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# Acute effect of fine particulate matter and respiratory mortality in Changsha, China: a time-series analysis

Qi Feng<sup>\*</sup>, Yan Chen, Sha Su, Xixing Zhang and Xijian Lin

## Abstract

**Background:** Previous studies have confirmed that exposure to fine particulate matter (PM<sub>2.5</sub>) is associated with respiratory disease mortality. However, due to the differences in PM<sub>2.5</sub> concentration, composition and population susceptibility within different regions, the estimates of the association between PM<sub>2.5</sub> concentration and mortality are different. Moreover, few studies have examined the potential hazard of excessive PM<sub>2.5</sub> exposure in terms of respiratory disease mortality.

**Methods:** Daily recorded data on meteorological indices, environmental pollutants, and causes of death data in Changsha from January 2015 to December 2018 were obtained. The potential relationship between PM<sub>2.5</sub> concentrations and respiratory disease mortality was determined using distributed lag nonlinear model (DLNM), which includes the relative risk (RR) and cumulative relative risk (CRR) of the lagged effect. The synergistic effects of other air pollutants were also considered.

**Results:** A total of 8,825 cases of respiratory disease mortality occurred in Changsha between 2015 and 2018. The acute effect of PM<sub>2.5</sub> concentration was associated with an increased risk of respiratory disease mortality. Regarding the lag specific effect, a 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub> concentration on respiratory disease mortality was statistically significant at lag day 0 and lag day 7 with a relative risk of 1.019 (95% CI 1.007- 1.031) and 1.013(95%CI: 1.002-1.024). As for the cumulative lag effect, a 4-day moving average of PM<sub>2.5</sub> concentrations was significantly associated with a cumulative relative risk of 1.027 (95%CI: 1.011-1.031). The single-day lag effect and cumulative 4-day lag effect for male individuals were more significant than those observed in females. The effect of PM<sub>2.5</sub> concentrations and respiratory disease mortality remained statistically significant in the multi-pollutant models (SO<sub>2</sub>, NO<sub>2</sub>, and O<sub>3</sub>). A higher risk was observed in the cold season than in the warm season.

**Conclusions:** Our findings show a potential association between exposure to PM<sub>2.5</sub> concentration and respiratory disease mortality in Changsha, with male individuals observed to have particularly higher risk.

**Keywords:** Environmental exposure, PM<sub>2.5</sub>, Respiratory disease mortality, Time series, Epidemiology

## Introduction

Air pollution is a significant environmental and public health problem, particularly in developing countries. Throughout this past decade, numerous studies have provided substantial evidence for the relationship between air pollution and mortality [1–4]. Fine particulate matter (PM<sub>2.5</sub>, particulate matter ≤ 2.5 µm in aerodynamic

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diameter) is a major particulate matter pollutant, previous studies have confirmed that the deterioration of air quality is related to high concentrations of PM<sub>2.5</sub>, resulting in tremendous pressure on public health. The Global Burden of Disease study indicated that global deaths due to acute exposure to PM<sub>2.5</sub> was 4.2 million (95% uncertainty interval 3.7 million to 4.8million) in 2015, compared with 3.5 million (95% uncertainty interval 3.0 million to 4.0 million) in 1990 [5]. Furthermore, adult cancer mortality data from 978 county-level surveillance sites in 31 Chinese provinces in 2014 showed that PM<sub>2.5</sub> has become one of the 23 carcinogenic risk factors in China [6].

Compared with other organs, high concentrations of pollutants in the lungs and respiratory tract can cause considerable damage to the respiratory system. Moreover, the risk of death from respiratory diseases caused by PM<sub>2.5</sub> is greater than that occurring due to non-accidental and cardiovascular mortality [7, 8]. In addition, earlier studies showed that short term exposure to PM<sub>2.5</sub> exhibits a linear relationship with respiratory diseases mortality that differs from the relationship with non-accidental mortality and cardiovascular mortality [3, 9]. Therefore, it is necessary to study PM<sub>2.5</sub> concentrations and respiratory disease mortality separately.

As the capital of China's equipment manufacturing, Changsha is the central city of the Yangtze River Economic Belt and the political, economic, and cultural center of the Hunan Province. In recent years, owing to the efficacious economic development and the rise in energy consumption, air pollution has become an increasingly serious problem. Currently, most research focuses on individual large cities [10–12]. Due to differences in PM<sub>2.5</sub> concentration, composition and population susceptibility within different regions, different countries or regions yield different estimates of the association between PM<sub>2.5</sub> concentration and mortality [2, 13]. Therefore, relevant research in specific cities or regions is necessary.

In the present study, we collected data on meteorological, environmental pollutants and cause of death from January 2015 to December 2018 in Changsha. The purpose of this study is to assess the potential association between exposure to PM<sub>2.5</sub> concentration and respiratory disease mortality in Changsha.

## Materials and methods

### Data collection

We collected daily respiratory disease mortality from the National population death information registration management system for residents in Changsha from January 1, 2015, to December 31, 2018. The cause of respiratory disease mortality was classified according to the

International Classification of Disease, Revision 10 (ICD-10, J00–J99).

We obtained PM<sub>2.5</sub>, inhalable particulate matter (PM<sub>10</sub>), sulfur dioxide (SO<sub>2</sub>), nitrogen dioxide (NO<sub>2</sub>), ozone (O<sub>3</sub>) data during the same period, which was collected and organized by the Changsha Environmental Protection Bureau. The air pollution data collected is the average of data from 10 environmental monitoring stations in the Changsha (Fig. 1). Average daily data collection requirements: ozone is the 8-h average concentration average, and other pollutants are the 24-h average concentration average. In addition, the environmental data in this article are publicly available on the website of the Ministry of Environment and Ecology of China (<http://english.mee.gov.cn/>).

We also collected daily temperature and relative humidity data of Changsha during the same period. The data comes from the Changsha Meteorological Bureau. The collected data are daily averages of all stations and can represent the city's average level. In addition, the meteorological data is publicly available on the website of the China Meteorological Administration (<http://www.cma.gov.cn/en2014/>).

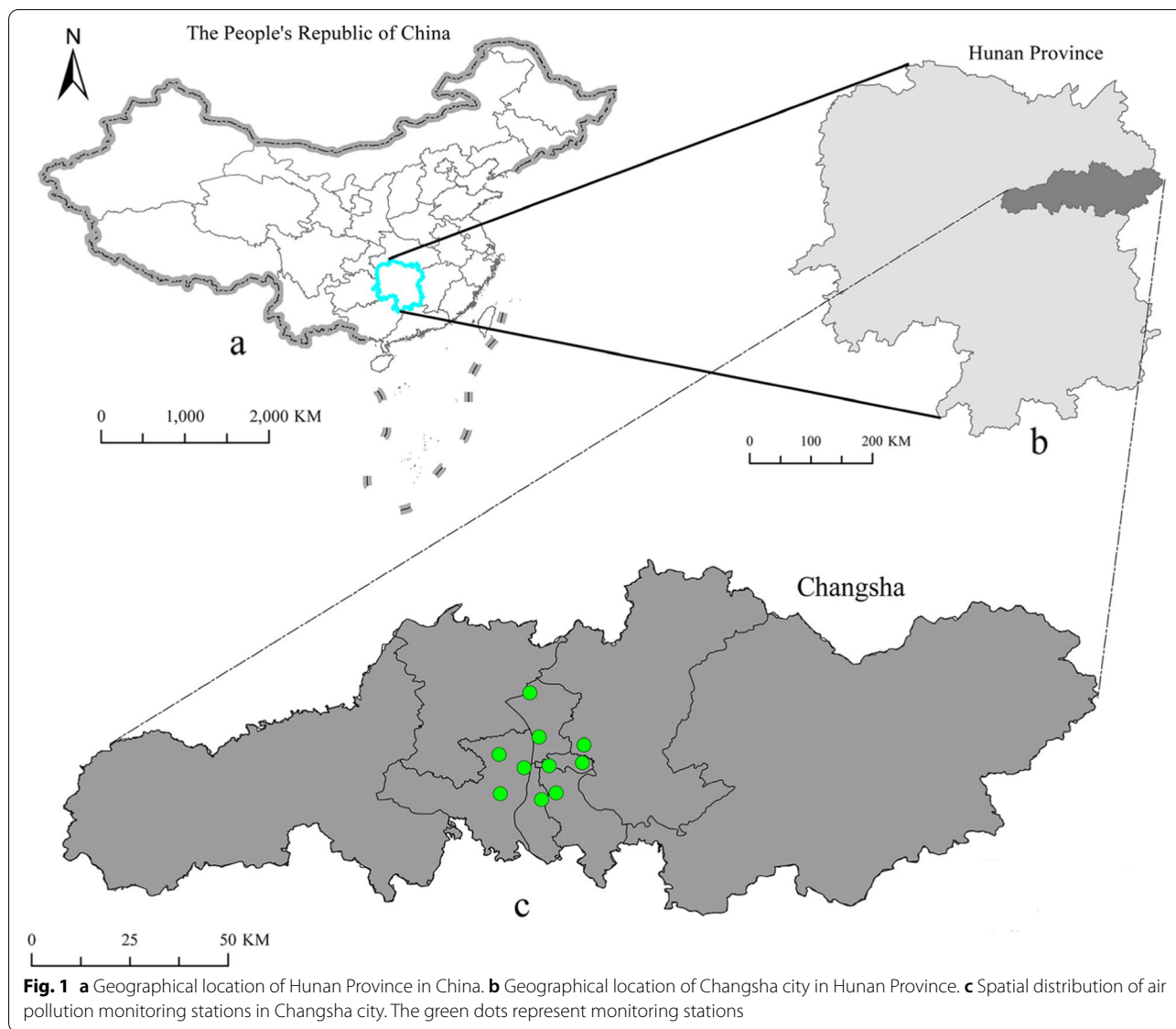
### Statistical analysis

We used the mean ± standard deviation as maximum and minimum indicators to describe whole year or seasonal health data, and environmental data. We used raw scatter plots showing outcome (deaths) and exposure (PM<sub>2.5</sub>) data over time. The correlations between air pollutants and meteorological variables were analyzed using Spearman rank correlation.

R 3.6.2 software was used for the distributed lag non-linear model [14]. A "cross-basis" (i.e., the tension product of the two functions of the exposure response relationship and the lag response relationship) was performed to establish a bi-dimensional space of a function, simultaneously describing the distribution of the dependent variable in the lag time dimension and the independent variable dimension. This process is performed in three steps, as follows: 1) establishing a basis cross matrix, 2) establishing a model based on the basis cross matrix, and 3) model prediction. The general model formula is as follows:

$$\text{LogE}(Y_t) = \sum_{j=1}^J \beta_j \text{pollution}_{t-j} + \text{ns}(\text{meteorologicalfactor}_t, df = 3) + \text{ns}(\text{time}, df = 7 * 4) + \text{Dow}_t + \text{Holiday}_t + \text{intercept}$$

where  $E(Y_t)$  is the outcome variable, which represents the expected number of deaths on day  $t$ .  $\beta$  represents the regression coefficients, pollution is described by PM<sub>2.5</sub> and other air pollutants, ns represents the natural cubic splines, Dow is day of the week effect, and meteorological



factor refer to relative humidity. Simultaneously, considering the lag effect of temperature on respiratory disease mortality, we established a cross-basis function of temperature as a control variable. Since the proposed model follows the quasi-Poisson distribution, and the degrees of freedom (df) follows the Akaike Information Criterion for Quasi-likelihood models (Quasi-AIC), we set different df values and performed sensitivity analysis by calculating the Quasi-AIC values of different models. The smaller the Quasi-AIC value, the better the model. The calculation formula of QAIC was as follows:

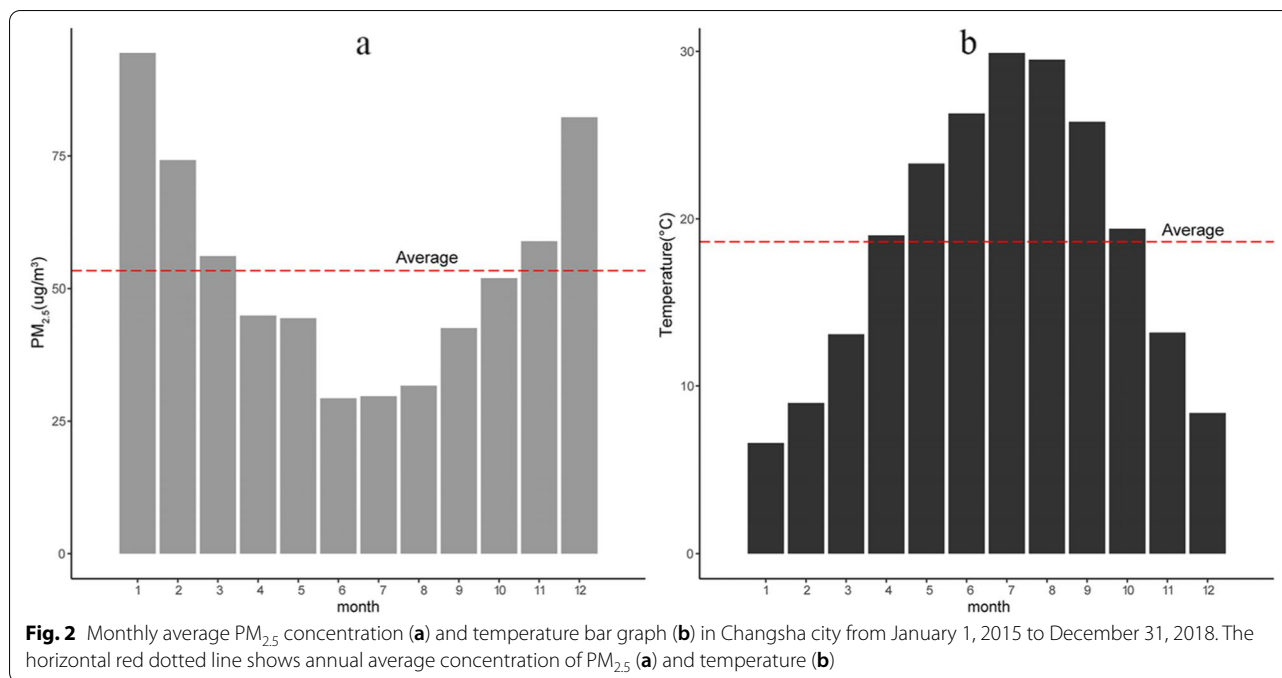
$$QAIC = -2\ln(L)/c + 2k$$

where L is the likelihood function, c is the variance expansion factor, and k is the number of model

parameters. According to the Quasi-AIC principle, we adjusted the degrees of freedom for multiple model fittings; we used 7 df per year for the time variable, and 3 df for the relative humidity. The day of the week (DOW) and holidays(11 days per year) were included as dummy variables.

The health effects of air pollutants are sometimes not immediately observable and the effects may be delayed or even persist for a time. Therefore, we used different lag structures to estimate the lag specific effect and cumulative lag effect, including single-day (lag0 to lag7) and several-day moving averages (lag0-1 to lag0-7).

We first established a single-pollutant model of the relationship between daily PM<sub>2.5</sub> concentrations and respiratory disease mortality risk. In addition to PM<sub>2.5</sub>



**Table 1** Summary statistics daily levels of resident’s respiratory disease mortality and environmental indicators collected in Changsha, 2015–2018

Variable	Year-round (N= 1461)		Warm-season(April- October) (N= 856)		Cold-season(November -March) (N= 605)	
	Mean ± SD	Range(min, max)	Mean ± SD	range(min, max)	Mean ± SD	range(min, max)
PM <sub>2.5</sub> (µg/m <sup>3</sup> )	53.3 ± 35.2	(3,286)	39.2 ± 20.9	(3,160)	73.3 ± 41.3	(8,286)
PM <sub>10</sub> (µg/m <sup>3</sup> )	73.0 ± 41.7	(4,333)	62.8 ± 34.1	(4,257)	87.4 ± 46.9	(6,333)
SO <sub>2</sub> (µg/m <sup>3</sup> )	14.2 ± 7.7	(4,71)	12.7 ± 5.1	(4,42)	16.2 ± 9.9	(4,71)
NO <sub>2</sub> (µg/m <sup>3</sup> )	36.2 ± 16.3	(10,109)	29.3 ± 11.6	(10,73)	45.9 ± 17.1	(14,109)
O <sub>3</sub> (µg/m <sup>3</sup> )	92 ± 48.9	(7,260)	114.3 ± 45.0	(13,260)	60.5 ± 34.9	(7,200)
Temperature(°C)	18.67 ± 8.8	(-2.7,34.6)	24.8 ± 5.2	(9.6,34.6)	10.1 ± 4.7	(-2.7,25.1)
Relative humidity (%)	74.9 ± 14.0	(27,100)	74.4 ± 12.3	(40,99)	75.5 ± 16.1	(27,100)
Respiratory disease mortality	6.0 ± 3.4	(0,43)	5.6 ± 3.4	(0,43)	6.6 ± 3.4	(0,35)

Note: Cause of respiratory disease mortality was coded according to the International Classification of Disease, Revision 10 (ICD-10, J00–J99) (WHO 2016)

concentration, we focused on the other four indicators of air pollution: PM<sub>10</sub>, SO<sub>2</sub>, NO<sub>2</sub>, and O<sub>3</sub>, which were selected to identify typical air pollution concentrations. Air pollution mixtures have been considered in many cases because of their chemical and biological associations. Considering that the high collinearity between pollutants may lead to instability of the model, the correlation coefficient between PM<sub>2.5</sub> concentration and other pollutants is less than 0.7 as the standard for introducing multi-pollutants. The warm (April–October) and cold (November–March) seasons were divided according to the annual average temperature (Fig. 2). Coincidentally, the average monthly concentration of PM<sub>2.5</sub> in the warm

season is below the annual average PM<sub>2.5</sub> concentration, in the cold season, the reverse is true. Correspondingly, in seasonal classification analysis, we adjusted the spline function of the time variable to 3 df /year. In this study, the test level was set to α = 0.05.

**Results**

The data on atmospheric pollutants, meteorological factors, and death of residents from respiratory disease in Changsha from January 1, 2015 to December 31, 2018 are shown in Table 1. The daily average concentrations of PM<sub>2.5</sub>, PM<sub>10</sub>, SO<sub>2</sub>, NO<sub>2</sub>, and O<sub>3</sub> were 53.3 µg/m<sup>3</sup>, 73.0 µg/m<sup>3</sup>, 14.2 µg/m<sup>3</sup>, 36.2 µg/m<sup>3</sup>, and 92 µg/m<sup>3</sup>, respectively.



The concentrations of  $PM_{2.5}$ ,  $SO_2$ , and  $NO_2$  were much higher in the cold season than in the warm season, while this trend was reversed for  $O_3$ . A total of 8,825 cases of respiratory disease with reported mortality were observed in the same period. As with seasonal trends in pollutant concentrations, the daily mortality was higher in the cold season ( $6.6 \pm 3.4$ ) than in the warm season ( $5.6 \pm 3.4$ ).

Figure 3 presents the raw plots for respiratory disease mortality and  $PM_{2.5}$  concentration, the subgroup of respiratory diseases mortality showed higher daily deaths among male individuals than among female individuals

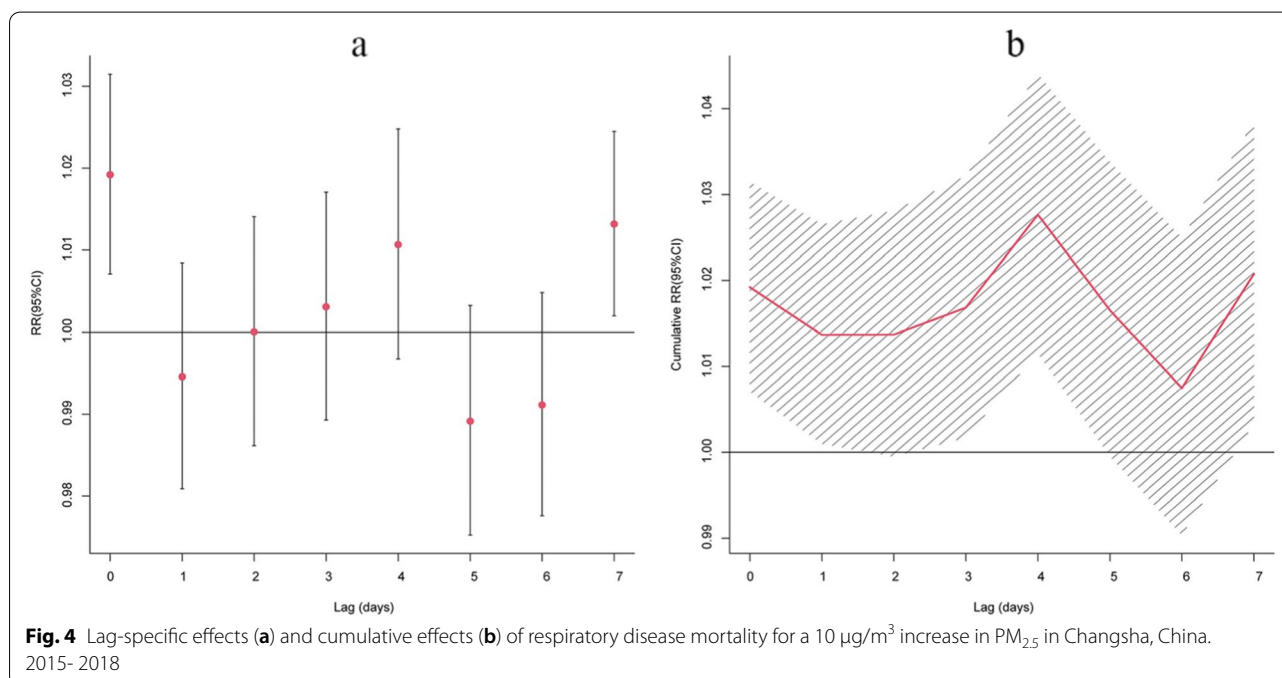
and higher mortality among individuals over 65 years of age than among those aged less than 65 years. Compared with the time series chart describing the number of deaths from respiratory diseases, the  $PM_{2.5}$  concentration showed a more obvious seasonal fluctuation, with the daily mean  $PM_{2.5}$  concentrations being much lower in the warm season than in the cold season.

Table 2 shows the Spearman correlations matrix between air pollutants and meteorological variables.  $PM_{2.5}$  concentration was positively correlated with  $PM_{10}$ ,  $SO_2$  and  $NO_2$ , and negatively correlated with  $O_3$

**Table 2** Spearman correlations between air pollutants and meteorological factors in Changsha, 2015–2018

Variables	PM <sub>2.5</sub>	PM <sub>10</sub>	SO <sub>2</sub>	NO <sub>2</sub>	O <sub>3</sub>	Temperature	Relative humidity
PM <sub>2.5</sub>	1.000	0.871**	0.508**	0.692**	-0.085**	-0.429**	-0.223**
PM <sub>10</sub>		1.000	0.691**	0.696**	0.137**	-0.183**	-0.510**
SO <sub>2</sub>			1.000	0.569**	0.108**	-0.012	-0.604**
NO <sub>2</sub>				1.000	-0.131**	-0.447**	-0.307**
O <sub>3</sub>					1.000	0.631**	-0.535**
Temperature						1.000	-0.253**
Relative humidity							1.000

Note: \*\*  $P < 0.01$



**Table 3** The percent change of daily respiratory disease mortality in every 10 µg/m<sup>3</sup> increase of PM<sub>2.5</sub> to different genders and age groups under different lag days

Lag day	Total	Male	Female	Age < 65	Age ≥ 65
Lag0	1.019(1.007–1.031) *	1.023(1.009–1.0367) *	1.013(0.994–1.0312)	1.027(0.997–1.057) *	1.018(1.005–1.031) *
Lag0-4	1.027(1.011–1.031) *	1.032(1.014–1.0367) *	1.018(0.994–1.0312)	1.018(1.005–1.031) *	1.029(1.012–1.031) *

Note: \*  $P < 0.05$

concentration, air temperature and relative humidity. Additionally, the correlation between PM<sub>2.5</sub> and each individual variable was statistically significant ( $P < 0.01$ ).

We calculated single-day (lag 0–7) and cumulative (lag 01–07) lags for a 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub> concentration. After applying control for temperature, relative humidity, DOW, long-term trend of time (Fig. 4), we found that the impact of PM<sub>2.5</sub> concentration on respiratory diseases mortality was statistically significant at lag

day 0 and lag day 7, with a cumulative relative risk (lag0-4) of 1.027 (95%CI: 1.011-1.031).

Table 3 shows the daily respiratory disease mortality in every 10 µg/m<sup>3</sup> increase of PM<sub>2.5</sub> concentration for different sexes and age groups under different lag days. We observed that that the single-day lag effect and cumulative 4-day lag effect were both higher in male individuals than in female individuals. Moreover, the cumulative 4-day lag effect for those aged over 65 years was higher

**Table 4** Relative risk and cumulative relative risk of respiratory disease mortality associated with 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub> concentration under different multi-pollutant model

Adjusting for pollutants	Lag0	95%CI	Lag0-4	95%CI
PM <sub>2.5</sub>				
+SO <sub>2</sub>	1.018	(1.007–1.031)	1.024	(1.007–1.042)
+NO <sub>2</sub>	1.019	(1.007–1.032)	1.032	(1.015–1.051)
+O <sub>3</sub>	1.019	(1.006–1.031)	1.026	(1.009–1.044)
+SO <sub>2</sub> +NO <sub>2</sub>	1.019	(1.006–1.032)	1.029	(1.011–1.048)
+SO <sub>2</sub> +O <sub>3</sub>	1.018	(1.005–1.031)	1.023	(1.005–1.043)
+NO <sub>2</sub> +O <sub>3</sub>	1.019	(1.006–1.032)	1.031	(1.011–1.050)
+SO <sub>2</sub> +NO <sub>2</sub> +O <sub>3</sub>	1.019	(1.006–1.032)	1.029	(1.010–1.049)

Note: The correlation coefficient between PM<sub>2.5</sub> and PM<sub>10</sub> is greater than 0.7 (0.871), considering the collinearity problem, we did not add PM<sub>10</sub> to the multi-pollutant model for analysis

The analyses were adjusted for time trends, temperature, relative humidity, weekend, and holiday by using the distributed lag non-linear model

**Table 5** Relative risk and cumulative relative risk of respiratory disease mortality from different PM<sub>2.5</sub> guidelines

Guideline	Lag0	95%CI	Lag0-4	95%CI
WHO AQG2021	1.029	(1.011–1.048)	1.042	(1.017–1.048)
WHO AQG2005	1.049	(1.018–1.081)	1.071	(1.029–1.081)
GB Grade I	1.069	(1.025–1.115)	1.100	(1.041–1.115)
GB Grade II	1.153	(1.054–1.262)	1.227	(1.090–1.262)

Note: WHO AQG, The World Health Organization Air Quality Guideline 24-h daily average: 25 µg/m<sup>3</sup>(2005), 15 µg/m<sup>3</sup>(2021);

China National Ambient Air Quality Standards (2012)-Chinese 24-h standard, GB Grade I: 35 µg/m<sup>3</sup>, GB Grade II: 75 µg/m<sup>3</sup>

than that for those aged less than 65 years; on the contrary, the single-day lag effect was lower than that of those aged less than 65 years.

Table 4 shows the relative risks and cumulative relative risk of respiratory mortality associated with 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub> concentration under multiple pollutant models. The SO<sub>2</sub>, NO<sub>2</sub>, and O<sub>3</sub> concentrations were substituted into the model for fitting to the multiple pollutant models and demonstrated similar lag curves in association with respiratory disease mortality. We observed that the lag-specific effect between PM<sub>2.5</sub> concentration and respiratory mortality remained statistically significant and was not affected by other air pollutants. With regards to the cumulative effect, only the multiple pollutant models of PM<sub>2.5</sub> and NO<sub>2</sub> concentrations showed a relative increase.

We simulated the relative risk and cumulative relative risk of respiratory disease mortality in association with different PM<sub>2.5</sub> guidelines (Table 5). As the PM<sub>2.5</sub> concentration increased, both the lag specific effect and cumulative lag effect increased significantly. When

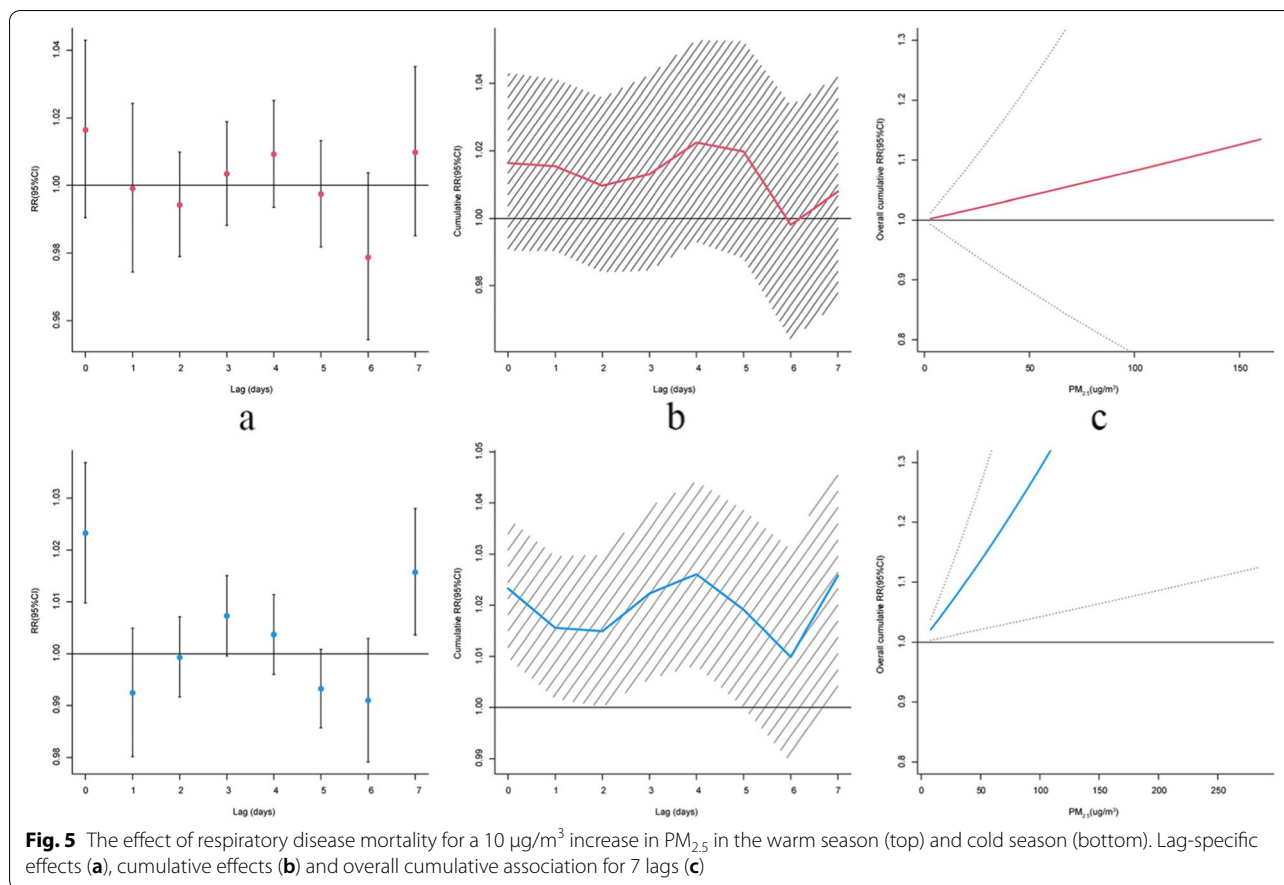
PM<sub>2.5</sub> concentrations rose to 75 µg/m<sup>3</sup>, the relative risk of respiratory disease increased by 15.3% (1.153, 95%CI: 1.054–1.262), and the cumulative relative risk (lag0-4) increased by 22.7% (1.227, 95%CI: 1.090–1.262).

The association between PM<sub>2.5</sub> concentration and respiratory mortality varies by season (Fig. 5). We observed stronger associations between PM<sub>2.5</sub> concentration and respiratory disease mortality in the cold season, with a cumulative relative risk (lag0-4) of 1.026 (95%CI: 1.008–1.044). Although the lag effect was not statistically significant during the warm season, we found that the confidence interval for the overall cumulative effect was wider than that observed in the cold season.

### Discussion

Respiratory diseases are one of the leading causes of death in Chinese residents [15, 16]. In total, 8,825 case of respiratory disease mortality occurred in Changsha between 2015 and 2018. We calculated the lag specific and cumulative effects on respiratory mortality for each 10-µg/m<sup>3</sup> increase in PM<sub>2.5</sub> concentration. We found evidence of an association between PM<sub>2.5</sub> concentration and respiratory disease mortality in Changsha. Furthermore, we observed clear evidence of associations between PM<sub>2.5</sub> concentration, independent of other air pollutants, and respiratory disease mortality. We found that high concentrations of PM<sub>2.5</sub> may pose a more serious risk to respiratory disease mortality. In addition, we also found PM<sub>2.5</sub> concentration in the cold season was associated with a greater risk of respiratory disease mortality compared to that in the warm season.

According to environmental epidemiology, the effects of environmental exposure on health not only appear immediately but are also delayed [17, 18]. Therefore, we calculated the lag specific and cumulative lag effects comprehensively. In this study, we found significant associations between daily respiratory disease mortality and PM<sub>2.5</sub> concentration at lag days 0 and 7, and a cumulative relative risk (lag0-4) of 1.027 (95%CI: 1.011-1.031). A study of 652 cities across the globe reported that a 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub> concentration was associated with a 0.74% increase (95%CI, 0.53–0.95) in respiratory disease mortality [1]. In a U.S. study of 75 cities, there was a 1.18% (95%CI, 0.93–1.44%) increase in all-cause mortality and a 1.71% (95%CI 1.06- 2.35%) increase in respiratory disease-related deaths [8]. Another multicity time-series study in East Asia found that each 10-µg/m<sup>3</sup> increase in PM<sub>2.5</sub> concentration (lag01) was associated with a 1% increase (95%CI 0.23 -1.78%) in respiratory disease mortality [19]. In Guangzhou, Wu et al. found that 2-day moving average (lag01) PM<sub>2.5</sub> concentration corresponded to 0.95% (95% CI 0.16–1.73%) increase in respiratory disease mortality[12]. One study from Shanghai



noted evidence of stronger associations between ambient particulate matter and respiratory disease mortality in individuals aged >65 years [11]. Part of our results are inconsistent with those of previous studies. First, this may be related to the difference in PM<sub>2.5</sub> concentration [20]; in contrast, Zhang et al. observed a stronger association between the level of particulate matter and the rate of mortality. Considering that China has experienced unprecedented severe air pollution events since 2011, with northern regions most affected, the discrepancies in our results might be, at least in part, due to the relatively southern position of Changsha [7]. Secondly, these inconsistencies may be due to the different toxic components of PM<sub>2.5</sub>. Several studies have found that coal combustion emissions may have a more significant toxic effect, particularly on the respiratory system [8, 13]. Yin et al. reported that northern China had generally higher coal combustion emissions than those found in southern China because of more intense industrial emissions by thermal power generation, for instance [21]. Finally, differences related to the ethnicity, age, physical constitution, and population tolerance to pollutants within

different regions may contribute to the discrepancies observed in our study.

Previous studies have also considered age and sex to be important factors contributing to the impact of PM<sub>2.5</sub> concentration on respiratory disease mortality. Likewise, we note significant sex differences influencing the effects of PM<sub>2.5</sub> concentration on respiratory disease mortality in male individuals; each 10-µg/m<sup>3</sup> increase in PM<sub>2.5</sub> concentration increased the risk of respiratory disease mortality by 2.3% and cumulative risk of mortality by 3.2%. Results from large nationwide cohort of Chinese males [21] reported that each 10-µg/m<sup>3</sup> increase in PM<sub>2.5</sub> concentration was associated with a 9%, 12% and 12% increase in the risk of death due to non-accidental conditions, chronic obstructive pulmonary disease, and lung cancer, respectively. Zeng et al. suggested that younger populations are more vulnerable to exposure to PM<sub>2.5</sub> [22]. One study found that in terms of age, PM<sub>2.5</sub> exposure was significantly associated with respiratory disease mortality in the subgroup aged ≤ 64 years, while there was no significant risk in the subgroup aged ≥ 65 years [23]. However, some studies suggest that sensitive individuals



aged older than 65 years have a higher risk of death, even at low  $PM_{2.5}$  concentrations [24]. The findings of the current study illustrate that individuals aged < 65 years had a higher respiratory diseases risk of death in a single day, and while the cumulative risk of death was higher, the risk of death was lower in individuals older than 65 years as compared to risk in younger individuals. Consistent with findings from other studies [7, 25], the described differences in age and sex are thought to be due to the diverse nature pertaining to the subgroups of disease types and environmental factors sensitivities [26]. In addition, the present study reports that while the cumulative relative risk (lag0-4) is evidently higher for older individuals, the single-day lag effect is stronger for the younger ones. The probable cause is hereby ascribed to the coexistence of chronic diseases and multiple conditions in the elderly. Hence, the harmful consequences of  $PM_{2.5}$  to a single organ or system may also be involved implicated in multi-organ and multi-system diseases, resulting in persistent damage.

Air quality guidelines have been developed to guide policies on addressing efforts to reduce the health impact of air pollution in the population. Epidemiological studies have confirmed that when reaching a certain concentration, air pollution alters the corresponding morbidity and mortality of the respective population. The World Health Organization (WHO) Air Quality Guideline (AQG) estimates a critical value causing health hazards, and recommends that the atmospheric environmental quality standards in the guidelines be used as threshold. Most countries, including China, have not yet reached the WHO 2005 AQG [27] guidance value; furthermore, the latest WHO 2021 AQG [28] guidance value brings to light greater challenges to air pollution control globally. Chien et al. reported that a  $PM_{2.5}$  index greater than  $35 \mu\text{g}/\text{m}^3$  affects sensitive populations, and the spline for  $PM_{2.5}$  concentration was centered at this threshold [17]. A 2019 study using concentration–response functions estimated excess deaths at three counterfactual  $PM_{2.5}$  thresholds ( $7.5$ ,  $25$ , and  $75 \mu\text{g}/\text{m}^3$ ) [9]. Here, we compared the difference in mortality risk at four different  $PM_{2.5}$  guidelines: WHO AQG 2021 ( $15 \mu\text{g}/\text{m}^3$ ), WHO AQG 2005 ( $25 \mu\text{g}/\text{m}^3$ ), Grade I ( $35 \mu\text{g}/\text{m}^3$ ) and Grade II ( $75 \mu\text{g}/\text{m}^3$ ) national standards outlined by the National Ambient Air Quality Standards of China [29]. In addition to other health factors, we found that high  $PM_{2.5}$  concentrations may lead to a more serious risk of respiratory disease mortality in this study. A previous report concluded that when estimating health effects under a population-weighted  $PM_{2.5}$  threshold, setting more specific emission limits or penalties for controlling pollution activities in China and other developing countries can be

considered [30]. It is worth noting that many countries have not adopted the WHO guidelines. The United States revised the  $PM_{2.5}$  standard in 2006 [31], reporting annual and daily average values were  $15 \mu\text{g}/\text{m}^3$  and  $35 \mu\text{g}/\text{m}^3$ , respectively, which did not meet WHO guidelines. Given that standard setters must balance air pollution levels, health risks, economic capabilities, and comprehensive governance capabilities, air quality standards vary across different countries and regions.  $PM_{2.5}$  concentration was included in the National Ambient Air Quality Standards for the first time in 2012, although it did not meet the WHO standards [27] or those of other countries [31–33]. Nevertheless, this reflects progress of the Chinese government in protecting public health.

Consistent with previously reported data [34], we found  $PM_{2.5}$  concentration in the cold season to be associated with a higher risk of respiratory disease mortality than that noted in the warm season. Cohort studies have confirmed that higher  $PM_{2.5}$  concentrations result in a greater observed rates of respiratory disease mortality [21]. A review reported that pollutant emissions increased during the central heating period (November to March) in northern China [9]. Furthermore, some scholars believe that the  $PM_{2.5}$  concentration in the cold season corresponds to a higher risk of respiratory diseases mortality in consequence of its relationships with low temperature and atmospheric inversion [35, 36]. These effects are more pronounced in southern China [37]. Therefore, we used meteorological factors, such as temperature and humidity to act as control variables in our study, and our results remained significant. In addition, the frequent occurrence of severe pollution during the cold season is related to the climate and topographical characteristics of Changsha. Changsha has a subtropical monsoon humid climate, with northwest wind dominating the cold season. The terrain altitude of Changsha is high in the south and low in the north, forming a horseshoe shaped opening to the north, causing air pollutants to remain trapped.

Although the acute health hazards of particulate pollutants in high concentration during the cold season are more significant, the long-term hazards of low concentration cannot be ignored [38, 39]. Both short-term and long-term exposure to particulate pollutants in low concentration ranges are linked with adverse health effects. We found that although the relative risk values were indeed lower during the warm season, the 95% confidence intervals overlapped considerably. Moreover, we found that the concentration of fine particulate matter in the warm season is far from the average concentration ( $53.3 \mu\text{g}/\text{m}^3$ ) and that the range of the confidence interval significantly widens. These findings highlight

the impacts that short-term exposure and low concentrations of particulate pollutants have over respiratory disease mortality rates. According to twenty-two European cohorts observed in studies assessing air pollution effects, the relative hazard ratio of population exposure to PM<sub>2.5</sub> remains high, even with long-term exposure below the European average annual limit (25 µg/m<sup>3</sup>) [40]. A U.S. study found statistically significant association between short-term exposures to PM<sub>2.5</sub> and the relative hazard to the population, with a relative increase of 1.05% (95% CI, 0.95%–1.15%) during 2000–2012, even though the average daily concentration of PM<sub>2.5</sub> was below 25 µg/m<sup>3</sup> for 93.6% of the days recorded [24]. However, nowadays more individuals wear masks, close windows, and reduce outdoor activities on heavily polluted days. Nonetheless, few studies have examined the health effects of low-level exposures and lax prevention.

Our study had several limitations. First, the research methods were limited, compared with extensive sample epidemiological cohort studies. Time-series studies use ecological methods. Their power and reliability are limited in inferring the causal relationship between air pollution and health. Second, the potential underreporting of death data from the cause of death monitoring system used may have had an impact on the results, whereas the fixed-point monitoring data may have introduced a bias in analyzing the exposure levels of the city's population. Third, the study did not include a questionnaire on factors, such as lifestyle, disease history, or other influencing factors that could not be studied or analyzed as control variables.

## Conclusion

Our study demonstrated an association between PM<sub>2.5</sub> concentrations and respiratory disease mortality in Changsha, China. Younger people (age < 65 years) and males might be more vulnerable to exposure to PM<sub>2.5</sub>, while older people have a higher cumulative risk of death; therefore, the protective measures for specific groups should be strengthened. In addition, we found stronger associations between air pollutants and respiratory disease mortality during the cold season compared to those observed during the warm season. Regardless, the harm caused by low-concentration particulate matter during the warm season should not be ignored. In view of the high concentration of PM<sub>2.5</sub> that may pose a more serious risk of respiratory disease mortality, we believe that relevant government departments should start a new round of standard revision as soon as possible under the dual goals of promoting carbon neutrality and continuously improving air quality.

## Abbreviations

PM<sub>2.5</sub>: Fine particulate matter; RR: Relative risk; CRR: Cumulative relative risk; DLNM: Distributed lag nonlinear model; PM<sub>10</sub>: Inhalable particulate matter; SO<sub>2</sub>: Sulfur dioxide; NO<sub>2</sub>: Nitrogen dioxide; O<sub>3</sub>: Ozone; Quasi-AIC: Akaike Information Criterion for Quasi-likelihood models; DOW: Day of the week; AQG: Air Quality Guideline.

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## Authors' contributions

Q.F. designed the study, contributed the statistical analysis, interpreted the results and wrote the original draft. Y.C. and S.S. contributed data curation, software, and materials/analytic. X.X.Z. and X.J.L. contributed designed, administration, and supervision. All authors reviewed and approved the manuscript prior to submission.

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## Availability of data and materials

The environmental data (PM<sub>2.5</sub>, NO<sub>2</sub>, SO<sub>2</sub> and O<sub>3</sub>) in this article are publicly available on the website of the Ministry of Environment and Ecology of China (<http://english.mee.gov.cn/>). Meteorological data (temperature, relative humidity) is publicly available on the website of the China Meteorological Administration (<http://www.cma.gov.cn/en2014/>). The death data that support the findings of this study are available from the CDC's population death information registration management system, but restrictions apply to the availability of these data, which were used under license for the current study. In addition, other ways to obtain the death data: 1. Contact the Center for Chronic and Non-Communicable Diseases of the Chinese Center for Disease Control and Prevention (e-mail: [ncncdoffice@chinacdc.cn](mailto:ncncdoffice@chinacdc.cn)), 2. Purchase the annual "China Death Cause Surveillance Dataset" compiled by the Chinese Center for Disease Control and Prevention. 3. The China Public Health Science Data Center is regularly published (<https://www.phsciencedata.cn/Share/en/index.jsp>).

## Declarations

### Ethics approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Competing interests

The authors declare that they have no competing interests.

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