

# Short-term effect of PM<sub>2.5</sub> and O<sub>3</sub> on non-accidental mortality and respiratory mortality in Lishui District, China

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## Research

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# Abstract

## Background

In recent years, air pollution has become an imminent problem in China. Few studies have investigated the impact of air pollution on the mortality of middle-aged and elderly people. Therefore, this study aims to evaluate the impact of PM<sub>2.5</sub> and O<sub>3</sub> on non-accidental mortality and respiratory mortality of the middle-aged and elderly in Lishui district of China and provide the scientific basis for the prevention and control measures of air pollution.

## Method:

Using daily mortality and atmospheric monitoring data from 2015 to 2019, we applied a generalized additive model with time-series analysis to study the association of PM<sub>2.5</sub> and O<sub>3</sub> exposure with daily non-accidental mortality and respiratory mortality in Lishui district of China. Using attributable risk to estimate the death burden attributable to short-term exposure to O<sub>3</sub> and PM<sub>2.5</sub>.

## Result

PM<sub>2.5</sub> and O<sub>3</sub> were associated with non-accidental and respiratory mortality. For every 10µg/m<sup>3</sup> increased in PM<sub>2.5</sub>, non-accidental mortality increased 0.94% (95%CI: 0.05%-1.83%), and PM<sub>2.5</sub> had a more significant impact on women. For every 10µg/m<sup>3</sup> increased in O<sub>3</sub>, respiratory mortality increased 1.35% (95%CI: 0.05%-2.66%). and O<sub>3</sub> had a more significant impact on men. Compared with single pollutant model, the impact of the two-pollutant model on non-accidental mortality and respiratory mortality slightly decreased. Besides, in summer and winter, O<sub>3</sub> had a more obvious impact on non-accidental mortality. The Population Attributable Fractions of non-accidental mortality were 0.839% (95%CI:0.004–1.626%) for PM<sub>2.5</sub> and the PAF of respiratory mortality were 0.135% (95%CI:0.005–0.263%) for O<sub>3</sub>.

## Conclusion

PM<sub>2.5</sub> and O<sub>3</sub> could significantly increase the risk of non-accidental and respiratory mortality in middle-aged and elderly people in Lishui district, China. Exposing to air pollutants, men were more susceptible to O<sub>3</sub> damage, and women were more susceptible to PM<sub>2.5</sub> damage.

## Background

With economic development, air pollution has become an important risk factor to people's health. In 2019, air pollution ranked fourth among the major risk factors of mortality in the world[1], causing 667 million

mortality[2], with air pollutants mainly particulate matter (PM) and ozone (O<sub>3</sub>). Since the Chinese government implemented China's Action Plan of Prevention and Control of Air Pollution in 2013, PM<sub>2.5</sub> (Particulate matter less than 2.5µm in aerodynamic diameter) concentration has dropped significantly[3]. However, with more infrastructure, rapid industrial development, and rapid vehicle growth, sometimes the china's daily PM<sub>2.5</sub> concentration sometimes exceeds the national air quality standards, and ozone pollution has become more and more serious in recent years[4]. Clearly, O<sub>3</sub> and PM<sub>2.5</sub> have become the two most serious air pollutants in China.

PM<sub>2.5</sub> can penetrate deep into the lungs, cause continuous oxidative stress and inflammation[5], stimulate and corrode alveolar walls[6], thereby impairing lung function. Exposure to PM<sub>2.5</sub> has increased the risk of mortality in the Chinese population[7, 8]. Furthermore, O<sub>3</sub> enters the human body through breathing and stimulates the human respiratory system, causing mucosal irritation and airway inflammation symptoms[9]. Exposure to O<sub>3</sub> can activate the oxidation pathway, leading to cell mortality and chronic bronchial inflammation[10]. Studies found that O<sub>3</sub> exposure contributes to respiratory death[11]. A large-scale prospective study in China also shows that the elevated ambient ozone concentration would increase the risk of respiratory and circulatory mortality[12]. Even if exposed to low levels of O<sub>3</sub> and PM, the body would produce ROS, which has a high potential for DNA damage and would increase the incidence rate and mortality of respiratory diseases and lung cancer[13, 14].

The atmospheric environment is closely related to people's health. With increasing age, the physiological functions of the respiratory system and multiple organs of middle-aged and elderly people decline, the immune response slows down, and allergic reactions increases[15, 16], so they are the susceptible population to air pollution[17, 18]. As one of the first national healthy practice demonstration zone, Lishui district is exploring a new model of health care to preserve residents' health. Therefore, in order to subsequently formulate effective policies to improve the environment and the quality of life of the people, it is necessary to investigate the effects of short-term exposure to PM<sub>2.5</sub> and O<sub>3</sub> on non-accidental mortality and respiratory mortality among middle-aged and elderly people in Lishui district.

## Materials And Methods

### Study area and population

Lishui district, the first national healthy practice demonstration zone, is located in the south of Nanjing, the capital of Jiangsu Province. It has a northern subtropical monsoon climate with four distinct seasons, hot and humid in summer, cold and dry in winter. As of 2019, Lishui district has approximately 446,750 permanent residents, with an area of 1067 square kilometers.

### Study design

### Data collection

The daily mortality records and the daily average concentration of atmospheric pollutants in Lishui district from January 1, 2015 to December 31, 2019, were derived from the Lishui Smart City Operating Command Center of Nanjin, the big data integration center of Lishui district government. The daily mortality records included the mortality data of the permanent population. Specific information included age, gender, date of birth and death. We classified the causes of mortality based on the sole primary diagnosis coded by ICD-10 (International Statistical Classification of Diseases and Related Health Problems 10th Revision), including non-accidental mortality (A00-R99), and respiratory diseases (J00-J99). The environmental data included daily meteorological data and atmospheric pollutants data.

## Statistical analysis

We used daily aggregated data from 2015 to 2019 to quantitatively assess the impact of  $PM_{2.5}$ , and  $O_3$  exposure on non-accidental mortality and respiratory mortality. Daily mortality, air pollution, and meteorological data were described with average standard deviations and quartiles. The relationship between air pollutants and meteorological conditions was evaluated using the spearman correlation. The data of mortality, air pollution levels, and meteorological factors were linked by the date. For the total population, the daily mortality of residents was a small probability event and obeyed the Poisson distribution and the correlation between explanatory variables and the number of mortalities per day was mainly non-linear. Thus, we constructed a generalized additive model (GAM) based on the Poisson distribution in which time-series analysis was used to establish the core model to estimate the association between mortality and air pollutant exposure. The model was as follows:

$$\text{Log}[E(Y_t)] = \alpha + \beta X_t + \text{ns}(\text{Time}, \text{df}) + \text{ns}(Z_t, \text{df}) + \text{DOW}$$

In this equation,  $t$  refers to the day of the observation;  $Y_t$  is the number of daily mortalities observed on day  $t$ ;  $E(Y_t)$  is the expected daily mortality rate on day  $t$ .  $\alpha$  is the intercept;  $\beta$  represents the regression coefficient of the corresponding air pollutants;  $X_t$  represents the pollutant concentration on day  $t$ ;  $Z_t$  represents the meteorological data on day  $t$ ; DOW is a binary dummy variable;  $s$  is a non-linear variable with smoothing spline function. Previous studies[19-22] have usually set the degrees of freedom(df) of time to 5 to 7 and meteorological factors to 3 to 6. The degree of freedom was selected according to the minimum value of the Akaike information criterion (AIC) of the Poisson model, and the smaller AIC value indicates the preferred model[23]. Considering the applicability and AIC value of the model, 6 df was used to adjust the time trend, seasonality, and temperature, and 3 df was used to adjust relative humidity in the model.

The lag effect of air pollutants on non-accidental mortality and respiratory mortality was studied from the current day up to the 7th day (lag0-lag7). Previous studies have shown that cumulative effects may be underestimated by the single-day lag model[24]. Therefore, we further used the moving average of air pollutant concentrations from the 2ed day to the 8th day (lag01 to lag07) in the analysis. In addition, research has found that the decrease of  $PM_{2.5}$  leads to the increase of photochemical flux and the acceleration of atmospheric oxidation, increasing of  $O_3$  concentration[25]. As a result, we explored

whether there is an interactive effect on the death of the two main pollutants in Lishui district, the two-pollutant model was used to evaluate the confounding effect of pollutants. After establishing a statistical model that includes all control variables and checking the applicability, we separately included air pollutants into the model. In addition, the data were stratified by gender (female and male), age (45-64 years, 65-84 years, 85 years or older), and seasons (spring, summer, autumn, winter). The results were expressed as excess risk (ER) and 95% confidence intervals (95% CI) of daily deaths associated with  $10\mu\text{g}/\text{m}^3$  increase in pollutants' concentration.

We further estimated the death burden attributable to short-term exposure to  $\text{O}_3$  and  $\text{PM}_{2.5}$ . The counts of different death outcomes attributable to air pollutants were estimated using:  $\text{AC}_{ij} = N_{ij} * (\text{RR}_{ij} - 1) / \text{RR}_{ij}$ .  $\text{RR}_{ij}$  is the relative risk for disease  $j$  at  $i$  based on the relative risk functions.  $N_{ij}$  is the death number of disease  $j$  at  $i$ .  $\text{AC}_{ij}$  is the attributable counts of disease  $j$  at  $i$ . Then we calculate the total attributable counts of disease  $j$  ( $\text{AC}_j$ ) by summing the  $\text{AC}_{ij}$  of the study period. Finally, the population attributable fractions (PAF) were calculated by dividing the total  $\text{AC}_j$  by the total number of deaths among middle-aged and elderly people in Lishui district.

All Statistical analysis was performed using R software, version 4.0.3. The statistical significance of all analyses was defined as  $P < 0.05$ .

## Result

Table 1 shows the descriptive summary for daily mortality, air pollutants, and meteorological data in Lishui district, China, during 2015–2019. From 2015 to 2019, the total number of non-accidental mortality and respiratory mortality among the middle-aged and elderly ( $\geq 45$  years) in Lishui district was 13,160 and 1,478 respectively. At the same time, a seasonal pattern of daily mortality was also observed, with higher mortality in winter (Fig. 1). The daily average temperature was  $16.9^\circ\text{C}$  (Range:  $-6.7^\circ\text{C}$ - $34.7^\circ\text{C}$ ), the daily average relative humidity was 73.0% (Range: 28%-100%). The 24-hour average concentration of  $\text{PM}_{2.5}$  was  $43.57\mu\text{g}/\text{m}^3$  (Range:  $26\mu\text{g}/\text{m}^3$ - $171\mu\text{g}/\text{m}^3$ ), and the maximum daily 8-hour average concentration of  $\text{O}_3$  (MDA8  $\text{O}_3$ ) was  $100.13\mu\text{g}/\text{m}^3$  (Range:  $2\mu\text{g}/\text{m}^3$ - $285\mu\text{g}/\text{m}^3$ ).  $\text{O}_3$  was moderately positively correlated with average temperature ( $r = 0.52$ ,  $P < 0.05$ ), was moderately positively correlated with the relative humidity ( $r = -0.38$ ,  $P < 0.05$ ), and was slightly negatively correlated with  $\text{PM}_{2.5}$  concentration.  $\text{PM}_{2.5}$  was moderately correlated with the temperature ( $r = -0.45$ ,  $P < 0.05$ ), and was slightly negatively correlated with the relative humidity (Fig. 2).

Table 1

Description for daily deaths, air pollutants, and meteorological factors in Lishui district, 2015–2019.

<b>Variables</b>	<b>Mean</b>	<b>SD</b>	<b>Min</b>	<b>P50</b>	<b>Max</b>
Daily mortality counts					
Non-accidental mortality	7.21	2.90	0	7	19
Respiratory mortality	0.81	0.96	0	1	6
Gender					
Male	4.10	2.07	0	4	13
Female	3.11	1.86	0	3	11
Age					
45–64 years	1.60	0.82	1	1	6
65–84 years	3.77	1.73	1	4	12
85 years or older	2.08	1.09	1	2	7
PM <sub>2.5</sub> (µg/m <sup>3</sup> )					
All year	43.57	25.05	4	38	171
Spring	45.26	18.63	9	43	125
Summer	29.25	15.65	4	26	141
Autumn	36.84	18.19	10	34	146
Winter	63.26	30.98	14	56	171
O <sub>3</sub> (µg/m <sup>3</sup> )					
All year	100.13	50.58	2	93.6	285
Spring	117.68	45.36	11	113	252
Summer	120.90	52.66	10	118	285
Autumn	101.25	46.11	2	99	238
Winter	59.90	30.39	2	59	176
Average temperature (°C)					
All year	16.91	9.07	-6.7	17.8	34.7
Spring	16.64	5.54	2.9	17.2	31.7
Summer	27.36	3.28	18.7	27.2	34.7

<b>Variables</b>	<b>Mean</b>	<b>SD</b>	<b>Min</b>	<b>P50</b>	<b>Max</b>
Autumn	18.07	5.65	0.1	17.9	29.3
Winter	5.36	3.50	-6.7	5.3	14.9
Relative humidity (%)					
All year	72.99	13.99	28	73	100
Spring	68.46	15.09	28	68.5	100
Summer	76.95	10.70	49	77	100
Autumn	75.20	12.77	42	75	100
Winter	71.33	15.33	32	71	100
Notes: The data were set by spring (Mar-May), summer (Jun-August), autumn (Sept-Nov) and winter (Dec-Feb) seasons.					

After adjusting the time, day of the week, and weather conditions, we evaluated the single-day lag effect (lag0-lag7) and multi-day moving average lag effect (lag01-lag07) on non-accidental mortality and respiratory mortality (Fig. 3). For every increase in PM<sub>2.5</sub> concentration by 10µg/m<sup>3</sup>, the greatest excessive risk of non-accidental mortality on the current day (lag0) increased by 0.94% (95%CI: 0.05%-1.83%). For every increase in O<sub>3</sub> concentration by 10µg/m<sup>3</sup>, the greatest excessive risk of respiratory mortality at lag 7 increased by 1.35% (95%CI: 0.05%-2.66%). The increase of PM<sub>2.5</sub> and O<sub>3</sub> concentration had no statistical significance on the moving average lag effects of non-accidental mortality and respiratory mortality. To avoid multiple collinearities, only the two-pollutant model was used to detect the robustness of the model, and the multi-pollutant model was not considered. Compared with the single pollutant model, the results of the two-pollutant model had no significant change, as a result, the model we built had good robustness (Table 2).

Table 2

The excess risk (95% CI) of daily mortality associated with 10  $\mu\text{g}/\text{m}^3$  increase.

Variables	Non-accidental mortality	Respiratory mortality
<b>PM<sub>2.5</sub></b>		
Single pollutant model	0.9363%(0.0492%-1.8312%)*	0.6029%(-1.5060%-2.7571%)
+O <sub>3</sub>	0.9359%(0.0366%-1.8434%)*	0.6026%(-1.5069%-2.7572%)
<b>O<sub>3</sub></b>		
Single pollutant model	0.1501%(-0.2682%-0.5701%)	1.3469%(0.0479%-2.6627%)*
+PM <sub>2.5</sub>	0.1460%(-0.2722%-0.5659%)	1.3384%(0.0363%-2.6574%)*
Note. * $P < 0.05$ .		

Table 3 and Table 4 show the effect modification, after stratifying daily mortality by age, sex, and season. Figure 4(a) shows that the single pollutant model, for every 10  $\mu\text{g}/\text{m}^3$  increase in PM<sub>2.5</sub>, the greatest excessive risk of non-accidental mortality among middle-aged and elderly women on the current day (lag0) increased by 1.77% (95%CI: 0.43%-3.12%). There was no statistically significant difference in the effect of PM<sub>2.5</sub> on male non-accidental mortality ( $P < 0.05$ ). Figure 4(b) shows that in every 10  $\mu\text{g}/\text{m}^3$  increase in O<sub>3</sub> led to 1.38% (95% CI: 0.30%-2.47%) increase in respiratory mortality at lag7. And the effect of women was no statistical significance. Figure 5 shows that for every 10  $\mu\text{g}/\text{m}^3$  increase in O<sub>3</sub>, non-accidental mortality in summer and winter increased by 0.75% (95% CI: 0.01% -1.50%) and 1.38% (0.30%-2.47%) at lag2 and lag5 respectively. The effect of O<sub>3</sub> on non-accidental mortality was not statistically significant in spring and autumn ( $P > 0.05$ ). The increase of PM<sub>2.5</sub> and O<sub>3</sub> concentrations has different maximum lag effects in different age groups, but the effect is not statistically significant.

Table 3  
The non-accidental maximum ER (95%CI) in lag days, stratified by age, sex and season.

Variables	Non-accidental deaths			
	Lag	PM <sub>2.5</sub>	Lag	O <sub>3</sub>
All	Lag 0	0.94%(0.05%-1.83%)*	Lag 1	0.15%(-0.27%-0.57%)
Age(yeas)				
45–64	Lag 0	0.99%(-1.34%-3.37%)	Lag 1	0.31%(-0.92%-1.54%)
65–84	Lag 5	1.04%(-2.30%-4.51%)	Lag 7	0.25%(-0.40%-0.90%)
85+	Lag 0	1.13%(-0.63%-2.91%)	Lag 0	0.52%(-0.63%-1.68%)
Sex				
Male	Lag 4	0.29%(-0.70%-1.29%)	Lag 1	0.16%(-0.40%-0.71%)
Female	Lag 0	1.77%(0.43%-3.12%)*	Lag 0	0.67%(-0.18%-1.53%)
Season				
Spring	Lag 0	1.12%(-1.43%-3.72%)	Lag 4	0.60%(-0.33%-1.53%)
Summer	Lag 5	2.38%(-0.11%-4.94%)	Lag 5	0.75%(0.01%-1.50%)*
Autumn	Lag 3	1.09%(-1.02%-3.24%)	Lag 0	0.45%(-0.93%-1.85%)
Winter	Lag 0	0.96%(-0.38%-2.33%)	Lag 2	1.38%(0.30%-2.47%)*
Note. * <i>P</i> < 0.05.				

Table 4

The respiratory maximum ER (95%CI) in lag days, stratified by age, sex and season.

Variables	Respiratory deaths			
	Lag	PM <sub>2.5</sub>	Lag	O <sub>3</sub>
All	Lag 2	0.60%(-1.51%-2.76%)	Lag 7	1.35%(0.05%-2.66%)*
Age(year)				
45–64	Lag 0	0.39%(-15.11%-18.71%)	Lag 4	0.39%(-11.35%-13.67%)
65–84	Lag 5	1.04%(-2.30%-4.51%)	Lag 5	0.69%(-1.36%-2.79%)
85+	Lag 0	0.59%(-3.27%-4.60%)	Lag 4	0.11%(-2.21%-2.48%)
Sex				
Male	Lag 4	1.03%(-1.65%-3.78%)	Lag 7	2.06%(0.41%-3.74%)*
Female	Lag 0	2.21%(-1.73%-6.30%)	Lag 0	1.12%(-1.55%-3.87%)
Season				
Spring	Lag 0	2.49%(-4.92%-10.47%)	Lag 5	1.50%(-1.41%-4.50%)
Summer	Lag 6	7.76%(-0.11%-16.25%)	Lag 3	1.19%(-1.14%-3.58%)
Autumn	Lag 6	3.26%(-3.81%-10.85%)	Lag 6	0.14%(-2.93%-3.31%)
Winter	Lag 7	1.97%(-0.87%-4.90%)	Lag 4	2.16%(-0.87%-5.29%)
Note. * $P < 0.05$ .				

Table 5 shows the numbers and fractions of non-accidental mortality and respiratory mortality among the middle-aged and elderly attributable to air pollutants in Lishui district. The Population Attributable Fractions (PAF) of non-accidental mortality were 0.839% (95%CI:0.004–1.626%) for PM<sub>2.5</sub> and the PAF of respiratory mortality were 0.135% (95%CI:0.005–0.263%) for O<sub>3</sub>. For every 10 µg/m<sup>3</sup> decrease in PM<sub>2.5</sub> could save 122 (95% CI: 6-237) people from non-accidental death, and for every 10 µg/m<sup>3</sup> decrease in O<sub>3</sub> could save 10 (95% CI: 1–38) people from respiratory death.

Table 5  
PAC(95%CI) and PAF(95%CI) of deaths due to air pollutants in 2015–2019.

	Pollutants	PAC(95% CI)	Total number	PAF(95%CI)
Non-accidental mortality	PM <sub>2.5</sub>	122(6-237)	14550	0.839%(0.044%-1.626%)
Respiratory mortality	O <sub>3</sub>	20(1–38)	14550	0.135%(0.05%-0.263%)
Note: PAC: Population Attributable Counts; PAF: Population Attributable Fractions				

## Discussion

This study used a time-series model to investigate the relationship between exposure of air pollutants (PM<sub>2.5</sub> and O<sub>3</sub>) and non-accidental mortality and respiratory mortality in Lishui district, Jiangsu Province, China from 2015 to 2019. Research results showed that short-term exposure to PM<sub>2.5</sub> and O<sub>3</sub> was positively correlated with an increased risk of non-accidental and respiratory mortality.

The daily average concentration of PM<sub>2.5</sub> in Lishui district is 43.57µg/m<sup>3</sup>, which was higher than the National Ambient Air Quality Standard (NAAQS) first-level standard, but lower than the second-level standard (the first-level standard is 35µg/m<sup>3</sup>, the second-level standard is 75µg /m<sup>3</sup>). The MDA8 O<sub>3</sub> was 100.13µg/m<sup>3</sup>, which was also higher than the NAAQS first-level standard, but lower than the second-level standard (the first-level standard is 100µg/m<sup>3</sup> and the second-level standard is 160µg/m). The seasonal fluctuation of pollutant concentration was mainly manifested as follows. PM<sub>2.5</sub> was higher in spring and winter than in summer and autumn and reached its peak in summer. O<sub>3</sub> was higher in summer and autumn than in spring and winter, and peaks in winter. A seasonal pattern in the number of daily mortalities was also observed, with higher mortality in winter. This observed seasonal fluctuation may be related to the increase in sources of pollutants and meteorological factors. In winter, industrial production, motor vehicle, and combustion emissions (such as coal, biofuels) are the most direct factors that produce PM<sub>2.5</sub>[26]. High temperature and sufficient sunshine in summer are favorable conditions for photochemical reaction to produce O<sub>3</sub>[27]. Using chemical industrial solvents and emitting the volatile organic compounds and nitrogen oxides from automobile exhaust may cause high levels of O<sub>3</sub>[28].

In this study, we found that in the single pollutant model, PM<sub>2.5</sub> had acute effects on non-accidental mortality. Every 10µg/m<sup>3</sup> increase in PM<sub>2.5</sub> was associated with a 0.94 % (95%CI: 0.05%-1.83%) increase in non-accidental mortality at lag0. A study conducted in a highly polluted area in China found that 10µg/m<sup>3</sup> increase in PM<sub>2.5</sub> was associated with 0.36% (95% CI: 0.10%-0.63%) increase of non-accidental mortality[29]. Lin found that every 10µg/m<sup>3</sup> increase in PM<sub>2.5</sub> was associated with 1.5% (95% CI: 0.5%-2.5%) of non-accidental mortality among the elderly over 65 years old [30]. A study conducted in 75 cities in the United States showed that for every 10µg/m<sup>3</sup> increase in PM<sub>2.5</sub>, the non-accidental mortality rate increased by 1.18% (95% CI: 0.93%-1.44%)[31]. Another large-scale study involving multiple countries

and regions found that for every  $10\mu\text{g}/\text{m}^3$  increase in  $\text{PM}_{2.5}$ , the daily non-accidental mortality rate increased by 0.68% (95% CI: 0.59–0.77%)[32]. Although our data analysis results showed that the impact of  $\text{PM}_{2.5}$  on non-accidental mortality in Lishui district was slightly higher, it was generally consistent with the results of previous research reports in China. This difference may be mainly related to the age difference of the exposed population. Moreover, the sources and chemical composition of  $\text{PM}_{2.5}$  in different regions are different, which may also lead to different effects on mortality.

Besides, we also found that  $\text{O}_3$  had acute effects on respiratory mortality. Every  $10\mu\text{g}/\text{m}^3$  increase in  $\text{O}_3$  was associated with an increase in respiratory disease mortality by 1.35% (95%CI: 0.05%-2.66%) at lag7. A study in Jinan showed that Every  $10\mu\text{g}/\text{m}^3$  increase in  $\text{O}_3$  was associated with a 0.975% (95% CI: 0.463, 1.489) increase in respiratory mortality at lag3[33]. Another study in Hefei showed that every  $10\mu\text{g}/\text{m}^3$  increase in  $\text{O}_3$  led to a 2.22% (95%CI: 0.56%-3.90%) increase in respiratory mortality[29]. A Sichuan study found that every  $10\mu\text{g}/\text{m}^3$  increase in  $\text{O}_3$  led to a 0.78% (95%CI: 0.12%-1.44%) increase in respiratory mortality[34]. Since the middle-aged and elderly population was the research object this time, the impact of  $\text{O}_3$  in Lishui district on respiratory mortality would be slightly higher, but it was consistent with the results of domestic and foreign research[35–37]. With the rapid development of the economic level and the acceleration of the urbanization process, the output of industrial manufacturing was also increasing, which may lead to the increase of volatile organic compounds (VOCs) emissions[38]. This may be one of the reasons that  $\text{O}_3$  in Lishui district had a greater impact on the respiratory mortality of the middle-aged and elderly. In this study, the impact of multi-day moving average lag was higher than that of single-day lag, but the effect was not statistically significant, which was consistent with Costa's research results[39].

Subgroup analysis showed that air pollutants were significantly related to non-accidental and respiratory mortality in different genders and seasons. Women were more sensitive to be affected by  $\text{PM}_{2.5}$  on non-accidental mortality. This was consistent with the research of Shin[40]and Hu[41]. Because women may have stronger airway responsiveness, combined with hormones or other factors, and therefore had a stronger physiological response to air pollutants[42, 43]. However, there was also conflicting research evidence that men were more susceptible to the impact of  $\text{PM}_{2.5}$  on non-accidental mortality[44, 45]. In contrast, we found that men were more susceptible to the effects of  $\text{O}_3$  on respiratory mortality than women. A research carried out in Shenzhen also found the same result[46]. This can be explained by the fact that pneumonia and bronchitis were more common in men, and many men have a smoking history and different occupational exposures, which may exacerbate the impact of  $\text{O}_3$  on respiratory mortality[47].

As far as the seasonal effect is concerned, the  $\text{O}_3$  concentration in summer had a statistically significant effect on non-accidental mortality. This is consistent with the research of Zanobetti[48]. In summer, as the temperature rises, the ozone precursor substances in the air produce  $\text{O}_3$  faster, which has harmed the health of the population[49]. Arch also found that although the concentration of  $\text{O}_3$  in winter is at the lowest level throughout the year, the effect of  $\text{O}_3$  on non-accidental mortality was also great. Wang's

research results were consistent with ours. A study in Nanjing found that the concentration of indoor  $O_3$  in winter may be greater than that of outdoor  $O_3$ , and indoor  $O_3$  produced by electrical equipment is harmful to people's health[50]. This may be because the middle-aged and elderly spend more time indoors in winter, and outdoor  $O_3$  exposure cannot represent the actual  $O_3$  exposure of them. Our research also found that ozone in spring and autumn had an effect on non-accidental mortality but was not statistically significant. Research conducted in many regions of East Asia found that  $O_3$  levels in different seasons have varying degrees of impact on non-accidental mortality[51]. This may be due to geographical heterogeneity[52]. To identify susceptible groups, we also explored the potential modification effects of age, but in our study, we did not observe significant modification effects of age groups.

In the two-pollutant model, after  $O_3$  was included in the  $PM_{2.5}$  model, the effect of  $PM_{2.5}$  on non-accidental and respiratory mortality was reduced. After  $PM_{2.5}$  was included in the  $O_3$  model, the effect of  $O_3$  on non-accidental and respiratory mortality was reduced too. The results of this study were the opposite of previous studies[29, 53]. From our time-series analysis of  $PM_{2.5}$  and  $O_3$ , it can be seen that  $PM_{2.5}$  was higher in winter, and  $O_3$  was higher in summer in Lishui district. The seasonal difference between  $PM_{2.5}$  and  $O_3$  may be the main reason for the reduction of the effect in the two-pollutant model.

In the attributable fraction analysis, nearly 0.84% of non-accidental mortality can be attributable to  $PM_{2.5}$ , and reducing the concentration of  $PM_{2.5}$  could save 122(95%CI:6-237) lives of the middle-aged and elderly. In addition, 0.14% respiratory mortality can be attributable to  $O_3$  and reducing the concentration of  $O_3$  could save 20(95%CI:1–38) lives of middle-aged and elderly. This finding highlights the deleterious effects of air pollution on people. Therefore, Lishui district authorities take measures to improve the atmospheric environment, which has a positive role in promoting the construction of the senior care demonstration zone.

This study has some limitations. First, we used the average concentration of air pollutants at the monitoring station as the population exposure level, without considering the indoor exposure. This would lead to exposure measurement errors and deviations in the accuracy and intensity of risk estimates. Secondly, time-series analysis was an ecological study that requires a large sample size. The sample size of respiratory mortality in this study was relatively small, which may lead to unstable results. Finally, this study did not collect information on smoking history, body mass index, drug history, and educational level. These potential confounding factors may also have a potential impact on the association between air pollution and mortality.

## Conclusion

In conclusion, this study shows that among the middle-aged and elderly in Lishui district, China, short-term exposure to  $PM_{2.5}$  and  $O_3$  would increase the risk of non-accidental death and respiratory death, and air pollutants have a lag effect on the health of the population. This finding would help Lishui district

authorities to adjust the existing air pollution management standards and implement more stringent air pollutant emission control policies, accelerating the construction of national health demonstration zones.

## Abbreviations

O<sub>3</sub>: Ozone; PM: Particulate matter; PM<sub>2.5</sub>: Particulate matter less than 2.5µm in aerodynamic diameter; CI: Confidence intervals; MDA8 O<sub>3</sub>: Maximum daily maximum 8-hour average concentration; TEMP: temperature; RH: relative humidity; NAAQS: National Ambient Air Quality Standard; ICD-10 : International Statistical Classification of Diseases and Related Health Problems 10th Revision; GAM: Generalized additive model; ER: Excess risk; df: degrees of freedom; AIC: Akaike information criterion; PAF: Population attributable fractions; PAC: Population Attributable Counts.

## Declarations

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### Ethics approval and consent to participate

The Institutional Ethics Committee for Clinical Research of Zhongda Hospital Affiliated to Southeast University, approved the study protocol (No. 2020ZDSYLL266-P01). Data were analyzed at the aggregate level and no participants were contacted.

### Authors' contributions

YQC, LHY and WD conceived and designed the work. YQC, LJF, PC, XDZ, WD, YPP and LHY contributed to data acquisition and preparation, YQC and ZGJ were involved in the study design and the interpretation of the results. LHY provided important feedback on how the study can be improved. YQC and ZGJ drafted the manuscript and LHY revised the manuscript. All authors approved the final manuscript.

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### Availability of data and materials

The datasets generated and/or analyzed during the current study are not publicly available due to the sensitive nature of the raw data but are available from the corresponding author on reasonable request.

## Consent for publication

Not applicable.

## Competing interests

The authors declare that they have no actual or potential competing financial interests.

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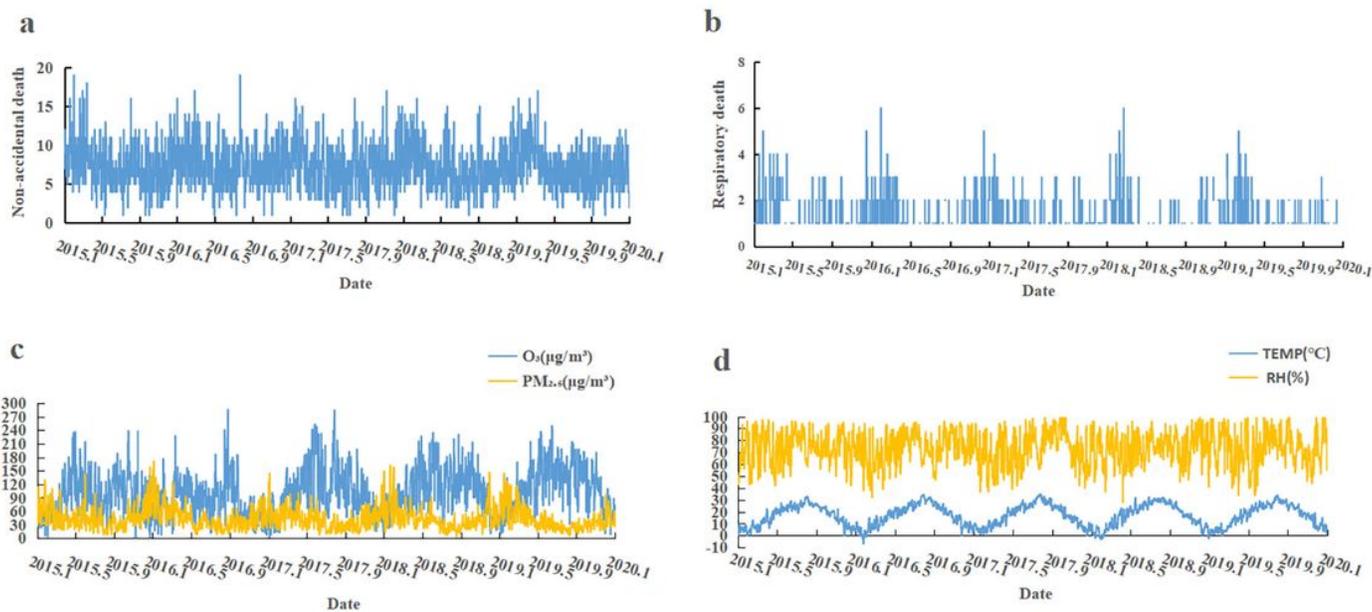
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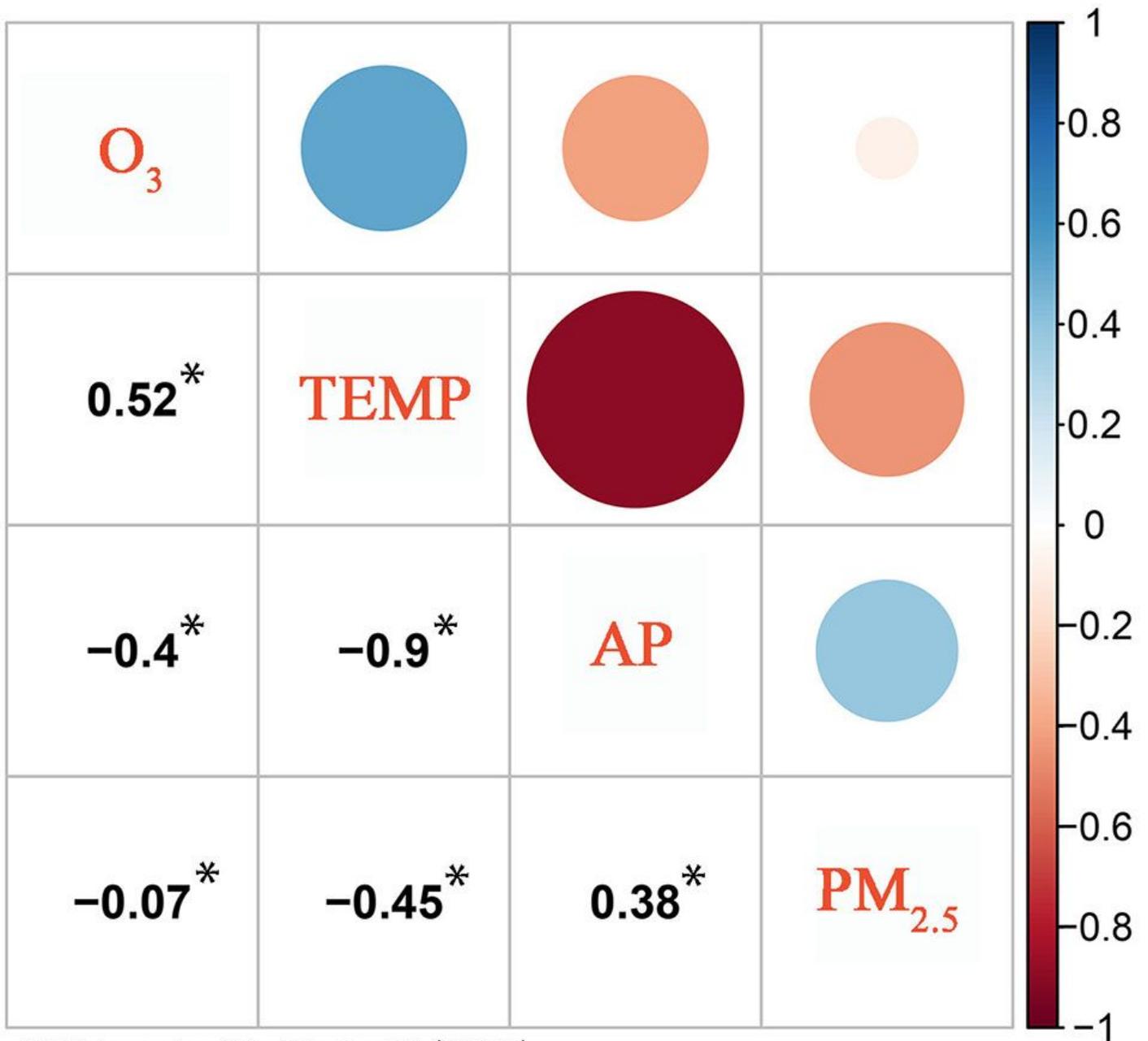
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## Figures



**Figure 1**

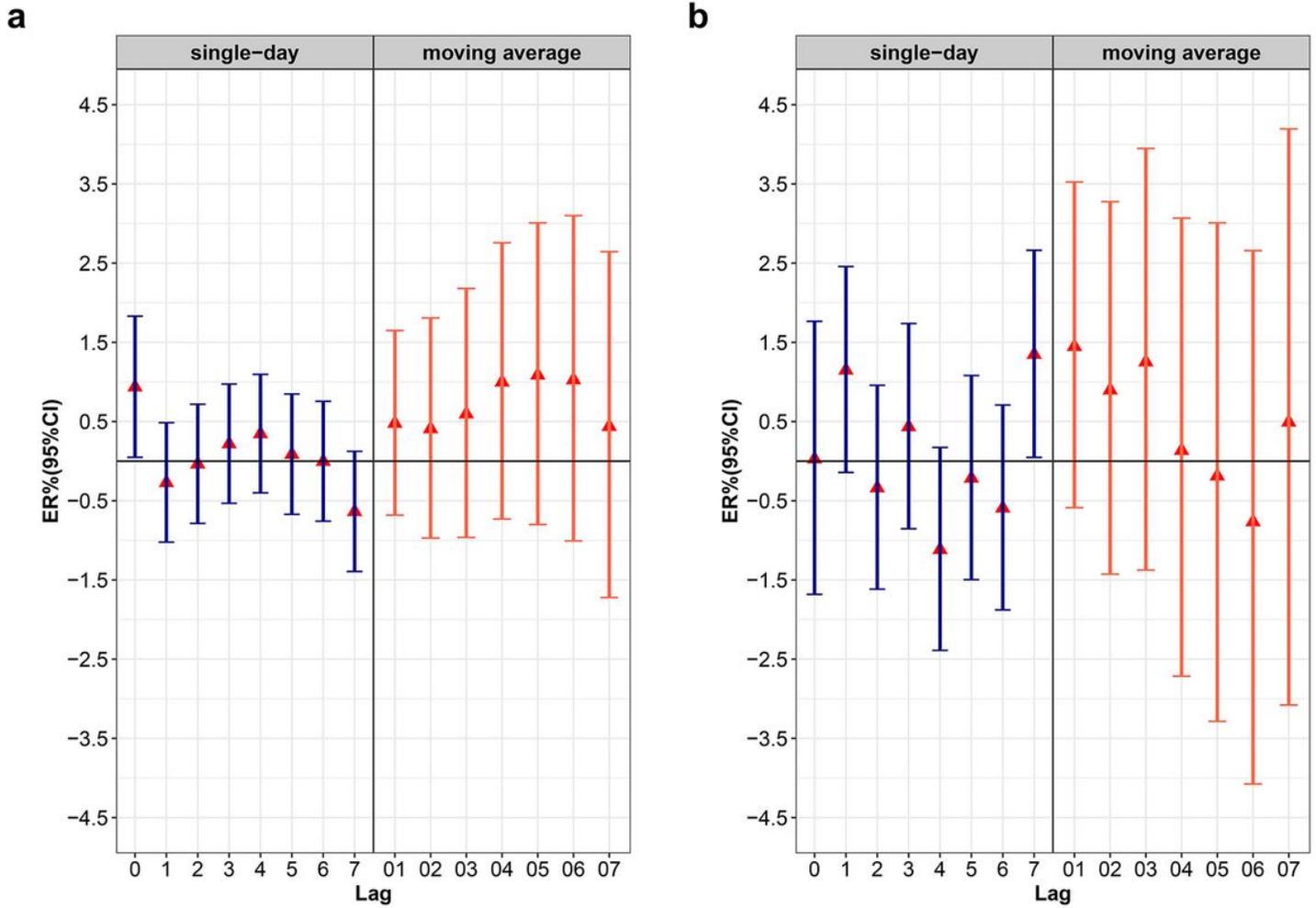
Time-series of pollutants, meteorological factors and daily death counts in Lishui district from 2015 to 2019. (a) Time-series of non-accidental mortality; (b) Time-series of respiratory mortality (c) Time-series of O<sub>3</sub> and PM<sub>2.5</sub>; (d) Time-series of temperature and relative humidity.



TEMP: temperature; RH: relative humidity (\*P<0.05)

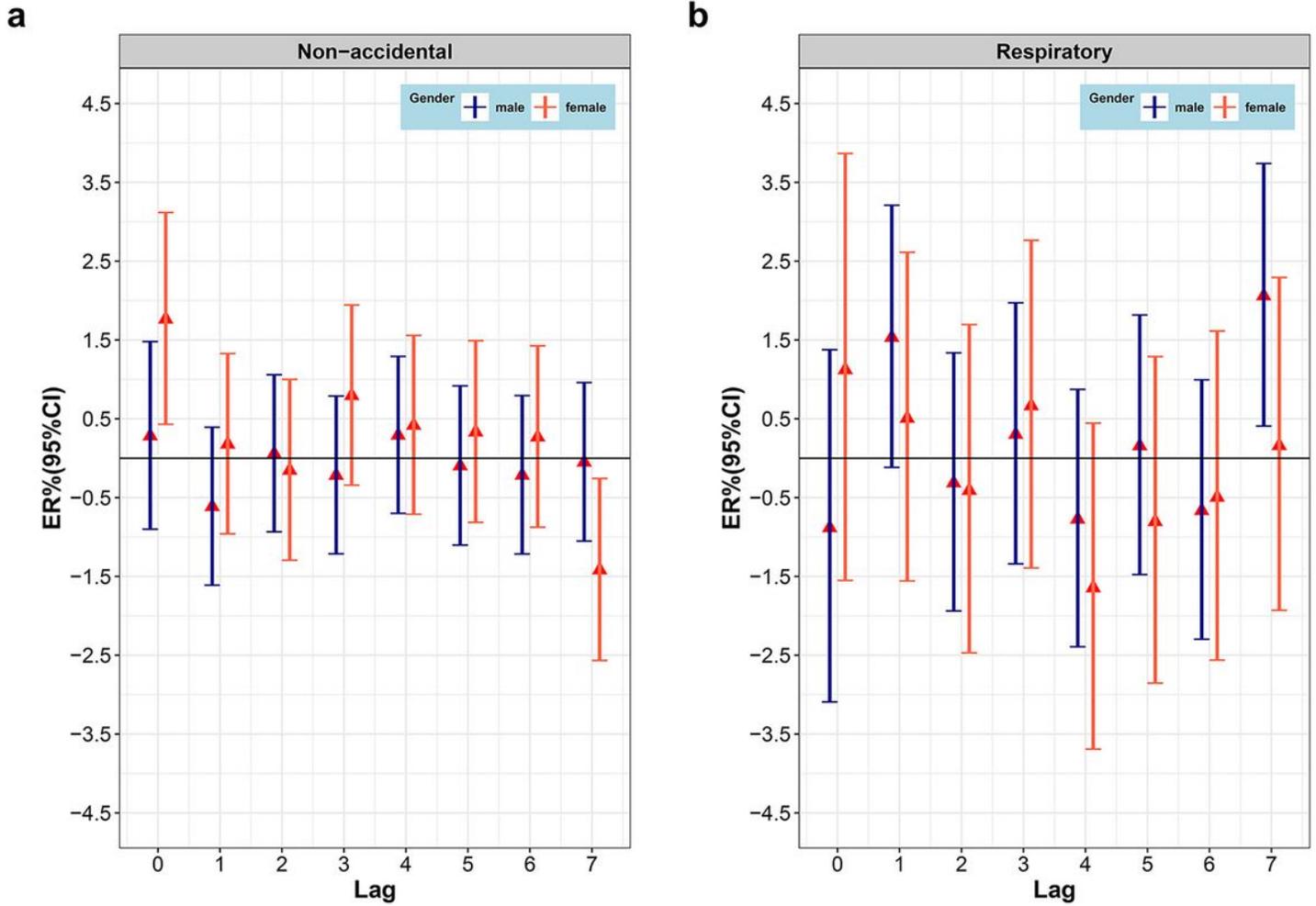
Figure 2

Spearman correlation coefficients between daily air pollutants and meteorological parameters.



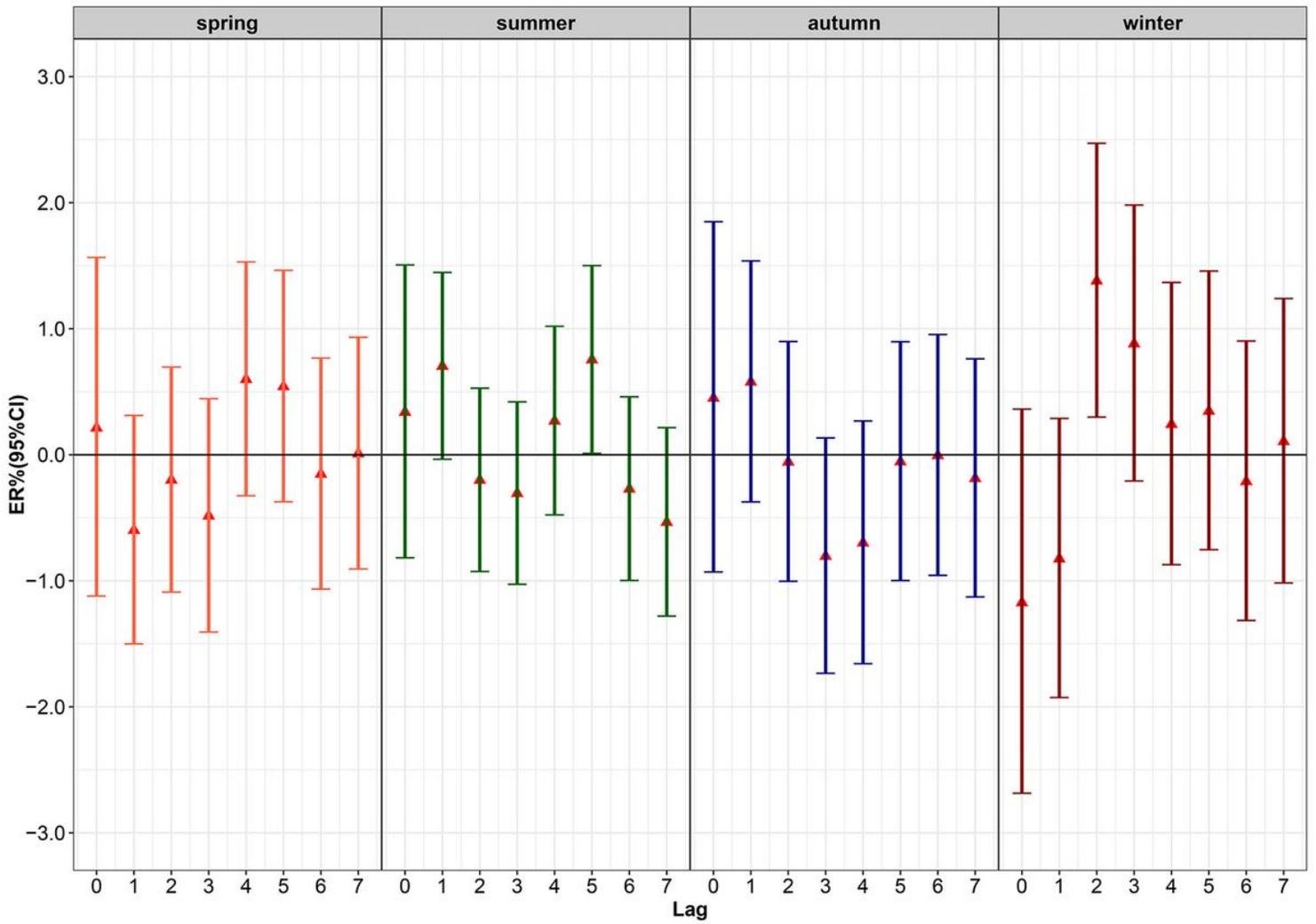
**Figure 3**

The ER (95%CI) associated with 10  $\mu\text{g}/\text{m}^3$  increase of mortality; (a) PM<sub>2.5</sub> led to non-accidental mortality;(b) O<sub>3</sub> led to respiratory mortality.



**Figure 4**

The ER (95%CI) in gender lag-response relationship associated with 10  $\mu\text{g}/\text{m}^3$  increase of mortality; (a) PM<sub>2.5</sub> led to non-accidental mortality; (b) O<sub>3</sub> led to respiratory mortality.



**Figure 5**

The ER (95%CI) in season lag-response relationship associated with 10  $\mu\text{g}/\text{m}^3$  increase of O<sub>3</sub> led to non-accidental mortality.