Interactive Effects of Meteorological Factors and Particulate Pollutants on Childhood Asthma: A Time Series Analysis in Shanghai, China

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Abstract

Background: Previous studies have revealed that meteorological factors or ambient air pollutants were associated with childhood asthma, but their interactive effects are scarcely known.

Methods: In order to investigate the potential interactions between meteorological factors and air pollutants on childhood asthma, we obtained daily data on meteorological factors (mean temperature, mean relative humidity, and mean air pressure), air particulate matter (PM) with diameter < 2.5 μm ($PM_{2.5}$) and < 10 μm (PM_{10}), and outpatient visits for childhood asthma during 2007-2017 in Shanghai, China. Independent effects of meteorological factors and PM on childhood asthma were estimated using distributed lag non-linear model (DLNM), and then relative excess risk due to interaction (RERI) was calculated to assess their potential interactions.

Results: A total of 976, 350 outpatient visits for childhood asthma were included in this study. Significant lagged and non-linear effects of meteorological factors and PM exposure on childhood asthma were observed in DLNM analyses. Further, in interaction analysis, we found statistically significant antagonistic interaction between mean temperature and PM (RERI: -0.14, 95%CI: -0.15, -0.12 for $PM_{2.5}$; RERI: -0.09, 95%CI: -0.10, -0.08 for PM_{10}) and synergistic interaction between mean air pressure and PM (RERI: 0.16, 95%CI: 0.14, 0.18 for $PM_{2.5}$; RERI: 0.17, 95%CI: 0.15, 0.19 for PM_{10}) on childhood asthma. Subgroup analyses by sex and age as well as sensitivity analyses of alternative degree of freedoms for calendar time, meteorological factors and PM are performed and confirmed the robustness of our results.

Conclusion: Our findings provide supporting evidence that meteorological factors and PM might interactively affect childhood asthma, including antagonistic interaction between temperature and PM and synergistic interaction between air pressure and PM.

Background

Asthma, generally characterized by the recurrent respiratory symptoms of wheezing, breathlessness, chest tightness and coughing, is one of the most common chronic respiratory diseases and ranks among the top 20 conditions for global disability-adjusted life years (DALYs) in children [1–2]. Its prevalence, incidence and related mortality are markedly increasing in many countries, especially in the transition countries that are undergoing rapid industrialization [3–4]. For example, in China, the asthma prevalence in children aged 0–14 years progressively increased from 0.91% (0.09 to 2.60%) in 1990, 1.54% (0.52%-3.34%) in 2000, to 2.32% (0.42%-5.37%) in 2010 [5–7]. According to the Global Burden of Disease in 2017, asthma approximately accounted for 2.77% in total DALYs among children aged 5–14 years old in China [8]. Given asthma cannot be completely cured with current treatments, a better understanding of its risk factors, effective clinical symptom control, intervention and management is of particular importance to public health.

Although the underlying causes of asthma remain unclear, it has been generally accepted that asthma is complicated genetic disorder that closely correlated with environmental exposures [9–12]. Sufficient epidemiological studies have demonstrated that ambient air pollutants could exacerbate asthma across a variety of symptoms and outcomes [13–17]. For example, Khreis et al. systematically reviewed forty-one epidemiological studies to estimate the effects of exposure to traffic-related air pollutions on childhood asthma, and indicated positive associations of childhood asthma with black carbon (BC), nitrogen dioxide (NO_2), particulate matter < 2.5 μm in diameter ($PM_{2.5}$) and particulate matter < 10 μm in diameter (PM_{10}) [15]. Kuo et al. determined the impacts of air pollution on hospitalization for childhood asthma in Taiwan over the period 2001–2012, and found $PM_{2.5}$, PM_{10}, NO_2 and sulfur dioxide (SO_2) were positively associated with increased risk of childhood asthma hospitalization [16]. A recent multi-city study on air pollution and outpatient visits for asthma in 17 cities in China reported that exposure to PM_{10} and NO_2 increased asthma outpatient visits on the current day, and exposure to $PM_{2.5}$ and SO_2 increased the asthma outpatient visits on lagged days [17]. In addition to ambient air pollutants, meteorological factors have also been found to be significantly associated with childhood asthma, including extreme temperature [18], relative humidity [19], air pressure [12, 20], precipitation [21] and wind speed [22].

Significant associations of childhood asthma with either meteorological factors or ambient air pollutants appear to have been established, but their possible interactive effects on childhood asthma are little known. Therefore, in the present study, we aimed to estimate the potential interactions of meteorological factor and ambient air pollutants on childhood asthma by employing an 11-year time series data of meteorological factors (mean temperature, mean relative humidity, and mean air pressure), $PM_{2.5}$ and PM_{10}, and outpatient visits for childhood asthma in Shanghai, China.

Methods

Study setting

Shanghai, a municipality directly under the Central Government, is located in the Eastern China (120°52' to 122°12' east longitude, 30°40' to 31°53'north latitude) with a total area of 6340.5 square kilometers and the population of 24.28 million. Shanghai belongs to subtropical monsoon climate, with hot and humid summer and mild winter. The second and third national surveys of childhood asthma in urban areas of China found that Shanghai had the highest prevalence of asthma in 0–14 years old children across the country, with 4.52% in 2000 and 7.57% in 2010 [6–7].

Data Collection

In this study, daily counts of outpatient visits for childhood asthma from January 1, 2007 to December 31, 2017 were obtained from Shanghai Children's Medical Center and Xinhua Hospital, two tertiary pediatric hospitals affiliated to Shanghai Jiao Tong University School of Medicine (2/4 pediatric hospitals in Shanghai, China). Pediatric patients were defined as those aged less than 18 years old, and asthma was defined according to International Classification of Diseases-10th Revision (ICD-10: J45-J46). Daily meteorology data (mean temperature, mean relative humidity, and mean air pressure) during the same period were acquired from Pudong monitoring stations, Shanghai Meteorological Service, which have been well corrected and highly correlated with records from other stations [23]. Daily particulate matter concentrations ($PM_{2.5}$ and PM_{10}) during 2007–2017 were obtained from the Shanghai Environmental Protection Agency. As residential addresses of study participants were unavailable, the value of PM used in the present study was the daily average value monitored by 19 stations located in 16 districts of Shanghai with broad geographic coverage.

Statistical analysis

Descriptive statistical analyses were conducted for meteorological factors, PM and outpatient visits for childhood asthma, using mean ± standard deviation (SD), range and percentiles as appropriate. Spearman correlations were performed for the independent and response variables. Distributed lag non-linear model (DLNM) was applied to estimate the independent effect of meteorological factors and PM on childhood asthma. Then, according to the cutoff points from DLNM models, we divided meteorological factors and PM into binary variables. Furthermore, Poisson regression and stratified analysis were performed to estimate the interactive effects between meteorological factors and PM on childhood asthma, and relative excess risk due to interaction (RERI) with its 95% confidence interval (CI) were calculated to assess the potential interaction. Bivariate response surfaces were used to visualize the combined effect of meteorological factors and PM. Finally, sensitivity analyses by changing the degree of freedom (*df*) for calendar time, meteorological factors and PM were conducted to validate our results.

Distributed lag non-linear model

In this study, considering environmental factors often show delayed effects, DLNM was utilized to investigate the delayed and nonlinear effects of meteorological factors and PM on outpatient visits for childhood asthma. The DLNM model is described as follows:

$Y_t \sim \text{Poisson}\ (\mu_t)$

$\text{Log}\ (Y_t) = \alpha + cb(X_t) + ns\ (\text{time}, 6\ df/\text{year} *11) + \text{as.factor (dow)} + \text{as.factor (holiday)}$

where Y_t was the number of childhood asthma clinical visits on day t; α is the model intercept; X_t was independent variable in the present study, including mean temperature, mean relative humidity, mean air pressure, $PM_{2.5}$ and PM_{10} exposure; cb is the “cross-basis” function to X_t which modeling the delayed and nonlinear effects of independent variable; ns (time, *df*/year) was a day variable with natural cubic spline (ns) for day to control the long-term trend and seasonality, and 6 *df*/year was chosen in the model according to the lowest Akaike information criterion (AIC) value [24]; dow, a categorical variable, was used to adjust for the potential confounding effect of day of the week; holiday, a categorical variable, was used to adjust for the potential confounding effect of holiday. The maximum lag period was set as 14 days in this study after considering findings of previous studies [25–26].

Interaction analysis

Before the implementation of interaction analysis, meteorological factors and PM were divided into binary variables according to the cutoff points from DLNM models in which daily value ≤ the cutoff was assigned with 0 while > the cutoff was assigned with 1. Therefore, daily mean temperature (T), relative humidity (R), air pressure (AP), $PM_{2.5}$ and PM_{10} were transformed into T = 0 or T = 1, R = 0 or R = 1, AP = 0 or AP = 1, $PM_{2.5}$=0 or $PM_{2.5}$=1, as well as PM_{10} = 0 or PM_{10} = 1, respectively. The interaction model is described as follows:

$Y_t \sim \text{Poisson}\ (\mu_t)$

$\text{Log}\ (Y_t) = \alpha + T\ (\text{or } R \text{ or } AP) + PM_{2.5}\ (\text{or } PM_{10}) + T\ (\text{or } R \text{ or } AP) * PM_{2.5}\ (\text{or } PM_{10})$

+ as.factor (dow) + as.factor (holiday)

From the regression, we could get RR_{10}, RR_{01} and RR_{11} values for meteorological factor (T, R or AP), PM ($PM_{2.5}$ or PM_{10}) and the interaction term, respectively. Further, we calculated the RERI on the basis of multiplicative and additive model of interaction theory [27–28]. The formula is as follows:

$RERI = RR_{11} - RR_{01} - RR_{10} + 1$

Significant interaction was observed when RERI with 95% confidence interval (CI) didn't overlap the value of 0, where RERI > 0 indicated the synergistic interaction and RERI < 0 indicated the antagonistic interaction while 0 implied no interaction.

Subgroup and sensitivity analyses

Subgroup analyses by sex (boys vs girls) and age (≤ 5 year old vs 6–18 years old) as well as sensitivity analyses by using alternative *df* for calendar time, meteorological factors and PM were conducted to validate our results. In this study, we used 3–14 *df*/year for calendar time and 3–9 *df* for meteorological factors and PM.

Statistical analyses were conducted using R packages and SPSS software, and a p value less than 0.05 was considered to be statistically significant (two tailed). The “dlnm” and “epiR” package (R software, Version 4.0.3) and response surface analysis in SPSS (Version 16.0, SPSS Inc., Chicago, IL) were mainly used in this study.

Results

Descriptive statistics of meteorological factors, PM and childhood asthma

Table 1 shows the descriptive statistics of daily data on meteorological factors, PM and outpatient visits for childhood asthma. During the study period, the daily mean (SD) of meteorological factors included 17.53 (8.77) °C for mean temperature, 74.85 (12.51) % for mean relative humidity, and 1016.04 (8.87) hPa for mean air pressure. The median values (inter-quartile range, IQR) of daily PM concentrations were 41.00 (33.00) $\mu g/m^3$ for $PM_{2.5}$ and 61.88 (49.97) $\mu g/m^3$ for PM_{10}, with the corresponding range of 5.00 to 447.00 $\mu g/m^3$ and 6.00 to 803.75 $\mu g/m^3$, respectively. During 2007–2017, a total of 976, 350 outpatient visits for childhood asthma were included in the analysis. The mean value (SD) of daily outpatient visits for childhood asthma was 242.97 (150.08) in total, 162.42 (97.97) for boys, 80.55 (51.21) for girls, 163.23 (103.03) for children aged ≤ 5 year old, and 79.72 (49.12) for children aged 6–18 years old. Besides, Additional file 1 Fig. S1 presented the detailed distributions of daily data on meteorological factors, PM, and outpatient visits for childhood asthma from 2007–2017.

Table 1
Distribution of daily data on meteorological factors, PM, and outpatient visits for childhood asthma from 2007 to 2017 in Shanghai, China

Variables	Mean ± SD	Min[a]	Percentile [b]							Max[a]	IQR[c]
			P_5	P_{10}	P_{25}	P_{50}	P_{75}	P_{90}	P_{95}		
Meteorological factors											
Mean temperature (°C)	17.53 ± 8.77	-5.60	3.10	5.10	9.50	18.20	24.40	28.91	30.30	34.80	14.90
Mean relative humidity (%)	74.85 ± 12.51	24.00	51.00	57.00	67.00	75.00	83.00	89.00	92.00	100	16.00
Mean air pressure (hPa)	1016.04 ± 8.87	993.00	1002.80	1004.50	1008.50	1016.05	1023.10	1028.00	1030.50	1039	14.60
PM											
$PM_{2.5}$ (μg/m^3)	48.26 ± 32.19	5.00	15.00	15.00	27.00	41.00	60.00	88.00	110.00	447.00	33.00
PM_{10} (μg/m^3)	74.54 ± 50.07	6.00	26.00	31.75	42.17	61.88	92.14	131.00	165.02	803.75	49.97
Outpatient visits for childhood asthma											
Total	242.97 ± 150.08	21	57	74	126	212	329	456	548	802	203
Boys	162.42 ± 97.97	12	37	50	85	143	218	302	360	498	133
Girls	80.55 ± 51.21	2	17	23	39	69	108	151	183	273	69
≤ 5 years old	163.23 ± 103.03	0	34	46	83	143	218	313	375	529	135
6–18 years old	79.72 ± 49.12	4	19	25	40	67	108	148	175	313	68

[a] Min: minimum; Max: Maximum.

[b] P_5, 5th centile; P_{10}, 10th centile; P_{25}, 25th centile; P_{50}, 50th centile; P_{75}, 75th centile; P_{90}, 90th centile; P_{95}, 95th centile.

[c] IQR: interquartile range.

Correlation Between Meteorological Factors, Pm And Childhood Asthma

Figure 1 indicates Spearman correlations coefficients among meteorological factors, PM and outpatient visits for childhood asthma. Outpatient visits for childhood asthma were inversely correlated with mean temperature (r_s = -0.290) and mean relative humidity (r_s = -0.079) but positively correlated with mean air pressure (r_s = 0.351) and $PM_{2.5}$ (r_s = 0.074). PM exposure was significantly and negatively correlated with mean temperature (r_s = -0.224 for $PM_{2.5}$, r_s = -0.226 for PM_{10}) and mean humidity (r_s = -0.166 for $PM_{2.5}$, r_s = -0.380 for PM_{10}) but positively correlated with mean air pressure (r_s = 0.143 for $PM_{2.5}$, r_s = 0.188 for PM_{10}). A strong correlation was found between $PM_{2.5}$ and PM_{10} (r_s = 0.828). The daily outpatient visits for childhood asthma in total, in sex subgroups (boys vs girls) and in age subgroups (≤ 5 year old vs 6–18 years old) had strongly positive correlation, with spearman correlation coefficients ranging from 0.896 to 0.997 (see Additional file 1: Table S1).

Distributed Lag Non-linear Model

Figure 2 depicts the exposure-response curves of meteorological factors and PM on outpatient visits for childhood asthma up to the lag of 14 days using DLNM. The non-linear exposure-response curve for mean temperature was an approximate V-shape with the minimum risk at 29°C. Similar V shapes were also observed for mean relative humidity and mean air pressure, with corresponding minimum risk at 82% and 1003 hPa, respectively. $PM_{2.5}$ and PM_{10} were positively associated with increased risk for childhood asthma, and the turning point of exposure-response curve was found at 35 μg/m^3 for $PM_{2.5}$ and 50 μg/m^3 for PM_{10}, respectively. Therefore, we used 29°C, 82%, 1003 hPa, 35 μg/m^3 and 50 μg/m^3 as the cutoff points to divide mean temperature, mean relative humidity, mean air pressure, $PM_{2.5}$ and PM_{10}, respectively, into binary variables. Meteorological factors, $PM_{2.5}$ and PM_{10} were assigned with 0 if their daily mean values ≤ their corresponding cutoff points otherwise assigned with 1.

Interaction Analyses

Table 2 displays the interactive effects between meteorological factors and PM on outpatient visits for childhood asthma. The RERIs for mean temperature and PM were − 0.14 (-0.15, -0.12) for $PM_{2.5}$ and − 0.09 (-0.10, -0.08) for PM_{10}, indicating significant antagonistic interaction between temperature and PM. But, the RERIs for mean air pressure and PM were 0.16 (0.14, 0.18) for $PM_{2.5}$ and 0.17 (0.15, 0.19) for PM_{10}, suggesting significant synergistic interaction between air pressure and PM. As for mean relative humidity, antagonistic interaction was found for PM_{10} (RERI: -0.03, 95%CI: -0.04, -0.02) while no interactive effect was observed for $PM_{2.5}$ (RERI: 0.01, 95%CI: -0.00, 0.02). To visualize the interactive effects of meteorological factors and PM exposure on childhood asthma, bivariate response surfaces were conducted and the results are presented in Fig. 3.

Table 2

Interactive effects between meteorological factors and PM on childhood asthma in Shanghai, 2007–2017 [a]

PM	Mean temperature		Mean relative humidity		Mean air pressure	
	Groups	RR (95%CI)	Groups	RR (95%CI)	Groups	RR (95%CI)
$PM_{2.5}$	T = 0, $PM_{2.5}$ = 0	Ref	H = 0, $PM_{2.5}$ = 0	Ref	AP = 0, $PM_{2.5}$ = 0	Ref
	T = 1, $PM_{2.5}$ = 0	0.67 (0.66, 0.68)	H = 1, $PM_{2.5}$ = 0	0.98 (0.97, 0.98)	AP = 1, $PM_{2.5}$ = 0	1.50 (1.48, 1.53)
	T = 0, $PM_{2.5}$ = 1	1.05 (1.04, 1.05)	H = 0, $PM_{2.5}$ = 1	1.04 (1.04, 1.05)	AP = 0, $PM_{2.5}$ = 1	0.93 (0.91, 0.94)
	T = 1, $PM_{2.5}$ = 1	0.58 (0.57, 0.59)	H = 1, $PM_{2.5}$ = 1	1.03 (1.02, 1.04)	AP = 1, $PM_{2.5}$ = 1	1.58 (1.56, 1.61)
	RERI	-0.14 (-0.15, -0.12)	RERI	0.01 (-0.00, 0.02)	RERI	0.16 (0.14, 0.18)
PM_{10}	T = 0, PM_{10} = 0	Ref	H = 0, PM_{10} = 0	Ref	AP = 0, PM_{10} = 0	Ref
	T = 1, PM_{10} = 0	0.66 (0.65, 0.67)	H = 1, PM_{10} = 0	0.99 (0.99, 1.00)	AP = 1, PM_{10} = 0	1.45 (1.43, 1.49)
	T = 0, PM_{10} = 1	1.00 (1.00, 1.01)	H = 0, PM_{10} = 1	1.01 (1.00, 1.01)	AP = 0, PM_{10} = 1	0.84 (0.82, 0.86)
	T = 1, PM_{10} = 1	0.57 (0.57, 0.58)	H = 1, PM_{10} = 1	0.97 (0.96, 0.98)	AP = 1, PM_{10} = 1	1.46 (1.44, 1.49)
	RERI	-0.09 (-0.10, -0.08)	RERI	-0.03 (-0.04, -0.02)	RERI	0.17 (0.15, 0.19)

[a] meteorological factors and PM were divided into binary variables according to the cutoff points from DLNM models in which daily value ≤ the cutoff was assigned with 0 while > the cutoff was assigned with 1. The cutoff point was 29°C for mean temperature (T), 82 % for mean relative humidity (H), 1003 hPa for mean air pressure (AP), 35 μg/m^3 for $PM_{2.5}$ and 50 μg/m^3 for PM_{10}, respectively.

Subgroup And Sensitivity Analyses

Subgroup analyses by sex and age as well as sensitivity analyses of alternative *df* for calendar time, meteorological factors and PM were conducted to validate the robustness of the results. Additional file 1 Fig. S2 and Fig. S3 display the DLNM analyses for sex subgroup and age subgroup, respectively. Additional file 1 Fig. S4 shows the DLNM sensitivity analyses for calendar time by changing *df* from 4 *df/year* to 13 *df/year*. Additional file 1 Fig. S5 reveals the results of the DLNM sensitivity analyses for meteorological factors and PM ranging from 3 to 9 *df*.

According to the cutoff points in DLNM results for subgroup and sensitivity analyses, corresponding RERIs were further calculated to validate the interactive effects. The interactive results of sex subgroup and age subgroup are presented in Additional file 1 Table S2 and Table S3, respectively. Besides, Additional file 1 Table S4 indicates the interactive results of alternative df for calendar time by c changing *df* from 4 *df/year* to 13 *df/year*. Additional file 1 Table S5 shows the interactive results of alternative df for meteorological factors and PM ranging from 3 to 9 *df*. These consistent results in subgroup and sensitive analyses verify the robustness of our findings.

Discussion

In this study, we estimated the possible interactions of meteorological factors and PM on childhood asthma by using an 11-year time series data of 976, 350 outpatient visits for childhood asthma in Shanghai, China. Firstly, we found meteorological factors and PM had significantly lagged and non-linear effects on childhood asthma. Further, in interaction analysis, our results suggest significant antagonistic interaction between temperature and PM (RERI: -0.14, 95%CI: -0.15, -0.12 for $PM_{2.5}$; RERI: -0.09, 95%CI: -0.10, -0.08 for PM_{10}) but synergistic interaction between air pressure and PM (RERI: 0.16, 95%CI: 0.14, 0.18 for $PM_{2.5}$; RERI: 0.17, 95%CI: 0.15, 0.19 for PM_{10}) on childhood asthma.

In DLNM models, we found an approximate V-shape for the exposure-response curve of mean temperature on childhood asthma, indicating exposure to high and low temperatures was associated with an increased risk of childhood asthma. This finding is consistent with the majority of previous findings [11, 12, 18, 21, 29]. For instance, Xu et al. observed both hot (95th percentile of mean temperature) and cold (5th percentile of mean temperature) temperature increased the emergency department admissions for childhood asthma relative to the reference temperature of 24.0°C in Brisbane, Australia [29]. Soneja et al. found the occurrence of extreme heat events was associated with higher risk of asthma hospitalization in Maryland, U.S.A. [21]. A systematic review summarized available information about the relationship between temperature and childhood asthma, and called for special attention to extreme temperatures [11]. Except for temperature, previous studies have reported that exposure to low relative humidity or high air pressure was associated with increased risk of childhood asthma [8, 19, 20]. In our study, relative humidity (< 82%) and air pressure (> 1003 hPa) were found to be positively connected with outpatient visits for childhood asthma in this study. In addition, we observed that exposure to $PM_{2.5}$ and PM_{10} was positively associated with an increased risk of childhood asthma, which were align with prior findings in Chongqing (China) [14], Shanghai (China) [30], Seoul (Korea) [31], Québec (Canada) [13], and New York (USA) [32]. Meteorological factors have been suggested to impact asthma through directly affecting airway hyperventilation or inflammation pathway and by indirectly affecting asthma through viral infections, allergens, bacterial activity or outdoor time [12, 29, 33]. The effects of PM on asthma are largely determined by the size and chemical composition, deposition in respiratory tract and immune response to the particles [34]. Potential mechanisms of PM exposure on asthma exacerbation include oxidative stress [35], inflammatory response [36], mucosal barrier function disruption [37], and airway hyperresponsiveness [38]. In general, align with the majority of previous findings, our study provides consistent evidence for associations of meteorological factors and PM with childhood asthma.

Even though a mounting body of evidence has suggested the independent impacts of meteorological factors or PM on childhood asthma, limited studies have explored their possible interactive effects to date [22, 39, 40]. In a multifactorial study of meteorological factors and ambient air pollutants (CO, NO_2, SO_2, $PM_{2.5}$ and PM_{10}) on asthma acute exacerbation in Taiwan, Yu et al. found ambient air pollutants showed different effects with or without meteorological factors, and suggested that meteorological factors should be simultaneously considered when identifying the impacts of ambient air pollutants on asthma [40]. Mokoena et al. observed an antagonistic interaction between temperature and air quality index (AQI) on respiratory mortality (RERI = -0.235, 95%CI: -0.269, -0.163) in a time-series study conducted in Xi'an, China during 2014 and 2016 [22]. The results of this study indicate antagonistic interaction between temperature and PM and synergistic interaction between air pressure and PM on the outpatient visits for childhood asthma. The antagonism between air temperature and PM might be related to adaptive behaviors such as the use of air conditioning and the reduction of outdoor activities under high temperature [41]. It is well known that meteorological factors could influence the concentration of ambient air pollutants [42], and high air pressure has been reported to worsen air quality [43]. This might partially explain the synergistic interaction of air pressure and PM on childhood asthma in this study. However, given to the limited knowledge of interactive effects of meteorological factors and ambient air pollution on childhood asthma, our findings should be interpreted with caution and need to be confirmed by further studies in different populations.

This study has several strengths. To our knowledge, this is the first study to explore the potential interactive effects of meteorological factors and PM on childhood asthma in Shanghai, China. Then, a large sample size of 976, 350 outpatient visits during a long-time span of 11 years was utilized in our study. In addition, consistent results in sensitivity analyses of interactions between temperature, air pressure and PM enhanced the reliability of our findings for the interactions between meteorological factors and particulate pollutants on childhood asthma. However, this study also has several limitations. Firstly, data of meteorological factors and air pollutants obtained from monitoring stations were used to reflect individual exposure levels, which might lead to measurement bias [44–45]. Secondly, information on some confounding factors, such as parental smoking, indoor air pollutants, aeroallergens and allergic constitution, was unable to acquire in the present study and might influence the risk assessment of meteorological factors and PM on childhood asthma. Thirdly, the generalizability of our study is limited considering the single city study design. Since dynamic changes in meteorological factors and ambient air pollutants simultaneously coexist in the real world, the assessment of their interactive effects on childhood asthma is imperative and strongly encouraged [16, 40].

Conclusions

Our findings provide supporting evidence that meteorological factors and PM interactively impacted childhood asthma, including antagonistic interaction between temperature and PM and synergistic interaction between air pressure and PM. These findings may have important implications for developing effective asthma control and prevention strategies in China and other transition countries.

Abbreviations

AIC
Akaike information criterion; AQI:Air quality index; BC:Black carbon; CI:Confidence interval; DALYs:Disability-adjusted life years; DLNM:Distributed lag non-linear model; df:Degree of freedom; NO_2:nitrogen dioxide; ns:Natural cubic spline; PM:Air particulate matter; $PM_{2.5}$:Air particulate matter with diameter < 2.5 μm; PM_{10}:Air particulate matter with diameter < 10 μm; RERI:Relative excess risk due to interaction; SD:Standard deviation; SO_2:Sulfur dioxide.

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of Shanghai Children's Medical Center (Approval No. 18411951600). Informed consent of patients was not necessary in the present study considering that only aggregated data were analyzed.

Consent for publication

Not applicable.

Availability of data and materials

Data of the present study are available from the corresponding author upon reasonable request.

Competing interests

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.

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Author contributions:

Yi Hu: Data curation, Formal analysis, Writing - original draft. Dan Wu: Methodology, Validation. Yabin Hu: Data curation, Methodology, Validation. Shenghui Li: Data curation. Shijian Liu: Data curation. Jianguo Tan: Data curation. Yong Yin: Data curation. Chonghuai Yan: Data curation. Xiaolei Wang: Methodology, Validation. Hui Lu: Writing - review & editing. Guangjun Yu: Supervision, Conceptualization, and Writing - review & editing. Shilu Tong: Supervision, Writing - review & editing.

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Figures

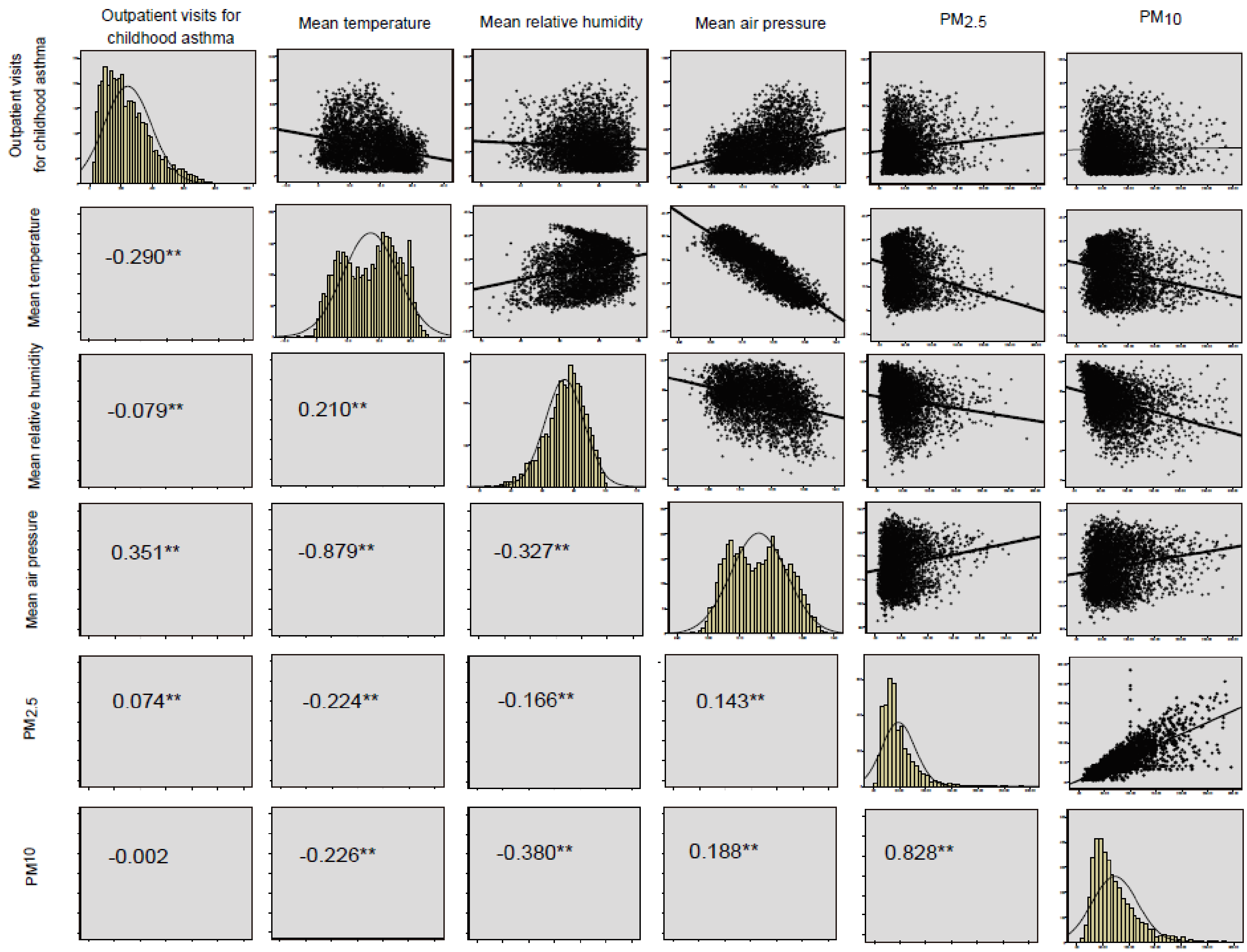

Figure 1

The matrix of histograms, scatter plots and spearman correlations among meteorological factors, PM and outpatient visits for childhood asthma

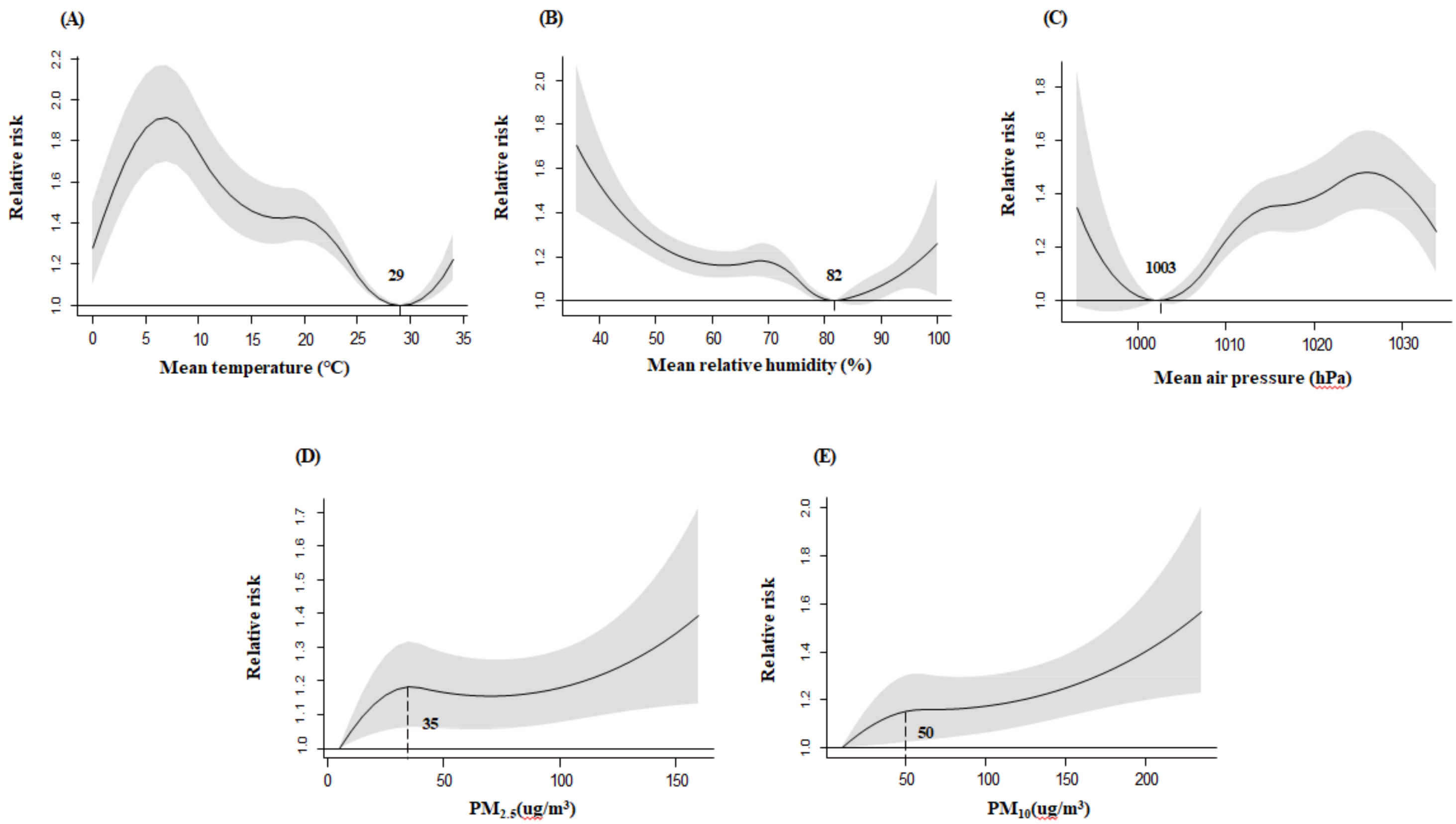

Figure 2

Relative risk (RR) and 95% confidence interval of meteorological factors and PM on childhood asthma for 14 days lag. Meteorological factor or PM corresponding to the minimum risk of outpatient visits for childhood asthma in our study was selected as reference for null hypothesis line, the black line indicated the relative RR, and the gray area represented the 95%CI. (A) Mean temperature; (B) Mean relative humidity; (C) Mean air pressure; (D) PM2.5 ; (E) PM10.

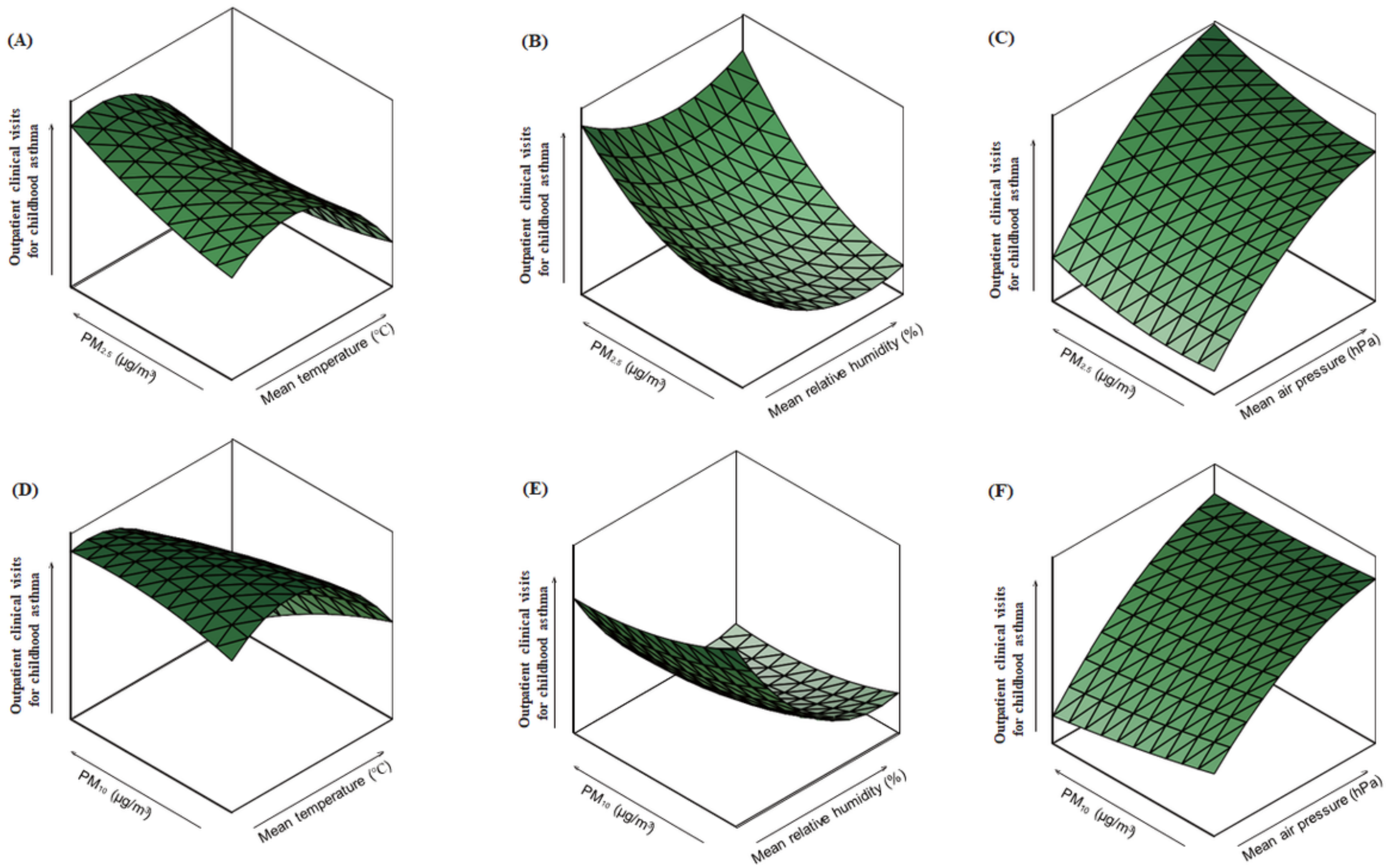

Figure 3

Bivariate response surfaces for meteorological factors and PM on childhood asthma. (A) Mean temperature and PM2.5; (B) Mean relative humidity and PM2.5; (C) Mean air pressure and PM2.5; (D) Mean temperature and PM10; (E) Mean relative humidity and PM10; (F) Mean air pressure and PM10.

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