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Association between ambient air pollution and the risk of hospitalization for acute exacerbation of chronic obstructive pulmonary disease: modifying effects of meteorological factors

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Abstract

Background

Ambient air pollution is a major risk factor for acute exacerbation of chronic obstructive pulmonary disease (AECOPD). However, evidence on the modifying effects of meteorological factors on air pollutants remains limited and inconsistent.

Methods

Daily hospitalization data for acute exacerbation of chronic obstructive pulmonary disease (AECOPD) in Wanzhou District, Chongqing Municipality, from 2018 to 2022, along with concurrent air pollution and meteorological factor data, were collected. A distributed lag nonlinear model (DLNM) was employed to evaluate the association between ambient air pollutants and the risk of AECOPD hospitalization, and to analyze the modifying effects of wind speed and rainfall on air pollutants. The quantile g-computation (Qgcomp) model was applied to estimate the joint effects of multi-pollutant mixtures.

Results

DLNM revealed that NO_2 exposure exhibited a significant acute effect on the day of exposure (lag0) (RR = 1.020, 95% CI: 1.001, 1.038). The effect of $PM_{2.5}$ was characterized by a lag pattern, peaking at lag7 (RR = 1.010, 95% CI: 1.002, 1.018). Furthermore, significant cumulative exposure effects were observed for $PM_{2.5}$ (RR = 1.028, 95% CI: 1.008, 1.049) and NO_2 (RR = 1.044, 95% CI: 1.015, 1.075), with the cumulative risk for NO_2 peaking at lag0-4 (RR = 1.056). Interaction analysis indicated that wind speed significantly amplified the effects of $PM_{2.5}$ and PM_{10} on hospitalization risk, while rainfall increased the risk associated with NO_2. Additionally, the Qgcomp model revealed that the joint effect of pollutant mixtures was particularly pronounced during the cold season, among males, and in the elderly population, with NO_2 identified as the primary contributing component.

Conclusions

Short-term exposure to NO_2 and $PM_{2.5}$ significantly increased the risk of AECOPD hospitalization. Notably, this study provides the first evidence that wind speed and rainfall act as important effect modifiers of this association. We provide epidemiological evidence elucidating the role of coexposure to ambient air pollutants and meteorological factors in triggering AECOPD, and underscores the importance of implementing targeted measures to control particulate matter and NO_2 emissions, as well as enhancing the protection of susceptible populations, for the prevention of AECOPD.

1. Introduction

Chronic obstructive pulmonary disease (COPD) is a condition characterized by persistent airflow limitation[1]. According to the latest report released by the Global Initiative for Chronic Obstructive Lung Disease (GOLD) in 2024, COPD has become the third leading cause of death worldwide, resulting in over 3 million deaths annually[2]. Studies indicate that more than 480 million adults aged 40 years and older are affected by COPD globally, imposing a substantial disease burden [3]. Acute exacerbation of COPD (AECOPD) is a clinical event marked by acute worsening of symptoms and is a major contributor to increased mortality and disease burden in COPD patients[4]. Research shows that the five-year mortality rate among patients hospitalized for AECOPD exceeds 65%, approximately 20% are admitted to the intensive care unit, and in-hospital mortality ranges from 12% to 24%[5]. Therefore, preventing the occurrence of AECOPD is a key goal in COPD management[6].

Ambient air pollutants serve as critical external risk factors for triggering AECOPD[5]. Existing time-series and case-crossover studies have demonstrated that short-term exposure to fine particulate matter ($PM_{2.5}$, PM_{10}) and gaseous pollutants (NO_2, SO_2, O_3) is significantly positively associated with emergency department visits and hospitalization risk for AECOPD[7, 8]. The underlying biological mechanisms primarily involve oxidative stress and systemic inflammatory responses: upon entering the body, pollutants can induce airway epithelial cells to generate excessive reactive oxygen species (ROS), activating inflammatory signaling pathways such as NF-κB, leading to airway mucosal damage and immune homeostasis imbalance, thereby precipitating AECOPD[9]. Furthermore, meteorological factors (e.g., temperature, humidity) not only directly affect respiratory defense function but also modify the biological toxicity of pollutants through complex physical processes (such as dilution, diffusion, or secondary transformation)[10]. Studies suggest that wind speed and rainfall can alter the actual exposure levels of populations through mechanical scavenging or dilution effects, consequently influencing health outcomes[11]. However, evidence regarding the interactive effects between meteorological factors and air pollutants on AECOPD hospitalization risk remains limited and inconsistent[12]. Moreover, previous studies have largely relied on single-pollutant models, which struggle to capture the complex mixture effects of "coexisting multiple pollutants" in real-world environments, and traditional statistical methods face challenges with multicollinearity when handling highly correlated environmental data[13].

This study primarily focuses on the risk of hospitalization for AECOPD associated with ambient air pollutants and its interaction with environmental factors, specifically wind speed and rainfall. This research aims to facilitate the assessment of respiratory health risks related to meteorological factors and air pollutants, identify the predominant risk factors for AECOPD occurrence, and provide evidence for air quality management in the region.

2. Methods

2.1 Research area

This study was conducted in Wanzhou District, Chongqing Municipality, China (30°24'–31°14'N, 107°55'–108°54'E). Located in the northeastern part of Chongqing and situated in the hinterland of the Three Gorges Reservoir area, Wanzhou District is the largest resettlement city within this region. According to the results of the seventh national census, the resident population of Wanzhou District is approximately 1.5644 million, with individuals aged 60 years and above accounting for about 25.67% (of which those aged 65 years and above comprise approximately 19.47%). The terrain in this area is complex, characterized predominantly by mountains and hills, with the Yangtze River flowing through the entire region, forming a typical landscape of deep valleys and basin margins. Wanzhou District has a subtropical humid monsoon climate, with an annual average temperature of approximately 18.0°C, and is notable for its high humidity, low wind speed, and frequent fog. The district exhibits a marked trend of population aging, and as a regional transportation hub, it experiences relatively concentrated vehicular emissions and industrial activities.

2.2 Data Sources

Data on hospitalized AECOPD patients were obtained from the Big Data Management Bureau of Wanzhou District, Chongqing Municipality, encompassing electronic medical records from all hospitals in Wanzhou District between January 2018 and December 2022. Therefore, these inpatient data could reflect the incidence of AECOPD in this region. The electronic medical record system is used to document all patients visiting healthcare facilities, including those in emergency departments, outpatient clinics, and inpatient wards. All hospitalized patients with a primary or secondary diagnosis of AECOPD were included in the analysis. All AECOPD hospitalizations were confirmed according to the standard diagnostic criteria for AECOPD (codes J44.100 and J44.101) based on the International Classification of Diseases, 10th Revision (ICD-10). Concurrent air pollution data, including $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3, were provided by the Wanzhou District Environmental Monitoring Station. Meteorological factor data, including average temperature, average relative humidity, average pressure, average rainfall, and daily average wind speed, were provided by the Wanzhou District Meteorological Bureau. This study conformed to the Declaration of Helsinki and was approved by the Ethics Committee of Chongqing Three Gorges Medical College (Approval No. SYXZ-H-2504-0013).

2.3 Statistical analysis

Descriptive analysis was performed on the baseline characteristics of AECOPD patients, as well as air pollutant concentrations and meteorological data in Wanzhou District from 2018 to 2022. Continuous variables were presented as means, standard deviations, and percentiles, while categorical variables were expressed as percentages. Spearman correlation analysis was employed to assess the relationships between air pollutants and meteorological factors.

DLNM based on a quasi-Poisson regression framework was utilized to evaluate the association between short-term exposure to ambient air pollutants and the risk of AECOPD hospitalization. A cross-basis function was constructed to analyze the nonlinear exposure–response relationship and the lag patterns of the effects. Natural cubic spline functions were used to fit the pollutant concentration and lag

dimensions. Long-term trends and seasonal variations were controlled by incorporating a natural spline function with 7 degrees of freedom per year. Meteorological factors such as daily mean temperature were adjusted using natural spline functions, and dummy variables were introduced to control for day-of-week effects and public holidays. Furthermore, stratified analyses were conducted by sex (male, female), age (≥ 65 years, < 65 years), and season (warm season, cold season). The same DLNM strategy was applied to each subgroup to estimate cumulative lag effects (lag0–7).

To examine the modifying effects of meteorological factors, wind speed and rainfall were categorized, and multiplicative interaction terms between pollutants and these meteorological factors were introduced into the DLNM. The differences in pollutant effect estimates across different meteorological conditions were compared using the Z-test, and the likelihood ratio test (LRT) was employed to assess the modifying effects of meteorological factors on pollutants. Additionally, the Qgcomp model was applied to evaluate the association between mixed exposure to air pollutants and the risk of AECOPD hospitalization. The contribution weights of individual pollutants were normalized, where a larger absolute weight indicated a greater contribution of that component to the joint effect.

Sensitivity analyses were conducted to verify the robustness of the main findings. First, cross-basis functions incorporating concurrent exposure terms for two different pollutants were constructed to assess whether the associations between specific pollutants and AECOPD hospitalization risk remained stable after adjusting for other gaseous pollutants or particulate matter components. Second, the degrees of freedom for the natural cubic spline of time trend (df = 6–8) were varied to refit the associations between each pollutant and AECOPD hospitalization risk, and the changes in cumulative effect estimates and the consistency of three-dimensional effect plots under different df settings were compared to evaluate the robustness of the model's time trend control strategy. Third, in the Qgcomp analysis, the number of quantiles was sequentially set to q = 3, 4, 5, 6, and 10 to re-estimate the joint effects of pollutant mixtures and the contribution weights of individual components. The stability of the overall effect estimates and the consistency in the ranking of core contributing components across different quantile settings were compared to verify the reliability of the findings regarding mixed air pollutant exposure. All statistical analyses were performed using R software, version 4.4.3. A two-sided p-value of less than 0.05 was considered statistically significant.

3. Results

3.1 Baseline characteristics

Table 1 presents the descriptive statistics for daily AECOPD hospitalizations, air pollutants, and meteorological factors. During the period from 2018 to 2022, a total of 17,435 AECOPD hospitalizations were recorded in Wanzhou District. Males accounted for 68.3% of the cases, and individuals aged 65 years and older accounted for 84.2%. The daily average concentrations of air pollutants were 34.83 $\mu g/m^3$ for $PM_{2.5}$, 49.33 μg/m³ for PM_{10}, 29.17 μg/m³ for NO_2, 12.37 μg/m³ for SO_2, 72.31 μg/m³ for O_3,

and 0.68 mg/m³ for CO. The daily average temperature, air pressure, relative humidity, wind speed, and rainfall were 18.98°C, 984.27 hPa, 75.54%, 1.38 m/s, and 3.43 mm, respectively.

Table 1
Characteristics of AECOPD hospitalizations, air Pollutants, and meteorological factors

Male	**Mean**	**SD**	**Min**	**P_{25}**	**P_{50}**	**P_{75}**	**Max**
	6.52	**4.56**	**0.00**	**2.00**	**5.00**	**9.00**	**49.00**
Female	3.03	1.48	0.00	1.00	2.00	4.00	24.00
<65age	1.51	0.64	0.00	0.00	1.00	2.00	10.00
≥ 65age	8.04	6.44	0.00	2.00	5.00	11.00	68.00
Warmseason	8.93	7.73	0.00	2.00	6.00	11.00	54.00
Coldseason	9.99	7.35	0.00	3.00	7.00	14.00	73.00
Total	9.55	7.53	0.00	3.00	7.00	13.00	73.00
PM_{10}(μg/m³)	49.33	28.79	8.00	28.00	42.00	64.00	221.00
SO_2(μg/m³)	12.37	3.53	4.00	10.00	12.00	14.00	35.00
NO_2(μg/m³)	29.17	9.56	7.00	22.00	28.00	35.00	66.00
$PM_{2.5}$(μg/m³)	34.83	21.78	6.00	19.00	30.00	44.00	170.00
O_3(mg/m³)	72.31	37.32	5.00	44.00	68.00	98.00	190.00
CO(μg/m³)	0.68	0.21	0.20	0.50	0.70	0.80	1.60
Temp(℃)	18.98	8.03	2.60	11.60	18.90	25.60	35.90
Pressure(hPa)	984.27	17.85	938.60	979.10	987.90	998.00	1013.5
RH(%)	75.54	10.65	35.00	69.00	77.00	83.00	98.00
WS(m/s)	1.38	0.83	0.00	0.90	1.20	1.60	7.30
Rain(mm)	3.43	10.34	0.00	0.00	0.00	1.5.00	143.90

The associations of air pollutants and meteorological factors with the number of AECOPD hospitalizations are shown in Figure S1. Spearman correlation analysis revealed a strong positive correlation between $PM_{2.5}$ and PM_{10} (r = 0.941, P< 0.001), and both were significantly positively correlated with NO_2 (P< 0.001). Temperature exhibited a significant positive correlation with O_3 (r = 0.664, P< 0.001). The number of AECOPD hospitalizations was significantly positively correlated with $PM_{2.5}$, PM_{10}, and NO_2 (P< 0.01), and significantly negatively correlated with temperature and wind speed (P< 0.05).

3.2 Lag effects of air pollutants on AECOPD hospitalizations

Table 2 presents the associations between air pollutants and AECOPD hospitalizations in single-day lag and cumulative lag models. Effect estimates are expressed as RR per 10 μg/m³ increment in pollutant concentrations, except for CO, which is per 1 mg/m³ increment. The single-day lag model revealed that NO_2 exhibited the strongest acute effect, with the risk peaking on the day of exposure (lag0) (RR = 1.020, 95% CI: 1.001, 1.038). The effect of SO_2 was more prolonged, maintaining a significant association during lag1-2. In contrast, $PM_{2.5}$ showed a pronounced delayed effect, with the risk beginning to increase at lag6 and reaching the highest single-day risk at lag7 (RR = 1.010, 95% CI: 1.002, 1.018). The cumulative lag model showed that the RR for $PM_{2.5}$ increased steadily with the number of lag days, reaching 1.028 (95% CI: 1.008, 1.049) at lag0-7. The cumulative effect of SO_2 remained statistically significant across the entire lag period and peaked at lag0-7 (RR = 1.044, 95% CI: 1.015, 1.075). The cumulative risk for NO_2 peaked at lag0-4 (RR = 1.056).

Table 2
Lag effects of air pollutants on AECOPD hospitalizations

Lag	PM2.5	CO	PM10	SO2	NO2	O3
Lag effect						
lag0	1.007 (0.999, 1.015)	1.008 (0.984, 1.034)	0.999 (0.987, 1.010)	1.006 (0.994, 1.018)	1.020 (1.001, 1.038)*	0.991 (0.972, 1.010)
lag1	1.004 (0.999, 1.008)	0.999 (0.986, 1.013)	1.000 (0.993, 1.006)	1.006 (1.000, 1.013)	1.015 (1.004, 1.027)*	0.990 (0.977, 1.002)
lag2	1.001 (0.997, 1.004)	0.992 (0.981, 1.002)	1.001 (0.996, 1.006)	1.007 (1.001, 1.012)*	1.011 (1.002, 1.020)*	0.989 (0.978, 1.000)
lag3	0.999 (0.994, 1.004)	0.987 (0.973, 1.002)	1.001 (0.995, 1.008)	1.007 (0.999, 1.014)	1.007 (0.996, 1.018)	0.990 (0.978, 1.003)
lag4	0.999 (0.995, 1.004)	0.988 (0.973, 1.002)	1.002 (0.995, 1.008)	1.006 (0.999, 1.013)	1.002 (0.991, 1.013)	0.993 (0.981, 1.005)
lag5	1.002 (0.998, 1.005)	0.992 (0.981, 1.004)	1.002 (0.997, 1.007)	1.005 (1.000, 1.011)	0.998 (0.989, 1.007)	0.998 (0.987, 1.008)
lag6	1.006 (1.001, 1.010)*	1.000 (0.987, 1.014)	1.001 (0.995, 1.008)	1.004 (0.998, 1.010)	0.993 (0.983, 1.004)	1.004 (0.992, 1.016)
lag7	1.010 (1.002, 1.018)*	1.010 (0.986, 1.035)	1.001 (0.990, 1.013)	1.003 (0.992, 1.014)	0.989 (0.971, 1.006)	1.011 (0.992, 1.030)
Cumulative effect						
lag0-1	1.011 (0.999, 1.023)	1.008 (0.971, 1.046)	0.998 (0.981, 1.016)	1.012 (0.995, 1.030)	1.035 (1.006, 1.065)*	0.981 (0.951, 1.011)
lag0-2	1.012 (0.998, 1.025)	0.999 (0.959, 1.041)	0.999 (0.980, 1.019)	1.019 (0.999, 1.039)	1.047 (1.012, 1.083)*	0.970 (0.934, 1.007)
lag0-3	1.011 (0.996, 1.025)	0.987 (0.945, 1.030)	1.000 (0.980, 1.021)	1.026 (1.004, 1.048)*	1.054 (1.015, 1.094)*	0.960 (0.920, 1.003)
lag0-4	1.010 (0.994,	0.974 (0.930,	1.002 (0.980,	1.032 (1.008,	1.056 (1.012,	0.954 (0.907,

*$p < 0.05$.

Lag	PM2.5	CO	PM10	SO2	NO2	O3
Lag effect						
	1.026)	1.020)	1.025)	1.056)*	1.101)*	1.003)
lag0-5	1.012 (0.995, 1.029)	0.967 (0.920, 1.016)	1.004 (0.979, 1.029)	1.037 (1.011, 1.064)*	1.053 (1.005, 1.104)*	0.952 (0.900, 1.006)
lag0-6	1.018 (0.999, 1.036)	0.967 (0.919, 1.018)	1.005 (0.978, 1.033)	1.041 (1.014, 1.070)*	1.046 (0.995, 1.100)	0.956 (0.900, 1.015)
lag0-7	1.028 (1.008, 1.049)*	0.977 (0.922, 1.035)	1.006 (0.974, 1.039)	1.044 (1.015, 1.075)*	1.034 (0.977, 1.094)	0.966 (0.904, 1.032)
*$p < 0.05$.						

Stratified analyses by sex, age, and season revealed significant differences in the strength of the associations between air pollutants and the risk of AECOPD hospitalization across subgroups (Figure S2). Specifically, among males, the hospitalization risks associated with NO_2 (lag0-4) and $PM_{2.5}$ (lag0-1) were higher than those in females, with RR of 1.064 (1.016, 1.114) and 1.019 (1.006, 1.032), respectively. Among individuals aged ≥ 65 years, exposure to NO_2, SO_2, and $PM_{2.5}$ at lag0-7 was associated with higher hospitalization risks, with RR of 1.060, 1.052, and 1.036, respectively. Furthermore, the association between SO_2 (lag0-7) and hospitalization risk was more pronounced during the cold season, with an RR of 1.054 (1.010, 1.101).

3.3 Effect Modification of Air Pollutants by Meteorological Factors

The likelihood ratio test was used to analyze the modifying effects of meteorological factors on air pollutants (Fig. 1). The results showed that when $PM_{2.5}$ concentrations exceeded 79.5 μg/m³ and PM_{10} concentrations exceeded 88 μg/m³, wind speed significantly increased the risk of AECOPD hospitalization, with RR values of 1.705 (1.221, 2.382) and 1.409 (1.079, 1.841), respectively. In addition, when NO_2 concentrations reached 28 μg/m³, the RR under rainy conditions was 1.042 (0.942, 1.153), which was significantly lower than that under non-rainy conditions (RR = 1.130, 95% CI: 1.049, 1.217).

3.4 Analysis of mixed exposure effects of air pollutants

The Qgcomp model was used to evaluate the contribution weights of mixed exposure to air pollutants on AECOPD hospitalizations (Fig. 2). The results showed that the weights for NO_2, O_3, and $PM_{2.5}$ were 0.374, 0.179, and 0.130, respectively, indicating that NO_2 played a dominant role in the mixed exposure leading to AECOPD hospitalizations. Stratified analyses by sex, age, and season revealed that the risk of AECOPD hospitalization associated with mixed exposure to air pollutants was higher among males (RR

= 1.091, 95% CI: 1.017, 1.170), individuals aged ≥ 65 years (RR = 1.091, 95% CI: 1.020, 1.167), and during the cold season (RR = 1.165, 95% CI: 1.060, 1.282). Furthermore, subgroup analyses consistently showed that NO_2 contributed a high positive weight across all subgroups (Fig. 3).

3.5 Sensitivity analysis

Sensitivity analyses showed that after adjusting for other pollutants, the associations between air pollutants and the risk of AECOPD hospitalization remained robust in the two-pollutant models (Table S1). Furthermore, the associations remained consistent when varying the degrees of freedom for time trend adjustment (Figures S3–S4). Third, quantile sensitivity testing indicated that the ranking of the contribution weights of individual air pollutants remained stable across different numbers of quantiles (Figure S5), and the exposure–response curve for mixed exposure and AECOPD hospitalization risk exhibited a significant linear increasing trend (Figure S6).

4. Discussion

Based on AECOPD hospitalization data from Wanzhou District, Chongqing Municipality, China from 2018 to 2022, this study revealed the associations between short-term exposure to ambient air pollutants and the risk of AECOPD hospitalization, as well as the modifying effects of meteorological factors. The findings demonstrated that NO_2 and $PM_{2.5}$ significantly increased the risk of AECOPD hospitalization. Notably, this study identified for the first time that high wind speed further amplified the risk of hospitalization associated with $PM_{2.5}$, whereas heavy rainfall attenuated the risk associated with NO_2. Furthermore, males and individuals aged ≥ 65 years were at higher risk of AECOPD hospitalization following exposure to air pollutants, particularly during the cold season.

The DLNM revealed a nonlinear positive association between $PM_{2.5}$ and the risk of AECOPD hospitalization. A 10 μg/m³ increase in $PM_{2.5}$ concentration was associated with a 2.8% increase in the risk of AECOPD hospitalization at lag7, a finding consistent with previous studies[14]. However, some studies have reported that the short-term effects (lag0–lag4) of $PM_{2.5}$ on AECOPD hospitalization risk are more pronounced [15], which may be attributable to the relatively low ambient $PM_{2.5}$ concentrations in Wanzhou District. Under low-concentration $PM_{2.5}$ exposure, several days may be required to activate oxidative stress and induce inflammatory responses, thereby triggering AECOPD[16, 17]. In addition, NO_2 exhibited an acute effect on the risk of AECOPD hospitalization on the day of exposure, with the highest cumulative risk observed at lag4. A meta-analysis encompassing 18 studies showed that NO_2 exposure on the same day was associated with a 3% increase in the risk of AECOPD hospitalization[18]. Furthermore, when the NO_2 concentration reached 126 μg/m³, the risk of AECOPD hospitalization on the day of exposure increased by 32%[19]. These findings are consistent with the nature of NO_2 as a strong irritant gas, which directly contacts the airway mucosa and rapidly induces inflammatory factors[20].

Meteorological factors and air pollutants jointly increase the risk of AECOPD hospitalization [11, 21]. However, few studies have focused on the modifying effects between meteorological factors and air

pollutants. It has been reported that low temperature and low humidity conditions influence the risk of AECOPD associated with $PM_{2.5}$ exposure [22]. Our study is the first to demonstrate that when $PM_{2.5}$ concentrations reach 79.5 μg/m³, high wind speed further amplifies the risk of hospitalization associated with $PM_{2.5}$, whereas heavy rainfall attenuates the risk associated with NO_2. This finding may be explained by the fact that high wind speeds resuspend particulate matter deposited on the ground along with attached bacteria and fungal spores into the breathing zone, thereby increasing the actual inhalation of hazardous particles [23]. In addition, heavy rainfall may reduce the risk of hospitalization associated with NO_2 by decreasing the duration of outdoor activities and physical exertion among COPD patients, resulting in lower exposure to the strong irritant NO_2[24, 25]. Notably, stratified analyses revealed that males aged ≥ 65 years were more susceptible to the effects of air pollutants, leading to an increased risk of AECOPD hospitalization, particularly during the cold season. This finding is consistent with previous studies[26, 27]. Therefore, it is necessary to implement targeted preventive measures, such as reducing outdoor activities during the cold season and issuing text message alerts to high-risk populations when pollutant concentrations are elevated, as recommended by meteorological authorities. Furthermore, previous studies have focused on the associations between individual air pollutants and AECOPD hospitalization risk but have overlooked the mixed effects[28]. Using the Qgcomp model, we evaluated the contribution weights of mixed exposure to air pollutants on AECOPD hospitalizations and identified NO_2 as the primary air pollutant driving the increased risk of AECOPD hospitalization. This finding underscores the need to strengthen the control of NO_2 emissions in this region to mitigate the associated health risks.

The primary strength of this study lies in providing the first evidence that wind speed and rainfall influence the risk of AECOPD hospitalizations associated with air pollutants, and in identifying NO_2 as the predominant factor affecting AECOPD hospitalization risk in this region, thereby offering a theoretical basis for the development of targeted prevention strategies. However, several limitations should be acknowledged. First, this study lacked individual-level patient information, such as lifestyle habits, medication use, and occupational exposure. Future research should incorporate more detailed individual-level data to control for confounding bias. Second, the timing of AECOPD onset was determined based on the date of hospital admission, which may deviate from the actual onset time. Additionally, patients with milder symptoms may not have sought medical care or been diagnosed, introducing potential information bias. Third, air pollutant and meteorological data were derived from average exposure levels measured at fixed monitoring stations within the region, which may not accurately reflect individual-level actual exposure. Subsequent studies could incorporate portable monitoring devices for personal exposure assessment to improve the accuracy of exposure measurement.

5. Conclusions

Based on time-series data from Wanzhou District, Chongqing Municipality, from 2018 to 2022, this study revealed that the air pollutants NO_2 and $PM_{2.5}$ significantly increased the risk of AECOPD hospitalization. Notably, it was discovered for the first time that high wind speed further amplified the hospitalization risk

associated with $PM_{2.5}$, whereas heavy rainfall attenuated the risk associated with NO_2. This study provides new evidence elucidating the modifying effects of meteorological factors on the health impacts of air pollutants, and underscores the importance of implementing targeted measures to control particulate matter and NO_2 emissions, as well as strengthening the protection of susceptible populations, for the prevention of AECOPD.

Declarations

Ethics approval and consent to participate: This study conformed to the Declaration of Helsinki and was approved by the Ethics Committee of Chongqing Three Gorges Medical College (Approval No. SYXZ-H-2504-0013). Individual patient consent was not necessary because all the protected health information was anonymized.

Consent for publication: Not applicable.

Availability of data and materials: Data analyzed can be made available to others upon reasonable requests to the lead contact, Daikun Zheng (zhengdaikun@cqtgmc.edu.cn), if access is granted. A proposal with a detailed description of the study objectives and the statistical analysis plan will be needed for evaluation of the reasonability of requests.

Competing interests: The authors declare no competing interests.

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Figures

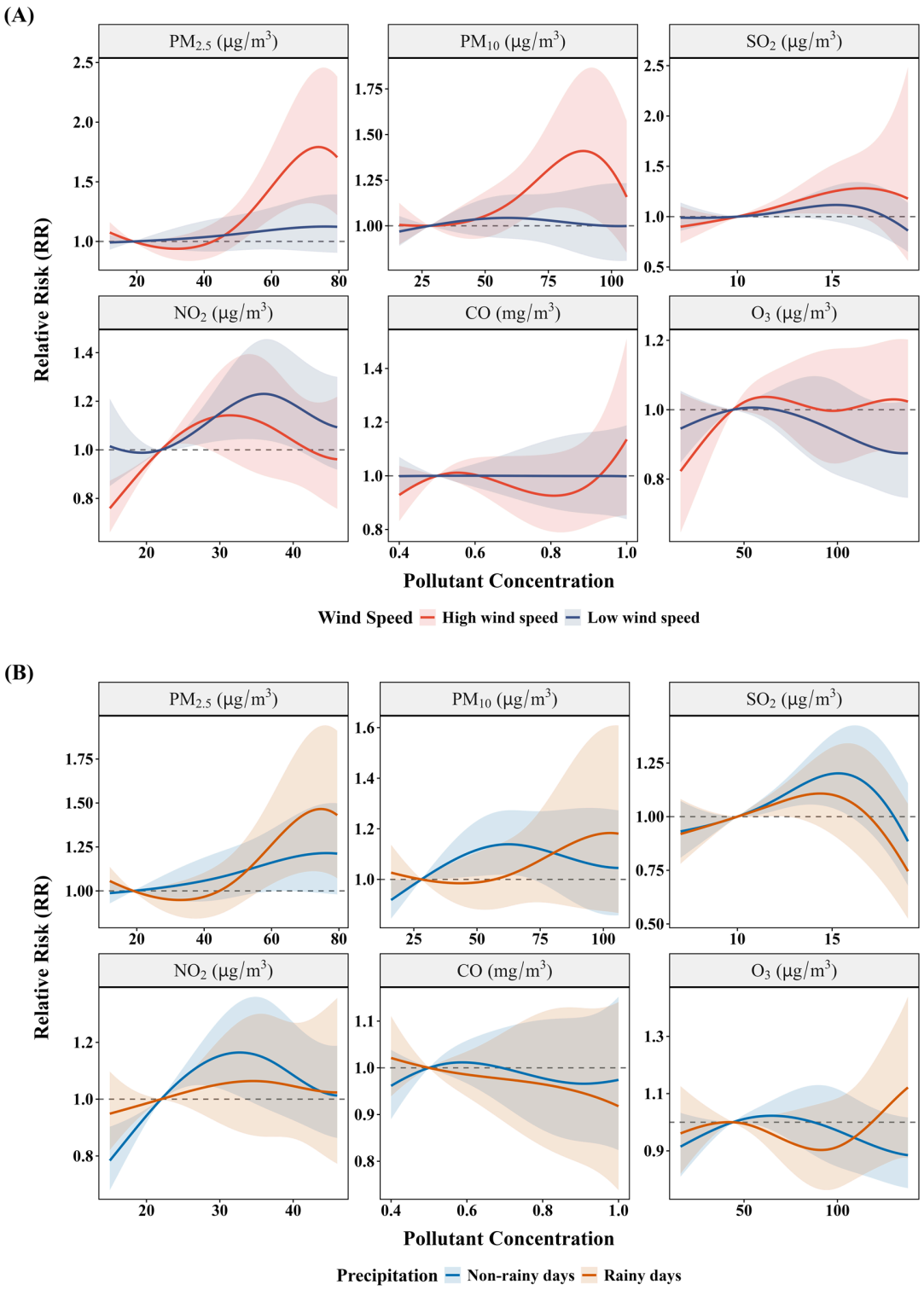


Figure 1

Modifying effects of meteorological factors on air pollutants. (A) Modifying effects of wind speed on air pollutants. (B) Modifying effects of precipitation on air pollutants.

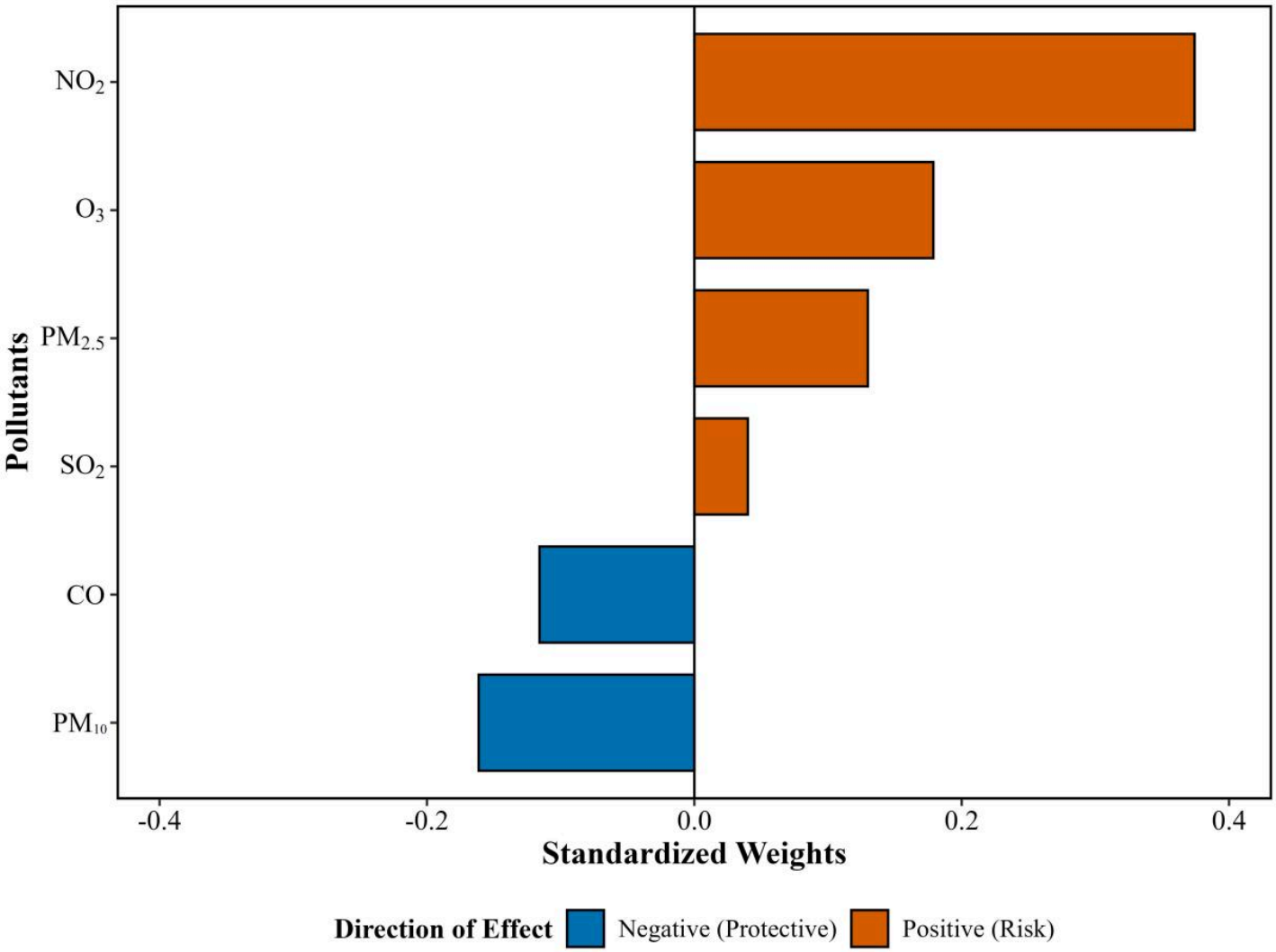


Figure 2

Contribution weights of mixed exposure to AECOPD hospitalizations analyzed by the Qgcomp model

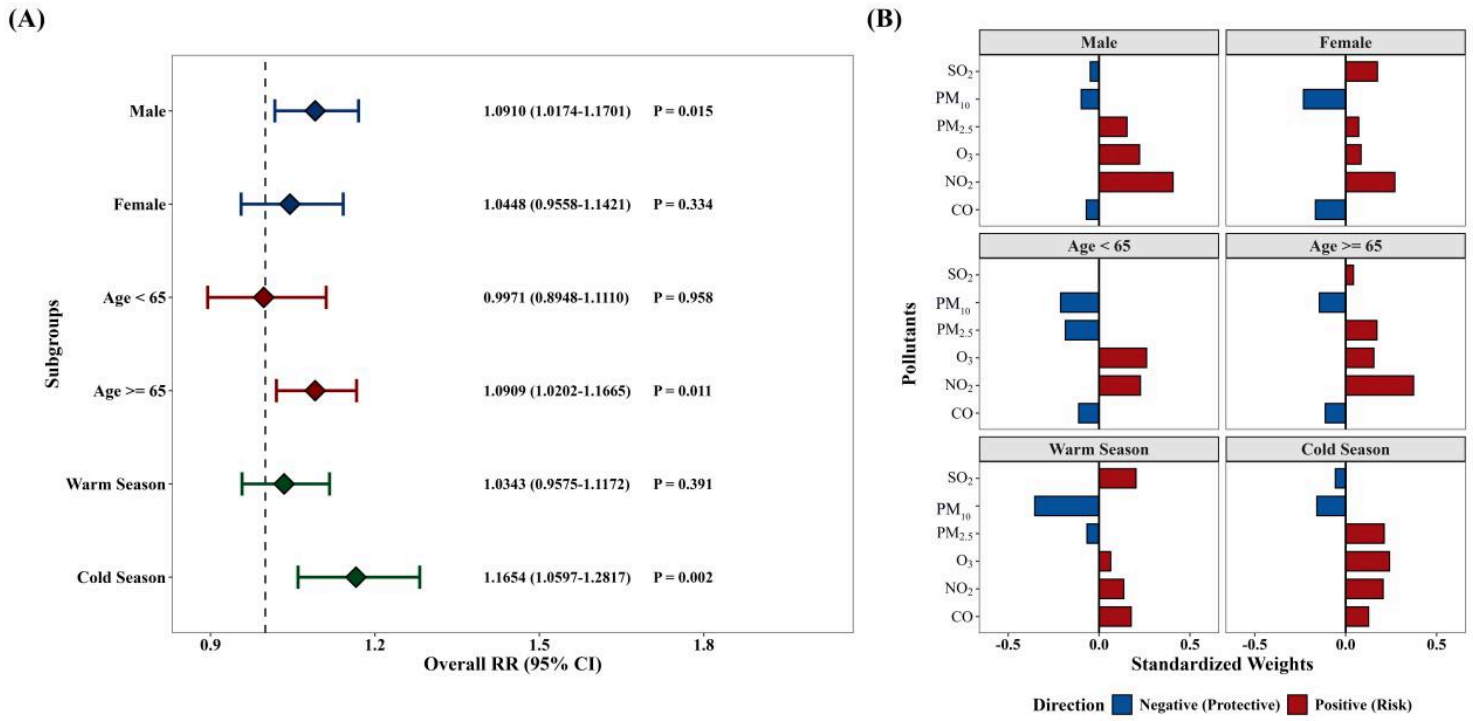


Figure 3

Stratified analysis of multi-pollutant mixtures and the risk of AECOPD hospitalization. (A) Association between mixed exposure to air pollutants and the risk of AECOPD hospitalization across different subgroups. (B) Contribution weights of ambient air pollutants to the risk of AECOPD hospitalization in each subgroup.

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