Chemosphere 364 (2024) 143101

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Short-term exposure to ambient fine particulate matter constituents and myocardial infarction mortality

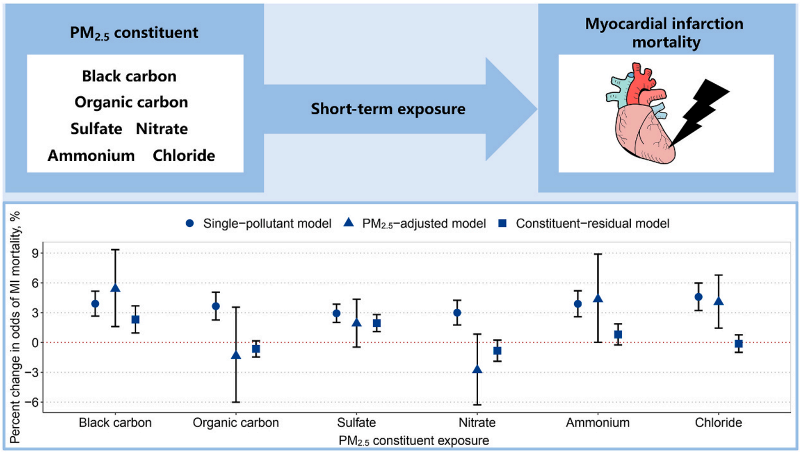
Yingxin Li [a,1], Bing Lu [b,1], Jing Wei [c], Qingqing Wang [d], Wancheng Ma [e], Rui Wang [e], Ruijun Xu [a], Zihua Zhong [a], Lu Luo [a], Xi Chen [f], Ziquan Lv [g], Suli Huang [h], Hong Sun [d,**], Yuewei Liu [a,*]

[a] *Department of Epidemiology, School of Public Health, Sun Yat-sen University, Guangzhou, Guangdong, China*
[b] *Department of Geriatrics, Geriatric Hospital of Nanjing Medical University, Nanjing, Jiangsu, China*
[c] *Department of Atmospheric and Oceanic Science, Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA*
[d] *Institute of Environment and Health, Jiangsu Provincial Center for Disease Control and Prevention, Nanjing, Jiangsu, China*
[e] *Luohu District Chronic Disease Hospital, Shenzhen, Guangdong, China*
[f] *National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, Beijing, China*
[g] *Department of Environment and Health, Shenzhen Center for Disease Control and Prevention, Shenzhen, Guangdong, China*
[h] *School of Public Health, Shenzhen University Medical School, Shenzhen University, Shenzhen, Guangdong, China*

HIGHLIGHTS

- A time-stratified case-crossover study was conducted to explore the associations.
- A high-quality dataset on fine particulate matter ($PM_{2.5}$) constituents was applied.
- Black carbon and sulfate in $PM_{2.5}$ were linked to myocardial infarction (MI) death.
- Black carbon and sulfate in $PM_{2.5}$ led to extensive excess mortality from MI.
- Older adults were more vulnerable to $PM_{2.5}$ constituent exposures in MI death.

GRAPHICAL ABSTRACT



---

[*] Corresponding author. Department of Epidemiology, School of Public Health, Sun Yat-sen University, 74 Zhongshan Second Road, Guangzhou, Guangdong, 510080, China.

[**] Corresponding author. Institute of Environment and Health, Jiangsu Provincial Center for Disease Control and Prevention, 172 Jiangsu Road, Nanjing, Jiangsu, 210009, China.

E-mail addresses: hongsun@jscdc.cn (H. Sun), liuyuewei@mail.sysu.edu.cn (Y. Liu).

[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.chemosphere.2024.143101
Received 29 April 2024; Received in revised form 10 August 2024; Accepted 13 August 2024

ARTICLE INFO

Handling editor: A. Gies

Keywords:
Myocardial infarction (MI)
Black carbon (BC)
Sulfate (SO_4^{2-})
Fine particulate matter ($PM_{2.5}$)
Case-crossover study

ABSTRACT

Short-term ambient fine particulate matter ($PM_{2.5}$) exposure has been related to an increased risk of myocardial infarction (MI) death, but which $PM_{2.5}$ constituents are associated with MI death and to what extent remain unclear. We aimed to explore the associations of short-term exposure to $PM_{2.5}$ constituents with MI death and evaluate excess mortality. We conducted a time-stratified case-crossover study on 237,492 MI decedents in Jiangsu province, China during 2015–2021. Utilizing a validated $PM_{2.5}$ constituents grid dataset at 1 km spatial resolution, we estimated black carbon (BC), organic carbon (OC), sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+), and chloride (Cl^-) exposure by extracting daily concentrations grounding on the home address of each subject. We employed conditional logistic regression models to evaluate the exposure-response relationship between $PM_{2.5}$ constituents and MI death. Overall, per interquartile range (IQR) increase of BC (lag 06-day; IQR: 1.75 μg/m^3) and SO_4^{2-} (lag 04-day; IQR: 5.06 μg/m^3) exposures were significantly associated with a 3.91% and 2.94% increase in odds of MI death, respectively, and no significant departure from linearity was identified in the exposure-response curves for BC and SO_4^{2-}. If BC and SO_4^{2-} exposures were reduced to theoretical minimal risk exposure concentration (0.89 μg/m^3 and 1.51 μg/m^3), an estimate of 4.55% and 4.80% MI deaths would be avoided, respectively. We did not find robust associations of OC, NO_3^-, NH_4^+, and Cl^- exposures with MI death. Individuals aged ≥80 years were more vulnerable to $PM_{2.5}$ constituent exposures in MI death (p for difference <0.05). In conclusion, short-term exposure to $PM_{2.5}$-bound BC and SO_4^{2-} was significantly associated with increased odds of MI death and resulted in extensive excess mortality, notably in older adults. Our findings emphasized the necessity of reducing toxic $PM_{2.5}$ constituent exposures to prevent deaths from MI and warranted further studies on the relative contribution of specific constituents.

1. Introduction

As a great public health threat, ischemic heart disease (IHD) appeared as a steadily upward trend for global mortality during the past 3 decades and contributed to approximately 9.14 million deaths worldwide in 2019, which was projected to be more serious in the future (Roth et al., 2020). Myocardial infarction (MI), the major clinical manifestation of IHD, continues to be a health challenge because of its characteristics of acute attack and high fatality rate (Thygesen et al., 2007). Given the huge MI death number, clarifying and managing its modifiable risk factors is a significant and effective way to reduce MI deaths and alleviate its disease burden. Fine particulate matter ($PM_{2.5}$) pollution in the atmosphere is considered one of the critical environmental risk factors for MI mortality, which has raised much attention globally (Chen et al., 2018; Dai et al., 2014; Liang et al., 2018; Mustafic et al., 2012; Rajagopalan et al., 2018; Zanobetti and Schwartz, 2009). Our previous studies in Jiangsu province and Hubei province, China offered reliable evidence that short-term exposure to $PM_{2.5}$ was significantly associated with increased odds of MI death (Liu et al., 2021a; Xu et al., 2023). Emerging investigations suggest that some toxic constituents in $PM_{2.5}$, including carbonaceous compound and water-soluble inorganic ion (WSII), may play a pivotal role in $PM_{2.5}$-induced MI death (Li et al., 2021; Mo et al., 2023; Yang et al., 2020; Zhang et al., 2021). Since $PM_{2.5}$ consists of various components with varying origins, toxicities, and health impacts, it is crucial to elucidate which constituents can exert harmful effects on MI mortality and how much the effects are, which can help understand their underlying cardiotoxicity and enact tailored measures to prevent $PM_{2.5}$-related MI mortality.

To date, only 3 population-based studies explored the acute effect of $PM_{2.5}$ constituent exposures on MI death, and their findings were mixed (Li et al., 2021; Mo et al., 2023; Yang et al., 2020). One study in southern China found significant associations between organic carbon (OC) and elemental carbon (EC) exposures and MI death; however, a nationwide study in China and a study in Guangzhou, China did not find consistent results. A significant association of ammonium (NH_4^+) exposure with MI death was identified in the nationwide study in China but not identified in the other 2 studies. A major concern in these studies is the limited accuracy of exposure assessment, because the $PM_{2.5}$ constituent exposure was estimated by the average concentration within a large region, which had difficulties in capturing the geographic variability of $PM_{2.5}$ constituents and may further affect the reliability of results. This exposure assessment problem is largely attributable to the deficiency of $PM_{2.5}$ constituent data with high spatiotemporal resolution.

To provide a more accurate assessment of $PM_{2.5}$ constituent exposures, we generated a daily and seamless $PM_{2.5}$ constituent product at high spatial resolution (1 km × 1 km) in China in our previous studies, which is a unique grid dataset offering high-precision estimation on $PM_{2.5}$-bound carbonaceous compounds and WSIIs (Wei et al., 2023a, 2023b). Here, we took advantage of this dataset to assess short-term exposure to $PM_{2.5}$ constituents at an individual level grounding on subjects' home addresses in Jiangsu province, China. A case-crossover study on over 0.2 million MI death cases was conducted in Jiangsu during 2015–2021 to systematically investigate the acute impact of $PM_{2.5}$ constituent exposures on MI death and evaluate the excess mortality.

2. Methods

2.1. Study population and outcome definition

Located in the eastern-central area of China, Jiangsu province had a population of 85.1 million in 2021, which accounted for 6.0% of the entire population in China. We ascertained 237,492 decedents who resided in Jiangsu province, China and died from MI during 2015–2021 grounding on the Jiangsu provincial mortality surveillance system. This system covered the overall population of Jiangsu and was under the administration of the Chinese Center for Disease Control and Prevention. We gathered information for each death case from this system, including sex, race, age, marital status, date of death, home address, and the underlying cause of death coded by the International Statistical Classification of Diseases and Related Health Problems 10th Revision (ICD-10). The outcome of this study was MI death as the underlying cause of death (ICD-10 code: I21 and I22), including acute MI and subsequent MI. This study has received approval from the Ethical Committee at the School of Public Health, Sun Yat-sen University with an exemption of informed consent.

2.2. Study design

We implemented a time-stratified case-crossover design to assess the impact of short-term exposure to $PM_{2.5}$ constituents on MI death. Under this design, exposure for a specific MI decedent on the case day was compared with exposures on days before and/or after the case day in the same time stratum (control days). The case day for each MI decedent was the date of death, whereas control days matched the case day by year, calendar month (the time stratum), and day of week with a matching ratio of 1 (case day) to 3 or 4 (control days). For instance, if an individual died from MI on a Thursday in August 2020 (case day), all other Thursdays in August 2020 were the matching control days. This design allowed for sufficient control of factors unlikely to vary within a calendar month (e.g., sex, economic condition, living habit) and the impact of seasonality, long-term trends, and day of week.

2.3. Exposure assessment

We retrieved a grid dataset on black carbon (BC), sulfate (SO_4^{2-}), nitrate (NO_3^-), NH_4^+, and chlorine (Cl^-) bounding to $PM_{2.5}$ in Jiangsu province during 2015–2021, which was generated by a four-dimensional spatiotemporal deep forest (4D-STDF) model that combined surface observations, satellite-derived big data, atmospheric reanalyzes, and model simulations (Wei et al., 2023a, 2023b). This dataset was available daily at a 1 km × 1 km spatial resolution, which had full-coverage $PM_{2.5}$ constituent estimations in China since 2000 and showed great agreement with surface measured values. The cross-validated coefficient of determinations (CV-R^2) for BC, SO_4^{2-}, NO_3^-, NH_4^+, and Cl^- were 0.82, 0.74, 0.75, 0.71, and 0.66, respectively. The pairwise Spearman's correlation coefficients of surface observation values with $PM_{2.5}$ constituent estimation values for BC, SO_4^{2-}, NO_3^-, NH_4^+, and Cl^- in Jiangsu province were 0.82, 0.69, 0.71, 0.72, and 0.81, respectively. To generate the grid data for OC, we computed the OC concentration for each grid cell by deducting the concentrations for BC, SO_4^{2-}, NO_3^-, NH_4^+, and Cl^- from that for $PM_{2.5}$ (Li et al., 2024). We also retrieved daily grid data (spatial resolution: 1 km × 1 km) on ambient $PM_{2.5}$ concentrations during 2015–2021 from the ChinaHighAirPollutant (CHAP) dataset. Grounding on each study subject's home address, daily exposure to $PM_{2.5}$ and its 6 constituents was assessed by extracting concentrations on both the case day and control days from the corresponding pollutant grid data. Besides examining the impact of $PM_{2.5}$ constituent exposures on the current day (lag 0-day), exposures on single-day lag (lag 1-day to lag 6-day) and moving mean day (lag 01-day to lag 06-day) were investigated to assess the hysteresis impact of $PM_{2.5}$ constituent on MI mortality (Liu et al., 2022a). For instance, lag 4-day exposure denotes the exposure on 4 days precedent to the case/control day, whereas lag 04-day exposure denotes the average concentration from the case/control day to its previous 4 days.

2.4. Covariates

From the China Meteorological Administration Land Data Assimilation System (CLDAS version 2.0), we retrieved grid data (spatial resolution: 0.0625° × 0.0625°; temporal resolution: daily) on temperature (unit: °C) and relative humidity (unit: %) in Jiangsu, China during the study period (Han et al., 2020; Liu et al., 2020; Tie et al., 2022). We assessed exposure to weather conditions for each subject by extracting his/her 24-h residential average values of temperature and relative humidity from the corresponding grid data. Personal covariates (e.g., sex, race, age, financial situation, and chronic comorbidities) were not included as confounders as they generally stayed constant within the time stratum (Liu et al., 2021a).

2.5. Statistical analysis

Conditional logistic regression models were utilized to evaluate the exposure-response relationship of $PM_{2.5}$ constituent exposures with MI death. We computed the percent change in odds ([odds ratio – 1] × 100%) of MI death and its 95% confidence interval (CI) associated with an interquartile range (IQR) increment of $PM_{2.5}$ constituent exposure. To visualize the exposure-response relationship, we included a natural cubic spline function for each $PM_{2.5}$ constituent exposure with 3 degrees of freedom in the conditional logistic regression model and tested the underlying nonlinearity utilizing a likelihood ratio test (Li et al., 2023). All models included temperature with 6 degrees of freedom (lag 03-day) and relative humidity with 3 degrees of freedom (lag 03-day) for a natural cubic spline function to adjust for weather conditions (Liu et al., 2019; Xu et al., 2022).

To assess the excess mortality from MI related to $PM_{2.5}$ constituent exposures, we applied the estimates in the exposure-response associations to compute the excess fraction and number of excess deaths:

$$Excess\ fraction = \frac{\sum_{i=1}^{i=N} 1 - \frac{1}{e^{\beta \times (C_i - C_0)}}}{N} \times 100\%$$

$$Number\ of\ excess\ deaths = Excess\ fraction \times N$$

where N is the MI death number; β is the point estimate of each $PM_{2.5}$ constituent exposure; C_i denotes the $PM_{2.5}$ constituent exposure with concentration exceeding C_0; C_0 denotes a counterfactual scenario of theoretical minimum risk exposure concentration.

To explore the potentially susceptible population and seasonal variation, we carried out stratified analyses by sex (male vs female), age (<80 years vs ≥ 80 years), and season (cool [January to March, October to December] vs warm [April to September]) and implemented 2-sample z tests to assess their effect modification (Fan et al., 2023). Sensitivity analyses were performed, including 1) building $PM_{2.5}$-adjusted models by controlling $PM_{2.5}$ to estimate the impact of a given $PM_{2.5}$ constituent retaining the concentrations of other constituents stable; 2) constructing constituent-residual models by including the residuals from a linear regression model with $PM_{2.5}$ and its specific constituent as the independent and the dependent variable, respectively, which assessed the effect of the constituent keeping the concentration of $PM_{2.5}$ stable; 3) restricting the analyses to acute MI death cases; 4) adjusting for exposure to temperature utilizing a natural spline function with 3 degrees of freedom; 5) adjusting for exposure to relative humidity using a natural spline function with 6 degrees of freedom; 6) restricting the analyses to subjects who died in 2015–2019 and 2020–2021, respectively, to evaluate the potential effect of the pandemic. A 2-sided test with $p < 0.05$ was statistically significant. We implemented all analyses by R version 4.1.2.

3. Results

We ascertained 237,492 MI death cases during the study period and included 237,492 case days and 806,169 control days (Table 1). Among the MI death cases, 98.50% died from acute MI, 52.25% were men, 52.50% died at or after 80 years of age, and 56.99% died in the cool season. Most study subjects were married (63.15%) or widowed (31.08%). The number of MI death cases was similar in each year during 2015–2021. The $PM_{2.5}$ mass exposure levels ranged from 2.68 $\mu g/m^3$ to 286.06 $\mu g/m^3$, with an average concentration of 51.87 $\mu g/m^3$ (Table 2). The mean exposure concentration to $PM_{2.5}$-bound BC, OC, SO_4^{2-}, NO_3^-, NH_4^+, and Cl^- was 3.04 $\mu g/m^3$, 16.60 $\mu g/m^3$, 10.16 $\mu g/m^3$, 12.30 $\mu g/m^3$, 7.64 $\mu g/m^3$, and 2.19 $\mu g/m^3$, respectively. The average concentration to BC, OC, SO_4^{2-}, NO_3^-, NH_4^+, and Cl^- in 2015–2019 was 3.14 $\mu g/m^3$, 18.80 $\mu g/m^3$, 10.49 $\mu g/m^3$, 13.17 $\mu g/m^3$, 8.07 $\mu g/m^3$, and 2.31 $\mu g/m^3$, respectively; the concentrations in 2020–2021 decreased to 2.74 $\mu g/m^3$, 10.69 $\mu g/m^3$, 9.20 $\mu g/m^3$, 10.01 $\mu g/m^3$, 6.44 $\mu g/m^3$, and 1.85 $\mu g/m^3$, respectively. Exposure to $PM_{2.5}$ was correlated with each $PM_{2.5}$ constituent exposure significantly and positively (Table S1). The pairwise Spearman's correlation coefficients of $PM_{2.5}$ with BC, OC, SO_4^{2-}, NO_3^-, NH_4^+, and Cl^- were 0.91, 0.96, 0.87, 0.93, 0.94, and 0.87, respectively (all $p < 0.05$).

In single-pollutant models, we identified significant associations of short-term $PM_{2.5}$ constituent exposures with MI death, and the strongest associations for BC, OC, SO_4^{2-}, NO_3^-, NH_4^+, and Cl^- exposure pronounced at lag 06-day, lag 06-day, lag 04-day, lag 06-day, lag 06-day, and lag 05-day exposure, respectively (Fig. 1). Per IQR increment of exposure to BC (lag 06-day; IQR: 1.75 $\mu g/m^3$), OC (lag 06-day; IQR: 18.55 $\mu g/m^3$), SO_4^{2-} (lag 04-day; IQR: 5.06 $\mu g/m^3$), NO_3^- (lag 06-day; IQR: 8.30 $\mu g/m^3$), NH_4^+

Table 1
Characteristics of the study subjects in Jiangsu province, China, 2015–2021.

Characteristic	Value
MI deaths, n	237,492
Acute MI, n (%)	233,921 (98.50)
Subsequent MI, n (%)	3571 (1.50)
Case days, n	237,492
Control days, n	806,169
Sex, n (%)	
Male	124,099 (52.25)
Female	113,393 (47.75)
Age	
Mean (SD), year	77.59 (13.32)
Median (IQR), year	80.70 (16.60)
<80 years, n (%)	112,809 (47.50)
≥80 years, n (%)	124,683 (52.50)
Race, Han, n (%)	232,258 (97.80)
Marital status, n (%)	
Married	149,971 (63.15)
Widowed	73,819 (31.08)
Unmarried	5852 (2.46)
Divorced	2034 (0.86)
Unknown	5816 (2.45)
Season at death, n (%)	
Cool (January to March, October to December)	135,339 (56.99)
Warm (April to September)	102,153 (43.01)
Year of death, n (%)	
2015	33,000 (13.90)
2016	34,471 (14.51)
2017	34,696 (14.61)
2018	34,500 (14.53)
2019	32,528 (13.70)
2020	34,447 (14.50)
2021	33,850 (14.25)

Abbreviations: MI, myocardial infarction; ICD-10, International Classification of Diseases 10th Revision; SD, standardized deviation; IQR, interquartile range.

Table 2
Distribution of exposure to ambient $PM_{2.5}$ constituents and weather conditions on the date of MI death in Jiangsu province, China, 2015–2021.

	Mean (SD)	Percentile				
		5th	25th	50th	75th	95th
$PM_{2.5}$, μg/m^3	51.87 (32.84)	16.60	28.52	43.34	65.79	117.56
$PM_{2.5}$ constituent, μg/m^3						
BC	3.04 (1.58)	1.34	1.94	2.62	3.70	6.15
OC	16.60 (15.91)	0.28	5.03	11.83	23.64	48.46
SO_4^{2-}	10.16 (4.72)	4.96	6.90	9.07	11.99	19.42
NO_3^-	12.30 (7.54)	3.78	7.06	10.63	15.41	26.99
NH_4^+	7.64 (3.84)	2.81	5.01	7.03	9.34	14.96
Cl^-	2.19 (1.51)	0.63	1.10	1.80	2.77	5.23
Weather condition						
Temperature, °C	14.63 (9.59)	0.45	6.12	14.30	23.28	29.41
Relative humidity, %	73.59 (13.44)	48.75	64.59	75.44	84.21	92.36

Abbreviations: $PM_{2.5}$, fine particulate matter; MI, myocardial infarction; SD, standardized deviation; BC, black carbon; OC, organic carbon; SO_4^{2-}, sulfate; NO_3^-, nitrate; NH_4^+, ammonium; Cl^-, chloride.

(lag 06-day; IQR: 4.34 μg/m^3), and Cl^- (lag 05-day; IQR: 1.66 μg/m^3) was significantly associated with increased odds of 3.91% (95% CI: 2.66%, 5.17%), 3.66% (95% CI: 2.27%, 5.07%), 2.94% (95% CI: 2.02%, 3.86%), 3.00% (95% CI: 1.77%, 4.25%), 3.89% (95% CI: 2.60%, 5.21%), and 4.60% (95% CI: 3.22%, 5.99%) for MI mortality, respectively (all $p < 0.05$). We did not identify any departure from linearity for BC, OC, SO_4^{2-}, NO_3^-, NH_4^+, and Cl^- exposure (p for nonlinear trend = 0.21, 0.15, 0.62, 0.55, 0.46, and 0.72, respectively; Fig. 2). In $PM_{2.5}$-adjusted models, the associations for BC, OC, SO_4^{2-}, NH_4^+, and Cl^- exposure kept stable (all p for difference >0.05), but the association between NO_3^- exposure and MI mortality turned to null (p for difference <0.05; Table 3). In constituent-residual models, the associations of each constituent exposure with MI death were significantly changed (all p for difference <0.05), and only the associations for BC and SO_4^{2-} exposure remained significant. Restricting analyses to acute MI, controlling temperature by 3 degrees of freedom, and controlling relative humidity by 6 degrees of freedom yielded similar results (Figs. S1–S3). When restricting analyses to 2015–2019 and 2020–2021, respectively, we found exposure to $PM_{2.5}$ constituents was significantly associated with increased odds of MI death in both periods, but the estimates in 2020–2021 were relatively low (Figs. S4–S7).

In the stratified analyses, stronger associations of exposure to BC, OC, SO_4^{2-}, NO_3^-, NH_4^+, and Cl^- with MI mortality were observed in subjects aged 80 years or older (all p for difference <0.05; Table 4). We also found a significantly stronger association of OC exposure with MI death in the warm season. No significant effect modification was identified in sex (all p for difference >0.05).

The excess fraction of MI death associated with BC and SO_4^{2-} exposure was 4.55% (95% CI: 3.15%, 5.92%) and 4.80% (95% CI: 3.34%, 6.22%), respectively (Fig. 3). If exposure to BC and SO_4^{2-} was reduced to theoretical minimal risk exposure concentration (0.89 μg/m^3 and 1.51 μg/m^3), an estimate of 10,808 (95% CI: 7482, 14,070) and 11,389 (95% CI: 7943, 14,774) MI deaths would be avoided, respectively. The excess fraction of MI death associated with exposure to BC was relatively higher in women, subjects aged 80 years or older, and cool season, accounting for 5.85% (95% CI: 3.85%, 7.80%), 6.51% (95% CI: 4.61%, 8.35%), and 5.11% (95% CI: 3.23%, 6.95%), respectively. The excess fraction associated with SO_4^{2-} exposure was relatively higher in women, subjects aged 80 years or older, and warm season, accounting for 5.39% (95% CI: 3.29%, 7.44%), 6.47% (95% CI: 4.50%, 8.39%), and 4.41% (95% CI: 1.74%, 7.01%), respectively.

4. Discussion

In this study on 237,492 MI death cases in Jiangsu province, China during 2015–2021, we identified that short-term exposure to BC and SO_4^{2-} bounding to $PM_{2.5}$ was consistently associated with increased odds of MI death. Per IQR increase in BC and SO_4^{2-} exposure was significantly associated with a 3.91% and 2.94% increase in odds of MI death, respectively. It was estimated that 4.55% and 4.80% of MI mortality was attributable to BC and SO_4^{2-} exposures, respectively. Individuals aged ≥80 years were more susceptible to $PM_{2.5}$ constituent exposure in MI mortality. We did not find robust relationships of $PM_{2.5}$-bound OC, NO_3^-, NH_4^+, and Cl^- exposure with MI death.

We comprehensively explored the acute impact of ambient $PM_{2.5}$ constituents on MI death grounding on an individual-level $PM_{2.5}$ constituent exposure estimation in this study, taking advantage of a high-precision $PM_{2.5}$ constituent grid dataset. Previous investigations on the exposure-response relationship of short-term exposure to $PM_{2.5}$ constituents with MI mortality failed to assess individual-level exposure and yielded inconsistent results. A nationwide study in 161 communities in China did not identify significant associations of EC, SO_4^{2-}, and NO_3^- exposures on MI mortality and found that each IQR increase of OC (lag 03-day; IQR: 5.1 μg/m^3) and NH_4^+ (lag 03-day; IQR: 6.8 μg/m^3) exposure was significantly associated with increments in MI death of 1.94% and 1.33%, respectively (Yang et al., 2020). Compared to our estimates in single-pollutant models, the estimates for OC between studies were very close, while the estimate for NH_4^+ in our study was relatively higher. One study in 32 counties of southern China observed that an IQR increase of EC (lag 02-day; IQR: 4.1 μg/m^3) and OC (lag 02-day; IQR: 9.1 μg/m^3) exposure was significantly associated with increased odds of 3.8% and 5.7% for MI mortality, respectively, but they did not detect significant

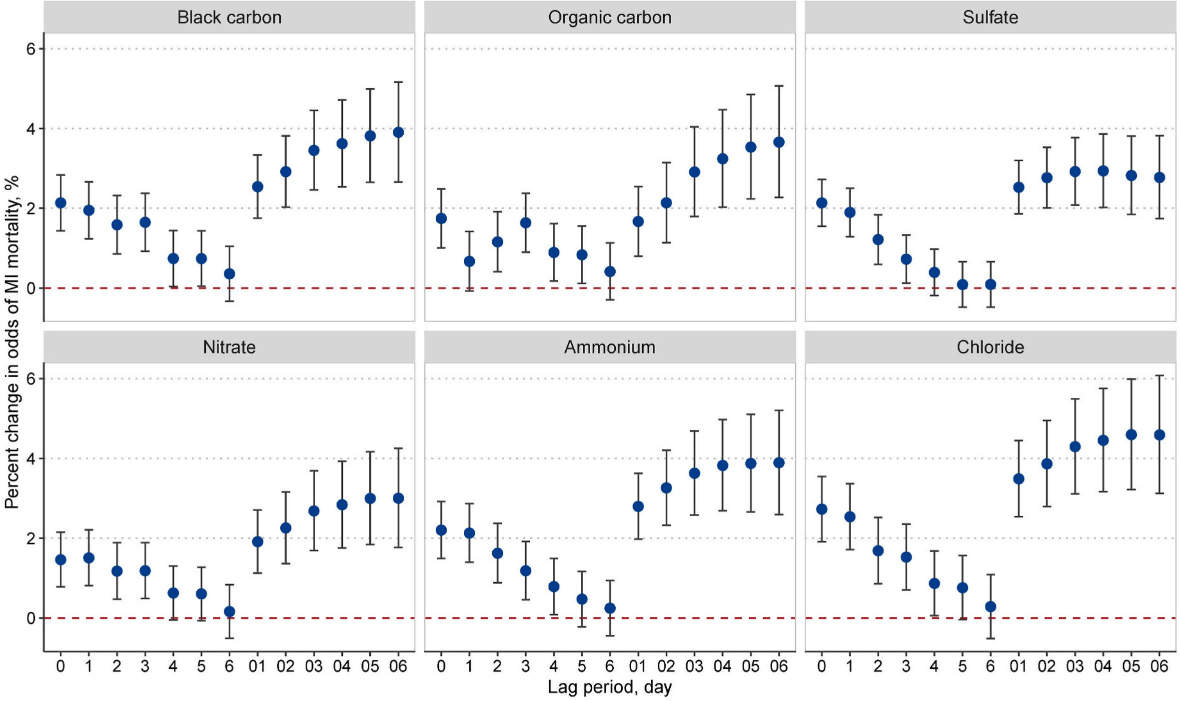


Fig. 1. Estimated percent change (95% CI) in odds of MI mortality associated with per IQR increase of exposure to $PM_{2.5}$ constituents with different lag periods. CI, confidence interval. Other abbreviations are in Tables 1 and 2. The IQR of BC, OC, SO_4^{2-}, NO_3^-, NH_4^+, and Cl^- is 1.75 μg/m^3, 18.55 μg/m^3, 5.06 μg/m^3, 8.30 μg/m^3, 4.34 μg/m^3, and 1.66 μg/m^3, respectively.

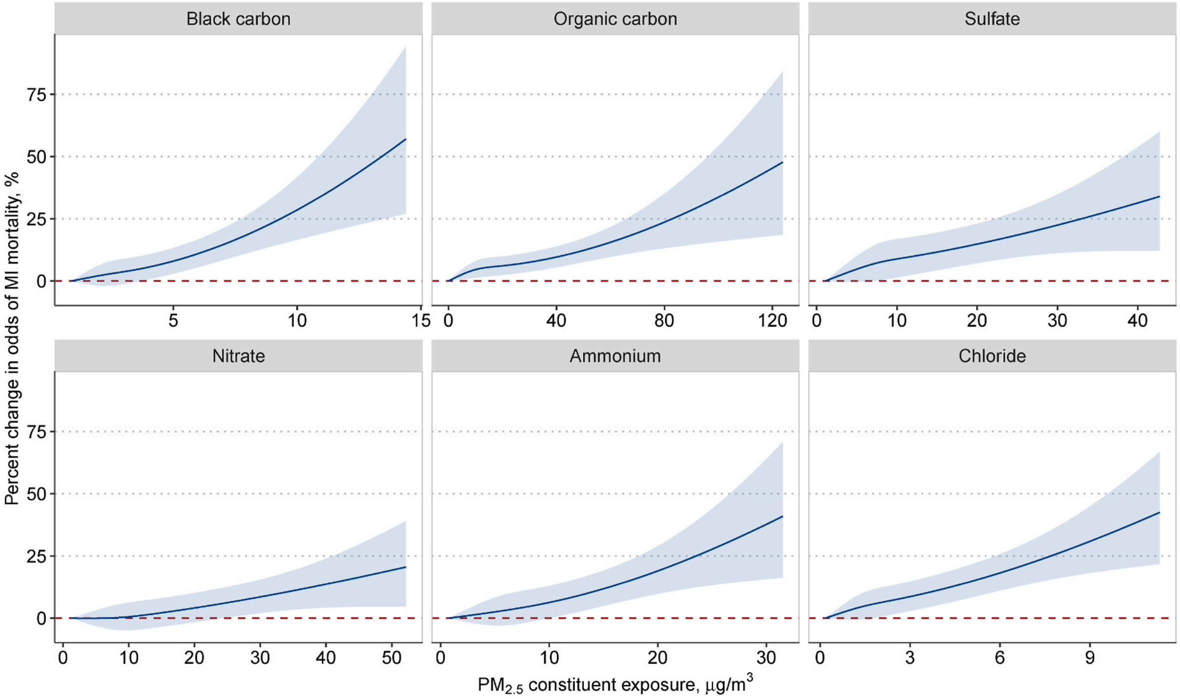


Fig. 2. Exposure-response associations of exposure to $PM_{2.5}$-bound BC (lag 06-day), OC (lag 06-day), SO_4^{2-} (lag 04-day), NO_3^- (lag 06-day), NH_4^+ (lag 06-day), and Cl^- (lag 05-day) with MI mortality.
CI, confidence interval. Other abbreviations are in Tables 1 and 2. The blue solid lines with shaded areas denote the percent change in odds of MI mortality and its corresponding 95% CI. All p for nonlinear trend were >0.05. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

associations for exposure to SO_4^{2-}, NO_3^-, and NH_4^+ on MI mortality (Mo et al., 2023). The estimate for EC in this study was relatively lower than our estimate for BC in the single-pollutant model, while the estimate for OC was relatively higher than our estimate. A time-series study in Guangzhou, China identified no significant associations of lag 03-day exposure to EC, OC, and NO_3^- with MI death (Li et al., 2021). In these

Table 3

Estimated percent change in odds of MI mortality associated with short-term exposure to $PM_{2.5}$ constituents estimated by different models.

$PM_{2.5}$ constituent	Model	Percent change (95% CI)[a]	p for heterogeneity
BC			
	Single-pollutant model	3.91 (2.66, 5.17)	-
	$PM_{2.5}$-adjusted model	5.41 (1.61, 9.35)	0.68
	Constituent-residual model	2.32 (0.96, 3.69)	<0.001
OC			
	Single-pollutant model	3.66 (2.27, 5.07)	-
	$PM_{2.5}$-adjusted model	−1.34 (−6.00, 3.56)	0.14
	Constituent-residual model	−0.64 (−1.45, 0.17)	<0.001
SO_4^{2-}			
	Single-pollutant model	2.94 (2.02, 3.86)	-
	$PM_{2.5}$-adjusted model	1.92 (−0.46, 4.36)	0.65
	Constituent-residual model	1.95 (1.10, 2.82)	<0.001
NO_3^-			
	Single-pollutant model	3.00 (1.77, 4.25)	-
	$PM_{2.5}$-adjusted model	−2.78 (−6.27, 0.85)	0.01
	Constituent-residual model	−0.83 (−1.89, 0.24)	<0.001
NH_4^+			
	Single-pollutant model	3.89 (2.60, 5.21)	-
	$PM_{2.5}$-adjusted model	4.37 (0.03, 8.90)	0.83
	Constituent-residual model	0.81 (−0.24, 1.87)	<0.001
Cl^-			
	Single-pollutant model	4.60 (3.22, 5.99)	-
	$PM_{2.5}$-adjusted model	4.09 (1.46, 6.79)	0.64
	Constituent-residual model	−0.11 (−0.99, 0.77)	<0.001

CI, confidence interval. Other abbreviations are in Tables 1 and 2.

[a] Percent change (95% CI) in single-pollutant models and $PM_{2.5}$-adjusted models is for each IQR increase in $PM_{2.5}$ constituent exposure. The IQR of BC, OC, SO_4^{2-},NO_3^-, NH_4^+, and Cl^- is 1.75 μg/m^3, 1855 μg/m^3, 5.06 μg/m^3, 8.30 μg/m^3, 4.34 μg/m^3, and 1.66 μg/m^3, respectively. Percent change (95% CI) in constituent-residual models is for each IQR increase in $PM_{2.5}$ constituent residual. The IQR for the residual to BC OC, SO_4^{2-}, NO_3^-, NH_4^+, and Cl^- was 0.64 μg/m^3, 3.29 μg/m^3, 2.15 μg/m^3, 2.43 μg/m^3, 1.15 μg/m^3, and 0.65 μg/m^3, respectively.

3 studies, the associations with insignificant or relatively low estimates may be partly attributable to the low accuracy of exposure assessment. Because these studies assessed the community/county/city-level exposure using a $PM_{2.5}$ constituents grid dataset evaluated by the modified Community Multiscale Air Quality (CMAQ) model (spatial resolution: 36 km × 36 km) as the substitute for exposure at an individual level, they assumed that ambient $PM_{2.5}$ constituent levels were homogeneous in a large spatial area. However, because the concentrations of some $PM_{2.5}$ chemical species, especially traffic-related constituents (e.g., BC), showed high spatial variability at a small spatial scale, (Bell et al., 2011; Ito et al., 2004; Wang et al., 2022; Yang et al., 2020) it may cause exposure misclassification for failing to capture the exposure variability within the study region, which may further underestimate associations (Hutcheon et al., 2010; Wu et al., 2023). In comparison, we used a $PM_{2.5}$ constituents grid dataset with high spatiotemporal resolution to evaluate the individual-level exposure on each study subject's home address, which provided more accurate estimations of $PM_{2.5}$ constituent exposure and reliable results on exposure-response analyses.

Our findings suggest that BC and SO_4^{2-} exposures play an important role in $PM_{2.5}$-induced MI mortality and alleviating exposure to BC and SO_4^{2-} in $PM_{2.5}$ mass may be feasible to prevent premature MI deaths. However, due to deficient knowledge of the deleterious effect linked to $PM_{2.5}$ constituents, there is no air quality standard on specific constituents to date. Our study emphasized the significance of controlling specific constituents in ambient particulate management and offered quantitative data to build tailored guidelines on toxic $PM_{2.5}$ constituents. Moreover, because BC is largely attributed to the incomplete combustion process of fossil fuels and biomass, while SO_4^{2-} primarily emitted from fuel-based transportation, coal-fired power plants, and industrial burning, (Cai et al., 2023; Shen et al., 2022) the importance of controlling anthropogenic combustion emissions needs to be highlighted, such as improving burning efficiency and giving priority to low-sulfur fuels or renewable energies.

The pathophysiological mechanism of the acute detrimental impact of $PM_{2.5}$ constituent exposures on MI death may mainly relate to the promotion of thrombosis and atherosclerosis (Feng et al., 2022; Zhao et al., 2021). Several epidemiological studies identified that exposure to $PM_{2.5}$ constituents, especially BC, was linked to elevated biomarkers associated with oxidative stress, inflammation, and cardiac injury, which may facilitate endothelium and vascular dysfunction, increase blood coagulability, and further accelerate thrombosis and atherosclerosis (Azzouz et al., 2023; Hu et al., 2021; Lin et al., 2015; Roy et al., 2014; Wang et al., 2022). Moreover, $PM_{2.5}$ constituent exposures can rise atherosclerotic plaque vulnerability and cause plaque instability (Xu et al., 2019). These mechanisms may induce stenosis or obstruction in the coronary artery and ultimately trigger MI. In this study, we identified that subjects aged ≥80 years were more susceptible to $PM_{2.5}$ constituent exposure in MI death, which may be related to their higher physiological vulnerability, comorbidities, chronic low-grade inflammation, and medication interaction (Liu et al., 2021b, 2022b).

Our study has some strengths. First, benefiting from the high-quality

Table 4

Estimated percent change (95% CI) in odds of MI mortality associated with per IQR increase of exposure to $PM_{2.5}$ constituents stratified by sex, age, and season.

	Sex			Age			Season		
	Male	Female	p[a]	<80 years	≥80 years	p[a]	Cool	Warm	p[a]
BC	2.82 (1.12, 4.55)	5.08 (3.26, 6.92)	0.08	1.90 (0.12, 3.72)	5.64 (3.92, 7.40)	0.003	3.49 (2.17, 4.84)	4.36 (0.81, 8.04)	0.66
OC	2.58 (0.68, 4.52)	4.80 (2.79, 6.86)	0.12	1.83 (−0.17, 3.87)	5.22 (3.30, 7.17)	0.02	2.62 (1.14, 4.13)	7.70 (3.74, 11.83)	0.02
SO_4^{2-}	2.58 (1.31, 3.86)	3.30 (1.98, 4.64)	0.44	1.71 (0.38, 3.05)	4.00 (2.73, 5.28)	0.02	2.21 (1.15, 3.28)	3.11 (1.19, 5.06)	0.42
NO_3^-	2.64 (0.94, 4.37)	3.38 (1.59, 5.19)	0.56	1.13 (−0.64, 2.94)	4.61 (2.90, 6.34)	0.01	2.30 (0.99, 3.62)	5.85 (2.10, 9.74)	0.08
NH_4^+	2.88 (1.09, 4.69)	4.95 (3.07, 6.87)	0.12	1.64 (−0.22, 3.53)	5.83 (4.03, 7.66)	0.002	2.86 (1.42, 4.32)	5.38 (2.33, 8.51)	0.14
Cl^-	4.09 (2.18, 6.04)	5.09 (3.12, 7.10)	0.48	1.90 (−0.09, 3.92)	6.87 (4.97, 8.80)	<0.001	3.95 (2.50, 5.43)	6.88 (2.69, 11.23)	0.20

CI, confidence interval. Other abbreviations are in Tables 1 and 2.

The IQR of BC, OC, SO_4^{2-}, NO_3^-, NH_4^+, and Cl^- is 1.75 μg/m^3, 18.55 μg/m^3, 5.06 μg/m^3, 8.30 μg/m^3, 4.34 μg/m^3, and 1.66 μg/m^3, respectively.

[a] p for difference.

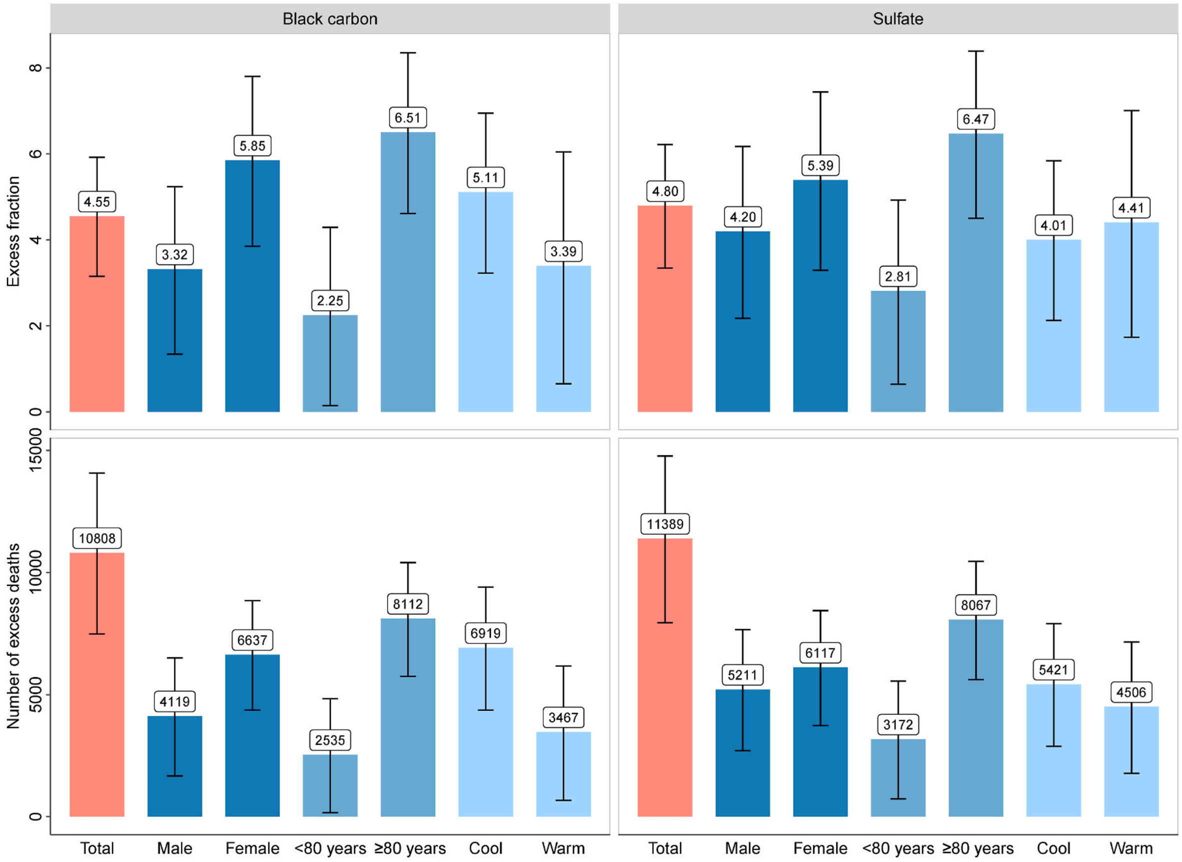


Fig. 3. Excess fraction (95% CI) and number of excess deaths (95% CI) from MI associated with black carbon and sulfate exposure above the theoretical minimal risk exposure concentration.
CI, confidence interval. Other abbreviations are in Tables 1 and 2. The theoretical minimal risk exposure concentration for black carbon and sulfate was 0.89 μg/m^3 and 1.51 μg/m^3, respectively.

$PM_{2.5}$ constituents grid dataset, we were able to evaluate short-term exposure to $PM_{2.5}$ constituents for each subject grounding on the home address, which offered a more precise exposure assessment in comparison with previous studies that relied on a single monitoring site or grid data with a relatively coarse spatial resolution to estimate region-scale exposure as the proxy of individual-level exposure. Second, we included a large number of MI death cases (over 0.2 million) from a provincial population exceeding 80 million in 7 years, which allowed us to detect the potential acute influence of $PM_{2.5}$ constituents on MI death with adequate statistical power and representative estimates. Finally, the case-crossover design enabled us to investigate the associations at an individual level and controlled time-invariant individual confounding variables, long-term trends, and weather conditions.

Some limitations need to be considered when interpreting our study findings. First, although we estimated relatively accurate $PM_{2.5}$ constituent exposure for each subject, we were incapable of evaluating the actual personal exposure because of the unavailable information on individual indoor pollutant exposure and time-activity patterns. However, its bias may be partly migrated because the pollutant exposures indoors were highly correlated with that at ambient (Krebs et al., 2021) and the time-activity pattern was less likely to vary dramatically in a calendar month under the case-crossover design. Second, we utilized the time-stratified case-crossover design to adjust for weather conditions and the time-invariant confounders, but there possibly remained some remanent confounding factors (e.g., medication use). Third, because the relationships between exposure to $PM_{2.5}$ constituents and MI death were only investigated within one single province of China, caution ought to be paid when extrapolating our results to populations of other regions. Fourth, we solely focused on the effect of carbonaceous compounds and WSIIs on MI mortality but did not investigate other constituents in $PM_{2.5}$ (e.g., metals), although carbonaceous compounds and WSIIs form the majority of $PM_{2.5}$ mass. Fifth, because OC concentrations were not measured directly but computed by deducting the concentration of other constituents from the total $PM_{2.5}$ in our study, there may be bias in the exposure assessment of OC and further affect the accuracy of the study results. Finally, since we did not have detailed information on the specific MI type of each study subject, our ability to investigate the association between $PM_{2.5}$ constituents and different type of MI death (e.g., ST-elevation MI [STEMI] and non-STEMI) was limited. Further studies are warranted to clarify the effect of $PM_{2.5}$ constituent exposures on specific MI, which could provide more significant implications to clinical practices.

5. Conclusions

In summary, we utilized a high-quality $PM_{2.5}$ constituents grid dataset to conduct individual-level exposure assessment for 237,492 MI deaths, and identified that short-term exposure to BC and SO_4^{2-} bounding to $PM_{2.5}$ was associated with increased odds of MI death and may result in extensive excess mortality, notably in older adults. Our findings offer useful evidence that BC and SO_4^{2-} may play an important role in $PM_{2.5}$-induced MI death, which highlights the necessity of developing air quality guidelines on specific constituents in ambient particulate management and reducing the emission of toxic constituents to prevent premature deaths from MI.

Funding

None.

CRediT authorship contribution statement

Yingxin Li: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Bing Lu:** Writing – review & editing, Methodology, Formal analysis. **Jing Wei:** Writing – review & editing, Data curation. **Qingqing Wang:** Writing – review & editing. **Wancheng Ma:** Writing – review & editing. **Rui Wang:** Writing – review & editing. **Ruijun Xu:** Writing – review & editing. **Zihua Zhong:** Writing – review & editing. **Lu Luo:** Writing – review & editing. **Xi Chen:** Writing – review & editing. **Ziquan Lv:** Writing – review & editing. **Suli Huang:** Writing – review & editing. **Hong Sun:** Writing – review & editing, Supervision, Project administration, Methodology, Data curation, Conceptualization. **Yuewei Liu:** Writing – review & editing, Supervision, Project administration, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgments

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2024.143101.

References

Azzouz, M., Xu, Y., Barregard, L., Zoller, B., Molnar, P., Oudin, A., Spanne, M., Engstrom, G., Stockfelt, L., 2023. Long-term ambient air pollution and venous thromboembolism in a population-based Swedish cohort. Environ. Pollut. 331, 121841 https://doi.org/10.1016/j.envpol.2023.121841.

Bell, M.L., Ebisu, K., Peng, R.D., 2011. Community-level spatial heterogeneity of chemical constituent levels of fine particulates and implications for epidemiological research. J. Expo. Sci. Environ. Epidemiol. 21, 372–384. https://doi.org/10.1038/jes.2010.24.

Cai, M., Lin, X., Wang, X., Zhang, S., Wang, C., Zhang, Z., Pan, J., Lin, H., 2023. Long-term exposure to ambient fine particulate matter chemical composition and in-hospital case fatality among patients with stroke in China. Lancet Reg. Health West. Pac. 32, 100679 https://doi.org/10.1016/j.lanwpc.2022.100679.

Chen, C., Zhu, P., Lan, L., Zhou, L., Liu, R., Sun, Q., Ban, J., Wang, W., Xu, D., Li, T., 2018. Short-term exposures to $PM_{2.5}$ and cause-specific mortality of cardiovascular health in China. Environ. Res. 161, 188–194. https://doi.org/10.1016/j.envres.2017.10.046.

Dai, L., Zanobetti, A., Koutrakis, P., Schwartz, J.D., 2014. Associations of fine particulate matter species with mortality in the United States: a multicity time-series analysis. Environ. Health Perspect. 122, 837–842. https://doi.org/10.1289/ehp.1307568.

Fan, Z., Li, Y., Wei, J., Chen, G., Wang, R., Xu, R., Liu, T., Lv, Z., Huang, S., Sun, H., et al., 2023. Long-term exposure to fine particulate matter and site-specific cancer mortality: a difference-in-differences analysis in Jiangsu province, China. Environ. Res. 222, 115405 https://doi.org/10.1016/j.envres.2023.115405.

Feng, S., Huang, F., Zhang, Y., Feng, Y., Zhang, Y., Cao, Y., Wang, X., 2022. The pathophysiological and molecular mechanisms of atmospheric $PM_{2.5}$ affecting cardiovascular health: a review. Ecotoxicol. Environ. Saf. 249, s114444 https://doi.org/10.1016/j.ecoenv.2022.114444.

Han, S., Liu, B., Shi, C., Liu, Y., Qiu, M., Sun, S., 2020. Evaluation of CLDAS and GLDAS datasets for near-surface air temperature over major land areas of China. Sustainability 12, 4311. https://doi.org/10.3390/su12104311.

Hu, D., Jia, X., Cui, L., Liu, J., Chen, J., Wang, Y., Niu, W., Xu, J., Miller, M.R., Loh, M., et al., 2021. Exposure to fine particulate matter promotes platelet activation and thrombosis via obesity-related inflammation. J. Hazard. Mater. 413, 125341 https://doi.org/10.1016/j.jhazmat.2021.125341.

Hutcheon, J.A., Chiolero, A., Hanley, J.A., 2010. Random measurement error and regression dilution bias. BMJ 340, c2289. https://doi.org/10.1136/bmj.c2289.

Ito, K., Xue, N., Thurston, G., 2004. Spatial variation of $PM_{2.5}$ chemical species and source-apportioned mass concentrations in New York City. Atmos. Environ. 38, 5269–5282. https://doi.org/10.1016/j.atmosenv.2004.02.063.

Krebs, B., Burney, J., Zivin, J.G., Neidell, M., 2021. Using crowd-sourced data to assess the temporal and spatial relationship between indoor and outdoor particulate matter. Environ. Sci. Technol. 55, 6107–6115. https://doi.org/10.1021/acs.est.0c08469.

Li, B., Yang, J., Dong, H., Li, M., Cai, D., Yang, Z., Zhang, C., Wang, H., Hu, J., Bergmann, S., et al., 2021. $PM_{2.5}$ constituents and mortality from a spectrum of causes in Guangzhou, China. Ecotoxicol. Environ. Saf. 222, 112498 https://doi.org/10.1016/j.ecoenv.2021.112498.

Li, Y., He, Z., Wei, J., Xu, R., Liu, T., Zhong, Z., Liu, L., Liang, S., Zheng, Y., Chen, G., et al., 2024. Long-term exposure to ambient fine particulate matter constituents and mortality from total and site-specific gastrointestinal cancer. Environ. Res. 244, 117927 https://doi.org/10.1016/j.envres.2023.117927.

Li, Y., Fan, Z., Lu, W., Xu, R., Liu, T., Liu, L., Chen, G., Lv, Z., Huang, S., Zhou, Y., et al., 2023. Long-term exposure to ambient fine particulate matter-bound polycyclic aromatic hydrocarbons and cancer mortality: a difference-in-differences approach. Chemosphere 340, 139800. https://doi.org/10.1016/j.chemosphere.2023.139800.

Liang, H., Qiu, H., Tian, L., 2018. Short-term effects of fine particulate matter on acute myocardial infraction mortality and years of life lost: a time series study in Hong Kong. Sci. Total Environ. 615, 558–563. https://doi.org/10.1016/j.scitotenv.2017.09.266.

Lin, W., Zhu, T., Xue, T., Peng, W., Brunekreef, B., Gehring, U., Huang, W., Hu, M., Zhang, Y., Tang, X., 2015. Association between changes in exposure to air pollution and biomarkers of oxidative stress in children before and during the Beijing Olympics. Am. J. Epidemiol. 181, 575–583. https://doi.org/10.1093/aje/kwu327.

Liu, J., Shi, C., Sun, S., Liang, J., Yang, Z., 2020. Improving land surface hydrological simulations in China using CLDAS meteorological forcing data. J. Meteorol. Res. 33, 1194–1206. https://doi.org/10.1007/s13351-019-9067-0.

Liu, T., Zhou, Y., Wei, J., Chen, Q., Xu, R., Pan, J., Lu, W., Wang, Y., Fan, Z., Li, Y., et al., 2022a. Association between short-term exposure to ambient air pollution and dementia mortality in Chinese adults. Sci. Total Environ. 849, 157860 https://doi.org/10.1016/j.scitotenv.2022.157860.

Liu, L., Luo, S., Zhang, Y., Yang, Z., Zhou, P., Mo, S., Zhang, Y., 2022b. Longitudinal impacts of $PM_{2.5}$ constituents on adult mortality in China. Environ. Sci. Technol. 56, s7224–s7233. https://doi.org/10.1021/acs.est.1c04152.

Liu, Y., Pan, J., Fan, C., Xu, R., Wang, Y., Xu, C., Xie, S., Zhang, H., Cui, X., Peng, Z., et al., 2021a. Short-term exposure to ambient air pollution and mortality from myocardial infarction. J. Am. Coll. Cardiol. 77, 271–281. https://doi.org/10.1016/j.jacc.2020.11.033.

Liu, L., Zhang, Y., Yang, Z., Luo, S., Zhang, Y., 2021b. Long-term exposure to fine particulate constituents and cardiovascular diseases in Chinese adults. J. Hazard Mater. 416, s126051 https://doi.org/10.1016/j.jhazmat.2021.126051.

Liu, Y., Pan, J., Zhang, H., Shi, C., Li, G., Peng, Z., Ma, J., Zhou, Y., Zhang, L., 2019. Short-term exposure to ambient air pollution and asthma mortality. Am. J. Respir. Crit. Care Med. 200, 24–32. https://doi.org/10.1164/rccm.201810-1823OC.

Mo, S., Hu, J., Yu, C., Bao, J., Shi, Z., Zhou, P., Yang, Z., Luo, S., Yin, Z., Zhang, Y., 2023. Short-term effects of fine particulate matter constituents on myocardial infarction death. J. Environ. Sci. (China) 133, 60–69. https://doi.org/10.1016/j.jes.2022.07.019.

Mustafic, H., Jabre, P., Caussin, C., Murad, M.H., Escolano, S., Tafflet, M., Périer, M.C., Marijon, E., Vernerey, D., Empana, J.P., et al., 2012. Main air pollutants and myocardial infarction: a systematic review and meta-analysis. JAMA 307, 713–721. https://doi.org/10.1001/jama.2012.126.

Rajagopalan, S., Al-Kindi, S.G., Brook, R.D., 2018. Air pollution and cardiovascular disease: JACC State-of-the-Art Review. J. Am. Coll. Cardiol. 72, 2054–2070. https://doi.org/10.1016/j.jacc.2018.07.099.

Roth, G.A., Mensah, G.A., Johnson, C.O., Addolorato, G., Ammirati, E., Baddour, L.M., Barengo, N.C., Beaton, A.Z., Benjamin, E.J., Benziger, C.P., et al., 2020. Global burden of cardiovascular diseases and risk factors, 1990-2019: update from the GBD 2019 Study. J. Am. Coll. Cardiol. 76, 2982–3021. https://doi.org/10.1016/j.jacc.2020.11.010.

Roy, A., Gong, J., Thomas, D.C., Zhang, J., Kipen, H.M., Rich, D.Q., Zhu, T., Huang, W., Hu, M., Wang, G., et al., 2014. The cardiopulmonary effects of ambient air pollution and mechanistic pathways: a comparative hierarchical pathway analysis. PLoS One 9, e114913. https://doi.org/10.1371/journal.pone.0114913.

Shen, Y., Yu, G., Liu, C., Wang, W., Kan, H., Zhang, J., Cai, J., 2022. Prenatal exposure to $PM_{2.5}$ and its specific components and risk of hypertensive disorders in pregnancy: a nationwide cohort study in China. Environ. Sci. Technol. 56, 11473–11481. https://doi.org/10.1021/acs.est.2c01103.

Thygesen, K., Alpert, J.S., White, H.D., 2007. Universal definition of myocardial infarction. J. Am. Coll. Cardiol. 50, 2173–2195. https://doi.org/10.1016/j.jacc.2007.09.011.

Tie, R., Shi, C., Wan, G., Hu, X., Kang, L., Ge, L., 2022. CLDASSD: reconstructing fine textures of the temperature field using super-resolution technology. Adv. Atmos. Sci. 39, 117–130. https://doi.org/10.1007/s00376-021-0438-y.

Wang, T., Xu, H., Zhu, Y., Sun, X., Chen, J., Liu, B., Zhao, Q., Zhang, Y., Liu, L., Fang, J., et al., 2022. Traffic-related air pollution associated pulmonary pathophysiologic changes and cardiac injury in elderly patients with COPD. J. Hazard. Mater. 424, 127463 https://doi.org/10.1016/j.jhazmat.2021.127463.

Wei, J., Li, Z., Chen, X., Li, C., Sun, Y., Wang, J., Lyapustin, A., Brasseur, G.P., Jiang, M., Sun, L., et al., 2023a. Separating daily 1 km $PM_{2.5}$ inorganic chemical composition in China since 2000 via deep learning integrating ground, satellite, and model data. Environ. Sci. Technol. 57, 18282–18295. https://doi.org/10.1021/acs.est.3c00272.

Wei, J., Wang, J., Li, Z., Kondragunta, S., Anenberg, S., Wang, Y., Zhang, H., Diner, D., Hand, J., Lyapustin, A., et al., 2023b. Long-term mortality burden trends attributed to black carbon and $PM_{2.5}$ from wildfire emissions across the continental US from 2000-2020: a deep learning modelling study. Lancet Planet. Health 7, e963–e975. https://doi.org/10.1016/S2542-5196(23)00235-8.

Wu, Y., Gasevic, D., Wen, B., Yu, P., Xu, R., Zhou, G., Zhang, Y., Song, J., Liu, H., Li, S., et al., 2023. Association between air pollution and telomere length: a study of 471,808 UK Biobank participants. Innovat. Med. 1, 100017 https://doi.org/10.59717/j.xinn-med.2023.100017.

Xu, H., Wang, T., Liu, S., Brook, R.D., Feng, B., Zhao, Q., Song, X., Yi, T., Chen, J., Zhang, Y., et al., 2019. Extreme levels of air pollution associated with changes in biomarkers of atherosclerotic plaque vulnerability and thrombogenicity in healthy adults. Circ. Res. 124, e30–e43. https://doi.org/10.1161/CIRCRESAHA.118.313948.

Xu, R., Huang, S., Shi, C., Wang, R., Liu, T., Li, Y., Zheng, Y., Lv, Z., Wei, J., Sun, H., et al., 2023. Extreme temperature events, fine particulate matter, and myocardial infarction mortality. Circulation 148, 312–323. https://doi.org/10.1161/CIRCULATIONAHA.122.063504.

Xu, R., Wei, J., Liu, T., Li, Y., Yang, C., Shi, C., Chen, G., Zhou, Y., Sun, H., Liu, Y., 2022. Association of short-term exposure to ambient PM_1 with total and cause-specific cardiovascular disease mortality. Environ. Int. 169, 107519 https://doi.org/10.1016/j.envint.2022.107519.

Yang, J., Zhou, M., Li, M., Yin, P., Hu, J., Zhang, C., Wang, H., Liu, Q., Wang, B., 2020. Fine particulate matter constituents and cause-specific mortality in China: a nationwide modelling study. Environ. Int. 143, 105927 https://doi.org/10.1016/j.envint.2020.105927.

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

Zhang, Z., Weichenthal, S., Kwong, J.C., Burnett, R.T., Hatzopoulou, M., Jerrett, M., Donkelaar, A.V., Bai, L., Martin, R.V., Copes, R., et al., 2021. Long-term exposure to iron and copper in fine particulate air pollution and their combined impact on reactive oxygen species concentration in lung fluid: a population-based cohort study of cardiovascular disease incidence and mortality in Toronto, Canada. Int. J. Epidemiol. 50, 589–601. https://doi.org/10.1093/ije/dyaa230.

Zhao, T., Qi, W., Yang, P., Yang, L., Shi, Y., Zhou, L., Ye, L., 2021. Mechanisms of cardiovascular toxicity induced by $PM_{2.5}$: a review. Environ. Sci. Pollut. Res. 28, s65033–s65051. https://doi.org/10.1007/s11356-021-16735-9.