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Short-term ambient particulate matter pollution of different sizes and respiratory hospital admission in the Beibu Gulf area of Southern China

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HIGHLIGHTS

- A time-stratified case-crossover design is constructed to estimate the associations.
- A large-scale, high-quality, and multisite representative dataset is used.
- Increased risk of respiratory hospitalizations associated with particulate matter.
- Male in the warm season is more vulnerable to the impacts of particulate pollution.
- 7% of respiratory hospitalizations is attributable to short-term exposure of $PM_{2.5}$.

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ABSTRACT

Background: Ambient particulate matter (PM) pollution is associated with occurrence of respiratory diseases; however, limited evidence exists on the effects of PM_1 due to lack of ground-based PM_1 measurements.
Objective: To examine the associations of short-term exposure to PM_1, $PM_{2.5}$ and PM_{10} with respiratory hospital admission, as well as the attributable burden.
Methods: A total of 558,012 respiratory hospital admissions records were collected from 15 cities in the northeast Beibu Gulf of China from 2013 to 2016. Short-term exposures to pollutants (PM_1, $PM_{2.5}$ and PM_{10}) were estimated using a bilinear interpolation approach at residential addresses. A time-stratified case-crossover design was constructed to estimate the associations and the burden of respiratory admissions attributable to ambient air pollution.
Results: We observed significant associations between PM and respiratory hospitalizations. Odds ratios per 10 μg/m^3 increment in two-day averaged concentration were 1.017 (95% CI: 1.012, 1.021) for PM_1, 1.010 (95% CI: 1.007, 1.013) for $PM_{2.5}$, and 1.007 (95% CI: 1.006, 1.009) for PM_{10}. Males in the warm season appeared to be more vulnerable to the impacts of ambient PM pollutants. We further estimated that 3.0% (95% CI: 2.7%, 3.2%), 6.5% (95% CI: 5.9%, 6.8%) and 1.8% (95% CI: 1.6%, 1.9%) of respiratory hospital admissions were attributable to short-term exposure of PM_1, $PM_{2.5}$ and PM_{10}, respectively.

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Conclusions: Short-term exposure to ambient PM might be an important risk factor for respiratory diseases hospital admissions. If environmental PM air pollutants were reduced to current guideline levels set forth by the government, a substantial proportion of respiratory hospitalizations would be mitigated as a result.

1. Introduction

Respiratory illnesses, including pneumonia, acute lower respiratory tract infections (ALRI), and chronic obstructive pulmonary disease (COPD), cause high mortality rates as well as steep health care costs (Özmen et al., 2018; Renzi et al., 2022). From 1990 to 2017, the disability-adjusted life years increased from 97.2 to 112.3 million a year across 195 countries and air pollution is an established risk factor for some of this increase (Li et al., 2020; Ruan et al., 2021). Exposure to ambient particulate matter diameter <2.5 μm ($PM_{2.5}$) and diameter <10 μm (PM_{10}) is linked with increased respiratory disease hospitalizations and mortality rate (Atkinson et al., 2014; Brunekreef and Holgate, 2002; de Oliveira Fernandes et al., 2020; Viegi et al., 2020). In a meta-analysis conducted in Italy on the excess risk of total respiratory disease due to ambient PM, it was reported that excess risks of total respiratory diseases were 1.20% and 1.22% for per 10 μg/m^3 increment in PM_{10} and $PM_{2.5}$ (Renzi et al., 2022). PM health effects are related to particle size and smaller particles cause greater toxic impact (Wang et al., 2021b). Therefore, extremely fine particles with aerodynamic diameter ≤1 μm (PM_1) have been of increased interest in recent years. However, due to the lack of ground-level PM_1 measurements, there is a gap in the research regarding large-scale, multisite evidence on the risk of PM_1 on the respiratory illness burden.

The relationships between air pollutants and respiratory disease in past studies varied by region (Dong et al., 2021; Jin et al., 2022; Sun et al., 2017); therefore, compiling reports from different regions can create a comprehensive profile of the PM adverse health impacts. Although air quality in China has improved significantly in recent years (Zhang et al., 2019), the annual concentrations of PM in China were still substantially greater than the guidelines set forth by the World Health Organization (WHO) (Al-Aly and Bowe, 2021) and the consequent disease burden remained substantial (Yang et al., 2020); it was estimated that around 1.2 million deaths were attributable to ambient PM in 2017 (Zhou et al., 2019). Therefore, large-scale, high-quality, and multisite evidence is needed to inform policies aimed at mitigating PM pollution in China. Previous studies in China have focused on economic hubs of the region (e.g., the Pearl River Delta region) (Han et al., 2019), and there was a lack of research focusing on the ethnic minority residents in the Beibu Gulf Region of China, who lacked access to public health and medical resources.

The current study aims to estimate the relationship between short-term exposure to three common particulate pollutants and respiratory hospitalizations in 15 cities of the northeast Beibu Gulf in Southern China. Analysis will include the evaluation of possible dose-response relationships and susceptibility characteristics as well as the assessment of respiratory hospitalizations attributable to ambient PM pollution.

2. Materials and methods

2.1. Study population

The research was carried on in 15 cities in the northeast Beibu Gulf, where 14 cities were located in Guangxi Zhuang Autonomous Region (Guangxi ZAR) and one was in Zhanjiang City in Guangdong Province. This area is situated in the coastal region of southwest China, with an area of more than 250,000 square kilometers and a population of more than 50 million (Fig. 1). Classified as subtropical and tropical monsoon climates, the weather is consistently warm with abundant rain, adequate light, and frequent meteorological disasters, such as tropical storms and typhoons (Han et al., 2019; Zhang et al., 2022a, 2022b).

Electronic admission records (EARs) data was obtained from all the hospitals in the study area; this data was collected by the local Health Commission from January 8, 2013 to November 30, 2016, and contained over 50 variables, including sociodemographic characteristics (e.g., age, sex, date of birth), diagnosis codes (i.e., outpatient and emergency diagnosis, principal diagnosis code, and up to two secondary diagnosis codes), length of stay, service charges in subcategories and discharge outcomes. The EARs were collected according to a national standard and using the International Classification of Diseases, Tenth Revision (ICD-10). All patient identifiers were excluded. Exclusionary criteria included patients who had missing information or unknown sex, whose difference between self-reported age and the age calculated by self-reported date of birth was more than one year, and whose addresses cannot be translated into latitude and longitude or whose longitude and latitude of the address were out of the geographical scope of the study. This study included 4,521,405 patients with complete basic information. Respiratory diseases were defined as the primary outcome of interest and were diagnosed based on the ICD-10 codes provided in the EARs. Particularly, the following ICD codes were determined to be of interest: total respiratory illnesses (ICD-10: J00-J99), ALRI (J10-J18, J20-J22 and J40), pneumonia (J12-J18), and COPD (J40-J44).

2.2. Study design

It was used that a time-stratified case-crossover design in this study to investigate the relationship between short-term exposure to ambient PM and hospital admission for respiratory diseases (Liu et al., 2019, 2021; Zhang et al., 2020b). This study design has unique advantages in controlling for individual inherent social and biological characteristics or time-trend bias in exposure, due to the cases themselves serving as matched controls (Zhang et al., 2020a, 2020b). For each admission patient, admission date was defined as the case day; control days of non-cases were the days surrounding the case day, sharing the same year, month, and day of week (DOW). This approach controlled for the effects of DOW, seasonality, and long-term trend. Therefore, a case day was allocated 3 to 4 control days to assess referent exposures. For example, if a patient was admitted to hospital on the second Tuesday of November 16 (November 8, 2016), all other Tuesdays (November 1, 15,

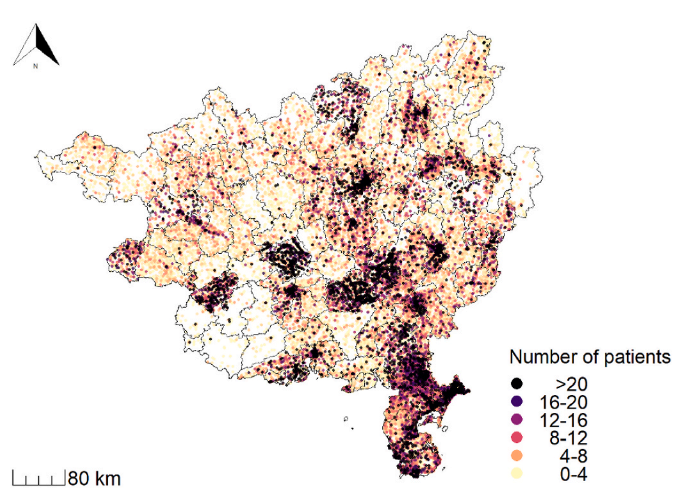

Fig. 1. Spatial distributions of 558, 012 total respiratory diseases admissions' home addresses (points) in 15 cities of the northeast Beibu Gulf, China.

22, and 29, 2016) in November 2016 were regarded as the control days.

2.3. Air pollution and meteorological data

Average daily concentrations of PM_1, $PM_{2.5}$, PM_{10}, sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbonic oxide (CO) were collected from the ChinaHighAirPollutants (CHAP) dataset (10 km × 10 km grids), which were generated combining satellite remote sensing, ground-based measurements, atmospheric reanalysis, and model simulations. A detailed description of this estimation and prediction procedure has been described in previous studies (Wei et al., 2019a, 2021a, 2021b, 2022a, 2022b). Daily mean temperatures and average daily dew point temperatures for each grid were obtained from ECMWF Reanalysis v5. Humidity was calculated using the *humidity* package in R software based on temperature and dew point temperature. Exposures to air pollutants and meteorological variables were estimated using the bilinear interpolation method (Cai et al., 2022a, 2022b). Specifically, the home addresses of hospitalized patients with respiratory diseases were geocoded applying Baidu Map API. For every hospitalized patient with a respiratory disease, exposure to environmental variables on the same day of hospital admission (lag 0) was assessed by computing interpolation of known values at four vertexes of the grid corresponding to the home address. Lag exposures of a single-day (lag 1 to lag 6) and moving average day (lag 01 to lag 06) were also estimated. The definition of the lag days has been described elsewhere (Xu et al., 2022).

2.4. Statistical analyses

The correlations between ambient pollutants and meteorological factors were assessed using Spearman's coefficients. Additionally, conditional logistic regression models were utilized to determine the association between PM exposures with different lags and the hospital admissions. The effects of temperature and relative humidity on same day hospitalization and 3-days prior to the hospitalization were controlled for in the model analyses (Zhang et al., 2020b). A spline function (6 degree of freedom (DOF) for temperature and 3 DOF for relative humidity) was used to control for the non-linear effect (Liu et al., 2019). Individual-covariates (e.g., sex) were not counted as potential confounding variables since they remained invariable for the duration of the study.

The respiratory admissions of each 10 μg/m^3 increment in PM_1, $PM_{2.5}$ and PM_{10} were assessed over 6 days, using odds ratios (ORs) and 95% confidence intervals (CIs) for every pollutant. Additionally, a natural cubic spline function was conducted with 3 DOF to explore nonlinearity of the relationship and to draw any exposure-response curves (Liu et al., 2019).

Stratified analyses by sex (male, female), age (≤14, 15–44, 45–74, ≥75 years), and season were conducted in order to identify if effect modification was occurring. Effect modification was identified by contrasting stratification-specific estimators of ORs using the point estimate and standard error (Liu et al., 2019). Seasons were categorized as "cool" and "warm", and their criteria were defined elsewhere (Chen et al., 2020).

Several sensitivity analyses were conducted, including two-pollutant model analyses. To avoid collinearity issues, analyses were not conducted if two pollutants had a correlation coefficient higher than 0.7 (Zhang et al., 2020a). Additionally, the DOF of temperature was modified to 3, 4 or 5 respectively, to examine the impact of the DOF selection. Furthermore, to better compare the impact of different air pollutants, the association between per Interquartile Range (IQR) increase of air pollutants and respiratory admission was evaluated.

2.5. Population attributable burden

Population attributable fraction (PAF) was calculated using the equation below (Chen et al., 2022b):

$$AN_i = \sum_{j=1}^{n} 1 - \frac{1}{exp(\beta_i * \Delta C_i)}$$

$$\text{PAF} = \text{AN} / \text{n}$$

where "*AN*" is the attributable number; "*i*" is the day when the effect is most pronounced; "*β*" is the point effect estimate (ln odds ratio) of PM exposure on the day *i*; "*ΔC*" is the difference between the PM exposure for each subject on the day *i* and the reference concentration of PM established by the National Ambient Air Quality Standards (NAAQS); since NAAQS did not develop standards for PM_1, the 95th percentile was used as the threshold. Thus, PAF is equal to the calculated AN divided by total number of hospital admissions for each pollutant.

All analyses were performed applying R version 4.1.1. We utilized the *survival* package for conditional logistic regression analysis. All *p* values were two-sided.

3. Results

3.1. Descriptive analysis

A total of 558,012 (12%) inpatient cases for respiratory illnesses from a total of over 4.5 million inpatient cases during the study period were comprised in the principal data analysis (Fig. 1 and Table 1). Of the 4,521,405 inpatient cases, 4% had the primary diagnosis of pneumonia and 2% had COPD. Among hospitalized individuals with respiratory diseases, the median age at hospitalization was 31 years (IQR: 1–68 years); 45% of the admitted were under 14 years old, 18% were over 75 years old. Additionally, 61% were male and 53% were hospitalized during the warm season (Table 1).

The mean concentrations of PM_1, $PM_{2.5}$, PM_{10}, SO_2, NO_2 and CO during the case days were 26.2 μg/m^3, 39.9 μg/m^3, 61.8 μg/m^3, 17.8 μg/m^3, 21.5 μg/m^3 and 1.0 mg/m^3, respectively. And during control days, those were 26.0 μg/m^3, 39.7 μg/m^3, 61.6 μg/m^3, 17.7 μg/m^3, 21.4 μg/m^3 and 1.0 mg/m^3, respectively (Table 2).

3.2. Correlations between pollutants and meteorological variables

PM_1, $PM_{2.5}$, PM_{10}, NO_2, and SO_2 were positively correlated with each other. The correlation coefficients were higher than 0.70 except for

Table 1
Baseline characteristics, 2013–2016.

Characteristics	Statistics
Total respiratory diseases	558, 012
ALRI (%)	267, 597 (47.96)
Pneumonia (%)	195, 566 (35.05)
COPD (%)	83, 582 (14.98)
Case days (%)	558, 012 (22.74)
Control days (%)	1, 896, 038 (77.26)
Sex (%)	
Male	340, 886 (61.09)
Female	217, 126 (38.91)
Age (year)	
Mean (SD)	35.16 (33.15)
Median (IQR)	31 (67)
0-14	252, 098 (45.21)
15-44	56, 281 (10.07)
45-74	150, 831 (27.03)
75+	98, 802 (17.69)
Season [a]	
Warm	295, 903 (53.11)
Cool	262, 109 (46.89)

Definition of abbreviations: SD = standardized deviation; IQR = interquartile range; ALRI = acute lower respiratory tract infection; COPD = chronic obstructive pulmonary disease.

[a] Warm season was from April to September, while cool season was from January to March, and from October to December.

Table 2
Distributions of pollutants and meteorological variables during case and control days in 15 cities of the northeast Beibu Gulf, China, 2013–2016.

type		Mean	SD	Min	P_{25}	Median	P_{75}	Max
case	Air pollutant [a]							
	PM_1, μg/m^3	26.155	14.785	0.001	16.027	22.820	32.778	165.805
	$PM_{2.5}$, μg/m^3	39.906	25.406	0.002	23.028	33.836	50.015	391.853
	PM_{10}, μg/m^3	61.842	34.744	0.004	39.300	53.720	76.219	429.713
	SO_2, μg/m^3	17.760	9.932	0.001	11.383	16.212	21.757	229.729
	NO_2, μg/m^3	21.513	10.369	0.002	15.099	19.765	26.047	114.934
	CO, mg/m^3	0.979	0.300	0	0.826	0.965	1.135	5.447
	Meteorological condition [a]							
	Temperature, °C	20.727	7.064	−2.468	15.638	22.830	26.526	32.783
	Relative humidity, %	76.142	16.613	0.006	71.187	80.659	86.322	99.845
control	Air pollutant [a]							
	PM_1, μg/m^3	26.033	14.733	0.001	15.978	22.623	32.607	166.464
	$PM_{2.5}$, μg/m^3	39.697	25.386	0.002	22.880	33.686	49.726	443.729
	PM_{10}, μg/m^3	61.577	34.883	0.003	39.063	53.456	75.891	448.405
	SO_2, μg/m^3	17.719	9.843	0.001	11.393	16.184	21.733	304.720
	NO_2, μg/m^3	21.423	10.258	0.002	15.069	19.733	25.945	116.338
	CO, mg/m^3	0.977	0.300	0	0.825	0.964	1.132	5.610
	Meteorological condition [a]							
	Temperature, °C	20.691	7.091	−3.108	15.535	22.823	26.533	32.845
	Relative humidity, %	76.168	16.631	0.006	71.169	80.678	86.386	99.825

Definition of abbreviations: SD = standardized deviation; P_{25} = the 25th percentile; P_{75}, the 75th percentile; PM_1 = particulate matter with an aerodynamic diameter ≤1 μm; $PM_{2.5}$ = particulate matter with an aerodynamic diameter ≤2.5 μm; PM_{10} = particulate matter with an aerodynamic diameter ≤10 μm; SO_2 = sulfur dioxide; NO_2 = nitrogen dioxide; CO = carbon monoxide.

[a] 24-h average concentration for pollutants, and 24-h average value for meteorological variables.

those between SO_2 and PM_1, SO_2 and NO_2, and CO and all other pollutants (all $p < 0.05$) (Fig. S1). Those with correlation coefficients higher than 0.70 were excluded due to collinearity concerns.

3.3. Associations between PM and respiratory hospital admissions

Fig. 2 features the positive relationships between PM_1, $PM_{2.5}$ and PM_{10} (lag 0 to lag 6, lag 01 to lag 06) and the hospital admissions; the associations at lag 01-days were the strongest. The ORs for each 10 μg/m^3 increment in PM_1 (lag 01), $PM_{2.5}$ (lag 01), and PM_{10} (lag 01) were 1.017 (95% CI: 1.012, 1.021), 1.010 (95% CI: 1.007, 1.013) and 1.007 (95% CI: 1.006, 1.009), respectively. PM_1, $PM_{2.5}$ and PM_{10} exhibited generally similar lag patterns, in which the respiratory hospitalizations associated with them showed a trend of increasing first and then decreasing as the lag day increases. Table S1 presents detailed estimates.

PM_1, $PM_{2.5}$, and PM_{10} significantly elevated hospital admissions for ALRI, pneumonia and COPD (Table S1). The results from Fig. 3 and Fig. S2 confirmed the assumption of linear correlations between PM_1, $PM_{2.5}$ and PM_{10} and hospitalization for respiratory diseases, ALRI, pneumonia, and COPD.

3.4. Subgroup analysis by sex, age, and season

In the sex, age and season stratified analyses (Table 3), the effects of PM were different among the subgroups, indicating effect modification. Males admitted to hospital with respiratory diseases were more likely to be affected by the effects of PM_1, $PM_{2.5}$ and PM_{10} than females with ORs of 1.023 (95% CI: 1.017, 1.029), 1.014 (95 CI%: 1.010, 1.017) and 1.010 (95% CI: 1.008, 1.012), respectively (all p for effect modification <0.05). Contrasted with those ≤14 years of age, people in the 15–44 and 45–74 age groups had significantly lower odds for all PM exposure ($p < 0.05$). The increasing concentration of particulate pollutants had a generally stronger effect on hospitalization for respiratory diseases in the warm season than in the cool season (except for the p value of effect modification of $PM_{10} > 0.05$). For instance, per 10 μg/m^3 increment in PM_1, the ORs were 1.027 (95% CI: 1.019 to 1.036) in warm season and 1.010 (95% CI: 1.005 to 1.016) in cool season. ($p < 0.05$).

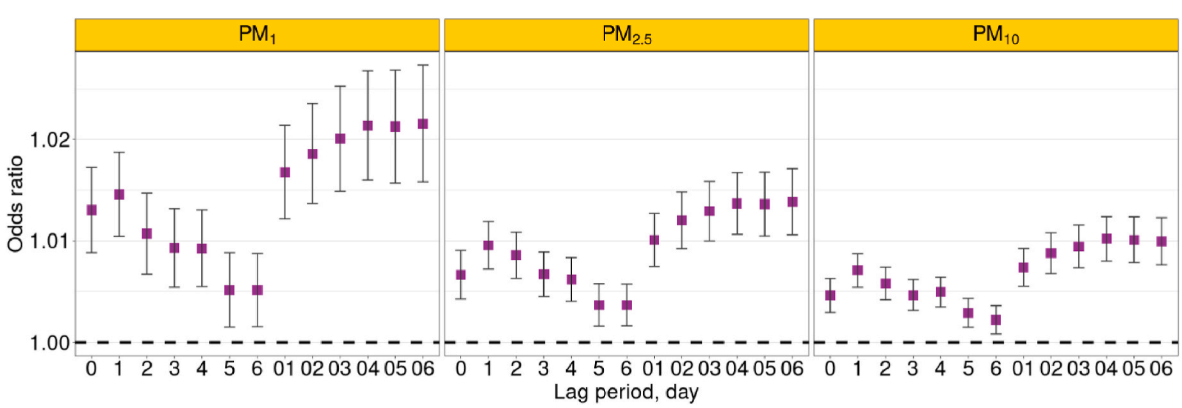

Fig. 2. ORs (95% CIs) for respiratory diseases admission associated with each 10 μg/m^3 increase in PM_1, $PM_{2.5}$ and PM_{10} with different lag periods.
ORs (95% CIs) were estimated using conditional logistic regression models, adjusting for temperature and relative humidity.
Definition of abbreviations: OR = odds ratio; CI = confidence interval; PM_1 = particulate matter with an aerodynamic diameter ≤1 μm; $PM_{2.5}$ = particulate matter with an aerodynamic diameter ≤2.5 μm; PM_{10} = particulate matter with an aerodynamic diameter ≤10 μm.

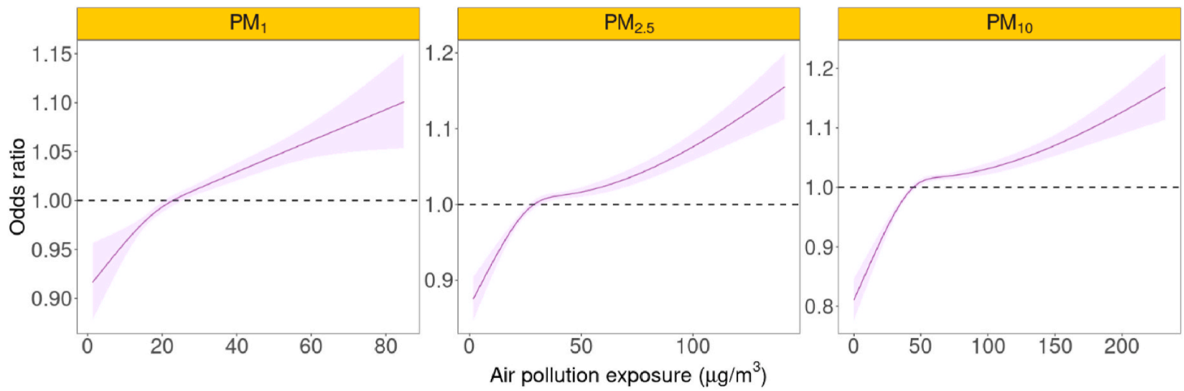

Fig. 3. The dose-response curves between PM_1, $PM_{2.5}$, PM_{10} and respiratory diseases admission.
The lines and ribbons represent ORs and the 95% CIs, respectively, which were estimated for continuous exposures using conditional logistic regression models, adjusting for temperature and relative humidity. Definition of abbreviations: OR = odds ratio; CI = confidence interval; PM_1 = particulate matter with an aerodynamic diameter ≤1 μm; $PM_{2.5}$ = particulate matter with an aerodynamic diameter ≤2.5 μm; PM_{10} = particulate matter with an aerodynamic diameter ≤10 μm.

Table 3
Odds ratios (95% CIs) for total respiratory diseases admission associated with each 10 μg/m^3 increase in PM_1, $PM_{2.5}$ and PM_{10} stratified by sex, age, and season[a].

	PM_1		$PM_{2.5}$		PM_{10}	
	OR (95% CI)	P value[b]	OR (95% CI)	P value[b]	OR (95% CI)	P value[b]
Sex						
Male	1.023 (1.017, 1.029)	0.001	1.014 (1.010, 1.017)	0.001	1.010 (1.008, 1.012)	0.001
Female	1.007 (1.000, 1.015)		1.004 (1.000, 1.009)		1.003 (1.000, 1.006)	
Age						
0–14	1.021 (1.014, 1.028)	Reference	1.014 (1.010, 1.018)	Reference	1.010 (1.007, 1.013)	Reference
15–44	0.991 (0.977, 1.005)	<0.001	0.994 (0.985, 1.002)	<0.001	0.995 (0.989, 1.001)	<0.001
45–74	1.008 (0.999, 1.017)	0.029	1.004 (0.999, 1.009)	0.001	1.002 (0.999, 1.006)	0.001
75+	1.034 (1.023, 1.045)	0.040	1.018 (1.012, 1.024)	0.307	1.014 (1.010, 1.018)	0.142
Season[c]						
Warm	1.027 (1.019, 1.036)	0.001	1.017 (1.011, 1.024)	0.005	1.010 (1.006, 1.014)	0.145
Cool	1.010 (1.005, 1.016)		1.008 (1.005, 1.011)		1.006 (1.004, 1.009)	

Definition of abbreviations: PM_1 = particulate matter with an aerodynamic diameter ≤1 μm; $PM_{2.5}$ = particulate matter with an aerodynamic diameter ≤2.5 μm; PM_{10} = particulate matter with an aerodynamic diameter ≤10 μm; OR = odds ratio; CI = confidence interval.
[a] ORs (95% CIs) were estimated using conditional logistic regression models, adjusting for temperature and relative humidity. And the lag periods for PM is lag 01.
[b] P value < 0.05 indicates significant effect modification.
[c] Warm season was defined as April to September, while cool season was defined as January to March, and October to December.

3.5. Population attributable fraction

Table 4 indicates the estimated PAF and AN attributable to ambient PMs concentrations higher than the NAAQS's guidelines. Overall, about 3.0% (95% CI: 2.7%, 3.2%), 6.5% (95% CI: 5.9%, 6.8%) and 1.8% (95% CI: 1.6%, 1.9%) of hospitalizations for respiratory diseases could be attributable to exceeding PM_1, $PM_{2.5}$ and PM_{10} exposure, respectively.

Table 4
Population fraction of hospital admission for total respiratory diseases attributable to PM_1, $PM_{2.5}$ and PM_{10}.

Pollutants	Attributable number		Attributable fraction	
	n	95%CI	%	95%CI
PM_1[a]	16589.68	14939.24, 17698.08	2.97	2.68, 3.17
$PM_{2.5}$	36024.68	32910.54, 38110.89	6.46	5.90, 6.83
PM_{10}	10072.90	9024.13, 10823.06	1.81	1.62, 1.94

Definition of abbreviations: CI = confidence interval; PM_1 = particulate matter with an aerodynamic diameter ≤1 μm; $PM_{2.5}$ = particulate matter with an aerodynamic diameter ≤2.5 μm; PM_{10} = particulate matter with an aerodynamic diameter ≤10 μm.
[a] Since National Ambient Air Quality Standards did not develop standards for PM_1, we used the 95th percentile as the threshold.

3.6. Sensitivity analysis

Adjusting for other gaseous pollutants did not significantly alter the estimated associations of PM_1, $PM_{2.5}$, PM_{10} exposures (Table S2). Changing the DOF from 3 to 5 for temperature showed the similar effects (Table S3). It also remained robust that the associations between each IQR increment of air pollution exposure and respiratory admission (Tables S4–S5).

4. Discussion

The current study examined impacts of three particulate pollutants on hospitalizations for respiratory illnesses in 15 cities in the northeast Beibu Gulf using the time-stratified case-crossover design from January 8, 2013 to November 30, 2016. Significant associations between hospitalizations for respiratory diseases and PM_1, $PM_{2.5}$ and PM_{10} were determined; this association was stronger in males than females as well as more powerful during the warm season than the cold season.

The study area included Guangxi ZAR and Zhanjiang City in Guangdong Province, which is the only coastal area in western China, the most convenient outlet to the sea in southwest China, and an important gateway and frontier for the Chinese mainland to access Southeast Asia, Africa, Europe, and Oceania. Ethnic minorities in the region account for a relatively large proportion of the permanent population; the Guangxi ZAR accounts for 40% of this population. Due to unbalanced development in China, this part of the southwest region is economically underdeveloped compared with the eastern coastal areas of China. Although the level of medical and health resources has improved, the allocation between different cities is uneven, and it is still requisite to continue to concern about the development of health services in the area.

These discoveries are broadly concordant with those from previous researches for PM. Particularly, current epidemiological evidence on the adverse effects of short-term exposure to ambient $PM_{2.5}$ on the number of hospitalizations for respiratory illnesses is generally consistent globally (Atkinson et al., 2014). For PM_{10}, our study also found similar results to previous studies carried out in different cities: positive associations existed between $PM_{2.5}$ and PM_{10} and total respiratory admission (Dong et al., 2021; Franck et al., 2015; Qiu et al., 2018).

The most marked finding in the study was the estimated association of respiratory diseases admission (OR = 1.017; 95% CI = 1.012, 1.021) with each 10 μg/m^3 increment in PM_1. Although few past studies have examined the short-term effects of PM_1 exposure on hospitalizations for respiratory illnesses, a case-crossover study using hospital data from Shenzhen, China, found similar results (OR: 1.09, 95% CI: 1.04 to 1.14 with per 10 μg/m^3 increment in PM_1) (Zhang et al., 2020b). One research in Vietnam also showed that each 10 μg/m^3 increase in PM_1 was associated with a 2.5% increase in the risk of respiratory hospitalization on the same day of exposure (Luong et al., 2017). The biological mechanisms of this association have been described before (Wang et al., 2021a); PM_1 possibly penetrated tracheobronchial regions due to Brownian diffusion and caused strong respiratory health effects (Wang et al., 2021a). PM_1 could also contain more toxic components due to its high surface-area-to-volume ratio (Wang et al., 2021a). All this suggests that the health hazards of smaller particles deserve attention. These findings may have significant public health implications for local and regionally targeted PM pollution control. In addition, positive associations between PM and hospital admissions were observed not only for total respiratory diseases but also for subgroups of respiratory diseases (ALRI, pneumonia, and COPD), which was comparable to other studies (Chen et al., 2022a; DeVries et al., 2017; Renzi et al., 2022; Song et al., 2014; Yee et al., 2021).

However, the results of effect modification by sex do not align with previous studies (Zhang et al., 2020b). Here, higher effect estimates were observed in males than in females across all three particulate pollutants on respiratory hospitalization. Similar findings were reported in Sichuan Basin, China, but the differences between effect estimates were not found to be statistically significant (Qiu et al., 2018). In contrast, one study including 213 USA counties observed that women were more vulnerable to $PM_{2.5}$-associated respiratory disease hospital admissions than men (Bell et al., 2015). Two other national $PM_{2.5}$/PM_{10}-hospitalization investigations, one from China (Liu et al., 2018) and one from Italy (Renzi et al., 2022), also showed inconsistencies in effect modification by sex; the national study conducted in China indicated that there had no statistical difference in the effect between sex (DeVries et al., 2017) while the study conducted in Italy found that females were more susceptible (Renzi et al., 2022). Possible explanations included different activity patterns and subsequent exposures of the study populations (Renzi et al., 2022).

The prevailing notion is that children and the elderly are more vulnerable to health hazards due to different physiological states, the length of time spent outdoors, or other reasons (Qiu et al., 2018; Renzi et al., 2022). The study observed that children (≤14 years) were more vulnerable to the PM exposures compared with people aged 15–74 years. The elderly population was more likely to be at risk for PM-related respiratory diseases than children to put down to impaired immune defenses and decreased respiratory function (Qiu et al., 2018). In addition to age-related physiological changes, indoor or outdoor activity patterns and social networks may play an important role in increased exposures for the elderly (Bell et al., 2013).

While seasonal patterns of short-term PM-hospitalization associations were investigated in this study, the results were not consistent. Stronger effects in the cold season than in the warm season of PM-associated risks of respiratory disease hospital admissions were observed in a subtropical city—Shenzhen (Zhang et al., 2020b), while others showed larger effects in the warm season, such as one study in Southern Europe (Stafoggia et al., 2016). In addition, both Italian studies observed that PM_{10}-related hospital admission risk estimates for respiratory diseases were stronger in the warm than in the cool seasons (Carugno et al., 2016; Faustini et al., 2013). Our study also observed stronger effects in the warm season than that in the cool season, which was similar to the results from the study in Sichuan basin, China (Qiu et al., 2018). The differences observed between the effect estimates may be due to the special climate conditions and participants' socioeconomic status (Qiu et al., 2018). Increased biomass burning during the warm season, which is served as the main source of pollution in the study area, may also result in the stronger effect of PM in the warm season (Mao et al., 2018). The potential causes of seasonal variation in these effect estimates should be further investigated.

This study estimated the burden of hospitalizations for respiratory illnesses in 15 cities of the northeast Beibu Gulf; these findings suggested that PMs were responsible for substantial respiratory burden of hospital admissions in the southwest city clusters. Using the 95th percentile (55 μg/m^3 for PM_1) and NAAQS's guideline (75 μg/m^3 for $PM_{2.5}$, 150 μg/m^3 for PM_{10}) as reference, 3.0% (95% CI: 2.7%, 3.2%), 6.5% (95% CI: 5.9%, 6.8%) and 1.8% (95% CI: 1.6%, 1.9%) of hospitalizations for respiratory diseases were attributable to PM_1, $PM_{2.5}$ and PM_{10}, respectively.

These discoveries are concordant with past researches (Cao et al., 2021; Stafoggia et al., 2016). Zhao et al. observed that 8.3% of the total respiratory morbidity were attributable to $PM_{2.5}$ in Dongguan, China, using the 25 μg/m^3 from WHO as reference concentration (Zhao et al., 2017; Zhu et al., 2019). Martinez et al. estimated that reducing $PM_{2.5}$ levels to the European Union limit (25 μg/m^3) could have averted an estimated 19.6% of PM-attributable hospital admissions for respiratory disease; while achieving the WHO Air Quality Guidelines (10 μg/m^3) could have averted an estimated 49.6% of PM-attributable hospitalizations for respiratory illness in the Metropolitan Area of Skopje (Martinez et al., 2018). In conclusion, this study adds to the evidence that PM-pollution might increase the burden of hospitalization for respiratory diseases, which underscores the great public health potential for local governments to reduce the burden of respiratory diseases ascribed to ambient PM through powerful air purification actions across the study area. Future epidemiological studies of air pollution are still needed to target vulnerable populations, which can go a long way towards effective public health intervention actions for policy makers.

There are several strengths to this study. Firstly, the study included almost all complete hospital admissions of the Guangxi ZAR and Zhanjiang City in Guangdong Province. Secondly, the CHAP database was created by utilizing satellite measurements. This approach facilitated estimating pollutants concentrations in fine spatial scale areas where monitoring sites are sparse or nonexistent and where the changes in daily PM concentrations could be better estimated. Thirdly, this study included 558,012 respiratory disease admissions; this large sample size increased the statistical power of the study and illuminated effect estimates that possibly would not have been discovered in a smaller study. Fourthly, this study also utilized statistical methods that are standard in this area of research. Lastly, the time-stratified case-crossover design minimized autocorrelation of multiple independent variables and confounding.

Several limitations should be noted. The study lacked indoor pollution data and individual movements; this might lead to significant exposure uncertainty, given that the present study used ambient PM outdoors (Cai et al., 2022b). In addition, PM composition was not characterized which may cause varying effect magnitudes (Strickland et al., 2016; Wang et al., 2022). Furthermore, given the strong correlation among PM_1, $PM_{2.5}$ and PM_{10}, it is difficult to investigate whether PM_1 has an independent effect. Lastly, due to restrictions in data availability, the first hospital admission could not be fully separated from repeated hospital admission for respiratory diseases (Wei et al., 2019b). The aforementioned limitations limited the ability to make a causal conclusion in the present study (Chen et al., 2020; Lu et al., 2020).

5. Conclusions

The results suggest a positive association between short-term exposure to PM_1, $PM_{2.5}$ and PM_{10} and hospitalization for respiratory illnesses. The estimated effect of PM is stronger in males and in patients admitted in the warm season. These findings are overall similar to previous studies. There are significant limitations to the study that inhibit a causal inference from being concluded.

Data statement

Due to the sensitive nature of the data used in this study, survey respondents were assured raw data would remain confidential and would not be shared.

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CRediT authorship contribution statement

Haopeng Li: Conceptualization, Formal analysis, Writing – original draft, Visualization. **Lizhong Liang:** Investigation, Resources. **Shiyu Zhang:** Methodology. **Zhengmin (Min) Qian:** Writing – review & editing. **Miao Cai:** Methodology. **Xiaojie Wang:** Writing – review & editing. **Stephen Edward McMillin:** Writing – review & editing. **Amy E. Keith:** Writing – review & editing. **Jing Wei:** Resources, Writing – review & editing. **Yan Geng:** Project administration. **Hualiang Lin:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2022.119524.

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