Ambient Ozone Pollution and Daily Mortality in Hohhot, China: A Time-Series Study

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Abstract

Evidence on the effects of ozone on chronic lower respiratory disease (CLRD), acute respiratory infections (ARI) is still not conclusive. This study aimed to investigate the association between them in Hohhot China. Daily death counts, concentrations of PM_{2.5}, PM₁₀, SO₂, NO₂, and O₃, and meteorological data were collected for Hohhot city from January 1, 2018, to December 31, 2019. We performed a time series analysis using generalized additive model (GAM). In single pollutant model, the estimated excess relative risks (EERs) for respiratory and CLRD mortality were 2.815% (95% CI: 0.075–5.630) at lag 04 and 4.409% (95% CI: 1.577–7.320) at lag 01, respectively, for each 10 µg/m³ increase in O₃. No significant association was found for ARI and the other respiratory diseases mortality. Subgroup analysis showed that the respiratory diseases for men were more susceptible to O₃ than women, while men had a lower association with CLRD than women. Concentrations of O₃ were significantly associated with respiratory disease and CLRD for older adults. The significant positive association between O₃ and respiratory mortality and CLRD mortality remained largely unchanged in the two-pollutant model and the multi-pollutant model. In conclusion, short-term exposure to O₃ is significantly associated respiratory diseases and CLRD mortality, and this association is dominated by gender and age.

1. Introduction

Due to the rapid industrialization, urbanization and economic development, air pollutants have become a common global concern that cannot be ignored in recent years. As the largest developing country in Asia, China may face the most serious air pollution problem, which has become a major public health issue (Kan et al. 2012). In China, ambient air pollution is the fourth largest burden of disease in 2020 (Yang et al. 2013). In 2017, 1.24 million people died from air pollution in China, of which 852,000 died from outdoor PM_{2.5} pollutant, 271,000 died from indoor air pollutant from solid fuels, and 178,000 died from ambient ozone pollutant (Yin et al. 2020). With the increase in the number of motor vehicles, the major source of air pollutants in China has gradually shifted from coal combustion to mixed coal motor vehicle or combustion emissions, which is also a major source of ozone (Kan et al. 2009, Wang 2019). Over the past few years, the government has taken many measures to improve air quality in China. It can be seen that the annual average concentrations of PM_{2.5}, PM₁₀ and SO₂ have shown a significant downward trend from 2015 to 2018, while the daily average concentrations of O₃ were increased during the four years (Zhao et al. 2021). It is unclear whether this change affects the relationship between ozone and mortality. Therefore, it is important to explore the association between ozone and health in Hohhot.

There is substantial evidence that short-term exposure to ambient ozone increases the risk of ill health, ranging from sub-health status to mortality, particularly respiratory disease (Srebot et al. 2009, Tian et al. 2018b, Wang et al. 2020a, Zhang et al. 2019a). It is believed that ozone can cause impairment of respiratory system function (Cole-Hunter et al. 2018). Ozone may cause oxidative stress on lung cells by stimulating or presenting the cells to produce inflammatory factors and reactive oxygen species (ROS), which play a major role in lung tissue injury (Michaudel et al. 2018, Mumby et al. 2019, Niu et al. 2018, Sokolowska et al. 2019).

In China, respiratory diseases (RD) contribute to an enormous health-care burden and chronic obstructive pulmonary disease (COPD) is the third leading causes of mortality (Zhu et al. 2018). Previous cohort and case-crossover studies has shown that ozone contributes to increase the incidence and prevalence of COPD and ARI (Cheng et al. 2021, Gao et al. 2020a, b, Heinrich & Schikowski 2018). Ozone exposure is associated with the risk of respiratory disorders, such as COPD exacerbation, asthma exacerbation, lung inflammation, decreased lung function and cystic fibrosis (Johannson et al. 2014, Liang et al. 2019). The World Health Organization (WHO) estimates that outdoor air pollutants were responsible for 3.7 million premature deaths worldwide in 2012, and 14% of which were due to acute lower respiratory infections/COPD (Organization 2016). It is important to further investigate the correlation between exposure to ambient air pollution and respiratory mortality.

There are numerous studies examining the health effects of air pollutants using cohort or time-series methods (Astudillo-García et al. 2019, Chen et al. 2017, Lai et al. 2016, Tian et al. 2018a), but few studies specifically evaluated the relationship between ambient ozone and respiratory mortality. Therefore, in this article, we conducted a time-series study using generalized additive models to investigate the relationship between the concentrations of ambient O₃ and respiratory disease (RD), chronic lower respiratory disease (CLRD), acute respiratory infections (ARI) mortality and the other respiratory disease in Hohhot, China. This study also provided the scientific research evidence for the formulation of emission restriction policies in China.

2. Methods

2.1 Data collection

In this study, we focus on four districts of Hohhot (110°46'–112°10' east, 40°51'–41°8' north) and the residents in the Household Register of Hohhot, China. Hohhot is the capital of Inner Mongolia Autonomous Region in China, with an area of 17,224 km² and a permanent population of 3.126 million, has a continental monsoon climate in the temperate zone.

We collected the mortality data from Mortality Register System in the Hohhot Center for Disease Control and Prevention, ranging from January 1, 2018, to December 31, 2019. The mortality data which were coded according to the International Statistical Classification of Disease, 10th Revision codes [ICD-10 (WHO 1994)], were classified into respiratory diseases (RD, ICD-10 codes J00–J99), chronic lower respiratory diseases (CLRD, ICD-10 codes J40–J47), acute respiratory infections (ARI, ICD-10 codes J00–J22), and the other respiratory diseases (ICD-10 codes J23–J39, J48–J99). The mortality data covers the personal information of residents in Hohhot, such as gender, age, date of birth, date of death, underlying the cause of death diagnosis.

We obtain the daily average concentrations of air pollutants from China's National Urban Air Quality Real-time Publishing Platform (<http://106.37.208.233:20035/>), ranging from January 1, 2018 to December 31, 2019, including the 8-hour average ozone (O₃) concentration, the 24-hour average particulate matter ≤

2.5 µm in diameter (PM_{2.5}) concentration, the 24-hour average particulate matter ≤ 10 µm in diameter (PM₁₀) concentration, the 24-hour average sulfur dioxide (SO₂) concentration, and the 24-hour average nitrogen dioxide (NO₂) concentration.

We also obtain the daily meteorological data, including daily average temperature (Temp) and relative humidity (RH) during the same period, from the Meteorological Science Data Sharing Center of the National Meteorological Administration.

2.2 Statistical analysis

Mortality, air pollutants, and meteorological data were characterized using mean, minimum (Min), maximum (Max), standard deviation (SD), and quartiles. To estimate the correlations between the meteorological factors and air pollutants, we compute the Spearman's correlation coefficient.

Given that daily mortality is of low probability event and follow the Poisson distribution, we performed the generalized additive Poisson regression (GAM) to smooth fluctuations. The model is as follows:

$$\log[E(Y_t)] = \alpha + \beta X_t + s(\text{time}, df) + s(Z_t, df) + \text{DOW}$$

Where: $E(Y_t)$ is the expectation of daily death count at day t , α indicates the model's intercept, β is the regression coefficient of each air pollutant, X_t indicates the concentration of the air pollutant at day t , Z_t is the Meteorological variables at day t , DOW is a dummy variable for the day of the week, df is the degrees of freedom, s represents the smoothing spline function for temperature, humidity and calendar time. We used the partial autocorrelation functions of residuals (PACF) to determine the degrees of freedom (df) through the preferred model with smaller PACF values. Eventually, we chose 7 df per year for the time to adjust for the temporal trends and seasonality based on previous expert experience (Yang et al. 2014, Zhao et al. 2014), and used 3 df for both temperature and humidity based on PACF. Considering the delayed effects of the air pollutants on respiratory mortality, we conducted the lag analysis using single-day lag from the current day up to the previous 5 days (lag 0–lag 5) and a multi-day lag defined as moving averages of the current and previous days (lag 01–lag 05).

However, ambient air pollutants may interact with each other and they may have a combined effect on the health outcome. Such possible combined effects may affect the functionality of the single-pollutant model in assessing the interaction between the single air pollutant and mortality variables. Therefore, to assess the stability of the single-pollutant model, we developed two-pollutant and multi-pollutant models by introducing other pollutants ($r < 0.7$, $p < 0.05$) into the single-pollutant model. Furthermore, we performed subgroup analyses by age (< 65 , ≥ 65), gender (male, female), and season (warm period (from April to September), cold period (from October to March)). The elderly, warm period and cold period were defined as older than 65 years old, above annual average temperature, and below annual average temperature, respectively.

The association between per 10 $\mu\text{g}/\text{m}^3$ increase in outdoor air pollutant concentration and mortality was expressed as excess relative risk (EER) with 95% confidence interval (CI). Descriptive analyses were performed in SPSS 25.0 (IBM SPSS, Armonk, NY, USA), and the other statistical analyses were performed using R (version 4.0.3) packages “mgcv” and “nlme”. Statistical significance in all analyses was defined as $P < 0.05$.

3. Results

Table 1 summarized the descriptive statistics for daily fatalities, air pollutant concentrations and meteorological data for the period from January 1, 2018, to December 31, 2019. During this 2-year period, 3,371 (4.62 deaths per day), 1,799 (2.46 deaths per day), 733 (1.00 deaths per day) and 839 (1.15 deaths per day) died from RD, CLRD, ARI and other respiratory diseases in Hohhot, respectively. Approximately 53% of these cases were caused by chronic lower respiratory diseases. We found that daily death counts were higher in males than in females (RD: 62.6% males, CLRD: 63.4% males, ARI: 63.4% males, the others: 60.0% males). The elderly daily death count of RD (89.0% elderly), CLRD (91.1% elderly), ARI (88.0% elderly) and the others (85.2% elderly) were 4.11, 2.24, 0.88 and 0.98, respectively. The daily average concentrations of O₃, PM_{2.5}, PM₁₀, SO₂ and NO₂ were 91.72, 36.45, 84.87, 16.08 and 38.29 $\mu\text{g}/\text{m}^3$, respectively. And the average of daily temperature and relative humidity were 7.37°C and 46.50%.

Table 1
Descriptive statistics of daily mortality, air pollutant concentrations, and meteorological parameters in Hohhot, China, 2018–2019

	Mean ± SD	Min	25th	50th	75th	Max
Air pollutant concentration (µg/m ³) ^a						
PM2.5	36.45 ± 28.14	3	17	28	49	212
PM10	84.87 ± 78.59	0	42	67	105	983
SO ₂	16.08 ± 9.80	0	9	13	21	72
NO ₂	38.29 ± 15.11	9	27	37	49	84
O ₃	91.72 ± 40.58	4	61	89	120	214
Meteorological variables						
Temperature (Temp, °C)	7.37 ± 12.68	-21.7	-3.9	9	18.8	28.3
Relative humidity (RH,%)	46.49 ± 18.66	11.5	31.73	44.5	59.3	96.5
RD						
Total	4.62 ± 2.50	0	3	4	6	14
< 65 years old	0.51 ± 0.74	0	0	0	1	5
≥ 65 years old	4.11 ± 2.37	0	2	4	5	13
Male	2.89 ± 1.84	0	2	3	4	10
Female	1.73 ± 1.46	0	1	1	3	8
CLRD						
Total	2.46 ± 1.73	0	1	2	3	8
< 65 years old	0.22 ± 0.46	0	0	0	0	3
≥ 65 years old	2.24 ± 1.65	0	1	2	3	8
Male	1.56 ± 1.30	0	1	1	2	7
Female	0.90 ± 1.01	0	0	1	1	5
ARI						
Total	1.00 ± 1.06	0	0	1	2	7
< 65 years old	0.12 ± 0.34	0	0	0	0	2
Notes: ^a 24-hour averages for PM _{2.5} , PM ₁₀ , SO ₂ , and NO ₂ ; the maximal 8-h average for O ₃ , SD: standard deviation; Px (xth percentiles)						

	Mean ± SD	Min	25th	50th	75th	Max
≥ 65 years old	0.88 ± 0.99	0	0	1	1	6
Male	0.64 ± 0.80	0	0	0	1	5
Female	0.37 ± 0.63	0	0	0	1	4
The others						
Total	1.15 ± 1.06	0	0	1	2	6
< 65 years old	0.17 ± 0.44	0	0	0	0	3
≥ 65 years old	0.98 ± 0.98	0	0	1	2	6
Male	0.69 ± 0.83	0	0	0	1	4
Female	0.46 ± 0.69	0	0	0	1	3
Notes: ^a 24-hour averages for PM2.5, PM10, SO2, and NO2; the maximal 8-h average for O3,						
SD: standard deviation; Px (xth percentiles)						

Table 2 shows that the daily average concentrations of PM2.5, PM10, SO2 and NO2 have a high positive correlation with each other. In contrast, the 8-hour average O3 concentration has a moderate negative correlation with the other pollutants. In addition, temperature was negatively correlated with all air pollutants except ozone ($r_{\text{tem-O}_3}=0.779$, $P < 0.01$). Relative humidity was negatively correlated with all air pollutant, though the estimates of ozone and NO2 were almost nonsignificant ($P < 0.01$).

Table 2
Spearman correlation coefficients between air pollutants and meteorological factors in Hohhot, China, 2018–2019

	Temperature	Relative humidity	PM2.5	PM10	SO2	NO2	O3
Temperature							
Relative humidity	0.110**						
PM2.5	-0.409**	-0.113**					
PM10	-0.360**	-0.284**	0.884**				
SO2	-0.686**	-0.262**	0.668**	0.654**			
NO2	-0.372**	-0.059	0.711**	0.619**	0.669**		
O3	0.779**	-0.033	-0.318**	-0.228**	-0.485**	-0.348**	
**P < 0.01							

Figure 1 presented a relatively stable seasonal trend for the daily average concentrations of O₃ and the daily death counts of respiratory diseases and CLRD deaths, except for ARI and other respiratory diseases deaths. The concentrations of O₃ reached their highest level during the warm season and their lowest levels during the cold season. However, daily respiratory diseases and CLRD death counts showed opposite trends, which were higher in the cold season and lower in the warm season.

Table 3 showed the estimated excess relative risks (EERs) of daily mortality at different lag days for an increase of 10 µg/m³ in the 8-hour average O₃ concentration in the single pollution model. We observe that all the four daily mortality were positively associated with O₃, but only respiratory disease at lag 1 and CLRD at lag 1 were tested for positive significant associations. The effects of O₃ on daily mortality were highest at lag 1 for respiratory diseases (ERR: 2.125%, 95% CI: 0.478–3.799) and CLRD (ERR: 4.110%, 95% CI: 1.826–6.446), at lag 3 for ARI (ERR: 2.396%, 95% CI: -0.740–5.631), and at lag 4 for the other respiratory diseases (ERR: 2.525%, 95% CI: -0.451–5.591). Except for the other respiratory diseases, the effect of single lags was lower than the moving average lag across time. In terms of the moving averages, positive significant associations were tested for respiratory diseases at lag 01 and lag 04, CLRD at lag 01 and lag 02. Mortality rates for respiratory diseases, CLRD, ARI, and the other respiratory diseases showed the strongest estimates at lag 04, lag 01, lag 03, and lag 4, respectively. For each increase of 10 µg/m³ in 8-hour average O₃ concentration, respiratory mortality at lag 04, CLRD mortality at lag 01, ARI mortality at lag 03, and the other respiratory diseases mortality at lag 4 increased by 2.815% (95%CI: 0.0752–5.630), 4.409% (95%CI: 1.577–7.320), 3.262% (95%CI: -1.342–8.081), and 2.525% (95%CI: -0.451–5.591), respectively.

Table 3

Estimated excess relative risks (ERRs) and 95% confidence intervals (95% CI) of daily mortality for each increase of 10 $\mu\text{g}/\text{m}^3$ in O₃ concentrations with different lag days in single pollutant models

Lag	Respiratory diseases	CLRD	ARI	The others
Lag 0	0.933 (-0.751, 2.645)	1.737 (-0.583, 4.111)	0.931 (-2.260, 4.226)	-0.434 (-3.334, 2.552)
Lag 1	2.125 (0.478, 3.799)*	4.110 (1.826, 6.446)***	1.977 (-1.214, 5.271)	1.272 (-1.645, 4.276)
Lag 2	-0.064 (-1.671, 1.568)	0.017 (-2.164, 2.247)	0.612 (-2.498, 3.821)	-0.849 (-3.733, 2.122)
Lag 3	0.874 (-0.737, 2.511)	-0.014 (-2.185, 2.205)	2.396 (-0.740, 5.631)	1.272 (-1.645, 4.276)
Lag 4	1.045 (-0.587, 2.704)	0.886 (-1.336, 3.159)	-0.506 (-3.633, 2.724)	2.525 (-0.451, 5.591)
Lag 5	-0.377 (-2.016, 1.289)	-0.335 (-2.560, 1.941)	-1.728 (-4.863, 1.510)	1.480 (-1.522, 4.573)
Lag 01	2.310 (0.271, 4.390)*	4.409 (1.577, 7.320)**	2.030 (-1.782, 5.991)	-1.646 (-5.054, 1.884)
Lag 02	1.962 (-0.336, 4.313)	3.724 (0.545, 7.003)*	2.227 (-1.972, 6.606)	-1.840 (-5.656, 2.130)
Lag 03	2.333 (-0.194, 4.924)	3.355 (-0.101, 6.930)	3.262 (-1.342, 8.081)	-1.005 (-5.190, 3.365)
Lag 04	2.815 (0.075, 5.630)*	3.671 (-0.070, 7.552)	2.705 (-2.183, 7.837)	0.252 (-4.288, 5.008)
Lag 05	2.515 (-0.422, 5.539)	3.35 (-0.642, 7.503)	1.832 (-3.228, 7.155)	0.956 (-3.926, 6.087)
*** P < 0.001; **P < 0.01; *P < 0.05				

Figure 2 illustrated the effects of O₃ on subjects by age and sex. Except for respiratory diseases at lag 3 and lag 5, ARI at lag 1 and lag 5, and the other respiratory diseases at lag 5, respiratory diseases, ARI, and other respiratory diseases estimates of males were higher than those for females. On the contrary, the associations of CLRD were lower for males than females. All daily mortality estimates of older adults were higher than those for < 65-year group, except for respiratory diseases at lag 3, lag 4, lag 5, CLRD at lag 3, and ARI at lag 3 and lag 5. For older adults, significant positive associations were observed for respiratory diseases and CLRD at lag 1, lag 01–lag 05.

As shown in Fig. 3, ERRs for respiratory diseases, CLRD, ARI, and the others mortality associated with each 10 $\mu\text{g}/\text{m}^3$ increase of O₃ concentrations in two pollutant models and multi-pollutant models at lag 04, lag 01, lag 03, and lag 4, respectively. These effect estimates were fairly reliable and did not vary

much in the size of the effect and statistical significance. The estimates for respiratory diseases and CLRD mortality were the most stable across the two and multiple pollutant models. On the contrary, the inclusion of PM_{2.5}, PM₁₀, SO₂, NO₂, and all air pollutants reduced the estimates of ARI mortality. In addition, the estimates of the other respiratory diseases mortality decreased after the inclusion of PM₁₀, and were statistically significant with the inclusion of PM_{2.5}. By adjusting for PM_{2.5}, PM₁₀, SO₂, and NO₂, a significant positive association between O₃ and respiratory diseases/CLRD mortality remained.

4. Discussion

In this study, we used a population-based time-series model to evaluate the relationship between short-term ozone exposure and mortality (respiratory diseases, CLRD, ARI and the others mortality) in Hohhot, China, at the period of January 1, 2018, to December 31, 2019. The results suggested that the concentration of O₃ showed a significant positive correlation with respiratory diseases mortality and chronic lower respiratory disease.

From 2018 to 2019, the levels of outdoor air pollutants were relatively high in Hohhot, China. The daily average concentrations of PM_{2.5} (36.45 µg/m³), PM₁₀ (84.87 µg/m³), and NO₂ (38.29 µg/m³) exceeded the WHO Air Quality Guidelines values (10, 20, and 40 µg/m³, respectively). Approximately 25.53% of the 24-hour average SO₂ concentration and 39.04% of the 8-hour average O₃ concentration exceeded the values of Air Quality Guidelines (20, 100 µg/m³), respectively. The concentrations of ozone keep relatively stable. The values of O₃ peaks in summer, which was caused by the conversion of nitrogen oxides and volatile organic compounds under the sufficient sunshine, high temperature, and low humidity (Wang et al. 2020b). In 2016, the number of motor vehicles increased to 987, 200 in Hohhot, and the vehicle emission also became one of the main sources of ambient ozone (Gu 2017, Zeng et al. 2018).

In our study, the results demonstrated that ambient ozone was positively associated with respiratory disease, CLRD, and ARI mortality in the single-pollutant models. The effects of ambient ozone on respiratory disease, CLRD, ARI, and the other respiratory diseases mortality peaked at lag 04, lag 01, lag 03, and lag 4, respectively, and the strongest association was observed for CLRD. An increase of 10 µg/m³ of 8-hour average O₃ concentration was associated with a 2.815% (95%CI: 0.075–5.630) increase in respiratory mortality. This is consistent with the studies by Zhang et al., where they found that a 10 µg/m³ increase in ozone associated with a 2.182% (95% CI: 1.014–3.363%) increase in respiratory mortality (Zhang et al. 2019b), while another time-series analysis in Xi'an, China, showed a lack of association between ozone and the relative risk of respiratory mortality (Mokoena et al. 2019). But the time-series analysis in Changchun reported that every increase of 10 µg/m³ of O₃ was associated with 1.850% (95% CI: 0.880–2.840%) increase in respiratory mortality, which was lower than the results reported in our studies (Ma 2020). Furthermore, similar with the results of our study, Yan et al. also demonstrated that aerosol pollutants had a stronger effect on respiratory mortality in Wuhan, China (Yan et al. 2020). The strongest association was observed for CLRD, and every increase of 10 µg/m³ of O₃ was associated with 4.409% (95%CI: 1.577–7.320) increase in CLRD mortality. Chen et al. also found that

ozone had a significantly effect on Chronic respiratory disease (ERR: 4.090%, 95%CI: 0.940–7.350%) in Fujian, China (Chen et al. 2019). Significant associations was not found between the concentrations of O₃ and the risk of death from ARI, while in a ARI cohort, Guo et al. concluded that the effects on ARI mortality were particularly elevated 0.100% (95% CI: -0.080–0.310%) from O₃ for each increase of 10 µg/m³ (Guo et al. 2018). Although the association for ARI in our study did not show statistical significance in the general analysis, the excess relative risks (EERs) was still high after adjusting for collinearity by principal-component-analysis (PCA) in two and multi pollutant models. Varied in different cities, several factors including the concentration, source of O₃, duration of exposure and susceptibility of the population which may contribute to this inconsistency (Agency 2013). The association between O₃ exposure and ARI mortality should be further testified in other cities.

We used the single day lag (0–5) and cumulative lag (01–05) for time-series analysis to investigate the lag association between ambient air pollution and respiratory mortality. For respiratory diseases, CLRD, and ARI, the effects estimates of moving average lags were larger than single lags in different period, which indicates that accumulated exposure of O₃ increases the risk of those death, and this phenomenon was also noted in previous studies (Middleton et al. 2008, Mokoena et al. 2019). Of all the mortality, the effect of ozone on respiratory diseases and CLRD mortality was observed more statistically significant lags than other mortality. The best lag of ozone on respiratory diseases was lag 04 [2.815 (0.07515, 5.63)], which was the strongest estimates, statistically significant, and remained largely unchanged after adjusting for collinearity by principal-component-analysis (PCA) in two and multi pollutant models, suggesting that confounding effects of other pollution did not influence O₃ lag effects. Another study in Yangzhou, China also reported similar statistically significant single model lag effects (precisely lag 04) on respiratory mortality (Zhang et al. 2019b). Moreover, a time series analysis by Zhang et al. also discovered that exposure to O₃ at lag 01 yielded the strongest estimates on CLRD mortality (Zhang 2016). Compared to the single pollutant model, although the excess relative risk of ARI increased both in two and multi pollutant model, no statistically significant lag effects were observed for ozone on ARI. In summary, in our study, the sensitivity analysis indicated that considering lag effects, the temporal aspect of air pollutant on health effects and fatalities should be an indispensable factor in the analysis of environmental exposure and public health effect.

Subgroup analysis showed that males appeared to be more vulnerable to ozone on respiratory diseases, ARI and other respiratory diseases, although the estimates of ARI and other respiratory diseases were barely significant. On the contrary, the significant association for CLRD were lower in men than in women. The results of our study revealed that air pollutant estimates were higher in the elderly than in the < 65-year group, with no statistically significant association in the < 65-year subgroup. However, some previous studies reported the different results with our findings. They found that the association between O₃ and respiratory disease is stronger in women than in man. Furthermore, they reported that the associations of CLRD is lower in woman than in man. Some studies have reported the greater susceptibility in the < 65-year subgroup than in the ≥ 65-year subgroup. The inconsistency of these results might be attributed to

the meteorological factors, pollution concentration, the components of air pollution, location, population size and other underlying health factors of the population.

5. Conclusion

In this study, we found that exposure to ozone significantly increased respiratory mortality and chronic lower respiratory mortality in Hohhot, China. More importantly, the elderly and female were more susceptible to ozone effects. These results suggest that government measures to reduce emissions in O₃ are necessary to protect people, especially men, the elderly, and people with respiratory diseases.

Declarations

Ethics approval and consent to participate The death data were surveillance data; there was no requirement for informed consent. This study was approved by the Ethical Committee of the Hohhot Center for Disease Control and Prevention.

Consent for publication Not applicable.

Availability of data and materials The datasets used or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests The authors declare that they have no competing interests.

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Authors' contributions LYD, NL, YJW, YLW contributed to the conception of the study; CYX, YL, HQZ, LWN contributed significantly to analysis and manuscript preparation; CYX, YL, JLX performed the data analyses and wrote the manuscript; NZ, HL, XH helped perform the analysis with constructive discussions. All authors read and approved the final manuscript.

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Figures

Figure 1

Time-series of O_3 (a) and respiratory diseases(b), CLRD(c), ARI(d), and the other respiratory diseases mortality (e) in Hohhot, China, 2018–2019

Figure 2

Age- and gender-specific estimated excess relative risks (ERRs) and 95% confidence intervals (95% CI) of daily mortality with each 10µg/m³ increase in O₃ using different lag days

Figure 3

Estimated excess relative risks (ERRs) and 95% confidence intervals (95% CI) of daily mortality with each 10µg/m³ increase in O₃ using single-, two-, and multi-pollution models.