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# The Effects of Air Pollutants on Mortality in the Elderly at Different Ages: A Case of the Prefecture with Most Serious Aging in China

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**Abstract:** The elderly population is the main group sensitive to air pollution; however, the risks of multiple air pollutants on the elderly at different ages are not very clear. For this study, daily concentrations of five major air pollutants ($PM_{10}$, $NO_2$, $SO_2$, CO, and $O_3$) and daily mortality information of 173,537 people who died between 2014 to 2017 in Nantong, a prefecture with the most serious aging rate in China in 2000, 2010, and 2020, were collected; the aging people were divided into 2–6 groups according to age. A generalized additive model with a thin-plate spline function was used to study the exposure–response relationship, the excess risk, and the lag period of various pollutants on each group of the elderly, and the synergistic effect between these pollutants and temperature was demonstrated. The results revealed that, after controlling confounding factors such as temperature, humidity, and wind speed, the lag period and relative risk of most pollutants increased with age, and the adverse effect of air pollutants on the elderly lasted for 2–3 days. Among the pollutants, $NO_2$, $SO_2$, CO, and $O_3$ had a longer lag period compared with $PM_{10}$. Linear and non-linear exposure–response relationships were observed between the pollutants and mortality. Women were at higher risk than men for the same pollutant concentrations. Synergistic effects were observed between the five pollutants and temperature. This study could contribute to the formulation of a strategy to mitigate the effects of air pollution on the elderly at different ages and play a positive role in reducing the negative impact of air pollution on aging societies.

**Keywords:** air pollutants; mortality risk; independent effects; synergistic effects; elderly



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## 1. Introduction

Air pollution (mainly including fine particulate matter ($PM_{2.5}$), particulate matter with particle size below 10 microns ($PM_{10}$), carbon monoxide (CO), nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$), and ozone ($O_3$)) is the main environmental risk factor for circulatory system and respiratory system diseases and is one kind of high-risk factor for global death [1–3]. In 2017, 1.2 million people died due to air pollution in China [4]. Global Disease Burden (GDB) 2019 showed that air pollution had become the fourth risk factor for both sexes, all ages, and all causes of death in the world and China (https://vizhub.healthdata.org/gbd-compare/, accessed on 3 March 2023). Studies in over 200 cities in China within three years found that the risk of death from cardiovascular disease increased by 0.7%, 0.9%, 0.27%, 0.27%, and 1.12%, respectively, with every 10 $\mu g/m^3$ increase in $SO_2$, $O_3$, $PM_{2.5}$, and $NO_2$, and every 1 $mg/m^3$ increase in CO [5–9]. A study among over 0.9 million diabetes deaths in China found that the risks of diabetes mortality increased by 2.81%, 1.92%, 3.96%, and 2.15%, respectively, with every 25% increment in $PM_{2.5}$, $PM_{2.5–10}$, $NO_2$, and $O_3$ concentrations [10]. A positive interactive association was found between air pollutants; a study reported a higher joint effect of $PM_{2.5}$ and $O_3$ on the risk of preterm birth [11]. Another study found a significant synergistic interaction between $PM_{2.5}$ and $O_3$ for total mortality [12].

Air pollution is particularly dangerous for aging people. According to GDB 2019, air pollution caused 438,868 (95% CI: 372,261–522,617) and 703,794 (95% CI: 590,020–817,063) cardiovascular disease deaths in China at 0–69 and 70+ years, respectively (https://vizhub.healthdata.org/gbd-compare/, accessed on 3 March 2023). A long-term cohort study of the elderly (aged 65 and above) in Hong Kong, China, found that with every 10 μg/m$^3$ increase in $PM_{2.5}$, the risk of all-cause and cardiovascular mortality increased by 14% and 22%, respectively [13]. Elderly people were particularly vulnerable to short- and long-term exposure to particulate matter [14–17]. In Beijing, China, the risk of a 25% increase in $PM_{2.5}$ was associated with a 1.81% increase in cardiovascular mortality in younger individuals and a 3.60% increase in the elderly [18]. Nationwide studies in China found that the associations between $PM_{2.5}$ and daily cause-specific mortality were stronger for the elderly [19,20].

Among the effects of the six above mentioned pollutants on the elderly, $PM_{2.5}$ has been the subject of widespread study; however, studies have rarely focused on the health effects of the other five pollutants on elderly populations. Age- and gender-related factors of the risk, lag period, and synergistic effects of the other five air pollutants on the elderly are not very clear. Therefore, the objectives of this paper are as follows: (1) to assess the excess risk, exposure–response relationship, and lag period of $PM_{10}$, CO, $NO_2$, $SO_2$, and $O_3$ for the elderly population in each age sub-group, consisting of both males and females; (2) to explore the synergistic effects between five air pollutants and temperature on the elderly.

## 2. Materials and Methods

### 2.1. Study Area

Nantong (121° E, 32° N) is an industrial prefecture with a population of 7.72 million in eastern China along the Yellow Sea and the north bank of the Yangtze River estuary; the yearly average temperature in Nantong is 16 °C, and the average elevation in Nantong is 3–5 m. According to the latest three population censuses (http://www.stats.gov.cn/tjsj/pcsj/, accessed on 15 January 2023), the proportion of the total population over 65 years in Nantong in 2000, 2010, and 2020 was 12.44%, 16.50%, and 22.67%, respectively. These results ranked highest among 340 prefectures in China. The 80+ percentage (the proportion of the total population over 80 years) in Nantong in 2000, 2010, and 2020 was 2.27%, 3.65%, and 5.15%, which also ranked first among 340 prefectures in China. Nantong is currently a super-aging society (according to international convention, an aging rate >21% represents a super-aging society). Furthermore, Nantong is located in the core area of the Yangtze River Delta, with a developed manufacturing industry. According to research by the National Climate Center of China, the Yangtze River Delta is one of the four major "smog belts" in China. An in-depth study of the air pollution–aging health in areas with serious air pollution and high aging rates could provide a reference for aging healthcare strategies in aging societies in the future.

### 2.2. Data Collection

We collected the all-cause mortality data of 173,537 people aged between 65 and 104 years from 1 January 2014 to 31 December 2017 from the health commission of Nantong. In order to conduct a sensitivity analysis on the relationship between the risk of air pollution and age, three kinds of age grouping methods were adopted. In the first method, the mortality data of the 173,537 people were divided into two age groups (65–81 and 82–104); in the second method, the data were divided into six age groups (65–72, 73–77, 78–81, 82–85, 86–89, and 90–104) according to the principle that the number of deaths in each group is approximately equal. In the third method, they were divided into four age groups (65–74, 75–79, 80–84, and 85–104), according to international age classifications defined by the WHO. There were 30,621, 26,803, 27,685, 31,472, 28,121, and 28,835 deceased people in groups 65–72, 73–77, 78–81, 82–85, 86–89, and 90–104, respectively. Daily air pollution data, including $PM_{10}$, $SO_2$, $NO_2$, $O_3$-8 h, and CO, were obtained from air pollutant monitoring stations in Nantong. There are five air pollutant monitoring stations in the urban area of Nantong, and the daily average concentration of each air pollutant was calculated by using the data collected from these stations (www.aqistudy.cn, accessed on 23 December 2022). Meteorological data, including wind speed and wind direction, mean temperature, and humidity, were collected through the national meteorological station in Nantong (station number: 58259, http://data.cma.cn, accessed on 23 December 2022).

*2.3. Statistical Analyses*

The study used a two-step model, with the first step investigating the independent effects of five air pollutants. Because daily mortality data approximately follow an over-dispersed Poisson distribution, the generalized additive model (GAM) based on the quasi-Poisson distribution was used to estimate the impact of each air pollutant on mortality in each age group. In the GAM, we used a spline smooth function to control the meteorological factors, such as temperature and humidity. The model is as follows:

$$\mathrm{Log}[\mathrm{E}(Y_t)] = \alpha + \beta Z_t + S(time_t, df = 7) + \sum_{i=1}^{n} S(u_{it}, df = 4) + DOW_t \quad (1)$$

where $Y_t$ is the number of daily deaths on day $t$; $\alpha$ is the intercept of the model; $Z_t$ is the air pollutant on day $t$; $S()$ is the non-parametric spline function; *time* is long-term and seasonality effects that need to be controlled; $u_{it}$ is various confounding factors, e.g., temperature, humidity, wind speed, and wind direction; *df* is the degree of freedom, which is calculated based on the minimized value of the quasi-Akaike information criterion (QAIC); and $DOW_t$ is the day of the week effect.

Several lag models were used to analyze the delayed effects of air pollutants on daily mortality in the elderly, including both single lag days (from lag0 to lag7) and multiple lag days (the average concentration of each air pollutant at the current day and the preceding several days, e.g., lag 0–1, lag 0–2, lag 0–3, until lag 0–7). The average concentration of each pollutant at lag 0–X (the current day and the preceding X-day moving average) was used in this study when the largest effects were observed at lag 0–X.

The second step was to study the synergy effect between each air pollutant and temperature. A non-parametric binary response model was constructed using a thin-plate spline function. The model is as follows:

$$\mathrm{Log}[\mathrm{E}(Y_t)] = \alpha + TS(Z_t, temp) + S(time_t, df = 7) + \sum_{i=1}^{n} S(u_{it}, df = 4) + DOW_t \quad (2)$$

where $Y_t$ refers to the daily deaths; $\alpha$ represents the intercept of the model; $TS()$ denotes the thin-plate spline function, and 3D surface plots were used to show the results of the synergistic effect between each air pollutant and temperature; $Z_t$ is the air pollutant on day t; $S$ is the non-parametric spline function, $u_{it}$ is various confounding factors, e.g., humidity; and $DOW_t$ is the day of the week effect.

The results are presented as the relative risk (RR), excess risk (ER), and their 95% confidence intervals (95% CIs). Data analysis was conducted using R software (version 4.0.2, R Foundation for Statistical Computing Platform). For all statistical tests, a two-tailed $p$-value < 0.05 was considered statistically significant.

## 3. Results

*3.1. Statistical Analyses*

Table 1 shows the statistical characteristics of daily air pollutants and daily mortality from 1 January 2014 to 31 December 2017. According to the global air quality guidelines issued by the World Health Organization [21], the concentrations of $PM_{10}$, $NO_2$, $SO_2$, and CO in 24 h should be lower than 45 μg/m$^3$, 25 μg/m$^3$, 40 μg/m$^3$, and 4 mg/m$^3$, respectively; the maximum 8 h mean concentration of $O_3$ should be lower than 100 μg/m$^3$. Concentrations of $PM_{10}$ (79 μg/m$^3$), $NO_2$ (37 μg/m$^3$), and $O_3$ (108 μg/m$^3$) in Nantong were 76%, 48%, and 8% higher than the WHO daily average standards. Fluctuation in daily mortality increases with age; with increasing age, the elderly are more likely to die in heavily polluted weather and extreme climate conditions. The comparison of daily mortality between groups is illustrated in Figure 1.

**Table 1.** Descriptive statistics of daily air pollutants and daily mortality in Nantong, 2014–2017.

| Air Pollutant | $\bar{X} \pm S$ | Percentile | | | | | Age | $\bar{X} \pm S$ | Percentile | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $P_5$ | $P_{25}$ | $P_{50}$ | $P_{75}$ | $P_{95}$ | | | $P_5$ | $P_{25}$ | $P_{50}$ | $P_{75}$ | $P_{95}$ |
| $PM_{2.5}$ (μg/m$^3$) | 50.80 ± 32.64 | 15 | 28 | 43 | 64 | 113 | 65–72 | 21.0 ± 6.2 | 12 | 17 | 20 | 25 | 32 |
| $PM_{10}$ (μg/m$^3$) | 78.89 ± 45.39 | 27 | 46 | 68 | 100 | 168 | 73–77 | 18.3 ± 5.6 | 10 | 14 | 18 | 22 | 28 |
| $NO_2$ (μg/m$^3$) | 36.52 ± 20.40 | 12 | 21 | 32 | 47 | 77 | 78–81 | 18.9 ± 6.1 | 11 | 15 | 18 | 23 | 30 |
| $SO_2$ (μg/m$^3$) | 25.56 ± 14.85 | 10 | 16 | 22 | 32 | 55 | 82–85 | 21.5 ± 7.1 | 12 | 16 | 21 | 26 | 35 |
| CO (mg/m$^3$) | 0.789 ± 0.310 | 0.4 | 0.6 | 0.7 | 1 | 1.4 | 86–89 | 19.2 ± 7.1 | 10 | 14 | 18 | 23 | 32 |
| $O_3$ (μg/m$^3$) | 108.2 ± 45.36 | 48 | 76 | 101 | 131 | 201 | 90+ | 19.7 ± 7.7 | 9 | 14 | 18 | 24 | 35 |

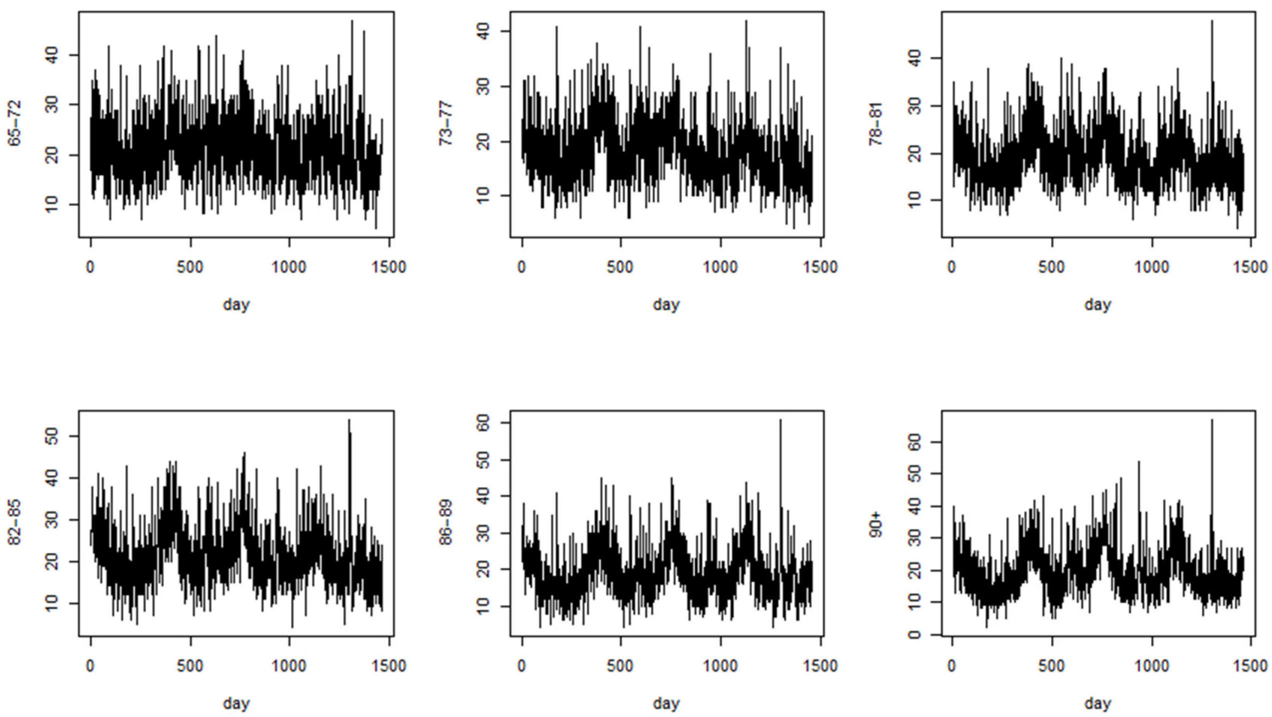


**Figure 1.** Comparison of time series of death between different age groups.

Figure 2 shows the Spearman's correlation coefficients between pollutants and meteorological factors. $PM_{2.5}$, $PM_{10}$, $NO_2$, $SO_2$, and CO were positively correlated with each other ($p < 0.01$) and negatively corrected with temperature and humidity; $O_3$ was not correlated with other air pollutants. The concentration of $O_3$ was higher in summer than in winter, but the other five pollutants were higher in winter than in summer.

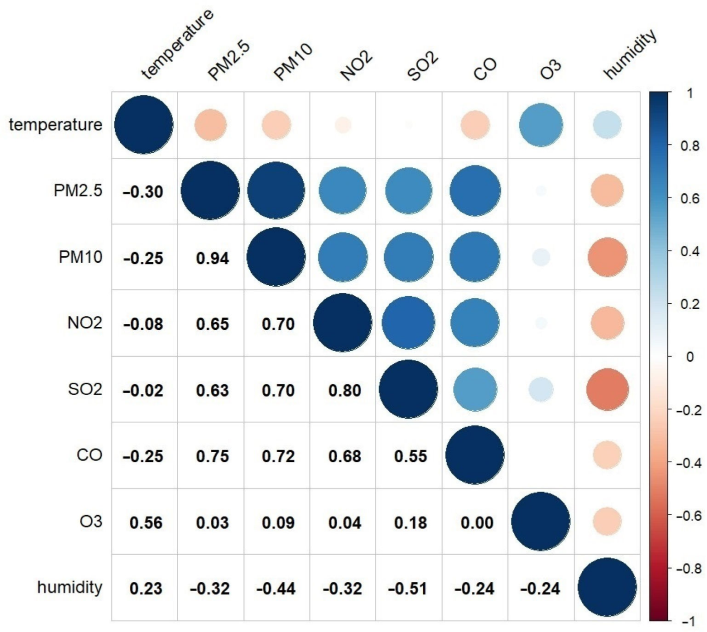


**Figure 2.** Spearman's correlation coefficients between the meteorological factors in Nantong, 2014–2017.

### 3.2. *Effects of Single Air Pollutants*

Figure 3 depicts the mortality risk for each age at lag 0, 1, 2, 3, 0–1, 0–2, and 0–3 days. The impact of five pollutants on different ages all showed both a single-day effect and a cumulative delay effect. Generally, the single-day effect was detected at lag 0 days and showed a decreasing trend; the most significant positive correlation appeared at lag 0 days for most ages, while the cumulative delay effect showed an increasing trend; and the most significant positive correlation appeared at lag 0–3 days for most ages. Among the five pollutants, $SO_2$ had the longest optimal lag period, followed by CO, $NO_2$, $O_3$, and $PM_{10}$. For group 65–72, the most significant positive relationship was observed at lag 0–2 days, while for the other four age groups, the most significant positive relationship was observed at lag 0–3 days; especially in groups 82–85 and 86–89, the oldest elderly would suffer from the effects of air pollution incidents longer. Generally, the risk of air pollutants was positively associated with age, concentration, and period of exposure.

Figure 4 summarizes the gender-specific and age-specific analysis at different lag periods. In order to test the sensitivity and robustness of our results, a different rule was used to define age groups in this part: males and females were divided into four groups (65–74, 75–79, 80–84, and 85–104). In males, we found significant positive associations with the pollutants as follows: $PM_{10}$ for the 65–74 group at lag 0 and lag 0–1; $PM_{10}$ for the above-75 group at lag 0, lag 0–1, and lag 0–2; and $NO_2$, $SO_2$, and CO for all age groups at lag 0, lag 0–1, and lag 0–2. No associations between $O_3$ and males were detected. For females, statistically significant associations with the pollutants were observed as follows: $PM_{10}$ for the 65–79 group at lag 0 and lag 0–1; $PM_{10}$ for the 80–84 group at lag 0, lag 0–1, and lag 0–2; $PM_{10}$ for the 85+ group at lag 0, lag 0–1, lag 0–2, and lag 0–3; $NO_2$, $SO_2$, and CO for the 65–84 group at lag 0, lag 0–1, and lag 0–2; and $NO_2$, $SO_2$, and CO for the 85+ group at lag 0, lag 0–1, lag 0–2, and lag 0–3. No significant associations between $O_3$ and females for death were detected. In addition, we observed different risks and lag periods between males and females in each age group: for the above four pollutants at age 65–74, females suffered more at lag 0, while males suffered more at lag 0–1 and lag 0–2. At age 75+, females seemed more vulnerable to CO, $NO_2$, $SO_2$, and $PM_{10}$. Therefore, females suffered more than males on most lag days and in most groups.

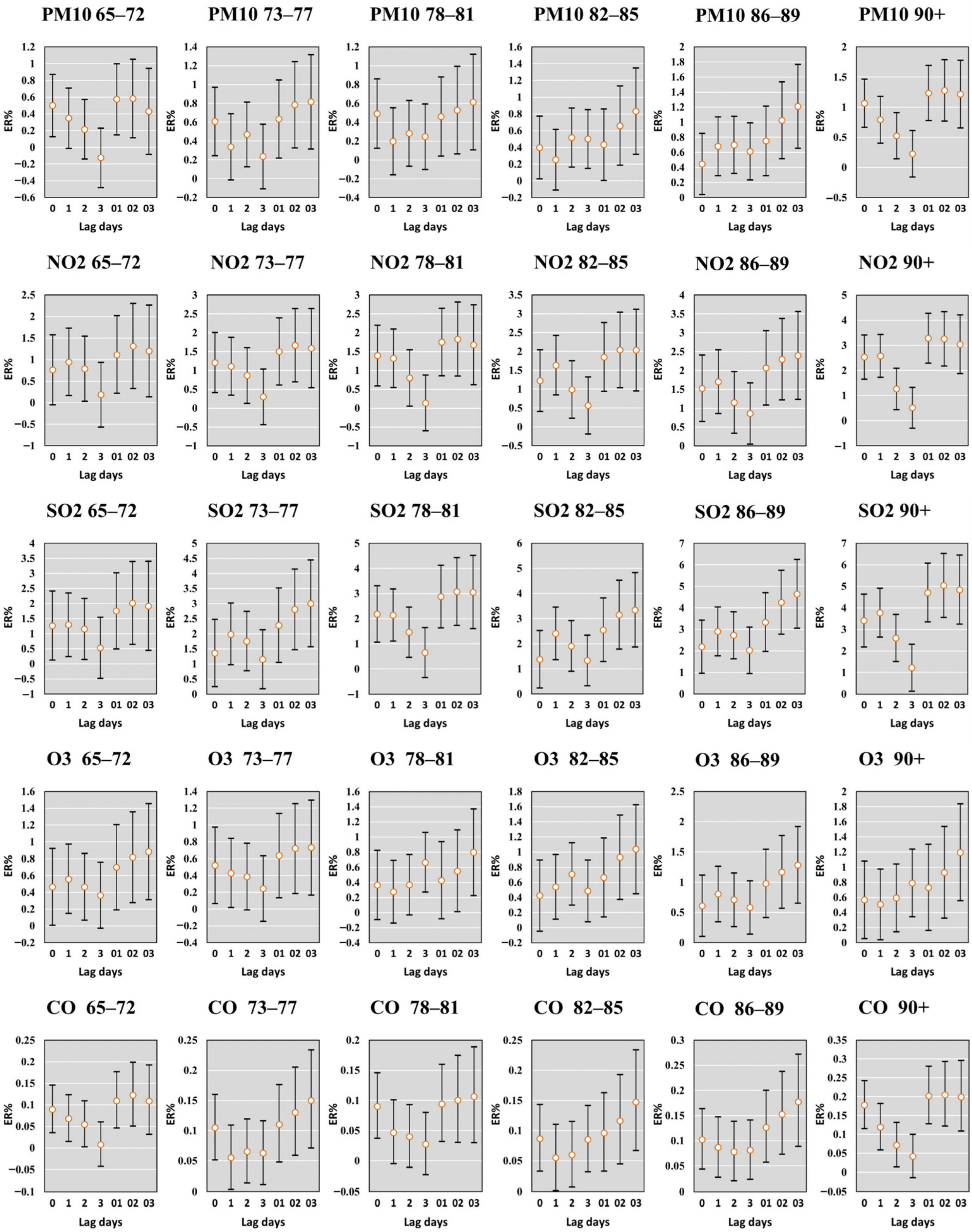


**Figure 3.** Percent increase (95% CI) in daily mortality for the elderly associated with an increase of 10 μg/m$^3$ in air pollutants (0.1 mg/m$^3$ in CO) at different lag days.

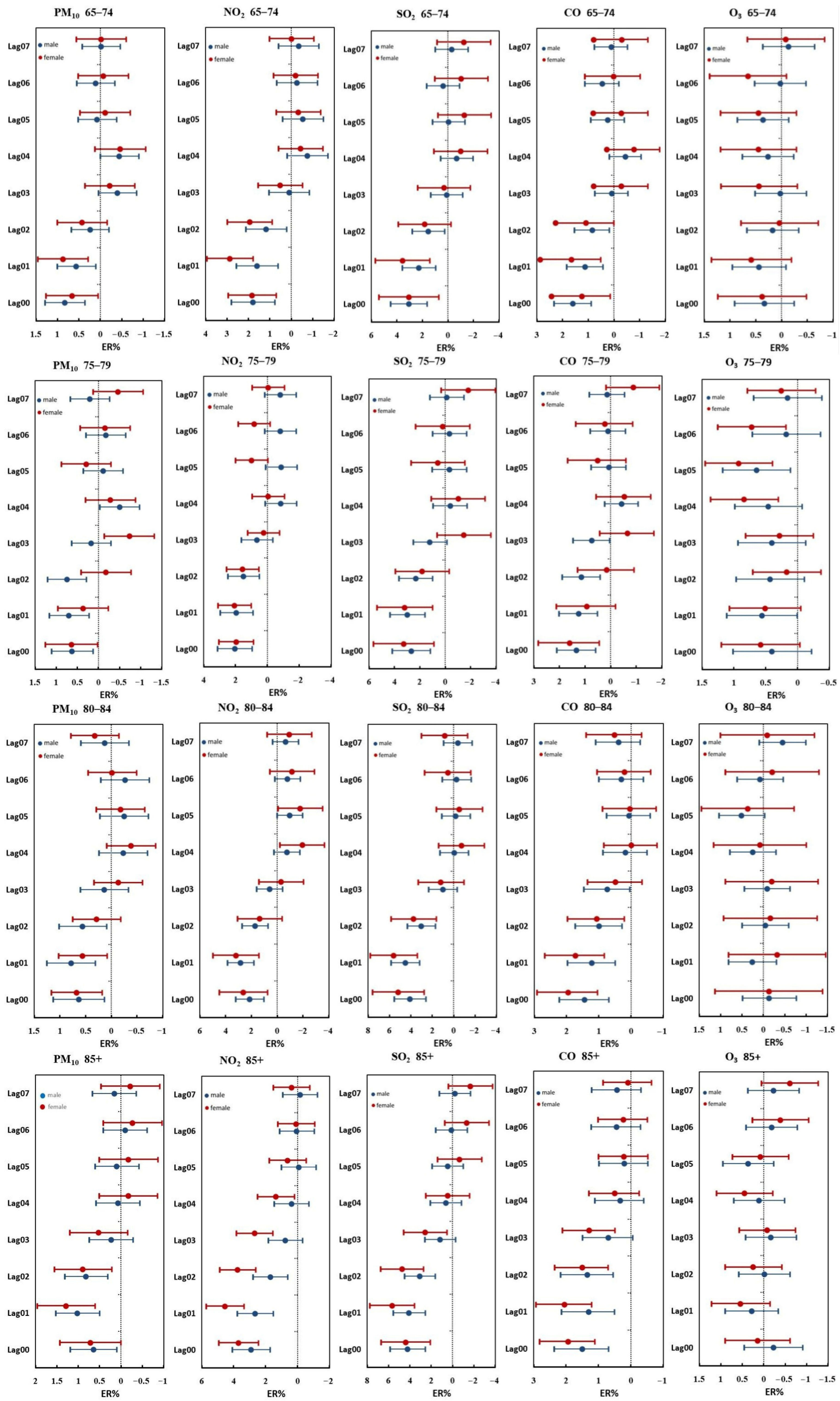


**Figure 4.** Percent increase (95% CI) in daily death for residents associated with an increase of 10 μg/m$^3$ in air pollutants (0.1 mg/m$^3$ in CO) at different lag days by gender and age.

Figure 5 shows the concentration–response relationship curves between air pollutants and daily mortality at lag 0–3 for ages 65–81 and 82–104. The curves of $SO_2$ and CO were linear while the curves of $PM_{10}$, $NO_2$, and $O_3$ were nearly S-shaped. For all the five air pollutants, the age group 82–104 was particularly vulnerable compared with the age group 65–81. For the younger of the elderly, the relative risk of $PM_{10}$ and $SO_2$ was less than 1.2, even at the highest dose, but higher than 1.2 for the older of the elderly. The relative risk of $NO_2$ for the younger elderly rose from 1.0 to 1.1 when the concentration was at 0–100 $\mu g/m^3$, while the relative risk for the older elderly rose from 1.0 to nearly 1.2 at the same concentration range. The relative risk of CO was also higher for the older elderly than the younger elderly.

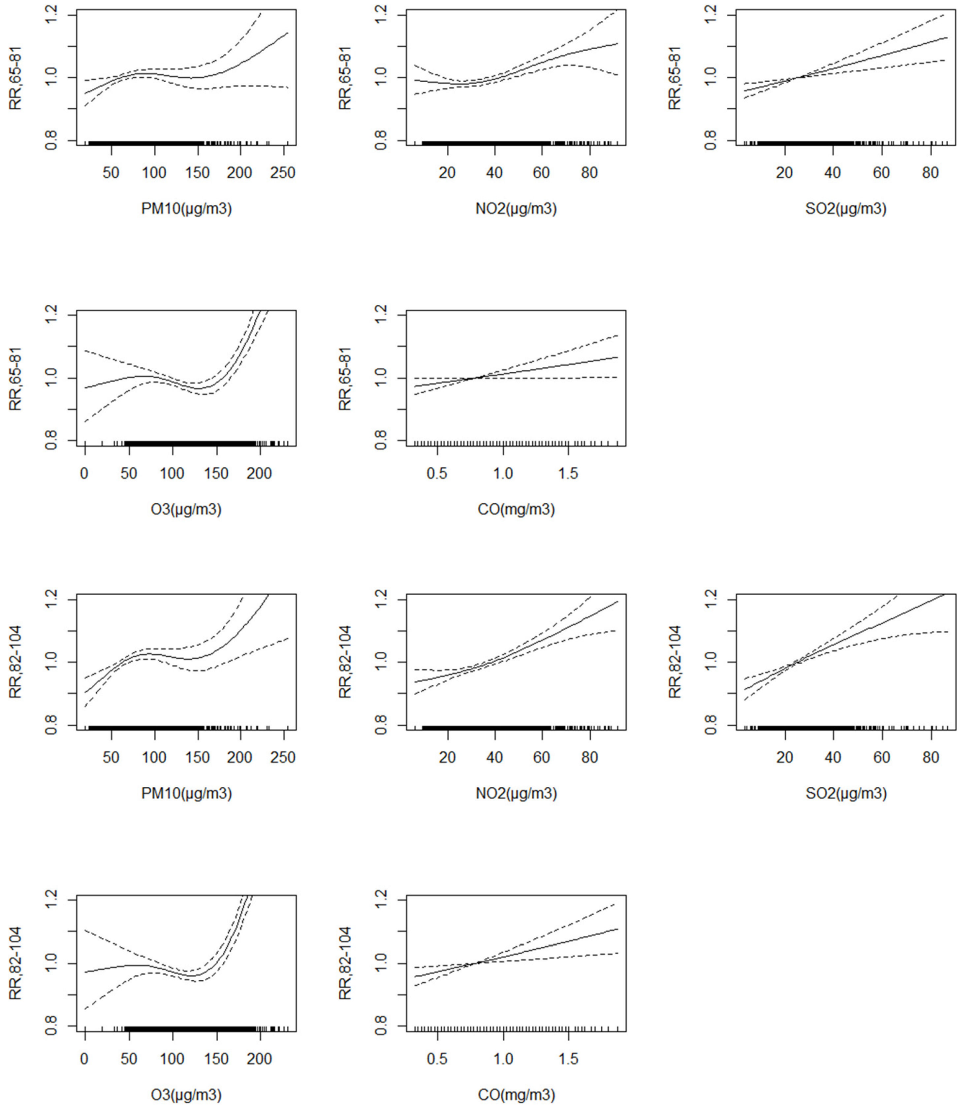


**Figure 5.** The exposure–response relationship curves between air pollutants and daily mortality at ages 65–81 and 82–104. The dashed line denotes the 95% confidence interval.

Table 2 shows the risk of single pollutants at the respective optimal lag days (0–2 days or 0–3 days). Generally, excess risk of each air pollutant increased with age except $O_3$; for instance, every 10 $\mu g/m^3$ increase in $PM_{10}$ was associated with an 0.572% (95% CI, 0.148%, 0.998%), 0.632 (95% CI, 0.219%, 1.048%), 0.458 (95% CI, 0.039%, 0.879%), 0.433 (95% CI, 0.006%, 0.862%), 1.329% (95% CI, 0.689%, 1.973%), and 1.217 (95% CI, 0.659%, 1.778%) increase in all-cause mortality at ages 65–72, 73–77, 78–81, 82–85, 86–90, and 90+, respectively.

**Table 2.** All-cause excess mortality risk due to changes in different pollutants under optimal lag period.

| Pollutant | | 65–72 | 73–77 | 78–81 | 82–85 | 86–89 | 90+ |
|---|---|---|---|---|---|---|---|
| $PM_{10}$ 10 μg/m$^3$ | ER (%) | 0.572 | 0.632 | 0.458 | 0.433 | 1.329 | 1.217 |
| | 95% CI (%) | 0.148–0.998 | 0.219–1.048 | 0.039–0.879 | 0.006–0.862 | 0.689–1.973 | 0.659–1.778 |
| | *p* | 0.009 ** | 0.003 ** | 0.033 * | 0.048 * | 0.000 *** | 0.000 *** |
| $NO_2$ 10 μg/m$^3$ | ER (%) | 0.758 | 1.587 | 1.677 | 2.029 | 2.433 | 3.038 |
| | 95% CI (%) | −0.049–1.572 | 0.542–2.642 | 0.622–2.743 | 0.953–3.117 | 1.191–3.690 | 1.872–4.217 |
| | *p* | 0.067 | 0.003 ** | 0.002 ** | 0.000 *** | 0.000 *** | 0.000 *** |
| $SO_2$ 10 μg/m$^3$ | ER (%) | 1.914 | 3.174 | 3.408 | 3.008 | 4.765 | 4.800 |
| | 95% CI (%) | 0.455–3.405 | 1.644–4.727 | 1.602–4.515 | 1.473–4.604 | 2.963–6.599 | 3.093–6.535 |
| | *p* | 0.011 * | 0.000 *** | 0.000 *** | 0.000 *** | 0.000 *** | 0.000 *** |
| CO 0.1 mg/m$^3$ | ER (%) | 1.090 | 1.501 | 0.940 | 1.462 | 1.938 | 1.989 |
| | 95% CI (%) | 0.315–1.922 | 0.661–2.408 | 0.320–1.598 | 0.601–2.392 | 0.925–3.044 | 1.089–2.962 |
| | *p* | 0.005 ** | 0.000 *** | 0.003 ** | 0.001 *** | 0.000 *** | 0.000 *** |
| $O_3$ 10 μg/m$^3$ | ER (%) | 0.883 | 0.719 | 0.363 | 0.423 | 1.370 | 0.448 |
| | 95% CI (%) | 0.314–1.455 | 0.185–1.255 | −0.094–0.822 | −0.047–0.896 | 0.684–2.602 | −0.003–0.902 |
| | *p* | 0.002 ** | 0.009 ** | 0.122 | 0.080. | 0.000 *** | 0.053 |

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. The optimal lag period means the largest effects were observed at lag 0–X.

### *3.3. Synergy Effect with Temperature*

Figure 6 depicts the synergy effect between $PM_{10}$, $NO_2$, $SO_2$, CO, and $O_3$ and daily temperature. The number of deaths calculated from each pollutant and temperature are shown on the *Z*-axis. There was a significant J-shaped relationship between mortality and temperature, and a linear relationship between mortality and air pollutants except $O_3$; the minimum mortality temperature was 20–22 °C. Mortality risk of the elderly varied between pollutants, indicating a synergistic effect between temperature and pollutants on mortality risk.

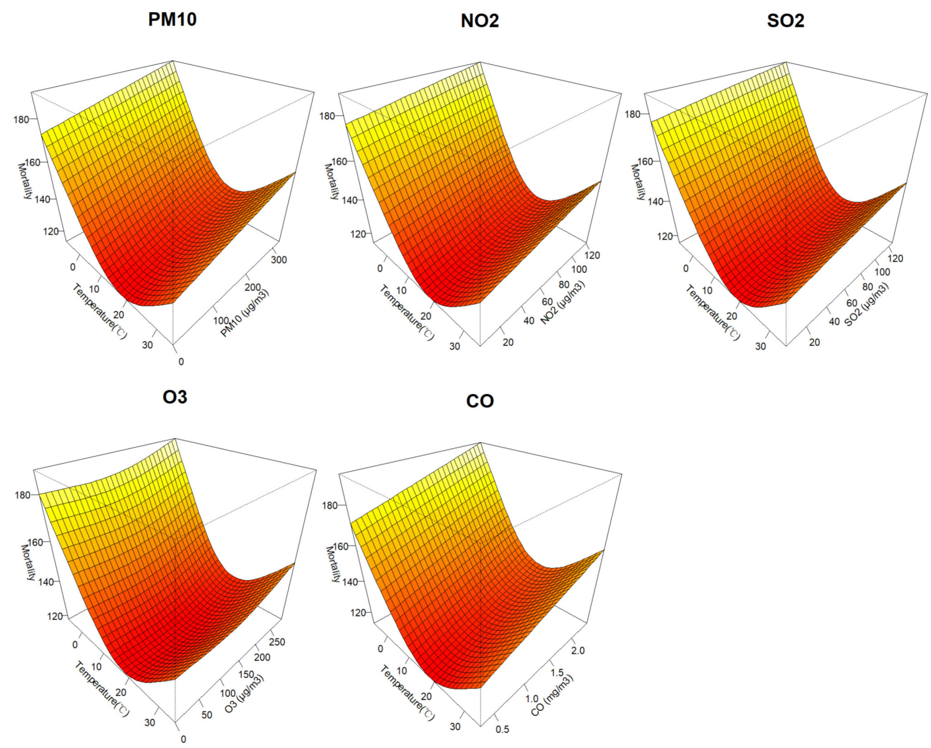


**Figure 6.** Bivariate response surfaces of mean temperature and five air pollutants for elderly people.

## 4. Discussion

Air pollution has been shown to initiate chronic illnesses related to cardiometabolic syndrome [22–24]. Compared with young and middle-aged populations, air pollution can influence elderly populations by increasing the mortality rate and by delaying the recovery rate [25]. China has the largest aging population in the world and has been a middle-aging society since 2021. There are 200.56 million people over 65 years old in China, accounting for 14.2% of the total population (http://www.stats.gov.cn/sj/ndsj/2022/indexch.htm, accessed on 1 December 2022). According to China's health statistics yearbook, circulatory system and respiratory system diseases are the first and third main causes of death for the elderly; about 50% and 12% of the elderly population in China died from circulatory system diseases and respiratory system diseases in recent years. Experimental evidence has revealed that air pollution has the potential to cause cell death and related diseases such as ischemic heart disease [26]. Therefore, air pollution has a greater impact on cardiovascular, cerebrovascular, and respiratory system diseases of the elderly, and with the increase in the aging rate, the disease burden caused by air pollution will become more severe.

In this study, the risk of $PM_{10}$ was relatively low compared with that of other pollutants; every 10 $\mu g/m^3$ increase in $PM_{10}$ was associated with a 0.774% increase in all-cause mortality in the 65+ group. Studies have shown that in elderly residents of 21 US cities, every 10 $\mu g/m^3$ increase in ambient $PM_{10}$ was associated with a 0.65% increase in hospitalization for myocardial infarction (MI) [27]. In southwestern China, stronger and more significant effects of $PM_{10}$ on hospital admissions for total cardiovascular diseases were observed in the elderly (aged above 65 years old) [28]. Studies in European countries showed an association between $PM_{10}$ exposure and lung cancer. In highly polluted areas in Italy, a 10 $\mu g/m^3$ $PM_{10}$ increase was associated with a 1.09% (95% CI: 1.04, 1.14) increase in lung cancer [29,30].

We found that the risk of $NO_2$ increased with age growth. When the concentration of $NO_2$ increased by 10 $\mu g/m^3$, the risk of mortality for those aged 65–72, 73–77, 78–81, 82–85, 86–89, and over 90 years old increased by 0.758%, 1.587%, 1.677%, 2.029%, 2.433%, and 3.038%, respectively. Although there were no studies about the age-specific health risks of $NO_2$ for the elderly available during our research, the results from different countries were consistent with this study in terms of the risk of $NO_2$. When the concentration of $NO_2$ increased by 10 $\mu g/m^3$, the risk of respiratory hospital admissions increased by 1.6% [31], and the corresponding daily cardiovascular mortality increased by 1.63% (95% CI: 1.11%, 2.13%) in Beijing, China [32]. In another study on non-accidental mortality in Civitavecchia, Italy, an association was found between NOx exposure with cancers (HR = 1.13, 95% CI: 1.01%, 1.26%) and neurological diseases (HR = 1.50, 95% CI: 1.01%, 2.20%) [33].

From 2014 to 2017, the average daily concentration of $SO_2$ in Nantong was lower than the national standard and the WHO standard, but its risk was relatively high. A 10 $\mu g/m^3$ increase in $SO_2$ was associated with significant 1.914%, 3.174%, 3.408%, 3.008%, 4.765%, and 4.800% increases in the risk of mortality in the six age groups, respectively. Previous studies also showed that a 10 $\mu g/m^3$ increase in $SO_2$ concentration was associated with a 2.1% (0.7–3.5%) increase in the risk of COPD-related emergency department and hospital admissions in India [34]. In Lanzhou, China, the association of hospital emergency visits with $SO_2$ (10.607% (95% CI: 5.819, 15.611)) was observed at lag 07 for an increase of 10 $\mu g/m^3$ in concentrations of the pollutant [35]. A study in Guangzhou, China, found that previous-day $SO_2$ concentrations were associated with a significant increase of 4.89% (95% CI: 2.86%, 6.95%) in neurologic emergency department visits [36]. The results of our study were lower than those in Lanzhou but higher than those in India, and they were similar to the results in Guangzhou. Although concentrations of $SO_2$ in three cities of China were all lower than the national standard (25.56 $\mu g/m^3$ in Nantong, 18.66 $\mu g/m^3$ in Guangzhou, and 21.81 $\mu g/m^3$ in Lanzhou), a relatively higher risk of $SO_2$ was observed among pollutants in these cities. These consistencies and inconsistencies may be caused by variations in age, type of diseases, and population susceptibility; for instance, the similarity between Nantong and Guangzhou may be a result of the similar climate and topography.

The association between CO and mortality or disease varies in different studies. In China, a nationwide study of 272 cities found that a 1 mg/m$^3$ increase in the average daily concentration of CO on lag 0–1 days caused a 1.12% (95% posterior interval of 0.42–1.83%) increase in cardiovascular disease, 1.75% (0.85–2.66%) increase in coronary heart disease, and 0.88% (0.07–1.69%) increase in stroke [7]. A study in Hefei, China, showed a 0.498% increase in the risk of upper respiratory tract infection for a 1 mg/m$^3$ increase in CO concentration [37]. CO is a serious issue, but as of now, no study has analyzed its effects on the elderly at different ages.

The independent effect of $O_3$ in this paper showed that for every 10 µg/m$^3$ increase in its concentration, the risk of mortality in age groups 65–72, 73–77, 78–81, 82–85, 86–89, and 90–104 increased by 0.883%, 0.719%, 0.363%, 0.423%, 1.370%, and 0.448%, respectively. A nationwide time-series analysis of 272 representative cities in China found that every 10 µg/m$^3$ increase in $O_3$ concentration was associated with 0.27% (95% PI: 0.10%, 0.44%) higher daily mortality from all non-accidental causes [9]. The association curves in Taiwan, Korea, Japan, and 272 Chinese cities all showed increased mortality with elevated $O_3$ [38,39]. For a 10 µg/m$^3$ increase in $O_3$ exposure, pooled effects on non-accidental mortality on low- and high-temperature days were increased by 0.48% (95% CI: 0.28%, 0.69%) and 0.47% (95% CI: 0.32%, 0.63%), respectively [40]. The concentrations of other air pollutants have been continuously declining in China since 2017, except for $O_3$. $O_3$ has become the primary air pollutant in China, and the mechanism of $O_3$ in the human body still requires further study.

The male–female difference in the effects of air pollutants remains controversial. For example, a study in Canada found a longer association between chronic obstructive pulmonary disease with $SO_2$ in males than in females [41]. Another study in 11 districts of three northeastern Chinese cities concluded that the association between exposure to $PM_{10}$ and $SO_2$ and increased stroke prevalence was more apparent in men than in women [42]. Moreover, researchers in Wuhan and Lanzhou, China, showed that $SO_2$ and $NO_2$ had a greater impact on upper respiratory tract infection visits in females than in males [35,43]. A nationwide study in China observed a higher risk of PM2.5 in females [5]. We found that, in general, females were more sensitive to air pollutants and more susceptible to the effects of pollutants in Nantong. The reasons for the differences between studies may be due to geographical differences, gender-linked biological patterns, etc., but the specific reasons still need to be further explored. In addition, Nantong is the region with the most serious aging in China, which leads to a lower male–female ratio. The increasing life expectancy has increased the gap in life expectancy between males and females, which raises the exposure and vulnerability of females in old age.

Given the low awareness of air-pollution-related risks among the elderly, the following are suggested: In order to further extend the lifespan of the elderly, it is necessary to actively respond to risk factors in the atmospheric environment. The government (health department, aging office, environment department, meteorological administration, and industry bureau) should not only take actions to continuously reduce pollutant emissions but also enhance elderly residents' awareness of air pollutants. For instance, most of the elderly in China do not have the experience of college education and are not aware of the health risks of air pollutants. Therefore, it is the government's duty to forecast air pollution and remind the elderly to reduce outdoor activities according to the risk and lag period of each air pollutant, especially for the oldest elderly who have longer lag days affected by air pollutants, according to our results. Temperature also plays an interaction effect with air pollutants on the elderly, which is in accordance with previous studies [19,39,40]. The concentrations of most of the pollutants ($PM_{10}$, CO, $SO_2$, and $NO_2$) are higher in winter than in summer in Nantong, and low temperatures also cause more deaths compared with high temperatures; therefore, outside activities for the elderly are more dangerous in winter during heavily polluted weather conditions.

There were some limitations in this study. First, the daily concentration of each pollutant was the average value of monitoring stations, and the emission difference between districts and counties was ignored. Second, the dead population was only divided by age and gender, without considering the factors of living habits and medical history. Third, we only used one prefecture mortality and air pollutant dataset to reflect the air pollution–mortality relationship. The results could not be directly generalized to other places due to a lack of data on different areas. In the future, we will collect more precise air pollutant data (for instance, using handheld pollutant detectors to collect samples in rural areas that lack national monitoring stations) to mitigate errors.

## 5. Conclusions

The risk and lag period of the effects of air pollutants on the elderly were positively related to age, as groups of people aged 82+ suffered more than groups of individuals aged 65–81. The adverse effect of air pollutants on the elderly can last 2–3 days, but it varies between males and females, among ages, and among types of air pollutants. Linear and non-linear concentration–response relationship curves were observed between air pollutants and daily mortality. Gender may have a potential effect on the association between air pollution and death. There were synergistic effects between the five pollutants and temperature. The results of this study can benefit the government in terms of managing the effects of air pollutants on the elderly population. Furthermore, the elderly should take action to mitigate the adverse effects of air pollutants.

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**Institutional Review Board Statement:** The mortality data used are not from a publicly accessible database. The mortality data were provided by the health commission of Nantong. All methods were carried out in accordance with relevant guidelines and regulations. All experimental protocols were approved by the Nantong University Ethics Committee. Informed consent was obtained from all subjects and/or their legal guardians.

**Informed Consent Statement:** Air pollution and meteorological data can be accessed publicly (www.aqistudy.cn, http://data.cma.cn, accessed on 23 December 2022). The mortality data are not publicly available (the authors signed a confidentiality agreement; therefore, the mortality data are not publicly available) but are available from the corresponding author upon reasonable request.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to confidentiality requirements of health commission of Nantong.

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