and increased mortalities from various cardiopulmonary diseases in China. The magnitude of associations was lower than those reported in Europe and North America. Our results provided abundant evidence regarding the acute health effects of $PM_{2.5}$ in a developing country with much higher particulate air pollution levels than in Europe and North America. Further investigations were needed to evaluate the short-term and long-term health effects of $PM_{2.5}$ compositions and sources in different regions of China.

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Table 1. Summary Statistics of Environment and Health Data in 272 Chinese Cities, 2013–2015

Variables	Mean	SD	Min	P25	P50	P75	Max
Annual $PM_{2.5}$ (μg/m^3)							
Nationwide	56	20	18	41	54	67	127
Northeast	52	14	26	43	53	60	78
North	69	27	28	50	59	87	127
East	59	20	26	43	58	67	105
Middle-south	56	19	18	41	55	72	94
Southwest	42	16	20	30	36	58	73
Northwest	55	19	36	43	49	61	119
Weather conditions							
Mean temperature (℃)	15	5	-0.5	12	16	18	25
Relative humidity (%)	68	10	35	61	71	77	91
Daily deaths							
Total non-accidental	16	16	3	7	12	20	165
CVD	8	7	1	3	6	10	65
Hypertension	1	1	0	0	0	1	7
CHD	3	3	0	1	2	3	28
Stroke	4	4	0	2	3	5	33
Respiratory diseases	2	3	0	1	1	3	34
COPD	2	2	0	0	1	2	29

Abbreviations: $PM_{2.5}$, particulate matter with an aerodynamic diameter less than or equal to 2.5 μm; CVD, cardiovascular diseases; CHD, coronary heart disease; COPD, chronic obstructive pulmonary disease.

Table 2. The national-average annual reduction (posterior mean and 95% posterior intervals) in cause-specific deaths (in thousands) attributable to a 10 μg/m^3 reduction in the daily $PM_{2.5}$ level in China.

Causes of deaths	Betas of the E-R relations*	Annual deaths[†]	Annual Reduction in deaths
Total	0.22 (0.15, 0.28)	8,088	17.55 (12.25, 22.86)
CVD	0.27 (0.18, 0.36)	3,904	10.47 (6.94, 14.00)
Hypertension	0.39 (0.13, 0.65)	3,046	1.19 (0.40, 1.98)
CHD	0.30 (0.19, 0.40)	1,458	4.31 (2.83, 5.79)
Stroke	0.23 (0.13, 0.34)	1,878	4.41 (2.45, 6.36)
Respiratory diseases	0.29 (0.17, 0.42)	1,050	3.06 (1.76, 4.37)
COPD	0.38 (0.23, 0.53)	800	3.03 (1.83, 4.24)

*Betas were expressed as the percentage increase (posterior mean and 95% posterior intervals) in daily mortality associated with a 10 μg/m^3 increase in the 2-day average $PM_{2.5}$ concentrations. Abbreviations as in Table 1.

[†] Data are calculated at the national level by the cause-specific mortality data derived from “China Health and Family Planning Statistical Yearbook 2015”

Figure legends

Figure 1. Percentage change (posterior mean and 95% posterior intervals) in daily cause-specific mortality per 10 μg/m^3 increase in $PM_{2.5}$ using different lag days on average across 272 Chinese cities. Abbreviations as in Table 1.

Figure 2. National-average exposure-response relationship curves between $PM_{2.5}$ concentrations (lag 01) and daily total mortality in 272 Chinese cities. The vertical scale can be interpreted as the relative change from the mean effect of $PM_{2.5}$ on mortality. $PM_{2.5}$, particulate matter with an aerodynamic diameter less than or equal to 2.5 μm.

Figure 3. Percent change (posterior mean and 95% posterior intervals) in daily mortality by regions and causes per 10 μg/m^3 increase in 2-day moving average (lag 01) $PM_{2.5}$ concentrations within each region. Abbreviations as in Table 1.

Figure 4*.* Regional-average exposure-response relationship curves between $PM_{2.5}$ (lag 01) and daily total mortality in China. The vertical scale can be interpreted as the relative change from the mean effect of $PM_{2.5}$ on mortality. Abbreviations: $PM_{2.5}$, particulate matter with an aerodynamic diameter less than or equal to 2.5 μm.

Figure 5. Percent change (posterior mean and 95% posterior intervals) in daily mortality per 10 μg/m^3 increase (lag 01) in $PM_{2.5}$ on average across 272 Chinese cities, classified by age, sex and educational attainment. Abbreviations as in Table 1.

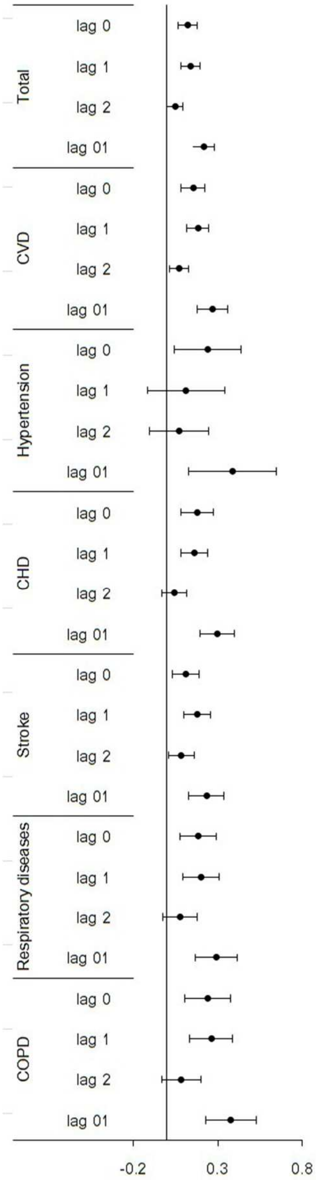

Figure 1. Percentage change (posterior mean and 95% posterior intervals) in daily cause-specific mortality per 10 μg/m3 increase in PM2.5 using different lag days on average across 272 Chinese cities. Abbreviations as in Table 1.

87x331mm (96 x 96 DPI)

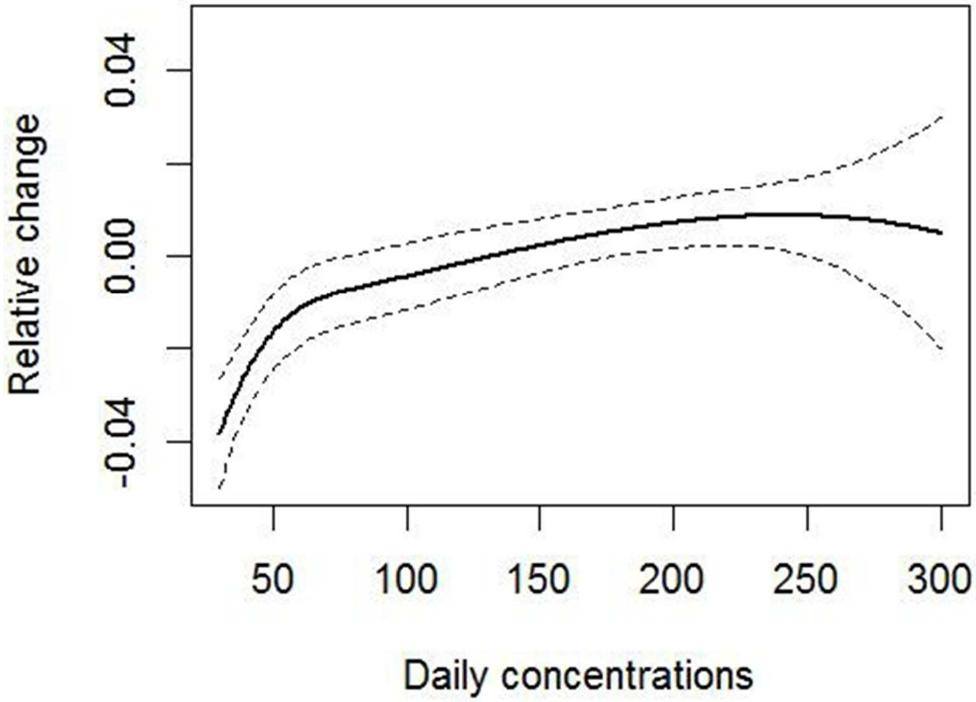

Figure 2. National-average exposure-response relationship curves between PM2.5 concentrations (lag 01) and daily total mortality in 272 Chinese cities. The vertical scale can be interpreted as the relative change from the mean effect of PM2.5 on mortality. Abbreviations: PM2.5, particulate matter with an aerodynamic diameter less than or equal to 2.5 μm.

131x96mm (96 x 96 DPI)

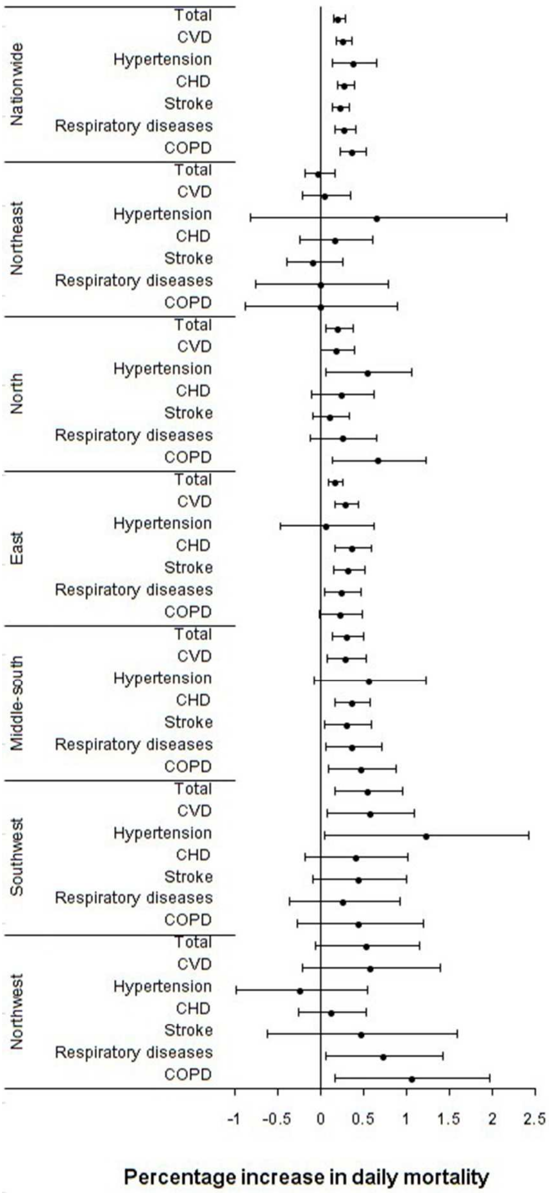

Figure 3. Percent change (posterior mean and 95% posterior intervals) in daily mortality by regions and causes per 10 μg/m3 increase in 2-day moving average (lag 01) PM2.5 concentrations within each region. Abbreviations as in Table 1.

112x244mm (96 x 96 DPI)

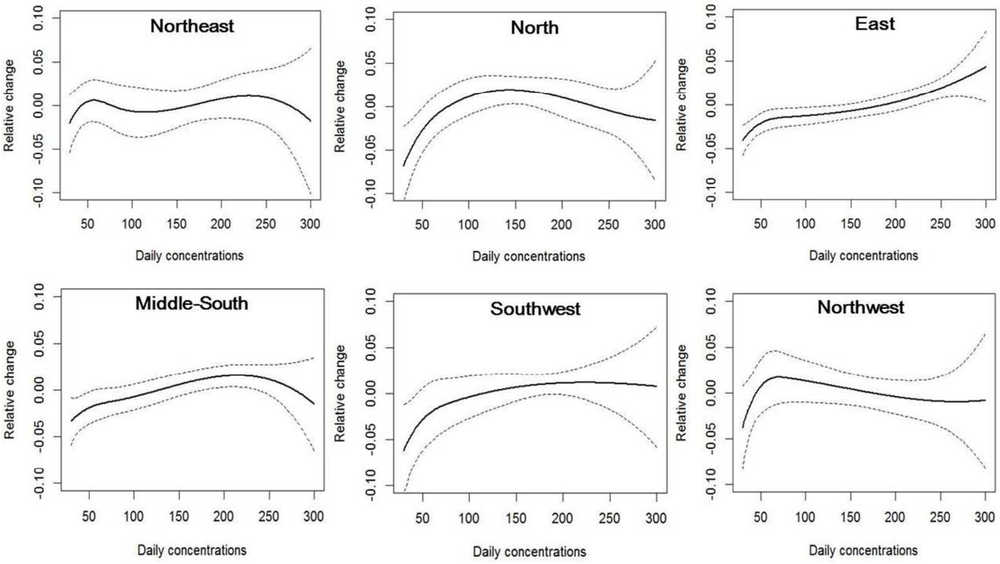

Figure 4. Regional-average exposure-response relationship curves between PM2.5 (lag 01) and daily total mortality in China. The vertical scale can be interpreted as the relative change from the mean effect of PM2.5 on mortality. Abbreviations: PM2.5, particulate matter with an aerodynamic diameter less than or equal to 2.5 μm.

338x190mm (96 x 96 DPI)

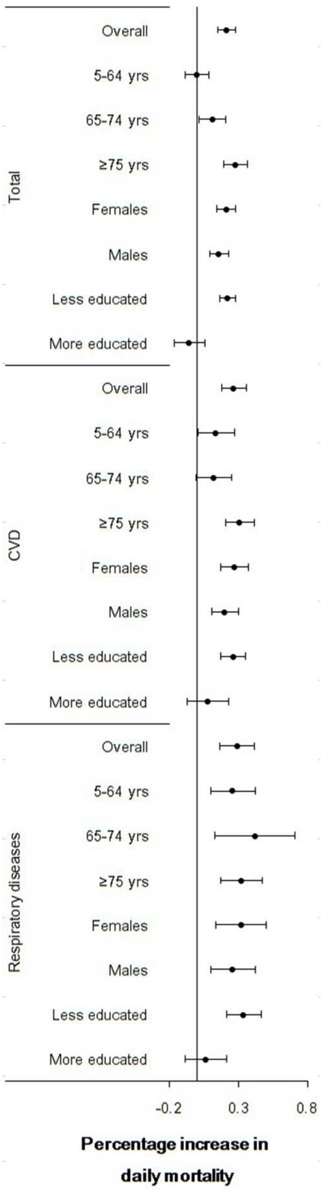

Figure 5. Percent change (posterior mean and 95% posterior intervals) in daily mortality per 10 μg/m3 increase (lag 01) in PM2.5 on average across 272 Chinese cities, classified by age, sex and educational attainment. Abbreviations as in Table 1.

85x320mm (96 x 96 DPI)

Table E1. Summary Statistics of Daily Total Deaths* in 6 Regions of China, 2013-2015.

Regions	Mean	SD	Min	P25	P50	P75	Max
Nationwide	16	16	3	7	12	20	165
Northeast	14	10	4	6	10	19	46
North	17	20	3	7	11	14	94
East	20	16	3	11	17	25	105
Middle-south	15	10	3	8	13	20	45
Southwest	19	28	3	9	12	20	165
Northwest	8	5	3	4	6	10	22

*Data are daily mean total (non-accidental) deaths averaged in all studied within each region.

Table E2. Summary Statistics of Population Size and Age Structure in 6 Regions of China.

	Population (×millions)*	Age structure (%)[†]		
		0~14	15~64	65 or above
Nationwide	1368	16.6	74.5	8.9
Northeast	110	11.7	79.1	9.1
North	172	14.9	77.0	8.1
East	401	15.4	75.0	9.6
Middle-south	384	18.2	73.3	8.4
Southwest	197	19.5	70.7	9.8
Northwest	99	17.7	74.6	7.7

*Data are from “China Social Statistical Yearbook 2015”.

[†] Data are from “the sixth national population census of China”.

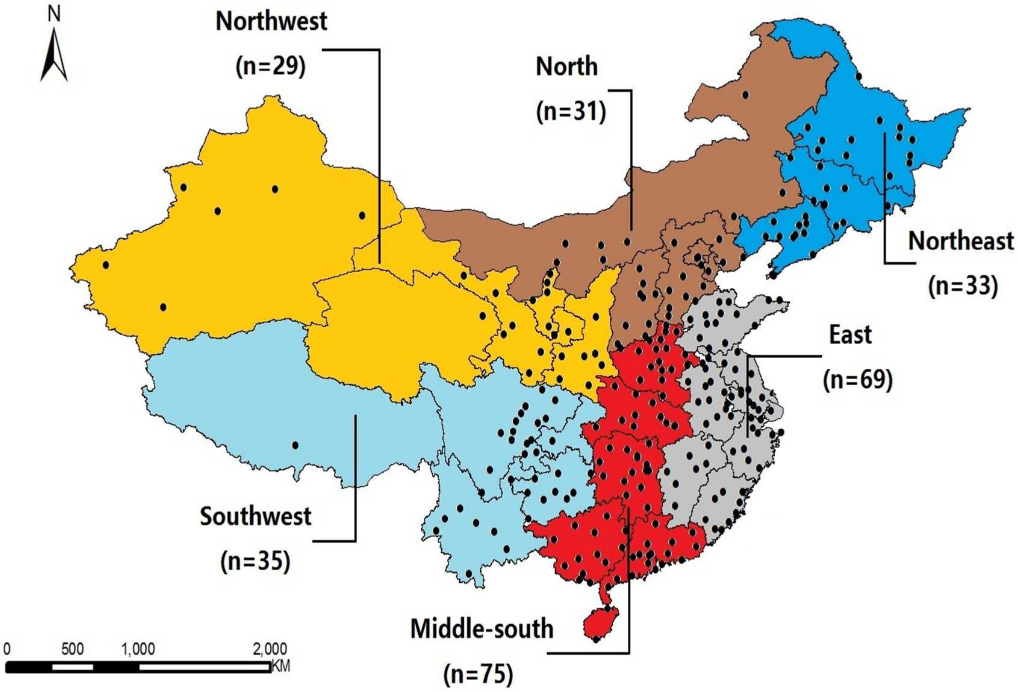

Figure E1. The location of study sites in Mainland China (n=272 cities).