A Section 508–conformant HTML version of this article is available at https://doi.org/10.1289/EHP2711.

Associations between Coarse Particulate Matter Air Pollution and Cause-Specific Mortality: A Nationwide Analysis in 272 Chinese Cities

Renjie Chen,[1] Peng Yin,[3*] Xia Meng,[4] Lijun Wang,[3] Cong Liu,[1] Yue Niu,[1] Yunning Liu,[3] Jiangmei Liu,[3] Jinlei Qi,[3] Jinling You,[3] Haidong Kan,[1,2] and Maigeng Zhou[3]*

[1]School of Public Health, Key Lab of Public Health Safety of the Ministry of Education and NHC Key Lab of Health Technology Assessment, Fudan University, Shanghai, China
[2]Children's Hospital of Fudan University, National Center for Children's Health, Shanghai, China
[3]National Center for Chronic Noncommunicable Disease Control and Prevention, Chinese Center for Disease Control and Prevention, Beijing, China
[4]Department of Environmental Health, Rollins School of Public Health, Emory University, Atlanta, Georgia, USA

Background: Coarse particulate matter with aerodynamic diameter between 2.5 and 10 μm ($PM_{2.5–10}$) air pollution is a severe environmental problem in developing countries, but its challenges to public health were rarely evaluated.

Objective: We aimed to investigate the associations between day-to-day changes in $PM_{2.5–10}$ and cause-specific mortality in China.

Methods: We conducted a nationwide daily time-series analysis in 272 main Chinese cities from 2013 to 2015. The associations between $PM_{2.5–10}$ concentrations and mortality were analyzed in each city using overdispersed generalized additive models. Two-stage Bayesian hierarchical models were used to estimate national and regional average associations, and random-effect models were used to pool city-specific concentration–response curves. Two-pollutant models were adjusted for fine particles with aerodynamic diameter ≤2.5 μm ($PM_{2.5}$) or gaseous pollutants.

Results: Overall, we observed positive and approximately linear concentration–response associations between $PM_{2.5–10}$ and daily mortality. A 10-$\mu g/m^3$ increase in $PM_{2.5–10}$ was associated with higher mortality due to nonaccidental causes [0.23%; 95% posterior interval (PI): 0.13, 0.33], cardiovascular diseases (CVDs; 0.25%; 95% PI: 0.13, 0.37), coronary heart disease (CHD; 0.21%; 95% PI: 0.05, 0.36), stroke (0.21%; 95% PI: 0.08, 0.35), respiratory diseases (0.26%; 95% PI: 0.07, 0.46), and chronic obstructive pulmonary disease (COPD; 0.34%; 95% PI: 0.12, 0.57). Associations were stronger for cities in southern vs. northern China, with significant differences for total and cardiovascular mortality. Associations with $PM_{2.5–10}$ were of similar magnitude to those for $PM_{2.5}$ in both single- and two-pollutant models with mutual adjustment. Associations were robust to adjustment for gaseous pollutants other than nitrogen dioxide and sulfur dioxide. Meta-regression indicated that a larger positive correlation between $PM_{2.5–10}$ and $PM_{2.5}$ predicted stronger city-specific associations between $PM_{2.5–10}$ and total mortality.

Conclusions: This analysis showed significant associations between short-term $PM_{2.5–10}$ exposure and daily nonaccidental and cardiopulmonary mortality based on data from 272 cities located throughout China. Associations appeared to be independent of exposure to $PM_{2.5}$, carbon monoxide, and ozone. https://doi.org/10.1289/EHP2711

Introduction

Particulate matter (PM) air pollution concentrations are recorded by monitors that measure particles in various aerodynamic diameters, with the earliest monitors measuring the concentration of particles ≤10 μm (PM_{10}), followed by monitors that measured fine particles ≤2.5 μm ($PM_{2.5}$). Particle size largely determines where ambient PM is deposited when inhaled, with $PM_{2.5}$ reaching the lung and smaller airways, while coarser particles (between 2.5 and 10 μm in diameter; $PM_{2.5–10}$) typically deposit in the upper respiratory tract and larger airways (Peng et al. 2008). Particle size also influences the surface area of individual particles and other characteristics that may contribute to adverse health effects of exposure. As $PM_{2.5}$ monitoring has become more widespread, and because smaller particles are assumed to have greater health effects due to their ability to reach smaller airways, epidemiologic studies have focused increasingly on the health effects of $PM_{2.5}$ vs. PM_{10} (Adar et al. 2014; Kim et al. 2015). Although the World Health Organization's 2005 Air Quality Guidelines include guideline values for both PM_{10} and $PM_{2.5}$ (WHO 2016), $PM_{2.5}$ was used as sole risk indicator when the disease burden of ambient air pollution was estimated for the Global Burden of Disease Study (GBD 2015 Risk Factors Collaborators 2016).

Recent epidemiologic studies (Chen et al. 2011; Peng et al. 2008; Powell et al. 2015; Samoli et al. 2013; Yorifuji et al. 2016; Zanobetti and Schwartz 2009) have also estimated health effects of exposure to $PM_{2.5–10}$. However, findings from these studies have been inconsistent. For example, a systematic review found significant heterogeneity in associations between short-term exposure to $PM_{2.5–10}$ and mortality or hospital admissions reported by 33 epidemiological studies published before December 2013 (Adar et al. 2014). However, pooled estimates from random-effects models were positive and were slightly attenuated but still positive after accounting for publication bias and when based on individual study estimates that were adjusted for coexposure to $PM_{2.5}$ (Adar et al. 2014). A recent analysis of data from 110 large urban counties in the United States reported that daily variation in $PM_{2.5–10}$ was associated with emergency cardiovascular hospitalizations on the same day among Medicare participants ≥65 y of age and that this association persisted when adjusted for $PM_{2.5}$ (Powell et al. 2015). Although ambient air pollution is a severe environmental problem in low- and middle-income countries, there have been relatively few studies of the health effects of $PM_{2.5–10}$ because of limited $PM_{2.5}$ monitoring. Consequently, there remains a critical gap in knowledge concerning the health effects of $PM_{2.5–10}$ in developing countries where particulate air pollution levels are high and the chemical composition and ratios of ambient $PM_{2.5}$ and $PM_{2.5–10}$ may differ from developed countries.

*These authors contributed equally to this work.
Address correspondence to M. Zhou, 27 Nanwei Rd., Xicheng District, Beijing 100050, China. Telephone: +86 (10) 6304 2350. Fax: +86 (10) 6304 2350. Email: maigengzhou@126.com; H. Kan, P.O. Box 249, 130 Dong-An Rd., Shanghai 200032, China. Telephone: +86 (21) 5423 7908. Fax: +86 (21) 5423 7908. Email: kanh@fudan.edu.cn

Supplemental Material is available online (https://doi.org/10.1289/EHP2711).
The authors declare they have no actual or potential competing financial interests.
Received 21 August 2017; Revised 14 January 2019; Accepted 15 January 2019; Published 31 January 2019.

The lack of clear evidence on the health effects of $PM_{2.5–10}$ (especially in developing countries), together with the uncertainties with respect to exposure assessment of $PM_{2.5–10}$, impedes the debate on its independent health effects (U.S. EPA 2009). As the largest developing county, China is now facing one of the severest particulate air pollution problems in the world. Our recent nationwide study reported significant associations between $PM_{2.5}$ and daily mortality from various cardiorespiratory diseases in 272 Chinese cities (Chen et al. 2017). In the present study, we used simultaneous monitoring data for $PM_{2.5}$ and PM_{10} to estimate short-term $PM_{2.5–10}$ exposures and conduct a parallel time-series study of associations with cause-specific mortality in Chinese populations.

Methods

Data Collection

This analysis was based on a national database of daily air pollutant concentrations, weather conditions, and cause-specific mortality that has been described elsewhere (Chen et al. 2017). A total of 272 Chinese cities were eligible for inclusion because they averaged >three nonaccidental deaths per day and had at least 1 y of daily PM_{10} and $PM_{2.5}$ measurements at collocated monitors during the January 2013–December 2015 study period, including 69 cities with 3 y of data, 74 cities with 2 y of data, and 129 cities with 1 y of data. There were no missing daily average data during the respective study periods. These cities are dispersed over all 31 provincial administrative regions and account for >20% of the total population of Mainland China. We further divided these cities into northern and southern regions ($n = 112$ and 160 cities, respectively) according to their locations relative to the commonly defined line of Qinling Mountains and Huaihe River (Figure 1).

Daily mortality data during the study period were obtained from China's Disease Surveillance Points System (DSPS), which is administrated by the Chinese Center for Disease Control and Prevention. To ensure representativeness at the provincial level, the DSPS collects mortality data from 605 surveillance points (counties and districts) located throughout China's 31 provincial administrative regions, which were selected to be representative of the populations in each province and the Chinese population as a whole (Liu et al. 2016). Mortality data collected by the DSPS have been widely used in policy formulation and disease burden assessment in China and worldwide (Zhou et al. 2016). We evaluated a range of mortality outcomes defined by the primary cause of death, including mortality due to nonaccidental causes (total, *International Classification of Disease, 10th revision* codes A00–R99), cardiovascular diseases (CVDs; codes I00–I99), coronary heart disease (CHD, codes I20–I25), stroke (codes I60–I69), respiratory diseases (codes J00–J98), and chronic obstructive pulmonary disease (COPD; codes J41–J44) (WHO 2016). Daily time series of cause-specific numbers of deaths for each city were constructed by aggregating all recorded deaths in each district within a city covered by the DSPS on each day. We further divided daily total deaths by gender, age group (5–64 y, 65–74 y, and 75 y or older), and educational attainment (low: ≤9 y of education; high: >9 y of education). 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 because data were analyzed at aggregate level and no participants were contacted.

Because $PM_{2.5–10}$ was not monitored directly, its concentrations were estimated by subtracting simultaneously measured concentrations of $PM_{2.5}$ from PM_{10} at collocated monitors, as in previous epidemiological studies (Chen et al. 2011; Powell et al. 2015). In brief, for each city, we derived hourly $PM_{2.5–10}$ concentrations for each monitor and then derived 24-h mean $PM_{2.5–10}$ concentrations by averaging the hourly estimates from all valid monitors within the city on each day. As of January 2015, the present study included data from 1,265 collocated state-controlled monitors, with a median of four monitors per city (range: 1–17). Hourly concentrations of $PM_{2.5}$ and PM_{10} from each monitor were obtained from the China's National Urban Air Quality Real-Time Publishing Platform, which is operated by China National Environment Monitoring Center (CNEMC 2016). All state-controlled monitors are operated under the China National Quality Control (GB3095-2012). They are

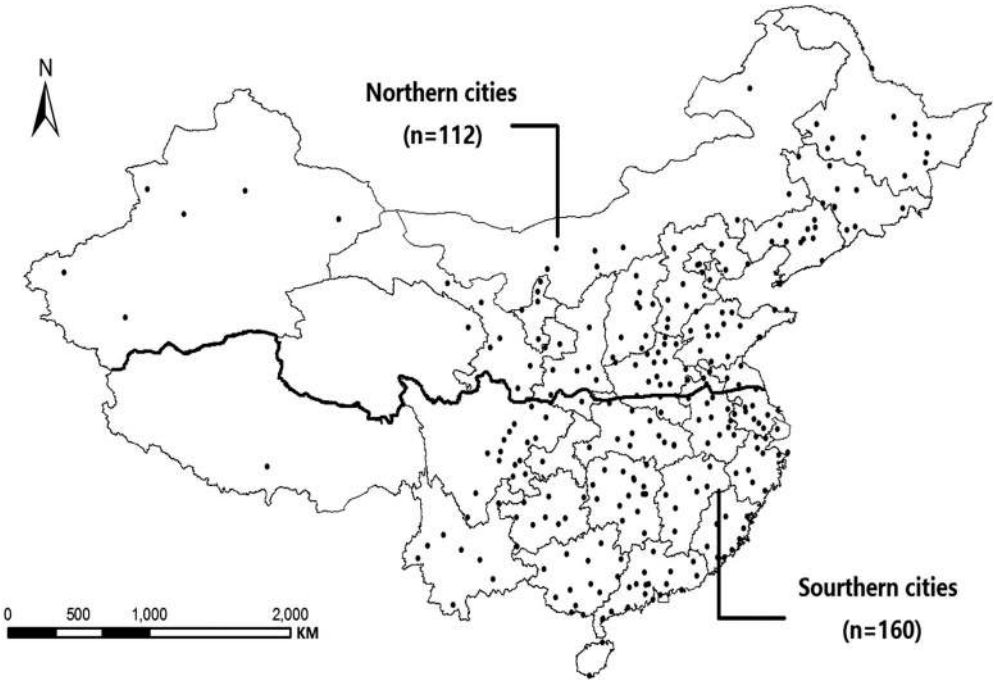

Figure 1. The location of study cities in Mainland China.

mandated to be not in the direct vicinity of apparent emission sources; thus, their measurements should reflect the general urban background level of air pollution. Both $PM_{2.5}$ and PM_{10} were measured using the method of tapered element oscillating microbalance. According to China's technical specifications and requirements for automatic monitoring, all PM monitoring instruments must be equipped with the membrane dynamic measurement system to correct for losses of semivolatile materials. To allow adjustment for concomitant exposure to gaseous pollutants, we also collected daily average concentrations of sulfur dioxide (SO_2, 24 h), nitrogen dioxide (NO_2, 24 h), carbon monoxide (CO, 24 h), and ozone (O_3, 8 h) from the same monitors. Daily measurements from individual monitors were excluded from the citywide average for a given day if <18 hourly measurements were available from the monitor for that day. In addition, we obtained daily mean temperature and relative humidity data for each city from the China's National Meteorological Information Center (China Meteorological Administration 2016), because both can potentially confound associations between air pollutants and mortality (Guo et al. 2014).

Statistical Analysis

We used a two-stage Bayesian hierarchical model to estimate regional and national average associations between daily $PM_{2.5–10}$ concentrations and cause-specific mortality (Peng et al. 2008; Powell et al. 2015).

In the first stage, we derived city-specific estimates by fitting overdispersed generalized additive models. In the main models, the covariates included: *a*) a natural-spline smooth function of calendar day with 7 degrees of freedom (df) per year to exclude unmeasured time trends longer than 2 mo in mortality, *b*) an indicator variable for "day of week" to account for possible variations in a week, and *c*) natural-spline smooth functions with 6 df for temperature and 3 df for relative humidity to exclude potential nonlinear and lagged confounding effects of weather conditions. This model has been widely used in previous time-series studies (Chen et al. 2012, 2017; Dominici et al. 2006). Because of collinearity between weather conditions on neighboring days, we modeled moving averages of temperature and humidity on the current day and previous 3 d (4-d moving average, lag 0–3) (Chen et al. 2017). We used the 2-d moving average of current- and previous-day $PM_{2.5–10}$ concentrations (lag 01) in our main analyses *a priori* because PM concentrations during this lag period have been strongly associated with mortality in previous studies (Chen et al. 2012, 2017). In addition to single-pollutant models, we used two-pollutant first-stage models that also included $PM_{2.5}$ (lag 01) to derive city-specific effect estimates for $PM_{2.5}$ and $PM_{2.5–10}$ and allow direct comparisons of mutually adjusted summary estimates for both pollutants. To evaluate potential confounding by concomitant exposures to gaseous pollutants, we also fit first-stage models adjusted for SO_2, NO_2, CO, or O_3, respectively. The association between $PM_{2.5–10}$ and mortality was considered robust or independent from concomitant exposure to a copollutant if the *p*-value for the dichotomous copollutant variable was greater than 0.05 in a meta-regression analysis with both single- and two-pollutant model estimates (Chen et al. 2018; Yin et al. 2017).

In the second stage, we applied a Bayesian hierarchical model to obtain regional and national average summary estimates. This model was selected because it can combine relative risk estimates across cities while accounting for within-city statistical error and between-city variability (heterogeneity) in the true risk, and has been widely used in multisite epidemiological studies (Chen et al. 2017; Peng et al. 2008; Powell et al. 2015).

We derived pooled concentration–response curves using the approach applied by the Air Pollution and Health: A European Approach project to estimate the average shape of $PM_{2.5–10}$–mortality associations at the national and regional levels (Chen et al. 2017; Samoli et al. 2005). Exploratory graphical analyses indicated that a linear association was dominant across cities (data not shown); therefore, we modeled cubic splines with two knots at the average value of the 25th percentile (20 $\mu g/m^3$) and 75th percentile (60 $\mu g/m^3$) across all cities. We then used random-effects models to combine the city-specific components of the spline estimates (five regression coefficients for the *bs* function of $PM_{2.5–10}$ and the 5×5 variance–covariance matrix) from the first-stage models for each city. We assessed the linearity of the summary concentration–response curves by comparing the goodness of fit (expressed by the generalized cross-validation statistic) of the spline model with the corresponding linear model (Samoli et al. 2005).

We used hierarchical models to derived summary estimates of associations between $PM_{2.5–10}$ and total, cardiovascular, and respiratory mortality according to age (5–64, 65–74, or ≥75 y), gender, and education (low or high). We then used likelihood ratio tests comparing the goodness of fit of a meta-regression model with the potential modifier to the simple meta-analysis model without this variable to derive *p*-values for the influence of each potential modifier on the estimated effect of $PM_{2.5–10}$ (Chen et al. 2018; Yin et al. 2017). We also applied meta-regression models to examine the difference of $PM_{2.5–10}$ effect estimates between cities in the north and south. In addition, we conducted meta-regression analyses to explore the influence of each of the following city-level characteristics on the association between lag 01 $PM_{2.5–10}$ and total nonaccidental mortality: annual mean concentrations of $PM_{2.5–10}$, $PM_{2.5}$, and gaseous pollutants; Pearson correlation coefficients for annual mean $PM_{2.5–10}$ and $PM_{2.5}$ concentrations; annual average daily temperature; and annual average daily humidity. In addition to evaluating each potential modifier in separate meta-regression models, we performed a multivariable meta-regression that included all of the potential modifiers.

Finally, we conducted several sensitivity analyses of associations with daily total mortality by altering the first-stage model to include: *a*) single-day lags for $PM_{2.5–10}$ (0, 1, 2, or 3 d); *b*) different df per year (6–10) for the smooth function of time; *c*) alternative lags for daily mean temperature and relative humidity [lag 0, lag 01, a 3-d moving average (lag 02), and lag 0 plus the cumulative average lag over 1–3 d (lag 1-3)] in the same model; and *d*) data from cities with only 1 y, 2 or more y, or 3 y of data, respectively. To determine whether the duration of available data modified the short-term association between $PM_{2.5–10}$ and mortality, we derived *p*-values for a three-level "available years" variable from meta-regression models.

All analyses were conducted using R (version 3.4.2; R Core Team) with the mgcv package for fitting the GAM, the tlnise package for the Bayesian hierarchical model, and the metafor package for meta-regression analyses. *p*-Values <0.05 were considered statistically significant. The effect estimates are reported as the percentage difference in mean daily mortality (with 95% posterior intervals; PIs) per 10-$\mu g/m^3$ or city-specific interquartile range (IQR) increases in lag 01 concentrations of PM.

Results

Descriptive Statistics

Table 1 presents descriptive statistics for environment and health data. During the study period, the annual mean daily number of total nonaccidental deaths ranged from 3 to 165 across cities (median = 12), >60% of which were due to cardiopulmonary diseases. Annual average $PM_{2.5–10}$ concentrations varied from 9 $\mu g/m^3$ to 249 $\mu g/m^3$, with a median value (33 $\mu g/m^3$) >three

Table 1. Summary statistics for annual-average daily data on environment and mortality outcomes in 272 Chinese cities, 2013–2015.

Variables	Mean ± SD	Min	P25	Median	P75	Max
$PM_{2.5–10}$ ($\mu g/m^3$)	—	—	—	—	—	—
Nationwide	39 ± 23	9	24	33	49	249
North	51 ± 29	18	33	47	59	249
South	30 ± 12	9	22	28	36	66
IQRs of $PM_{2.5–10}$ ($\mu g/m^3$)	—	—	—	—	—	—
Nationwide	26 ± 18	7	16	22	33	201
North	35 ± 23	11	23	31	40	201
South	20 ± 8	7	14	18	24	41
Copollutants ($\mu g/m^3$)	—	—	—	—	—	—
$PM_{2.5}$	56 ± 20	18	41	54	67	127
SO_2	30 ± 17	3	18	25	36	109
NO_2	31 ± 11	10	22	30	38	66
CO (mg/m^3)	1.2 ± 0.4	0.4	0.8	1.0	1.3	2.5
O_3	77 ± 14	36	68	77	87	113
Weather conditions	—	—	—	—	—	—
Temperature (°C)	15 ± 5	−1	12	16	18	25
Humidity (%)	68 ± 10	35	61	71	77	91
Daily deaths	—	—	—	—	—	—
Total	16 ± 16	3	7	12	20	165
CVD	8 ± 7	1	3	6	10	65
CHD	3 ± 3	0	1	2	3	28
Stroke	4 ± 4	0	2	3	5	33
RD	2 ± 3	0	1	1	3	34
COPD	2 ± 2	0	0	1	2	29

Note: The locations of northern cities ($n = 112$) and southern cities ($n = 160$) are shown in Figure 1. —, data not available; CHD, coronary heart disease; COPD, chronic obstructive pulmonary disease; CVD, cardiovascular disease; IQR, interquartile range; $PM_{2.5–10}$, particulate matter with an aerodynamic diameter between 2.5 and 10 μm; RD, respiratory disease; SD, standard deviation.

times the median concentrations reported for cities in Europe and North America (Powell et al. 2015; Samoli et al. 2013). The concentration at the 95th percentile was 74 $\mu g/m^3$. The median coefficients of variation across cities of for annual mean $PM_{2.5–10}$ and $PM_{2.5}$ concentrations were 59 and 36%, respectively. Median values for the range and coefficient of variation for daily concentrations of $PM_{2.5–10}$ were 179 $\mu g/m^3$ and 63%, respectively. Concentrations and variation (expressed by IQRs) in $PM_{2.5–10}$ were higher in northern cities than in southern cities, with median annual mean concentrations of 47 vs. 28 $\mu g/m^3$ and median coefficients of variation of 74 vs. 58%. The median number of average daily deaths per city was slightly lower for cities in the south than in the north (15 vs. 17 deaths/d).

Overall, daily $PM_{2.5–10}$ concentrations were moderately correlated with $PM_{2.5}$ (median $r = 0.46$), with a smaller correlation for cities in the north (median $r = 0.37$) than in the south (median $r = 0.53$). Median correlations between $PM_{2.5–10}$ and gaseous pollutants were 0.33 for SO_2, 0.39 for NO_2, 0.23 for CO, and 0.12 for O_3. Climatic conditions (annual mean temperature and humidity) also varied among the cities (Table 1). $PM_{2.5–10}$ was weakly inversely correlated with daily mean temperature (median $r = -0.06$) and moderately inversely correlated with daily mean relative humidity (median $r = -0.34$).

Regression Results

Figure 2 presents national average estimates for associations between a 10-$\mu g/m^3$ increase in lag 01 $PM_{2.5–10}$ concentrations and total and cause-specific mortality (see Table S1 for numeric data). $PM_{2.5–10}$ was significantly associated with total nonaccidental mortality (0.23% higher; 95% PI: 0.13, 0.33). Associations were slightly stronger for cardiovascular (0.25%; 95% PI: 0.13, 0.37), respiratory (0.26%; 95% PI: 0.07, 0.46), and COPD mortality (0.34%; 95% PI: 0.12, 0.57); and slightly smaller for mortality due to CHD (0.21%; 95% PI: 0.05, 0.36) and stroke (0.21%; 95% PI: 0.08, 0.35). These associations were much weaker for northern cities compared with southern cities, and the north–south differences were statistically significant for total and CVD mortality (p-values ranging from <0.01 for total nonaccidental mortality to 0.41 for respiratory mortality) (Figure 2; Table S1). When the estimates were expressed by per city–specific IQR increase in lag01 $PM_{2.5–10}$, associations remained stronger, with significant differences for total and CVD mortality (though p-values increased slightly), for cities in the south (median IQR = 18 $\mu g/m^3$) than in the north (median IQR = 31 $\mu g/m^3$) (Table S2).

In general, summary effect estimates for total and cause-specific mortality from single-pollutant models were similar for 10-$\mu g/m^3$ increases in lag 01 $PM_{2.5}$ and $PM_{2.5–10}$ concentrations (Figure 3 and Table S3). Corresponding summary estimates derived from two-pollutant first-stage models were closer to the null and less precise, but still statistically significant. PIs for each outcome were larger for $PM_{2.5–10}$ than $PM_{2.5}$. Summary effect estimates for $PM_{2.5–10}$ and total and cause-specific mortality based on first-stage models adjusted for CO and O_3 were similar to estimates from single-pollutant models, but were attenuated when adjusted for SO_2 and NO_2 (Figure 4 and Table S4). Meta-regression analyses indicated that adjusting for individual gaseous pollutants did not have a significant influence on summary effect estimates for $PM_{2.5–10}$, with the exception of modification of the association with total nonaccidental mortality by NO_2 (percentage

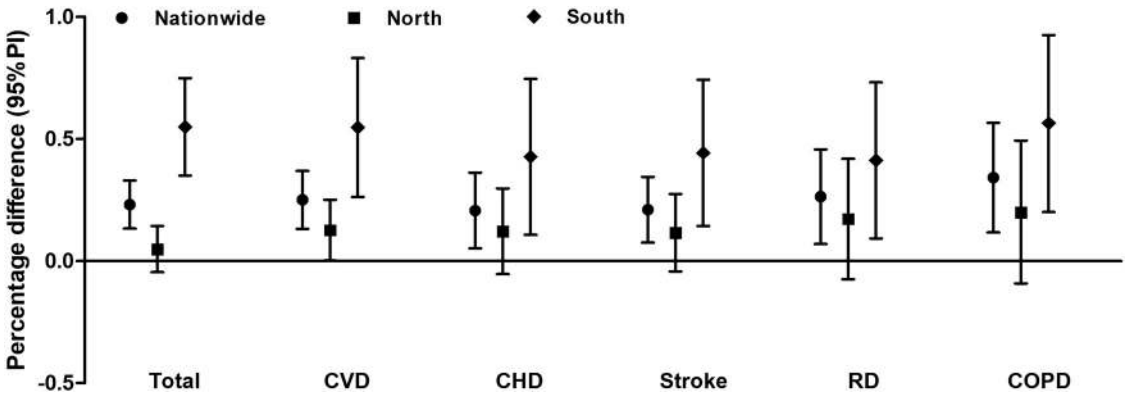

Figure 2. Percentage difference (posterior mean and 95% PI) in daily mortality by region and cause of death per 10-$\mu g/m^3$ increase in 2-d moving average $PM_{2.5–10}$ concentrations in 272 Chinese cities. Overdispersed generalized additive models were used to derive city-specific estimates adjusted for time trends, day of week, temperature, and humidity, and Bayesian hierarchical models were used to pool the estimates. Note: $PM_{2.5–10}$, particulate matter with an aerodynamic diameter between 2.5 and 10 μm; CVD, cardiovascular disease; CHD, coronary heart disease; RD, respiratory disease; COPD, chronic obstructive pulmonary disease. Corresponding numeric data are reported in Table S1.

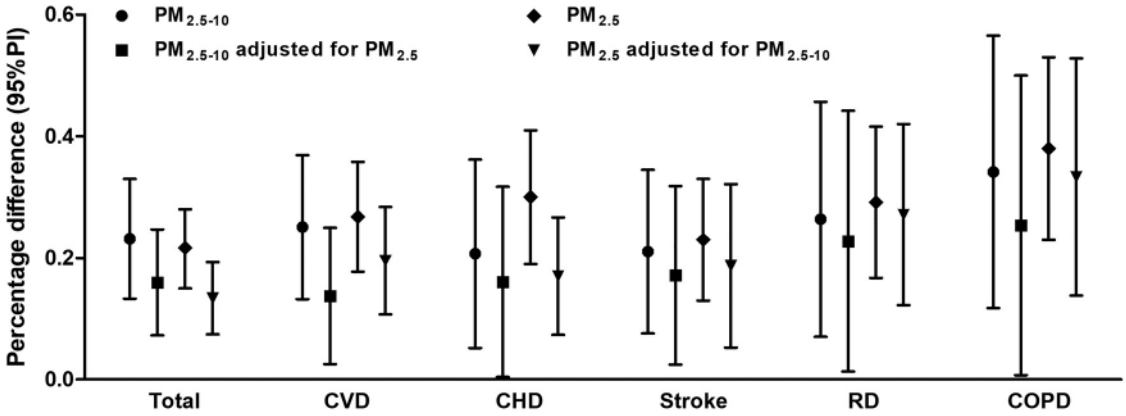

Figure 3. Associations of coarse particulate matter with aerodynamic diameter between 2.5 and 10 μm ($PM_{2.5–10}$) and PM with aerodynamic diameter ≤2.5 μm ($PM_{2.5}$) with cause-specific mortality based on single- and two- pollutant models in 272 Chinese cities. Associations are expressed as the percentage difference (posterior mean and 95% posterior interval) in daily mortality per 10-μg/m^3 increase in 2-d moving average concentrations. Overdispersed generalized additive models were used to derive city-specific estimates adjusted for time trends, day of week, temperature, and humidity, and Bayesian hierarchical models were used to pool the estimates. Note: PM, particulate matter; CVD, cardiovascular disease; CHD, coronary heart disease; RD, respiratory disease; COPD, chronic obstructive pulmonary disease. Corresponding numeric data are reported in Table S3.

difference with a 10-μg/m^3 increase in $PM_{2.5–10}$ of 0.10% with adjustment vs. 0.23% without adjustment, $p = 0.04$) (Table S4). The effect estimates for $PM_{2.5–10}$ after adjusting for SO_2 also decreased appreciably, but the difference did not reach statistical significance.

Modeling associations between total nonaccidental mortality and $PM_{2.5–10}$ using spline terms did not significantly improve model fit relative to linear models (p-values for differences from linear models: 0.83 for all cities, 0.80 for northern cities, and 0.90 for southern cities). Summary concentration–response curves were consistent with linearity across the exposure distribution, with a steeper positive slope for southern cities than northern cities (Figure 5).

Positive associations between $PM_{2.5–10}$ (lag 01) and total, cardiovascular, and respiratory mortality were stronger among those ≥75 y of age than for younger age groups, although differences by age were significant only for respiratory mortality (p-value <0.001) (Figure 6 and Table S5). Associations were slightly stronger and more precise for those with low education (<9 y) vs. higher education, although differences were not significant (Table S5). Associations were similar for women and men.

Single-variable meta regression models indicated significant differences in the association between a 10-μg/m^3 increase in lag 01 $PM_{2.5–10}$ and all nonaccidental mortality with a 1-unit increase in annual mean $PM_{2.5–10}$ (0.003% lower; 95% PI: −0.006, 0.000; $p = 0.01$) and $PM_{2.5}$ concentrations (0.006% lower; 95% PI: −0.011, −0.001; $p = 0.02$), and a 1-unit increase in city-specific Pearson correlation coefficients for $PM_{2.5–10}$ and $PM_{2.5}$ (0.376% higher; 95% PI: 0.014, 0.74; $p = 0.04$) (Table S6). Effect estimates for lag 01 $PM_{2.5–10}$ were not significantly modified by annual mean concentrations of SO_2, NO_2, CO, or O_3, or by annual mean temperature or relative humidity in each city (p-values of 0.10–0.52). When all above factors were simultaneously evaluated, only the annual mean Pearson correlation coefficients between $PM_{2.5–10}$ and $PM_{2.5}$ had a meaningful and positive impact. (0.408% higher; 95% PI: 0.001, 0.815; p-value = 0.05).

Figure S1 summarizes the results of sensitivity analyses on daily total mortality. The estimated effect of $PM_{2.5–10}$ decreased appreciably for single-day lags from lag 0 to lag 3, and was the strongest for lag 01. Effect estimates were similar when adjusted for time trends with different df and when adjusted for temperature and humidity using different lags. The associations were still

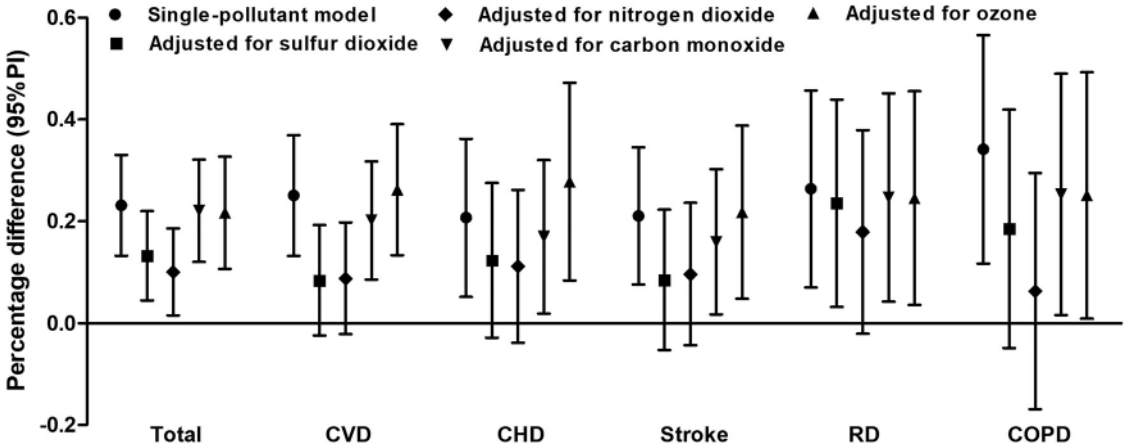

Figure 4. Percentage difference (posterior mean and 95% posterior interval) in daily mortality per 10-μg/m^3 increase in 2-d moving average $PM_{2.5–10}$ concentrations in single- and two-pollutant models with gaseous pollutants. Overdispersed generalized additive models were used to derive city-specific estimates adjusted for time trends, day of week, temperature, and humidity, and Bayesian hierarchical models were used to pool the estimates. Note: $PM_{2.5–10}$, particulate matter with an aerodynamic diameter between 2.5 and 10 μm; CVD, cardiovascular disease; CHD, coronary heart disease; RD, respiratory disease; COPD, chronic obstructive pulmonary disease. Corresponding numeric data are reported in Table S4.

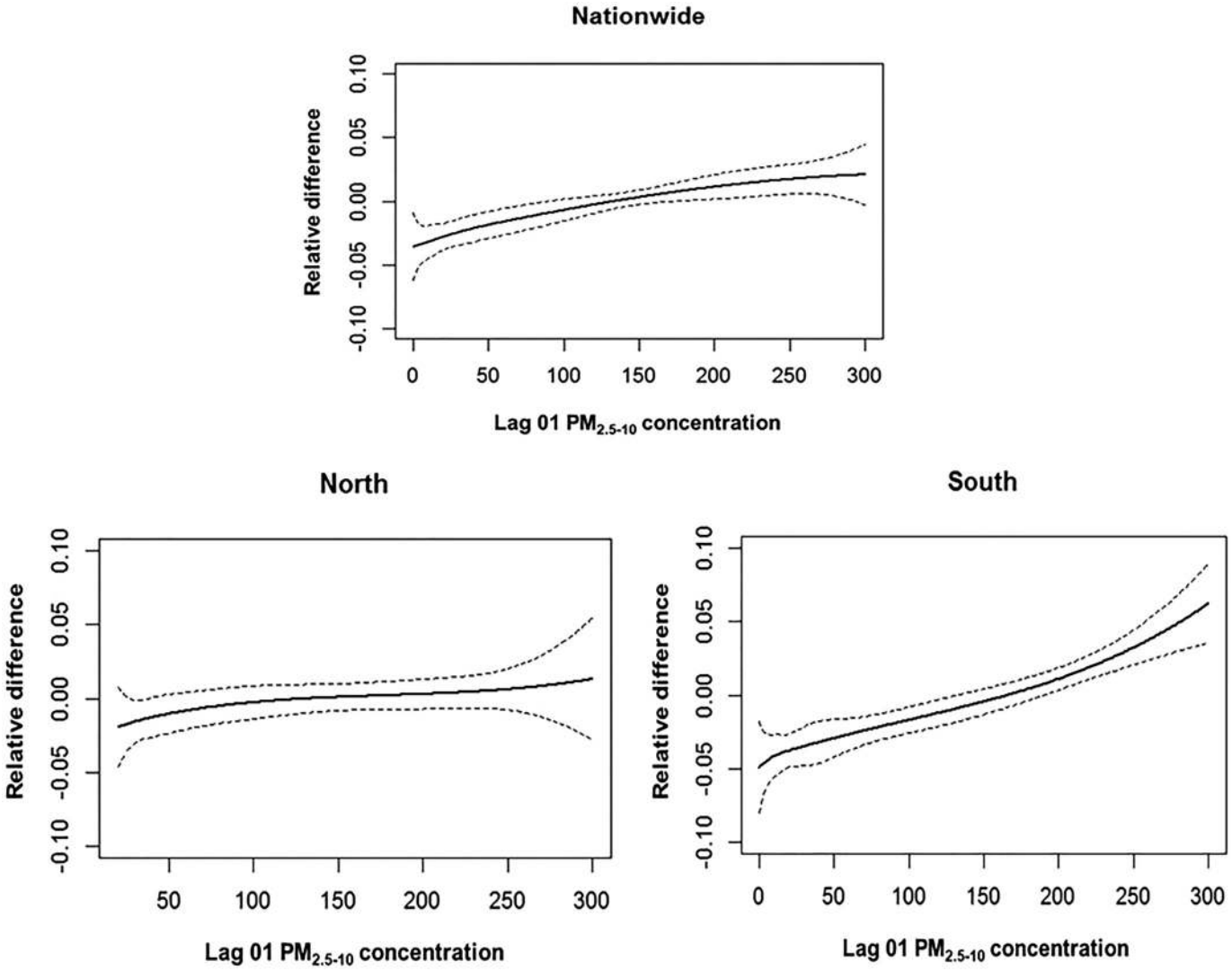

Figure 5. Concentration–response curves for 2-d moving average concentrations of $PM_{2.5–10}$ and daily total nonaccidental mortality in 272 Chinese cities. Overdispersed generalized additive models of $PM_{2.5–10}$ concentrations modeled using cubic splines with knots at 20 and 60 $\mu g/m^3$ were used to derive city-specific estimates adjusted for time trends, day of week, temperature, and humidity, which were pooled using random-effects models. The vertical scale represents the relative difference in mean mortality at each $PM_{2.5–10}$ concentration. The dotted lines indicate 95% confidence intervals for the mean effect estimates (plotted in solid lines). Note: $PM_{2.5–10}$, particulate matter with an aerodynamic diameter between 2.5 and 10 μm.

present, but the magnitude differed in subsets of cities with different years of data. Specifically, the percentage increase in total mortality per 10-$\mu g/m^3$ increase in $PM_{2.5–10}$ was 0.23% (95% PI: 0.13, 0.33) in all cities, 0.30% (95% PI: 0.10, 0.50) in 129 cities with only 1 y of data, 0.16% (95%PI: 0.05, 0.27) in 143 cities with 2 or 3 y of data, and 0.20% (95% PI: 0.05, 0.35) in 69 cities with 3 y of data. The number of years of data was not a significant modifier in meta-regression analyses (p-value = 0.28).

Discussion

In this national analysis of China, daily exposure to $PM_{2.5–10}$ was associated with increased mortality due to nonaccidental causes and cardiopulmonary diseases. Furthermore, associations with a 10-$\mu g/m^3$ increase in lag 01 $PM_{2.5–10}$ were similar in magnitude to associations with a 10-$\mu g/m^3$ increase in lag 01 $PM_{2.5}$ based on both single-pollutant models and two-pollutant models with mutual adjustment. The concentration–response curve for lag 01 $PM_{2.5–10}$ was almost linear. Associations between $PM_{2.5–10}$ and mortality were stronger in cities with higher correlations between $PM_{2.5–10}$ and $PM_{2.5}$.Our results were robust to the use of different model specifications. To our knowledge, this was the largest epidemiological study conducted in a developing country to evaluate the short-term effects of $PM_{2.5–10}$ on mortality.

Associations between $PM_{2.5–10}$ and daily mortality were smaller in magnitude than reported for other study populations. A literature review published in 2005 concluded that there was some evidence of associations between $PM_{2.5–10}$ and daily mortality (Brunekreef and Forsberg 2005). Furthermore, a recent meta-analysis based on 23 mortality studies published by the end of 2013, mostly conducted in North America and Europe, provided evidence of increased mortality in association with exposure to $PM_{2.5–10}$ (Adar et al. 2014). The authors reported a pooled estimate for total mortality with a 10-$\mu g/m^3$ increase in $PM_{2.5–10}$ of 0.60% [95% confidence interval (CI): 0.30, 0.80], which is >two times higher than our estimate (0.23%; 95% PI: 0.13, 0.33). A more recent multicountry study in 11 East Asian cities reported a summary estimate for mortality of 0.38% (95% CI: 0.21, 0.55) per 10-$\mu g/m^3$ increase in $PM_{2.5–10}$ (Lee et al. 2015). However, our previous estimate of a 0.25% (95% CI: 0.08, 0.41) increase in total mortality in Beijing, Shanghai, and

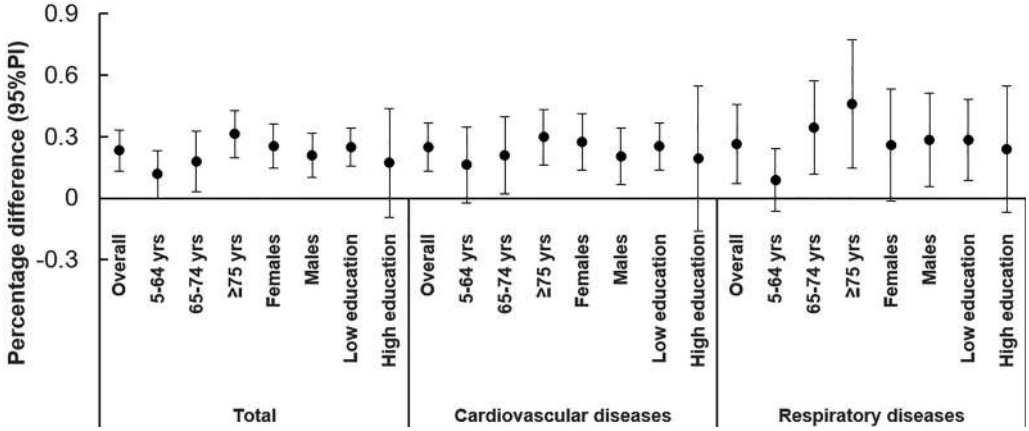

Figure 6. Percentage difference (posterior mean and 95% posterior interval) in daily mortality per 10-μg/m^3 increase in 2-d moving average concentrations of $PM_{2.5–10}$ in 272 Chinese cities, according to age, sex, and education attainment. Overdispersed generalized additive models were used to derive city-specific estimates adjusted for time trends, day of week, temperature, and humidity, and Bayesian hierarchical models were used to pool the estimates. Education: low, ≤9 y; high, >9 y. Corresponding numeric data are reported in Table S5.

Guangzhou with a 10-μg/m^3 increase in $PM_{2.5–10}$ on the previous day (Chen et al. 2011) was similar to our estimate for China as a whole. It is not clear why the association between short-term $PM_{2.5–10}$ exposure and nonaccidental mortality in China would be smaller in magnitude than associations reported for other countries, but it might be explained by factors such as the saturation effect at high concentrations, lower rate of population aging, and more adaptive behaviors (staying indoors, wearing masks, use of air purifiers, etc.) during haze events (Chen et al. 2017; Zhou et al. 2013, 2015). However, noncausal explanations should also be considered.

Comparing effect estimates for $PM_{2.5–10}$ and $PM_{2.5}$ in both single- and two- pollutant models can shed light on whether there is an independent effect of $PM_{2.5–10}$ and a need for separate regulatory measures for each. In our study population, associations between $PM_{2.5–10}$ and daily mortality were similar in magnitude to associations with $PM_{2.5}$, even after mutual adjustment in two-pollutant models. In general, associations with $PM_{2.5–10}$ were fairly robust to adjustment for CO and O_3, but were somewhat attenuated with adjustment for NO_2 and SO_2. In their 2005 literature review, Brunekreef and Forsberg reported that estimated effects of $PM_{2.5–10}$ on daily mortality from three out of four studies were positive but no longer significant after adjustment for $PM_{2.5}$, whereas effect estimates for $PM_{2.5}$ remained significant (Brunekreef and Forsberg 2005); only a study from Mexico City obtained robust results for $PM_{2.5–10}$ when adjusted for $PM_{2.5}$ (Castillejos et al. 2000). In their 2014 review, Adar and colleagues reported that effect estimates for short-term $PM_{2.5–10}$ were generally similar to those for $PM_{2.5}$ in mortality studies with paired single-pollutant analyses, but associations with $PM_{2.5–10}$ were attenuated when adjusted for $PM_{2.5}$ (Adar et al. 2014). More recently, a study in 11 East Asian cities also reported that associations between $PM_{2.5–10}$ and daily all-cause mortality were null after adjustment for $PM_{2.5}$ (Lee et al. 2015). Several factors may contribute to differences between our findings and those of previous studies, including greater statistical power and precision for two-pollutant models because of the large number of observations and range of exposures in our nationwide study (Powell et al. 2015). However, the use of different methods to estimate $PM_{2.5–10}$ and differences in the accuracy of exposure assessment, exposure sources, population susceptibility, and other causal and noncausal factors also may contribute to differences.

In the current study, we estimated significant associations between $PM_{2.5–10}$ and cardiopulmonary mortality that were similar in magnitude for mortality due to cardiovascular and respiratory diseases, and for more specific causes of death, including CHD, stroke, and COPD. Previous findings for outcome-specific associations with short-term $PM_{2.5–10}$ have been mixed. The 2014 meta-analysis by Adar et al. documented stronger associations for respiratory mortality and hospitalization than for cardiovascular outcomes (Adar et al. 2014). In contrast, associations of short-term $PM_{2.5–10}$ with hospital admissions in the extended U.S. Medicare dataset (Powell et al. 2015) and mortality in 11 East Asian cities were stronger for cardiovascular outcomes than respiratory diseases (Lee et al. 2015).

Adverse health effects of $PM_{2.5–10}$ are biologically plausible. $PM_{2.5–10}$ originates mainly from windblown soil and road dust, mechanical grinding processes, and biological aerosols (such as bacteria, molds, or pollens) that can induce inflammatory and allergic responses in the respiratory tract (Alexis et al. 2006; Steerenberg et al. 2006). Toxic constituents of $PM_{2.5–10}$ that accumulate in the bronchial passages, including ions, soluble carbon, soluble metals, and endotoxin, can be transferred to smaller airways where they may stimulate cytokine production by alveolar macrophages (Becker et al. 2003; Behbod et al. 2013; Gerlofs-Nijland et al. 2009). Oxidative stress can be stimulated by $PM_{2.5–10}$ as well as $PM_{2.5}$, resulting in damage to both the cardiovascular and respiratory system (Vignal et al. 2017). In addition, controlled human exposure studies have associated short-term $PM_{2.5–10}$ exposure with changes in markers of inflammation, coagulation, vascular endothelial function, and autonomic tone, DNA methylation, and blood pressure (Behbod et al. 2013; Bellavia et al. 2013; Brook et al. 2014).

Associations between $PM_{2.5–10}$ and daily mortality were stronger for cities in southern China than in northern cities, with percentage differences in total mortality with a 10-μg/m^3 increase in lag 01 $PM_{2.5–10}$ of 0.55; 95% PI: 0.35, 0.75 vs. 0.05; 95% PI: −0.05, 0.14, respectively ($p < 0.01$). Differences in estimated effects between the two regions may reflect multiple factors. The effect estimates remained stronger for the south than the north when based on IQR increases in exposure, even though the IQR for southern cities was almost half the IQR for northern cities (average: 14 and 26 μg/m^3, respectively) (Table S2). $PM_{2.5–10}$ might be less toxic in the north than in the south, for example, if $PM_{2.5–10}$ in the north contains a higher proportion of windblown dust. However, there is a lack of direct data on regional differences in the sources, chemical composition, and toxicological potential of $PM_{2.5–10}$ in China. Personal exposure patterns also may vary between the two regions, although one would expect a stronger association between ambient levels and

personal exposure in southern cities because people typically spend more time outdoors, and natural ventilation rates in buildings are higher than in the north (Chen et al. 2013, 2017; Zhou et al. 2013). Finally, stronger effect estimates in the south might reflect stronger correlations between $PM_{2.5}$ and $PM_{2.5–10}$, as suggested by the meta-regression analysis.

Several limitations should be noted. First, this analysis is inherently an ecological study, and thus, individual-level confounding cannot be fully excluded. Second, exposure measurement errors were inevitable in this time-series study because central site monitoring rather than personal measurements were used (Chang et al. 2011). Nonetheless, this kind of nondifferential error is generally expected to result in underestimation of the effects of airborne pollutants in time-series studies (Zeger et al. 2000). Third, as done in most previous epidemiological studies, we used the difference between PM_{10} and $PM_{2.5}$ to estimate $PM_{2.5–10}$ concentrations, and thus, our exposure estimates will be affected by measurement errors in both PM_{10} and $PM_{2.5}$ (Powell et al. 2015). $PM_{2.5–10}$ is a more spatially heterogeneous pollutant than $PM_{2.5}$, and differences in sources and deposition velocity of $PM_{2.5}$ and $PM_{2.5–10}$ on the ground further complicate potential measurement errors. However, we believe that such measurement errors would be largely nondifferential because $PM_{2.5–10}$ concentrations were derived from collocated monitors designed to reflect the urban background level of air pollution. Collinearity between $PM_{2.5–10}$, $PM_{2.5}$, and gaseous pollutants adds further uncertainty to estimates of the independent effects of $PM_{2.5–10}$ based on two-pollutant models (Bateson et al. 2007). Our findings also may not be generalizable to other countries, especially developed countries with low particulate air pollution levels. Therefore, additional experimental studies and observational studies based on direct monitoring and/or residential modeling are needed to confirm whether there are causal health effects of $PM_{2.5–10}$.

Conclusion

Our nationwide analysis in China demonstrated that short-term $PM_{2.5–10}$ exposure was associated with increased daily mortality from all nonaccidental causes and cardiopulmonary diseases, especially in southern cities. In general, these associations appeared to be independent of concomitant exposures to $PM_{2.5}$, carbon monoxide, and ozone. Our findings add to a growing body of epidemiological evidence suggesting detrimental health effects of $PM_{2.5–10}$ that merit further investigation. In addition, we believe that health risk assessment and guidelines or standards for $PM_{2.5–10}$ should be considered to fully address the health hazards of particulate air pollution.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (91643205 and 91743111), National Environmental Public Welfare Research Program of Ministry of Environmental Protection of China (201509062), and China Medical Board Collaborating Program (16-250).

References

Adar SD, Filigrana PA, Clements N, Peel JL. 2014. Ambient coarse particulate matter and human health: a systematic review and meta-analysis. Curr Environ Health Rep 1(3):258–274, PMID: 25152864, https://doi.org/10.1007/s40572-014-0022-z.

Alexis NE, Lay JC, Zeman K, Bennett WE, Peden DB, Soukup JM, et al. 2006. Biological material on inhaled coarse fraction particulate matter activates airway phagocytes in vivo in healthy volunteers. J Allergy Clin Immunol 117(6):1396–1403, PMID: 16751003, https://doi.org/10.1016/j.jaci.2006.02.030.

Bateson TF, Coull BA, Hubbell B, Ito K, Jerrett M, Lumley T, et al. 2007. Panel discussion review: session three–issues involved in interpretation of epidemiologic analyses–statistical modeling. J Expo Sci Environ Epidemiol 17(S2):S90–S96, PMID: 18079770, https://doi.org/10.1038/sj.jes.7500631.

Becker S, Soukup JM, Sioutas C, Cassee FR. 2003. Response of human alveolar macrophages to ultrafine, fine, and coarse urban air pollution particles. Exp Lung Res 29(1):29–44, PMID: 12652814, https://doi.org/10.1080/01902140303762.

Behbod B, Urch B, Speck M, Scott JA, Liu L, Poon R, et al. 2013. Endotoxin in concentrated coarse and fine ambient particles induces acute systemic inflammation in controlled human exposures. Occup Environ Med 70(11):761–767, PMID: 24143017, https://doi.org/10.1136/oemed-2013-101498.

Bellavia A, Urch B, Speck M, Brook RD, Scott JA, Albetti B, et al. 2013. DNA hypomethylation, ambient particulate matter, and increased blood pressure: findings from controlled human exposure experiments. J Am Heart Assoc 2(3):e000212, PMID: 23782920, https://doi.org/10.1161/JAHA.113.000212.

Brook RD, Bard RL, Morishita M, Dvonch JT, Wang L, Yang HY, et al. 2014. Hemodynamic, autonomic, and vascular effects of exposure to coarse particulate matter air pollution from a rural location. Environ Health Perspect 122(6):624–630, PMID: 24618231, https://doi.org/10.1289/ehp.1306595.

Brunekreef B, Forsberg B. 2005. Epidemiological evidence of effects of coarse airborne particles on health. Eur Respir J 26(2):309–318, PMID: 16055881, https://doi.org/10.1183/09031936.05.00001805.

Castillejos M, Borja-Aburto VH, Dockery DW, Gold DR, Loomis D. 2000. Airborne coarse particles and mortality. Inhal Toxicol 12(sup1):61–72, https://doi.org/10.1080/0895-8378.1987.11463182.

Chang HH, Peng RD, Dominici F. 2011. Estimating the acute health effects of coarse particulate matter accounting for exposure measurement error. Biostatistics 12(4):637–652, PMID: 21297159, https://doi.org/10.1093/biostatistics/kxr002.

Chen R, Kan H, Chen B, Huang W, Bai Z, Song G, et al. 2012. Association of particulate air pollution with daily mortality: the China Air Pollution and Health Effects Study. Am J Epidemiol 175(11):1173–1181, PMID: 22510278, https://doi.org/10.1093/aje/kwr425.

Chen R, Li Y, Ma Y, Pan G, Zeng G, Xu X, et al. 2011. Coarse particles and mortality in three chinese cities: the China Air Pollution and Health Effects Study (CAPES). Sci Total Environ 409(23):4934–4938, PMID: 21925709, https://doi.org/10.1016/j.scitotenv.2011.08.058.

Chen R, Yin P, Meng X, Liu C, Wang L, Xu X, et al. 2017. Fine particulate air pollution and daily mortality. A nationwide analysis in 272 Chinese cities. Am J Respir Crit Care Med 196(1):73–81, PMID: 28248546, https://doi.org/10.1164/rccm.201609-1862OC.

Chen R, Yin P, Meng X, Wang L, Liu C, Niu Y, et al. 2018. Associations between ambient nitrogen dioxide and daily cause-specific mortality: evidence from 272 Chinese cities. Epidemiology 29(4):482–489, PMID: 29621056, https://doi.org/10.1097/EDE.0000000000000829.

Chen R, Zhou B, Kan H, Zhao B. 2013. Associations of particulate air pollution and daily mortality in 16 Chinese cities: an improved effect estimate after accounting for the indoor exposure to particles of outdoor origin. Environ Pollut 182:278–282, PMID: 23954622, https://doi.org/10.1016/j.envpol.2013.07.024.

China Meteorological Administration. 2016. China's National Meteorological Information Center. http://data.cma.cn/ [accessed 29 January 2019].

CNEMC (China National Environmental Monitoring Centre). 2016. The China's National Urban Air Quality Real-Time Publishing Platform. http://106.37.208.233:20035/ [accessed 29 January 2019].

Dominici F, Peng RD, Bell ML, Pham L, McDermott A, Zeger SL, et al. 2006. Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. JAMA 295(10):1127–1134, PMID: 16522832, https://doi.org/10.1001/jama.295.10.1127.

GBD 2015 Risk Factors Collaborators. 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, PMID: 27733284, https://doi.org/10.1016/S0140-6736(16)31679-8.

Gerlofs-Nijland ME, Rummelhard M, Boere AJ, Leseman DL, Duffin R, Schins RP, et al. 2009. Particle induced toxicity in relation to transition metal and polycyclic aromatic hydrocarbon contents. Environ Sci Technol 43(13):4729–4736, PMID: 19673258, https://doi.org/10.1021/es803176k.

Guo Y, Gasparrini A, Armstrong B, Li S, Tawatsupa B, Tobias A, et al. 2014. Global variation in the effects of ambient temperature on mortality: a systematic evaluation. Epidemiology 25(6):781–789, PMID: 25166878, https://doi.org/10.1097/EDE.0000000000000165.

Kim KH, Kabir E, Kabir S. 2015. A review on the human health impact of airborne particulate matter. Environ Int 74:136–143, PMID: 25454230, https://doi.org/10.1016/j.envint.2014.10.005.

Lee H, Honda Y, Hashizume M, Guo YL, Wu CF, Kan H, et al. 2015. Short-term exposure to fine and coarse particles and mortality: a multicity time-series study in East Asia. Environ Pollut 207:43–51, PMID: 26340298, https://doi.org/10.1016/j.envpol.2015.08.036.

Liu S, Wu X, Lopez AD, Wang L, Cai Y, Page A, et al. 2016. An integrated national mortality surveillance system for death registration and mortality surveillance,

China. Bull World Health Organ 94(1):46–57, PMID: 26769996, https://doi.org/10.2471/BLT.15.153148.

Peng RD, Chang HH, Bell ML, McDermott A, Zeger SL, Samet JM, et al. 2008. Coarse particulate matter air pollution and hospital admissions for cardiovascular and respiratory diseases among Medicare patients. JAMA 299(18):2172–2179, PMID: 18477784, https://doi.org/10.1001/jama.299.18.2172.

Powell H, Krall JR, Wang Y, Bell ML, Peng RD. 2015. Ambient coarse particulate matter and hospital admissions in the Medicare Cohort Air Pollution Study, 1999-2010. Environ Health Perspect 123(11):1152–1158, PMID: 25872223, https://doi.org/10.1289/ehp.1408720.

Samoli E, Analitis A, Touloumi G, Schwartz J, Anderson HR, Sunyer J, et al. 2005. Estimating the exposure-response relationships between particulate matter and mortality within the APHEA multicity project. Environ Health Perspect 113(1):88–95, PMID: 15626653, https://doi.org/10.1289/ehp.7387.

Samoli E, Stafoggia M, Rodopoulou S, Ostro B, Declercq C, Alessandrini E, et al. 2013. Associations between fine and coarse particles and mortality in Mediterranean cities: results from the MED-PARTICLES project. Environ Health Perspect 121(8):932–938, PMID: 23687008, https://doi.org/10.1289/ehp.1206124.

Steerenberg PA, van Amelsvoort L, Lovik M, Hetland RB, Alberg T, Halatek T, et al. 2006. Relation between sources of particulate air pollution and biological effect parameters in samples from four european cities: an exploratory study. Inhal Toxicol 18(5):333–346, PMID: 16513592, https://doi.org/10.1080/08958370500515913.

U.S. EPA (Environmental Protection Agency). 2009. "Integrated Science Assessment (ISA) for Particulate Matter (Final Report, Dec 2009)." EPA/600/R-08/139F. Washington, DC:U.S. EPA.

Vignal C, Pichavant M, Alleman LY, Djouina M, Dingreville F, Perdrix E, et al. 2017. Effects of urban coarse particles inhalation on oxidative and inflammatory parameters in the mouse lung and colon. Part Fibre Toxicol 14(1):46, PMID: 29166940, https://doi.org/10.1186/s12989-017-0227-z.

WHO (World Health Organization). 2016. "International Statistical Classification of Diseases and Related Health Problems, 10th Revision. https://icd.who.int/browse10/2016/en [accessed 29 January 2019].

Yin P, Chen R, Wang L, Meng X, Liu C, Niu Y, et al. 2017. Ambient ozone pollution and daily mortality: a nationwide study in 272 Chinese cities. Environ Health Perspect 125(11):117006, PMID: 29212061, https://doi.org/10.1289/EHP1849.

Yorifuji T, Kashima S, Doi H. 2016. Associations of acute exposure to fine and coarse particulate matter and mortality among older people in Tokyo, Japan. Sci Total Environ 542(Pt A):354–359, PMID: 26519595, https://doi.org/10.1016/j.scitotenv.2015.10.113.

Zanobetti A, Schwartz J. 2009. The effect of fine and coarse particulate air pollution on mortality: a national analysis. Environ Health Perspect 117(6):898–903, PMID: 19590680, https://doi.org/10.1289/ehp.0800108.

Zeger SL, Thomas D, Dominici F, Samet JM, Schwartz J, Dockery D, et al. 2000. Exposure measurement error in time-series studies of air pollution: concepts and consequences. Environ Health Perspect 108(5):419–426, PMID: 10811568, https://doi.org/10.1289/ehp.00108419.

Zhou M, He G, Fan M, Wang Z, Liu Y, Ma J, et al. 2015. Smog episodes, fine particulate pollution and mortality in China. Environ Res 136:396–404, PMID: 25460661, https://doi.org/10.1016/j.envres.2014.09.038.

Zhou M, Wang H, Zhu J, Chen W, Wang L, Liu S, et al. 2016. Cause-specific mortality for 240 causes in China during 1990-2013: a systematic subnational analysis for the Global Burden of Disease Study 2013. Lancet 387(10015):251–272, PMID: 26510778, https://doi.org/10.1016/S0140-6736(15)00551-6.

Zhou B, Zhao B, Guo X, Chen R, Kan H. 2013. Investigating the geographical heterogeneity in PM10-mortality associations in the China Air Pollution and Health Effects Study (CAPES): a potential role of indoor exposure to PM10 of outdoor origin. Atmos Environ 75:217–223, https://doi.org/10.1016/j.atmosenv.2013.04.044.