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Short-term effects of low-level $PM_{2.5}$, PM_{10}, O_3, and tropical meteorological conditions on emergency department visits for respiratory diseases in Haikou, China

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ABSTRACT

Objective: To assess the correlation between atmospheric pollutants, meteorological factors, and emergency department visits for respiratory diseases in Haikou City.

Methods: Daily data on atmospheric pollutants, meteorological factors, and emergency department visits for respiratory diseases in Haikou City from 2018 to 2021 were collected. The Spearman rank correlation test was used to analyze the correlation, and a distributed lag non-linear model was employed to analyze the health effects and lag impacts of environmental factors. Subgroup analyses were conducted based on sex and age.

Results: According to the criteria of International Classification of Diseases (ICD-10: J00-J99), a total of 221 913 cases were included, accounting for 21.3% of the total emergency department visits in Haikou City. For every 1 ℃ increase in temperature, the risk of emergency department visits increased by 1.029% (95% *CI* 1.016%-1.042%). Relative humidity greater than 80% reduced the risk of visits, while higher atmospheric pressure (>1 010 hpa) also decreased the likelihood of daily emergency department visits. Higher concentrations of $PM_{2.5}$ (30-50 μg/m^3), PM_{10} (>60 μg/m^3), and O_3 (75-125 μg/m^3) were associated with increased visits. Higher temperatures (>25 ℃) have a greater impact on females and children aged 0-14 years, while males are more sensitive to low atmospheric pressure. Individuals aged 65 and above exhibited increased sensitivity to O_3 concentration, and the effects of $PM_{2.5}$, PM_{10}, and O_3 are more pronounced in individuals over 14 years old.

Conclusions: Short-term exposure to high temperatures, particulate matter pollutants ($PM_{2.5}$ and PM_{10}), and ozone (O_3) is associated with increased emergency department visits for respiratory diseases.

KEYWORDS: Distributed lag nonlinear model; Meteorological factors; Air pollution; Emergency department visits; Respiratory diseases

Significance

This study enhances comprehension regarding the impact of air pollutants and meteorological factors on emergency department visits by exploring both the exposure effect and lag effect. Furthermore, it aids in the allocation of emergency medical resources within hospitals, offering a scientific foundation for establishing a rational and efficient health early warning system in relevant departments.

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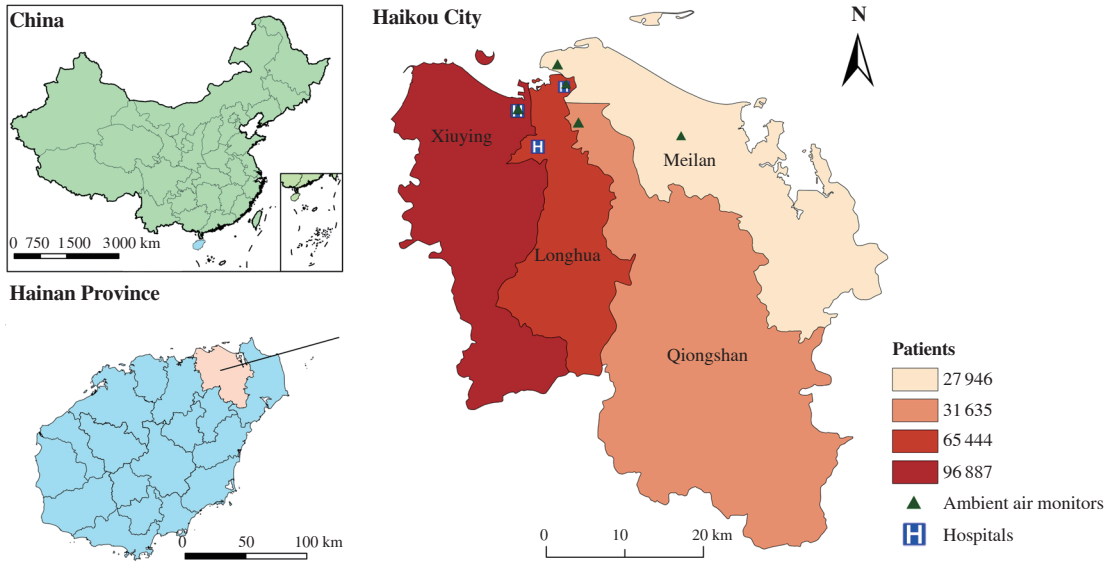

Figure 1. The geographical location of Haikou City, hospital sites, positions of ambient air monitors, and the catchment area of study participants.

1. Introduction

The global pandemic of corona virus disease 2019 (COVID-19), caused by SARS-CoV-2, has been recognized by the World Health Organization as a worldwide emergency in 2020[1]. The outbreak and continued prevalence of COVID-19 have had significant impacts on various aspects of human life worldwide. Studies indicate that during the COVID-19 pandemic, the reduction in human activities has led to substantial improvements in air quality[2,3]. It is well-established that atmospheric pollution and meteorological factors independently contribute to respiratory diseases[4,5]. Respiratory diseases, including chronic obstructive pulmonary disease, asthma, influenza, bronchopneumonia, upper and lower respiratory tract diseases, and interstitial lung diseases, pose a substantial economic burden on the society. Numerous studies have shown that respiratory diseases are associated with atmospheric pollution across all age groups[6-8]. Meteorological factors also influence the development and severity of respiratory diseases. Research indicates that both high and low temperatures are related to the incidence and mortality rates of respiratory diseases, and relative humidity is associated with the exacerbation of these diseases[9-11]. It is believed that relative humidity can reduce the total suspended particles in the air. Atmospheric pollutants include various harmful substances such as particulate matter pollutants, gas pollutants, metals, and organic compounds. Major pollutants in the air include particulate matter with aerodynamic diameters <2.5 μm ($PM_{2.5}$), particulate matter with aerodynamic diameters <10 μm (PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3), and both short-term and long-term exposure can impact human health and reduce lifespan.

Using emergency department-related data for assessing environmental factors and their health effects is more time-sensitive and representative. Current epidemiological research results vary, possibly due to factors such as geographical location, climate characteristics, and population demographics[12,13]. A study in Lanzhou City, China on atmospheric pollution and upper respiratory tract infections, revealed that short-term exposure to atmospheric pollutants, especially SO_2 and CO, was associated with an increased emergency department visits[14]. Research suggests that relative humidity between 40% and 60% may be healthier than levels between 20% and 30%[15]. A study from South Korea confirmed that $PM_{2.5}$, PM_{10}, CO, NO_2, O_3, SO_2, temperature, and humidity, in various patterns, affect the exacerbation of chronic obstructive pulmonary disease[16]. Another study by Lee *et al.*[17] confirmed that emergency department respiratory patients mostly presented with acute upper respiratory tract infections, influenza, and pneumonia, while temperature, atmospheric pressure, and PM_{10} had an impact on these diseases. When atmospheric pressure and temperature values are low and atmospheric pollution variables are high, the number of emergency department visits increases.

In the tropical regions of China, further research is needed to explore the association between meteorological factors, exposure to atmospheric pollutants, and emergency department visits for respiratory diseases. In recent years, as economic development has

progressed, there has been increasing attention to meteorological conditions and air pollution. Hainan has minimal heavy industry, and low air pollution levels in China. In this low-pollution context, the impact of tropical meteorological factors on emergency department visits for respiratory diseases is not clear yet. Therefore, this study aims to investigate the potential effects of low-level atmospheric pollution and tropical meteorological conditions on emergency department visits for respiratory diseases. The goal is to provide targeted protection and disease prevention measures for susceptible populations in similar regions.

2. Materials and methods

2.1. Study area and study population

Haikou is the capital city of Hainan Province in China, characterized by a tropical monsoon climate with an average annual temperature of 24.4 ℃ (Figure 1). The data, including both outpatient and inpatient medical records, were extracted from the hospitalization information system of three tertiary grade A comprehensive hospitals in Haikou, Hainan, China. The data spans from January 1, 2018, to December 31, 2021, encompassing daily emergency department visits. The International Classification of Diseases, 10th Revision was used for selecting the respiratory system diseases in the analysis (ICD-10: J00-J99). Key information encompasses patient names, ages, sex, visit dates, disease categories, and current addresses.

2.2. Pollutants and meteorological data

Data were collected from January 1, 2018, to December 31, 2021, including daily meteorological data and atmospheric pollutant concentrations. Meteorological data, including daily average temperature and atmospheric pressure, were obtained from the Hainan Provincial Meteorological Bureau. Atmospheric pollutant data was sourced from the China Air Quality Online Monitoring Platform (https://www.aqistudy.cn/historydata/), encompassing $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3. The average concentrations of NO_2, SO_2, CO, $PM_{2.5}$, and PM_{10} represent 24-hour averages, while the average concentration for O_3 was based on the maximum 8-hour value.

2.3. Statistical analysis

This study was conducted using Microsoft Excel 2019 for data cleaning and processing of raw data, and the daily emergency department visits related to respiratory diseases wss filtered out. The inclusion criteria were based on the International Classification of Diseases coding standards (ICD-10: J00-J99). Descriptive statistics were conducted on emergency case data, meteorological data, and atmospheric pollutant data using SPSS22.0. Through RStudio software, the Spearman rank correlation analysis method was employed to explore the correlation between emergency department visits and meteorological factors, as well as atmospheric pollutants. Relevant factors influencing emergency visits for respiratory diseases were identified. The Spearman correlation coefficient is a non-parametric measure of dependence between two ordinal variables, using a monotonic function to assess the correlation between two statistical variables[18]. As the data does not follow a normal distribution, Spearman correlation analysis was employed, and all correlation coefficients passed the *t*-test, indicating statistical significance ($P<0.05$). Previous studies have confirmed the complex relationship between atmospheric pollution and meteorological factors[19]. To avoid multicollinearity issues, when the absolute value of the correlation coefficient between two atmospheric pollutants or two meteorological factors exceeded 0.5, it was considered to have a moderately high linear correlation[20]. Therefore, when constructing the model, both factors were not simultaneously included.

The distributed lag non-linear model (DLNM) was established using mgcv, splines, dlnm, and ggplot2 packages in *R* 4.2.0 software. The median (P_{50}) of individual factors served as the reference value, and the relative risk (*RR*) with a 95% confidence interval (95% *CI*) was used to assess the impact of each factor on emergency department visits for respiratory diseases. Two-tailed tests were conducted, with $P<0.05$ considered statistically significant.

2.4. Construction of the distributed lag nonlinear model

The daily emergency department visits for respiratory diseases were combined with atmospheric pollutants and meteorological factors and linked by date. Time series analysis was employed to estimate the overall correlation during the entire study period (2018-2021). Throughout the study period, the population change in Haikou City was not significant, and the daily emergency department visits for respiratory diseases roughly followed a Poisson distribution. Due to the observed over-dispersion in the data, standard Poisson methods might lead to larger errors. Therefore, in this study, quasi-Poisson distribution was used instead of Poisson distribution[21,22]. Numerous studies indicate that environmental factors exhibit nonlinear and lagged effects on

human health outcomes[23,24]. Hence, we employed a distributed lag nonlinear model with quasi-Poisson distribution to investigate the lagged impact of atmospheric pollutants and meteorological factors on emergency department visits for respiratory diseases.

The core idea of the DLNM is to incorporate cross-basis functions into a generalized additive model, allowing for simultaneous estimation of exposure and lag effects[25]. In this study, individual models were developed for each atmospheric pollutant or meteorological factor. When constructing single-factor models, in addition to connecting the studied factor with daily emergency department visits for respiratory diseases in the form of a base function, other factors were included in the model as confounding factors in the form of natural spline functions. Simultaneously, to control the long-term trend of time variables, time variables were included in the model in the form of natural spline functions. To control for the "day of the week effect" and "holiday effect" on daily visits, day of the week variables and holiday variables were included in the model as dummy variables and binary categorical variables, respectively. The final model expression is as follows:

$$\text{Log}\,[E(Y_t)]=\alpha+\beta X_{t,l}+\text{ns}(\text{Time}_t, df * \text{year})+\sum \text{ns}(X_i, df)+\text{as. factor}(\text{dow}_t)+\text{as. factor}(\text{holiday}_t)$$

Where log [E (Y_t)] is the link function and Yt is the number of emergency department visits on day t; $E(Yt)$ is the mathematical expectation of emergency department visits on day t; α is the intercept of the model; $X_{t,l}$ is a two-dimensional matrix of the variables studied obtained by the "crossbasis" function in the DLNM model; l indicates the maximum lag days and β is the coefficient of the matrix; ns indicates the use of a natural cubic spline function as a smoothing function to control the effect of confounders, and $Time_t$ is a time series variable used to control long-term trends and seasonal effects, df is the degree of freedom, $year$ is the year of study; X_i is other air pollutants or meteorological factors not included in the model; *as. factor* is a function in *R* language used to convert the transmitted object into factor; dow_t is a categorical variable that refers to which day of the week has an impact and is included in the model as a dummy variable to control its impact. $holiday_t$ is a binary variable used to control the holiday effects.

Due to the observed over-dispersion in the data, we employed Akaike's quasi-Poisson information criterion (Q-AIC) to determine the degrees of freedom for each variable in the model[26]. Ultimately, we determined that the degrees of freedom for atmospheric pollutants or meteorological factors not included in the model were set to 3, and the degrees of freedom for time variables were set to 8. In reviewing previous literature, we set the maximum lag days to 14 days[27,28].

3. Results

3.1. Descriptive statistical analysis

From January 1, 2018, to December 31, 2021, spanning a total of 1 461 days, there were a total of 221 913 emergency department visits for respiratory diseases. Among these, there were 123 186 male visits, accounting for 55.5%, and 98 727 female visits, accounting for 44.5%. The male-to-female ratio was 1.25:1 (Table 1). During the years 2020-2021, the daily emergency department visits increased slightly, with minimal variations in meteorological conditions. Apart from an elevation in O_3 concentration, the concentrations of other pollutants showed a significant decrease (Table 2).

Table 1. Statistical characteristics of emergency department (ED) visits for respiratory diseases in Haikou City from 2018 to 2021.

Variables	ED visits (%)
Total	221 913 (100.0)
Male	123 186 (55.5)
Female	98 727 (44.5)
≤14 years	76 870 (34.6)
15-64 years	109 885 (49.5)
≥65 years	35 158 (15.9)

Table 2. Descriptive statistics of daily emergency department visits for respiratory diseases, meteorological factors, and atmospheric pollutants in Haikou City from 2018 to 2021.

Variables	2018-2021	2018-2019	2020-2021
Total	152.0±44.5	146.0±42.4	157.0±45.9
Male	84.0±25.6	79.0±23.8	89.0±26.2
Female	68.0±21.2	67.0±20.6	68.0±21.8
Age, years			
≤14	45 (40.0)#	41.0±19.0	63 (50.0)#
15-64	75.0±25.7	82.0±24.2	680±25.4
≥65	24.0±9.9	230.0±8.5	25.0±11.0
Meteorology			
Temperature (℃)	25.2±4.4	25.20±4.30	25.3±4.5
RH (%)	80.3±8.2	80.53±8.20	80.1±8.2
ST (h)	5.6 (7.5)#	5.9(7.4)#	5.2 (7.4)#
WS (m/s)	2.8±0.8	2.8±0.8	2.8±0.9
AP (hap)	1 004.0±3.2	1 003.9±6.4	1 004.2±6.0
Air pollution (μg/m^3)			
$PM_{2.5}$	13 (10.0)#	14 (10.0)#	12 (10.0)#
PM_{10}	30.2±13.2	31.9±13.4	28.4±12.8
NO_2	11.4±4.8	12.6±4.5	10.2±4.8
SO_2	4.6±1.8	4.9±1.4	4.3±2.1
CO	0.5±0.1	0.6±0.1	0.5±0.1
O_3	77.8±32.5	76.0±34.1	79.6±30.7

RH: Relative humidity, ST: Sunny time, WS: Wind speed, AP: Air pressure, 24-h averages for NO_2, SO_2, and CO; the maximal 8-h average for O_3. #: Non-normal data, expressed as median (IQR).

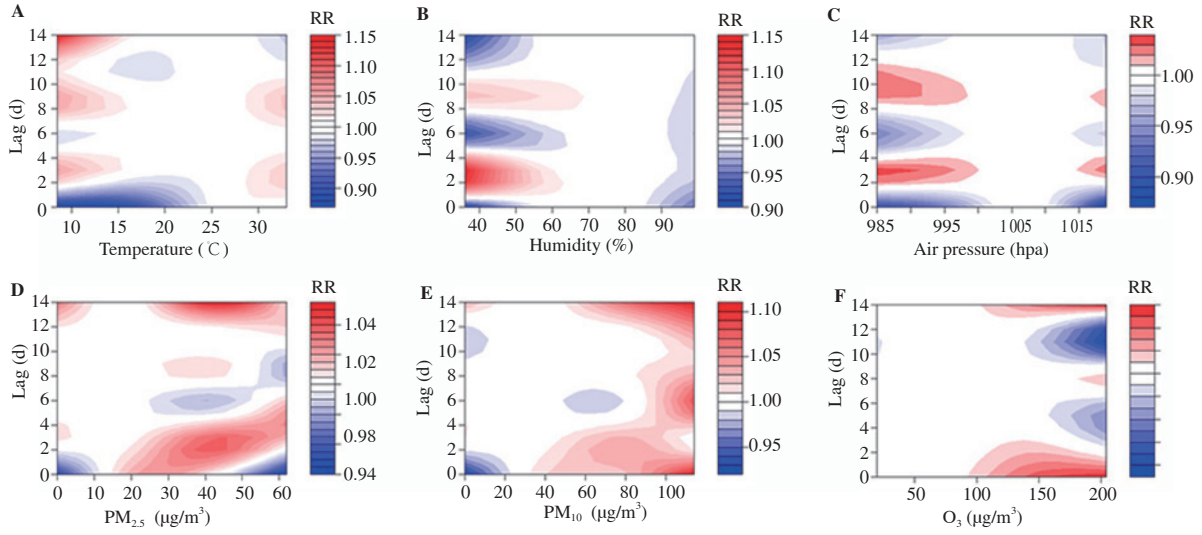

Figure 2. Contour graphs of different contributing factors on emergency department visits for respiratory diseases at different lag days from 2018 to 2021, red areas indicate hazardous effects and blue areas indicate protective effects, with the median of each factor as the reference value.

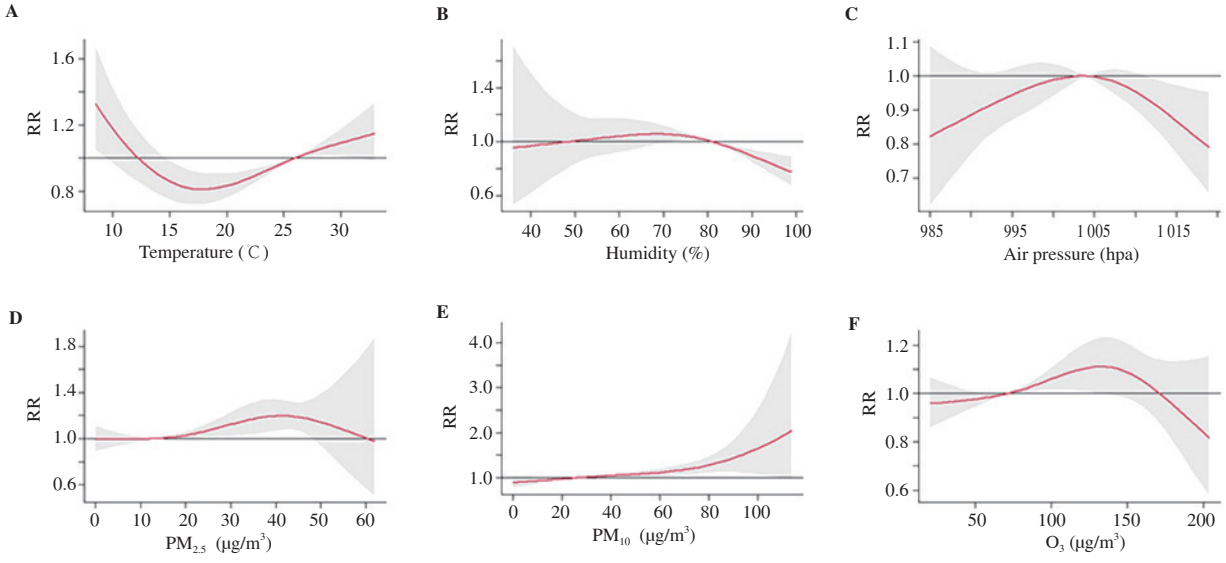

Figure 3. Exposure-response curves (red solid lines) and 95% confidence intervals (grey areas) between different contributing factors and relative risks of emergency department visits for respiratory diseases from 2018 to 2021, with the median of each factor as the reference value.

3.2. Correlation analysis

In Supplementary Material S1, daily emergency department visits for respiratory diseases were positively correlated with atmospheric pollutants, demonstrating significant correlations. They were positively correlated with atmospheric pressure (r=0.24) and negatively correlated with temperature (r=-0.14) and relative humidity (r=-0.12).

3.3. Analysis by DLNM

Based on the results of the Spearman correlation analysis, temperature, relative humidity, atmospheric pressure, $PM_{2.5}$, PM_{10}, and O_3 were individually included in the analysis model, with the results presented using the median of each factor as the reference value.

In Figure 2, the impact of each factor on emergency department visits exhibits a lag effect starting from day 0 and persists throughout the entire lag period. When the daily average temperature was 8 ℃

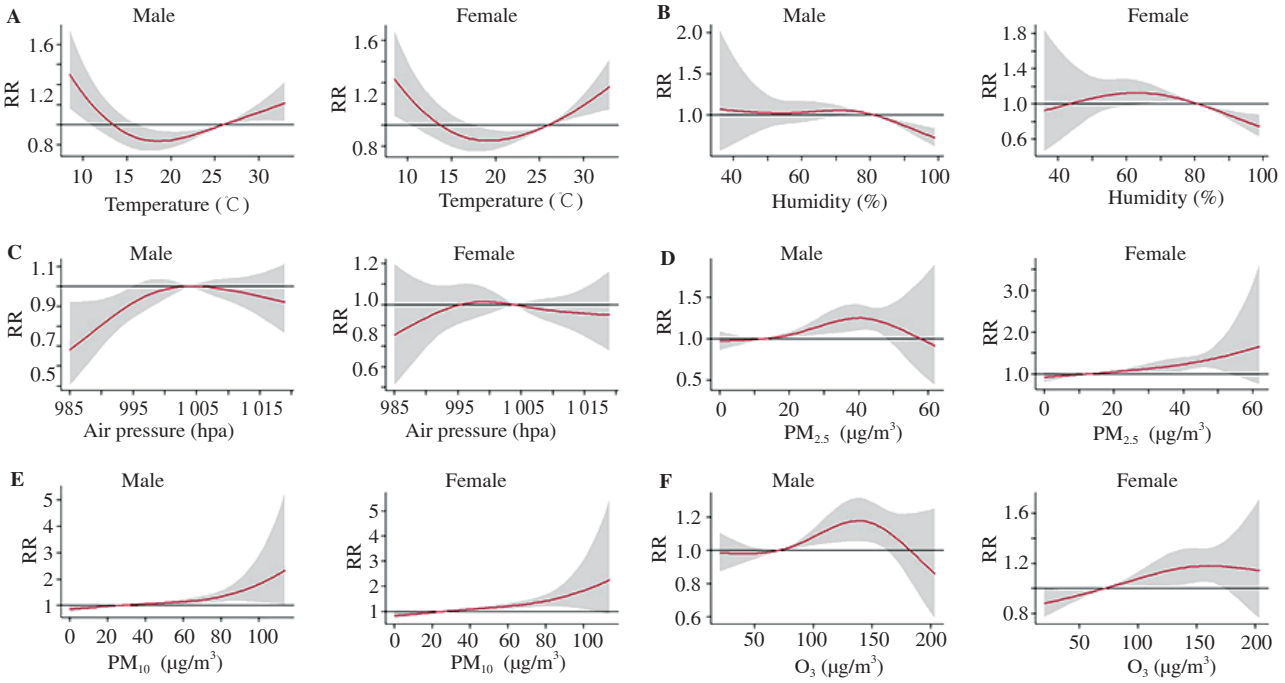

Figure 4. Exposure-response curves (red solid lines) and 95% confidence intervals (grey areas) between different contributing factors and relative risks of emergency department visits for respiratory diseases by sex from 2018 to 2021, with the median of each factor as the reference value.

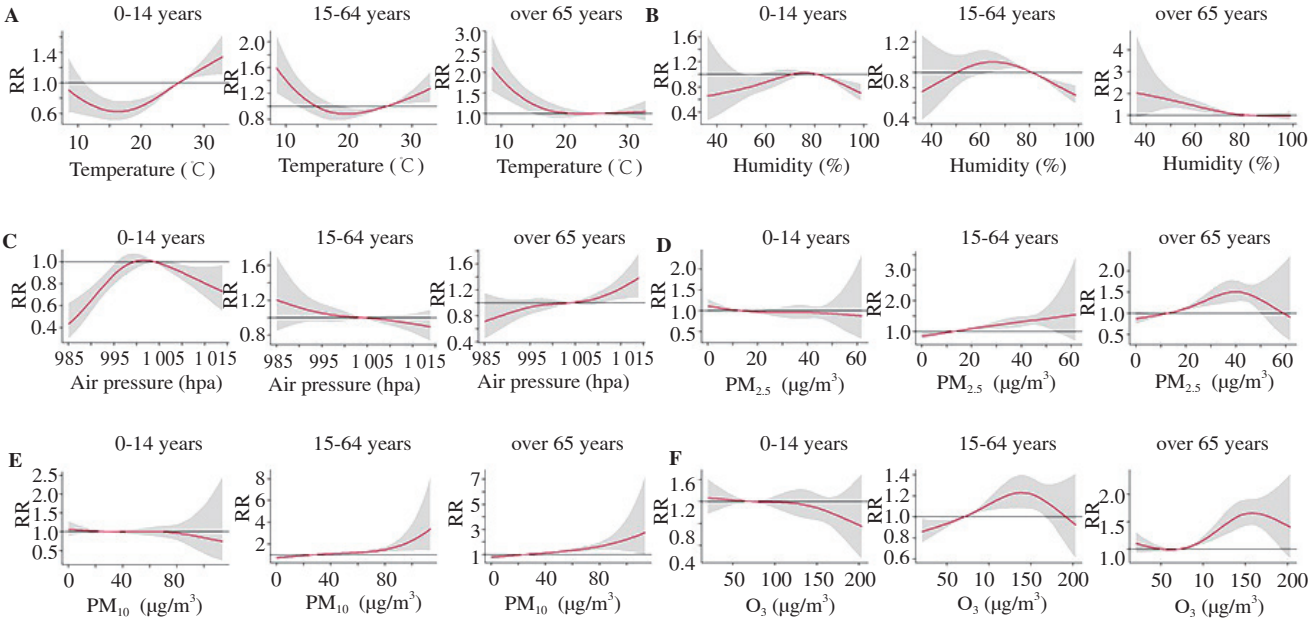

Figure 5. Exposure-response curves (red solid lines) and 95% confidence intervals (gray areas) between different contributing factors and relative risks of emergency department visits for respiratory diseases at different age groups from 2018 to 2021, with the median of each factor as the reference value. A: Temperature (℃), B: Humidity (%), C: Air pressure (hpa), D: $PM_{2.5}$ (μg/m^3), E: PM_{10} (μg/m^3), F: O_3 (μg/m^3).

Table 3. Single-day lag effects and cumulative lag effects and 95% confidence intervals of different temperatures and air pressure on emergency department visits for respiratory diseases.

Lag (d)	Temperature (℃)		Air pressure (hpa)	
	14	32	992	1 017
Lag 0	0.900 (0.828, 0.977)*	1.020 (0.943, 1.104)	0.914 (0.858, 0.975)*	0.884 (0.811, 0.964)*
Lag 1	0.948 (0.915, 0.983)*	1.022 (0.988, 1.056)	0.976 (0.949, 1.003)	0.955 (0.916, 0.996)*
Lag 3	1.006 (0.959, 1.055)	1.022 (0.979, 1.067)	1.042 (0.999, 1.086)	1.040 (0.997, 1.086)
Lag 5	0.985 (0.945, 1.027)	1.018 (0.979, 1.059)	0.990 (0.953, 1.029)	0.997 (0.958, 1.036)
Lag 7	1.003 (0.972, 1.035)	1.013 (0.984, 1.042)	0.972 (0.945, 1.001)	0.977 (0.946, 1.010)
Lag 9	1.010 (0.967, 1.054)	1.015 (0.976, 1.056)*	1.007 (0.969, 1.047)	0.996 (0.958, 1.034)
Lag 11	0.961 (0.916, 1.008)	1.015 (0.973, 1.059)	1.028 (0.987, 1.070)	0.988 (0.948, 1.029)
Lag 14	1.021 (0.946, 1.102)	0.952 (0.891, 1.017)	0.965 (0.907, 1.026)	0.918 (0.859, 0.980)*
Lag 0-1	0.853 (0.763, 0.954)*	1.042 (0.938, 1.158)	0.892 (0.820, 0.971)*	0.845 (0.746, 0.956)*
Lag 0-3	0.848 (0.753, 0.954)*	1.089 (0.980, 1.209)	0.952 (0.870, 1.042)	0.891 (0.780, 1.018)
Lag 0-5	0.834 (0.728, 0.957)*	1.131 (1.013, 1.262)*	0.964 (0.880, 1.057)	0.912 (0.786, 1.057)
Lag 0-7	0.825 (0.700, 0.972)*	1.162 (1.017, 1.328)*	0.910 (0.821, 1.009)	0.871 (0.725, 1.046)
Lag 0-9	0.848 (0.708, 1.014)	1.194 (1.032, 1.380)*	0.905 (0.811, 1.011)	0.856 (0.693, 1.057)
Lag 0-11	0.801 (0.658, 0.975)*	1.233 (1.059, 1.437)*	0.951 (0.850, 1.064)	0.842 (0.672, 1.055)
Lag 0-14	0.776 (0.614, 0.980)*	1.150 (0.964, 1.373)	0.927 (0.815, 1.055)	0.709 (0.544, 0.923)*

*P<0.05.

Table 4. Single-day lag effects and cumulative lag effects and 95% confidence intervals of different air pollutants on emergency department visits for respiratory diseases.

Lag (d)	PM_{10} (μg/m^3)		O_3 (μg/m^3)	
	9	68	30	168
Lag 0	0.959 (0.919, 1.001)	1.002 (0.926, 1.084)	0.995 (0.944, 1.048)	1.080 (1.007, 1.159)*
Lag 1	0.982 (0.962, 1.003)	1.000 (0.965, 1.037)	1.007 (0.981, 1.033)	1.040 (1.002, 1.080)*
Lag 3	1.009 (0.986, 1.031*	0.995 (0.951, 1.041)	1.018 (0.988, 1.048)	0.989 (0.950, 1.030)
Lag 5	0.998 (0.978, 1.019)	0.984 (0.945, 1.025)	1.007 (0.980, 1.036)	0.993 (0.956, 1.031)
Lag 7	1.000 (0.984, 1.017)	0.982 (0.951, 1.013)	1.007 (0.986, 1.029)	1.018 (0.987, 1.051)
Lag 9	0.997 (0.976, 1.018)	0.984 (0.944, 1.025)	1.005 (0.977, 1.033)	1.003 (0.965, 1.043)
Lag 11	0.976 (0.954, 0.999)*	0.993 (0.951, 1.037)	0.989 (0.960, 1.018)	0.961 (0.922, 1.002)
Lag 14	1.025 (0.990, 1.062)	1.072 (1.001, 1.148)*	0.991 (0.946, 1.038)	1.071 (1.007, 1.139)*
Lag 0-1	0.942 (0.887, 1.001)	1.002 (0.899, 1.117)	1.002 (0.931, 1.078)	1.124 (1.014, 1.245)*
Lag 0-3	0.951 (0.888, 1.018)	0.995 (0.886, 1.118)	1.035 (0.950, 1.126)	1.121 (0.987, 1.273)
Lag 0-5	0.954 (0.887, 1.026)	0.969 (0.857, 1.097)	1.056 (0.961, (1.161)	1.096 (0.950, 1.266)
Lag 0-7	0.951 (0.874, 1.034)	0.934 (0.807, 1.081)	1.069 (0.958, 1.192)	1.123 (0.954, 1.323)
Lag 0-9	0.951 (0.869, 1.041)	0.903 (0.766, 1.066)	1.083 (0.961, 1.221)	1.150 (0.962, 1.375)
Lag 0-11	0.913 (0.829, 1.006)	0.883 (0.738, 1.057)	1.067 (0.938, 1.215)	1.079 (0.888, 1.311)
Lag 0-14	0.919 (0.822, 1.028)	0.994 (0.814, 1.215)	1.029 (0.890, 1.191)	1.143 (0.908, 1.439)

*P<0.05.

and a lag of 13-14 days, the likelihood of emergency department visits reached the highest. For temperatures between 8 ℃ and 25 ℃, a lower temperature is associated with a lower visit risk during a lag of 0-2 days. Relative humidity peaks at 33%, with the highest number of daily visits observed at a lag of 3 days. Concerning atmospheric pressure, values between 984.9 hpa and 1 000 hpa are linked to a risk of increase in daily visits during Lag 2-Lag 4 and Lag 9-Lag 12. A $PM_{2.5}$ concentration of approximately 40 μg/m^3 results in the highest visit risk with a lag of 14 days. For PM_{10} concentration, ranging from 80 to 115 μg/m^3, higher visit risks are associated with Lag 0-Lag 1, Lag 4-Lag 7, and Lag 12-Lag 14. O_3 concentration exceeding 100 μg/m^3 corresponds to a risk of an increase in daily visits with a lag of 0-3 days.

In Figure 3, the effect curve of temperature on emergency department visits for respiratory diseases exhibits a "V" shape, indicating a lower visit risk when the temperature is between 15 ℃ and 25 ℃. The visit risk decreases when relative humidity exceeds 80%. When the atmospheric pressure >1 010 hpa, higher pressure is associated with less daily visits. A statistically significant risk of increase in daily visits is observed when $PM_{2.5}$ concentration ranges from 30 to 50 μg/m^3. For PM_{10} concentration, a higher concentration (>60 μg/m^3) is linked to a risk of increase in daily visits. O_3 concentration in the range of 75-125 μg/m^3 is associated with a risk of increase in daily visits.

In Figure 4, the effect curves for various factors on emergency department visits exhibit similar patterns for different sexes. Males are more susceptible to the impact of low temperatures (<10 ℃), while females are more affected by high temperatures (>25 ℃). The influence of relative humidity on sex differences is minimal, with less daily visits observed when relative humidity exceeds 80%. Lower atmospheric pressure is associated with a reduced possibility of emergency department visits for males. In addition, males' emergency department visits demonstrate greater sensitivity to O_3 concentration, while the impact of $PM_{2.5}$ and PM_{10} on sex differences is relatively slight.

In Figure 5, children (aged 0-14 years) are more susceptible to the impact of high temperatures (>25 ℃), while people aged 65 years and above are easier to be influenced by low temperatures (<15 ℃) and the age group experience a greater impact when humidity is between 40% and 60%. When humidity exceeds 80%, the visit risk for children decreases. Besides, children exhibit greater resilience to low atmospheric pressure, while people aged 65 years and above are more likely to be affected by higher atmospheric pressure. The effects of $PM_{2.5}$, PM_{10}, and O_3 are more pronounced in individuals aged 15 and above.

In Table 3 and Table 4, percentiles at the 1st and 99th percentiles for each factor in the years 2020-2021 were selected, with the median as the reference value. The relative risk (*RR*) values and 95% confidence intervals (*CI*) for specific factors influencing emergency department visits for respiratory diseases were calculated at different lag days. The lag effects of temperature are particularly pronounced. At a temperature of 14 ℃, with a cumulative lag of 7 days, daily visits reduced. Conversely, at a temperature of 32 ℃, with a cumulative lag from the 5th to the 11th day, a risk of increase in daily visits was observed. When the average daily concentration of PM_{10} was 9 μg/m^3, a lag effect began to appear on day 11, showing a protective effect, and when the average daily concentration of PM_{10} was 68 μg/m^3, a lag effect began to appear on day 14, showing a negative effect; when the average daily concentration of O_3 was 168 μg/m^3, a lag effect began to appear on the same day, showing a negative effect, which disappeared after 2 days, and when the average daily concentration of O_3 was 168 μg/m^3, a lag effect began to appear on the cumulative day, showing a negative effect, which disappeared after 1 day.

As shown in Supplementary Material S2, during the optimal lag period, a 1 ℃ increase in temperature increased the likelihood of daily emergency department visits by 1.029% (95% *CI* 1.016%-1.042%). A 1% increase in relative humidity increased the likelihood of daily emergency department visits by 0.998% (95% *CI* 0.997%-0.999%). For atmospheric pressure, $PM_{2.5}$, PM_{10}, and O_3, a 10-unit increase in concentration is associated with an increased likelihood of daily emergency department visits by 0.947% (95% *CI* 0.909%-0.986%), 1.056% (95% *CI* 1.029%-1.085%), 1.041% (95% *CI* 1.015%-1.067%), and 1.023% (95% *CI* 1.007%-1.039%), respectively.

3.4. Sensitivity analyses

The sensitivity analysis results are presented in Supplementary Material S3, where different factor total effect plots on the lagged impact of emergency department visits for respiratory diseases were generated by varying the degrees of freedom for the time variable (*df*=7-10). The results indicate that as the degrees of freedom for the time variable change, the effect plots remain close to each other, suggesting that the parameter settings are appropriate, and the model is stable.

4. Discussion

Haikou City is located in the northern part of Hainan Province, with a sub-tropical region and a tropical monsoon climate. The air pollution levels are relatively low in this area. Studies on the health effects of atmospheric pollutants and tropical meteorology in this area are scarce, making it essential to fill this research gap. In this study, temperature, humidity, atmospheric pressure, $PM_{2.5}$, PM_{10}, and O_3 demonstrated significant impacts on emergency department visits for respiratory diseases. These results have sparked interest in understanding the implications for public health in the region.

In terms of overall effect differences, the findings of this study indicate that when the temperatures are between 15 ℃ and 25 ℃, the daily emergency visits for respiratory disease are reduced, consistent with previous research results[29]. This suggests that a suitable temperature range may reduce the incidence of respiratory diseases. Higher temperatures (>25 ℃) increase the visit risk, aligning with the climatic characteristics of tropical regions where high temperatures and humidity create favorable conditions for the survival and proliferation of certain pathogens in the respiratory tract, promoting the occurrence of respiratory diseases. Another explanation could be that high temperatures contribute to increased concentrations of air pollutants, indirectly affecting respiratory systems. When humidity exceeds 80%, the number of visits decreases, contrary to the notion that high humidity pollution increases the risk of disease occurrence[30]. It is noteworthy that

Haikou has abundant precipitation and relatively low air pollution, yet may experience behavioral changes in patients during rainy days. In an open environment, lower temperatures and higher atmospheric pressure are associated with a reduced visit risk, possibly due to the climatic characteristics of the region, where people may be more susceptible to temperature influences. Exposure to atmospheric pollutants is closely linked to the occurrence of respiratory diseases in the population. The results reveal that when the concentrations of $PM_{2.5}$, PM_{10}, and O_3 reach certain levels, higher concentrations are associated with an increased visit risk. These findings align with previous reports[31,32]. $PM_{2.5}$, a known culprit for chronic obstructive pulmonary disease development and decreased lung function, can reach the respiratory tract through inhalation[33,34]. Furthermore, chemicals with oxidizing capabilities can impact the respiratory and immune systems[35]. Particulate matter carries metal components, and organic compounds possess the ability to generate oxygen-free radicals, stimulating cells to produce reactive oxygen species (ROS) and inducing oxidative stress and inflammatory reactions in the lungs, leading to the occurrence of respiratory diseases[36,37]. O_3, one of the most common air pollutants, reacts upon inhalation, generating ROS and enhancing local oxidative stress, inflammation, and damage to epithelial cells[38]. The impact of these factors varies among different demographic groups. Higher temperatures (>25 ℃) have a greater influence on females and children aged 0-15 years, possibly due to increased outdoor activities among younger individuals when temperatures are higher, while the number of elderly people (aged 65 and above) outdoors decreases. When humidity exceeds 80%, it reduces the visit risk for children, possibly because rainy weather keeps children indoors, either at school or at home. Elderly individuals are more susceptible to the influence of higher atmospheric pressure, and males exhibit greater sensitivity to O_3 concentrations. The effects of humidity, $PM_{2.5}$, and PM_{10} on sex differences are relatively small, possibly associated with Haikou's low pollution levels. $PM_{2.5}$, PM_{10}, and O_3 have a greater impact on individuals aged 14 and above. One explanation is that engage in fewer outdoor activities and experience lower pollution levels, while another explanation is that children have poorer self-reliance in seeking medical care. In terms of the lag effect, temperature and air pressure have a greater impact on the health of the population, and the cumulative lag effect is more obvious. PM_{10} and O_3 have a slightly smaller impact on the population, which may be due to the limited specific values selected and the low level of air pollution in Haikou City.

Overall, various factors have a greater impact on the elderly. When considering sex, differences in physiological factors and individual sensitivity lead to varying outcomes. Interestingly, this study found that the influence of $PM_{2.5}$ and PM_{10} on sex differences is minimal, contrary to previous reports suggesting that women are more susceptible to $PM_{2.5}$, and men are more sensitive to PM_{10}[39]. Similarly, previous research indicated that due to narrower airways, ongoing lung development, immature immune systems, and longer outdoor exposure, children and the elderly are more vulnerable to the effects of $PM_{2.5}$ and PM_{10}[40,41]. In this study, a minor impact of $PM_{2.5}$ and PM_{10} on children was observed, possibly due to lower levels of air pollution in Haikou and increased susceptibility to tropical meteorological influences. However, under this pollution pattern, the population's susceptibility warrants further investigation. The results of this study have profound implications for public health and climate change. In the short term, high concentrations of atmospheric pollutants such as $PM_{2.5}$, PM_{10}, and O_3 may stimulate the respiratory tract, leading to exacerbated acute respiratory symptoms including coughing, wheezing, and asthma attacks. Sudden changes in meteorological factors such as temperature, humidity, and air pressure may also induce respiratory discomfort in the short term[42]. During abrupt changes in meteorological conditions or increased exposure to atmospheric pollutants, individuals may experience stress responses, such as immune system modulation, resulting in decreased respiratory system adaptation to external environmental conditions and increased incidence of respiratory diseases[43–45]. In the long term, prolonged exposure to high-pollution environments may lead to the development of chronic respiratory diseases such as chronic obstructive pulmonary disease and bronchial asthma[46]. These diseases may gradually worsen over time, impacting patients' quality of life and life expectancy. Additionally, long-term exposure may affect immune system function, rendering individuals more susceptible to respiratory infections and inflammation, thereby increasing the incidence of chronic respiratory diseases. Furthermore, this can impose long-term burdens on society and the economy, including increased healthcare costs and reduced labor productivity. In summary, short-term and long-term effects intertwine, with short-term effects exacerbating acute symptoms and triggering sudden events, while long-term effects may lead to the progression of chronic diseases and increased socioeconomic burdens[47]. Therefore, it is imperative to comprehensively consider the implications of these results and formulate corresponding prevention and management strategies. For instance, strengthening air quality monitoring and meteorological warning systems, promoting emission reduction measures, providing health education, and implementing personal protective measures. It requires joint efforts from individuals and society to adopt proactive lifestyles and environmental management measures to effectively mitigate the impact of high pollution days and extreme

weather events on public health and safeguard the well-being of the population.

The potential limitations of this study should not be overlooked. The employed methodology, time-series analysis, is an ecological study that did not account for factors such as microbiology, socioeconomic status, education level, and individual lifestyle habits, which could introduce exposure bias. The study focused on a single city and collected emergency department case data from three major hospitals in Haikou, potentially excluding all potential patients. Moreover, the study did not collect data on individual exposure levels, which could have a certain impact on the results. Further efforts are needed to address the influence of environmental factors on population health. In addition, this study did not include COVID-19 patients as these patients were triaged to designated clinics.

Short-term exposure to adverse environmental factors such as high temperatures, fine particulate matter ($PM_{2.5}$ and PM_{10}) pollution, and O_3 imposes an additional burden on China's already overloaded healthcare system, particularly in hospital emergency departments. Given the anticipated worsening of air pollution with economic development and the rapid climate changes, this situation may be exacerbated. The findings of this study contribute to a better understanding of the association between air pollutants, meteorological factors, and emergency department visits for respiratory diseases. This understanding is crucial for evaluating the health effects of climate change on the population and provides a scientific basis for relevant authorities to formulate preventive measures.

Conflict of interest statement

There are no conflicts of interest in this manuscript, and the manuscript is approved by all authors.

Data availability

Meteorological data were obtained from the Hainan Meteorological Bureau, and air pollution data were collected from the China Air Quality Online Monitoring Platform (https://www.aqistudy.cn/historydata/). Because of the confidentiality requirements of this study, the emergency department dataset was not made publicly available but could be obtained from the corresponding author on reasonable request.

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Authors' contributions

JCP was responsible for the conception and design of the study, JQ, JCL, WXZ, ZYL, and ZL were responsible for data gathering, JC, XXW, YY, NL, YH, and ML were responsible for data analysis, JCP drafted the manuscript, XRL responsible for the critical review of the paper. All authors participated in the interpretation of the data.

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