The following publication Wang, X., Xu, Z., Su, H., Ho, H. C., Song, Y., Zheng, H., ... & Cheng, J. (2021). Ambient particulate matter (PM1, PM2. 5, PM10) and childhood pneumonia: the smaller particle, the greater short-term impact?. Science of The Total Environment, 772, 145509 is available at https://doi.org/10.1016/j.scitotenv.2021.145509.

Ambient particulate matter (PM1, PM2.5, PM10) and childhood pneumonia: The smaller particle, the greater short-term impact?

Highlights

- We examined PM1, PM2.5, PM10 effects on childhood pneumonia hospitalizations.
- The highest increase in pneumonia hospitalizations was from PM1, followed by PM2.5 and PM10.
- PM1 had larger effects on children by sex, age, and season than did PM2.5 and PM10.
- We observed a linear exposure-response curve for PM1 and pneumonia hospitalization.

Abstract

Background: Smaller sizes of ambient particulate matter (PM) can be more toxic and can be breathed into lower lobes of a lung. Children are particularly vulnerable to PM air pollution because of their adverse effects on both lung functions and lung development. However, it remains unknown whether a smaller PM has a greater short-term impact on childhood pneumonia.

Aims: We compared the short-term effects on childhood pneumonia from PM with aerodynamic diameters ≤1 μm (PM1), ≤2.5 μm (PM2.5), and ≤10 μm (PM10), respectively.

Methods: Daily time-series data (2016–2018) on pneumonia hospitalizations in children aged 0–17 years, records of air pollution (PM1, PM2.5, PM10, and gaseous pollutants), and weather conditions were obtained for Hefei, China. Effects of different PM were quantified using a quasi-Poisson generalized additive model after controlling for day of the week, holiday, seasonality and long-term time trend, and weather variables. Stratified analyses (gender, age, and season) were also performed.

Results: For each 10 μg/m3 increase in PM1, PM2.5, and PM10 concentrations over the past three days (lag 0–2), the risk of pneumonia hospitalizations increased by 10.28% (95%CI: 5.88%–14.87%), 1.21% (95%CI: 0.34%–2.09%), and 1.10% (95%CI: 0.44%–1.76%), respectively. Additionally, both boys and girls were at risk of PM1 effects, while PM2.5 and PM10 effects were only seen in boys. Children aged ≤12 months and 1–4 years were affected by PM1, but PM2.5 and PM10 were only associated with children aged 1–4 years.

Furthermore, PM1 effects were greater in autumn and winter, while greater PM2.5 and PM10 effects were evident only in autumn.

Conclusion: This study suggests a greater short-term impact on childhood pneumonia from PM1 in comparison to PM2.5 and PM10. Given the serious PM pollution in China and other rapid developing countries due to various combustions and emissions, more investigations are needed to determine the impact of different PM on childhood respiratory health.

Keywords

Particulate matter; Pneumonia; Children; China

1. Introduction

Children's respiratory health is particularly vulnerable to particulate matter (PM) air pollution (World Health Organization, 2005). As one of most common respiratory diseases and the leading cause of death in children worldwide, a number of studies have reported the short-term association between PM and pneumonia (Li et al., 2018; Nhung et al., 2017; Walker et al., 2013). However, most of these studies explored PM with aerodynamic diameter ≤2.5 μm (PM2.5) and ≤10 μm (PM10). So far, evidence is limited on the effects of PM with an aerodynamic diameter ≤1 μm (PM1) on childhood pneumonia (Nhung et al., 2018).

PM1 could be comprised of primary organic aerosols, sulfate, ammonium, nitrate and chloride (Niu et al., 2020), whereas PM2.5 and PM10 were also related to dusts and hazes (Gao et al., 2015). These chemical components of PM1 could be from traffic, cooking emissions, and coal combustions (Niu et al., 2020; Zhang et al., 2018). Because PM1 is a part of PM2.5 and PM2.5 is a part of PM10, PM1 could be more toxic in comparison with other components of PM2.5 and PM10 such as PM1–2.5 and PM7.5 (Lin et al., 2016; Chen et al., 2017b; Zhang et al., 2020a). Furthermore, the size (in diameter) of PM1 is much smaller than PM2.5 and PM10, which enables the pollutant to reach lower lobes of a lung and may cause a larger damage to respiratory health. In other words, parts of PM2.5 and PM10 components also go deep into respiratory system. However, despite the fact that PM1 is supposing to have a great threat on human health, the health impact of this air pollutant was still underestimated. To date, most of the PM1 studies were focused on the long-term effects (years of exposure) on community health risk (Chen et al., 2018; Li et al., 2019; Yang et al., 2018b; Yang et al., 2019). These studies suggested that several years of PM1 exposure increased the risk of autism spectrum disorder, hypertension, cardiovascular disease, and metabolic syndrome. Some studies also assessed the short-term effects (days of exposure) of PM1 on various health outcomes, suggesting elevated risk of mortality (all-cause and cardiovascular disease), emergency department visits, and respiratory hospitalizations (include pneumonia and chronic obstructive pulmonary diseases) within days after exposure (Chen et al., 2017b; Yin et al., 2020; Zhang et al., 2020a, Zhang et al., 2020b; Lin et al., 2016). However, there are no studies examining whether the short-term effects of PM1 on pneumonia in children were larger than PM2.5 and PM10 effects in countries or regions that are heavily polluted by particulate matter such as China, Iran, Poland and South America (Nhung et al., 2017; Hadei et al., 2020; Badyda et al., 2017; Gouveia and Fletcher, 2000).

In order to further explore whether the smaller particle could contribute to the greater short-term impact on human health, the present study sought to examine and compare the impacts of PM1, PM2.5, and PM10 on childhood pneumonia in Hefei, China. Stratified analyses by sex, age, and season were also performed to identify sensitive subgroups and exposure-time-window to the PM effects.

2. Material and methods

2.1. Data collection on pneumonia hospitalizations

Daily count of pneumonia patients (age: 0–17) from January 1, 2016 to December 31, 2018 were obtained from the computerized hospitalization database in Anhui Provincial Children's Hospital, which is a grade A tertiary hospital and the only children's hospital in Hefei (http://www.ahetyy.com/spinfo_1.html). Selection of this hospital is in line with previous studies looking at childhood respiratory disease such as asthma in Hefei (Pan et al., 2019; Zhang et al., 2019). Meanwhile, childhood pneumonia hospitalizations have obvious seasonal pattern with a peak in summer and trough in summer, which has also been noted in previous investigation of pneumonia hospitalizations of all ages in Hefei (Xie et al., 2019). Causes of diseases of all patients were coded based on the International Statistical Classification of Diseases and Related Health Problems (ICD-10). Based on ICD classification, patients with primary diagnosis coded as “J12-J18” were extracted as pneumonia cases. For each pneumonia case, date of hospital admission, sex, age, and residential address were reported. Based on residential address, we selected all pneumonia cases living in the urban area of Hefei city as our analytic dataset. The residential locations of these patients were covered by air pollution monitoring network operated during the study period.

With the use of our analytic dataset, we aggregated pneumonia cases to a series of daily time-series data based on age and sex: 1) daily count of childhood pneumonia hospitalizations (in total), 2) daily hospitalization of pneumonia (boy), 3) daily hospitalization of pneumonia (girl), 4) daily hospitalization of pneumonia (age ≤ 12 months), 5) daily hospitalization of pneumonia (age:1–4 years), and 6) daily hospitalization of pneumonia (age: 5–17 years). This age classification was motivated by previous studies to identify which subgroups were more vulnerable to environmental risk exposure (Barnett et al., 2005; Xu et al., 2014).

2.2. Data collection on air pollution

We then matched all data with daily concentrations of air pollutants based on the date of hospital admission. Particularly, we aggregated daily concentrations of PM2.5, PM10, ozone (O3), nitrogen dioxide (NO2), and sulfur dioxide (SO2) from air quality information retrieved from National Urban Air Quality Real-time Publishing Platform including a number of ground monitoring stations that constitute the National Air Pollution Monitoring System. Since January 2013, China's Ministry of Environmental Protection begun to display the air pollution data at the official website (http://106.37.208.233:20035/). This online platform reports real-time (hourly) concentrations of the above-mentioned air pollutants, including 10 monitoring stations with air quality information in Hefei during the study period (Fig. S1). By averaging hourly concentrations within a day across all monitoring stations, we obtained daily values of each air pollutant (i.e., one mean value of PM2.5 and PM10 concentrations for each day) (Chen et al., 2017a; Tian et al., 2019).

Different from ground-monitored PM2.5 and PM10 data, information of PM1 concentration was not reported in the above-mentioned platform, therefore, we additionally collected daily information of PM1 from China Atmosphere Watch Network (CAWNET). Since CAWNET only had one station in Hefei and the data from this location may not be able to represent the entire city, we thus used the processed spatial time-series data (resolution: 1 km) based on CAWNET from a recent study (Wei et al., 2019). These spatial time-series data are daily estimation of PM1 derived from an ensemble learning model based on air quality information from 153 stations of CAWNET, MAIAC AOD Product, MEIC Emission Data, land use information, road network, topographic characteristics, and night-time light (Wei et al., 2021). Briefly, a space-time extremely randomized trees model was performed in the above estimation with a high accuracy (R2: 0.74–0.77, root-mean-square error: 9.5–14.5 μg/m3, mean absolute error: 5.9–8.7 μg/m3). The ChinaHighPM1 dataset is available at https://weijing-rs.github.io/product.html. Based on an urban boundary, we averaged each pixel (1 km) of spatial time-series data to a daily mean of PM1 in Hefei, which enhances the spatial representative of air pollution data.

2.3. Data collection on weather conditions

Daily records of meteorological information (mean temperature, relative humidity, wind speed, and air pressure) were retrieved from the China Meteorological Data Sharing Service System (http://data.cma.cn/) in order to control for the influence of weather when fitting the PM-pneumonia association (Tian et al., 2019).

2.4. Two-stage data analysis

This study consisted of two-stage analysis. In the first stage, we decomposed the daily-level time-series data of pneumonia hospitalizations and three PM fractions to identify their long-term trend and seasonality. Following previous literature (Cheng et al., 2019b), a loess method was used to decompose the time-series data, which was split into three key components: long-term trend, seasonality, and residuals (also refers to noise or random component). We then visually check whether there was an obvious long-term trend and seasonality in the returned plots.

The second stage analysis was then applied to fit the PM-pneumonia associations, based on a generalized additive model with a quasi-Poisson to account for overdispersion (Cheng et al., 2019b; Tian et al., 2019; Chen et al., 2017a). Potential confounders included: (1) meteorological factors including mean temperature and relative humidity, each using a nature cubic spline with three degrees of freedom (df = 3), (2) day of week as a categorical variable, (3) holiday as a binary variable, and (4) long-term trend and seasonality using year and month as a factor. Furthermore, we examined the short-term effects up to a lag of two days due to an evidence of acute and delayed PM effects on pneumonia (Tian et al., 2019). Given that the model with a single-day lag may underestimate the adverse effects of PM pollution, we follow previous studies to apply a 3-day moving-window to estimate associations between PM and pneumonia hospitalizations within lag 0–2 days (Tian et al., 2019; Chen et al., 2017a). This model was further validated by a sensitivity analysis as detailed below as well as by checking residuals of each model, suggesting an approximate normal distribution and the random fluctuation over time. PM effects were reported as percentage change in pneumonia hospitalizations associated with each 10 μg/m3 increase in PM concentration using the equation: Percentage change = (RR − 1) ∗ 100 % ; RR is the relative risk. We repeated this analysis for different sex and age groups to identify potential sensitive subgroups.

2.5. Examination of the shape of exposure-response association

To check the shape of exposure-response curves for PM and pneumonia hospitalizations, we applied a non-linear smoothing function to the regression model. Specifically, a thin plate regression spline with three degrees of freedom for each particulate matter was used to allow for non-linear change in the risk of pneumonia hospitalizations associated with changes in PM concentration. We then plotted the relative risk of pneumonia hospitalizations against the change in PM concentration.

2.6. Sensitivity analysis

To check the robustness of our findings, we carried out several analyses. First, we utilized a two-pollutant model that controlled for the influence of gaseous pollutants to replace the single-pollutant model. Second, as an alternative of quasi-Poisson model, we also used a Poisson model. Third, we altered the strategy to adjust for long-term trend and seasonality by using a natural cubic spline for time with six to eight degrees of freedom per year. Fourth, in addition to temperature and relative humidity, we additionally adjusted for wind speed and air pressure. We performed all data analyses and plots making in R software (version: 3.6.3). Two-side p-value <0.05 was considered statistically significant.

3. Results

A total of 15,683 pneumonia hospitalizations from 2016 through 2018 were recorded and included for data analysis. On average, there were 14 pneumonia cases (range: 0–43) per day, with more cases in boys than in girls, and in 1–4-year age group than in age groups of <1 year and 5–17 years (Table 1). During the 3-year study period, the daily mean concentrations of PM1, PM2.5, PM10, temperature and relative humidity were 31 μg/m3, 53 μg/m3, 82 μg/m3, 17 °C, and 75%, respectively.

Table 1. Summary statistics of data on daily childhood pneumonia and particulate matter in Hefei, China, 2016–2018.

Variables	Min	25th percentile	50th percentile	Mean	75th percentile	Max
Pneumonia (count)						
Total	0	10	14	14	18	43

Variables	Min	25th percentile	50th percentile	Mean	75th percentile	Max
Boys	0	6	8	9	11	27
Girls	0	3	5	6	7	22
<12 months	0	3	4	5	7	17
1–4 years	0	5	7	8	10	31
5–17 years	0	0	1	1	2	7
Air pollutants (µg/m3)						
PM1	13	22	28	31	39	81
PM2.5	6	30	45	53	67	228
PM10	11	52	75	82	105	327
O3	8	43	63	66	84	188
SO2	2	8	10	11	13	58
NO2	10	30	39	44	55	134
Weather factors						
Mean temperature (°C)	−6	9	18	17	25	36
Relative humidity (%)	33	68	76	75	85	98

PM1: particulate matter with aerodynamic diameter of ≤1 µm; PM2.5: particulate matter with aerodynamic diameter of ≤2.5 µm; PM10: particulate matter with aerodynamic diameter of ≤10 µm; O3: ozone; SO2: sulfur dioxide; NO2: nitrogen dioxide.

Spearman correlations between air pollutants and weather variables were shown in Table 2. PM1 were positively associated with SO2 ($\rho = 0.48$, p-value<0.05) and NO2 ($\rho = 0.56$, p-value<0.05) but negatively associated with O3 ($\rho = -0.49$, p-value<0.05), temperature ($\rho = -0.78$, p-value<0.05) and relative humidity ($\rho = -0.09$, p-value<0.05). Similar results were also observed for PM2.5 and PM10.

Table 2. Spearman correlation coefficients between air pollutants and weather variables.

	PM1	PM2.5	PM10	O3	NO2	SO2	Mean temperature	Relative humidity
PM1	1							
PM2.5	0.73*	1						
PM10	0.58*	0.86*	1					
O3	−0.49*	−0.21	−0.03	1				
NO2	0.56*	0.65*	0.72*	−0.28*	1			
SO2	0.48*	0.52*	0.57*	−0.15	0.54*	1		
Mean temperature	−0.78*	−0.45*	−0.27*	0.67*	−0.39*	−0.29*	1	

	PM1	PM2.5	PM10	O3	NO2	SO2	Mean temperature	Relative humidity
Relative humidity	−0.09*	−0.21	−0.47*	−0.34*	−0.31*	−0.39*	0.06*	1

PM1: particulate matter with aerodynamic diameter of ≤1 μm; PM2.5: particulate matter with aerodynamic diameter of ≤2.5 μm; PM10: particulate matter with aerodynamic diameter of ≤10 μm.

* p-Value < 0.05.

Fig. 1 presents the results of time-series decomposition for pneumonia hospitalizations and concentrations of PM1, PM2.5, and PM10. Pneumonia hospitalizations had an apparent seasonality, with more hospitalizations in winter and less hospitalizations in summer. A similar seasonal pattern was also observed for PM1, PM2.5, and PM10. Details of the median value of daily pneumonia hospitalizations and particulate matter within 3-year study period are displayed in Table S1. Besides, there was a rising trend in the number of pneumonia hospitalizations but a declining trend of the concentrations of PM1, PM2.5, and PM10 over the study period. Increasing pneumonia hospitalizations could be attributed to a number of factors such as changes in the population size of children, hospital bed's managing strategy, and popularity of the selected hospital. The continuous reduction in particulate matter concentrations over years could be explained by the implication of Air Pollution Prevention and Control Action Plan (APPCAP) across China since 2013, which has been proven to be an effective measure in mitigating the air pollution level (Huang et al., 2018).

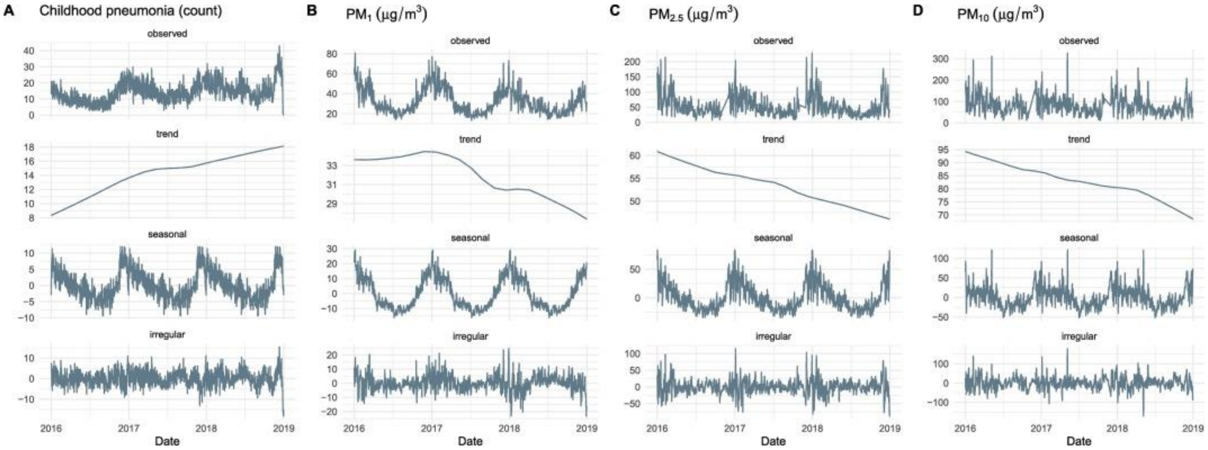

Fig. 1. The decomposition of daily time-series data for pneumonia hospitalizations (A) and three types of particulate matters (B–D) in Hefei, China, 2016–2018. PM1, PM2.5, and PM10 are particulate matters with an aerodynamic diameter ≤1 μm, 2.5 μm, and 10 μm, respectively. A seasonal-trend decomposition procedure based on loess smoothing method

was used to decompose daily time-series data including long-term trend, seasonality, and residuals (or irregular fluctuation) (Cheng et al., 2019b).

Fig. 2 shows the estimated percentage changes in the risk of pneumonia hospitalizations associated with each 10 μg/m3 increase in the concentrations of PM1, PM2.5, and PM10 at different lag days. In general, PM1, PM2.5, and PM10 were all associated with increases in pneumonia hospitalizations at lag 0, 1, 2, and 0–2 days. Notably, PM1, PM2.5, and PM10 had the largest effect at lag 0. Meanwhile, the effects of PM1 were seven to ten times larger than that of PM2.5 and PM10. For example, at lag 0–2, we estimated an increase in pneumonia hospitalizations of 10.28% (95%CI: 5.88%–14.87%) for PM1, followed by PM2.5 (1.21%, 95%CI: 0.34%–2.09%), and PM10 (1.10%, 95%CI: 0.44%–1.76%). Similar findings were also observed when estimating the percent change in the risk of pneumonia hospitalizations associated with each IQR increase in the concentrations of PM1, PM2.5, and PM10 (Fig. S2). For each IQR increase in PM1, PM2.5, and PM10 concentrations, the largest increase in the risk of pneumonia hospitalizations at lag 0 was 11.94% (95%CI: 6.67%–17.48%), 3.45% (0.83%–6.14%), and 4.05% (1.21%–6.98%), respectively.

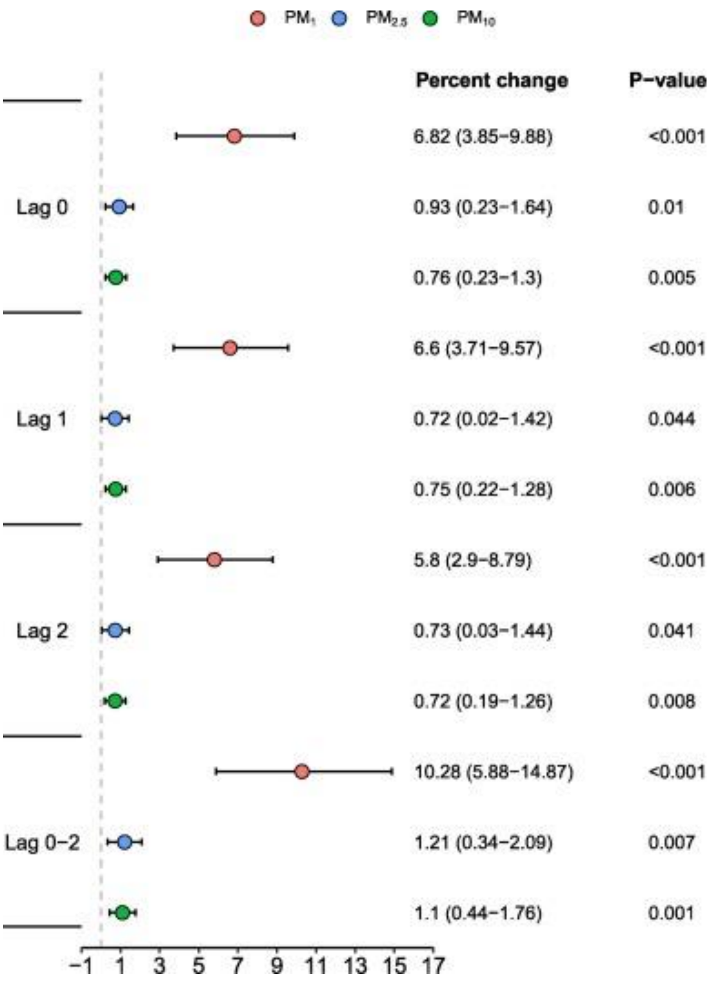

Fig. 2. The estimated percentage changes in childhood pneumonia hospitalizations per 10 μg/m3 increase in PM1, PM2.5, and PM10 concentrations at different lag days.

Table 3 displayed the results of stratified analyses by sex, age, and season. Both boys and girls were vulnerable to PM1 effects, with an estimated percentage increase of 8.85% (95%CI: 3.85%–14.1%) and 12.58% (95%CI: 5.99%–19.57%), respectively. Comparatively, PM2.5 and PM10 seemed to only affect boys and have a smaller effect, with the estimated percentage increase of 1.36% (95%CI: 0.35%–2.38%) and 1.28% (95%CI: 0.52%–2.06%), respectively. Among different age groups, PM1 was associated with increased pneumonia hospitalizations in age groups of <12 months (9.0%, 95%CI: 2.29%–16.15%) and 1–4 years (10.16%, 95%CI: 4.71%–15.88%). However, increased pneumonia hospitalizations associated with PM2.5 and PM10 were only seen in 1–4 years age group. In four different seasons, greater increases in pneumonia hospitalizations associated with PM1 were seen in autumn and winter, whereas PM2.5 and PM10 appeared to increase pneumonia hospitalizations only in autumn.

Table 3. Estimated percentage change (%) in childhood pneumonia hospitalizations associated with a 10 μg/m3 increase in PM1, PM2.5, and PM10 concentrations (lag 0–2), stratified by sex, age, and season.

	PM1		PM2.5		PM10	
	Percentage change (95% CI)	p-Value	Percentage change (95% CI)	p-Value	Percentage change (95% CI)	p-Value
Sex						
Boys	8.85 (3.85 to 14.1)	<0.001	1.36 (0.35 to 2.38)	0.009	1.28 (0.52 to 2.06)	0.001
Girls	12.58 (5.99 to 19.57)	<0.001	0.97 (−0.33 to 2.28)	0.144	0.79 (−0.18 to 1.78)	0.113
Age						
<12 months	9.0 (2.29 to 16.15)	0.008	0.50 (−0.82 to 1.83)	0.461	1.02 (0 to 2.05)	0.050
1–4 years	10.16 (4.71 to 15.88)	<0.001	1.65 (0.54 to 2.77)	0.003	1.18 (0.35 to 2.02)	0.005
5–17 years	13.29 (−0.05 to 28.42)	0.051	1.23 (−1.34 to 3.88)	0.352	0.79 (−1.1 to 2.72)	0.417
Season						
Spring	0.85 (−6.77 to 9.10)	0.832	−0.25 (−2.65 to 2.22)	0.844	0.60 (−0.48 to 1.68)	0.278
Summer	5.56 (−9.09 to 22.57)	0.479	0.25 (−3.79 to 4.45)	0.907	1.18 (−1.59 to 4.04)	0.408
Autumn	18.84 (7.63 to 31.21)	<0.001	6.85 (3.99 to 9.79)	<0.001	2.43 (0.22 to 4.69)	0.032
Winter	7.47 (1.07 to 14.26)	0.023	0.63 (−0.51 to 1.78)	0.281	0.15 (−0.93 to 1.23)	0.790

PM1: particulate matter with aerodynamic diameter of ≤1 μm; PM2.5: particulate matter with aerodynamic diameter of ≤2.5 μm; PM10: particulate matter with aerodynamic diameter of ≤10 μm; CI: confidence interval.

Bold figures indicate statistically significant findings.

The potential non-linear exposure-response relationships of pneumonia hospitalizations with PM1, PM2.5, and PM10 were shown in Fig. 3. PM1-pneumonia relationship had a linear and positive slope associated with increase in concentration. There was also a linear and positive trend in PM2.5-pneumonia relationship when concentration was below around 100 μg/m3, after which the relationship remained stable. PM10-pneumonia relationship was slightly non-linear, with a linear and positive slope at concentration not exceed about 80 μg/m3, then a stable slope at concentration of around 80-150 μg/m3, and finally a linear and positive slope at concentration above 150 μg/m3.

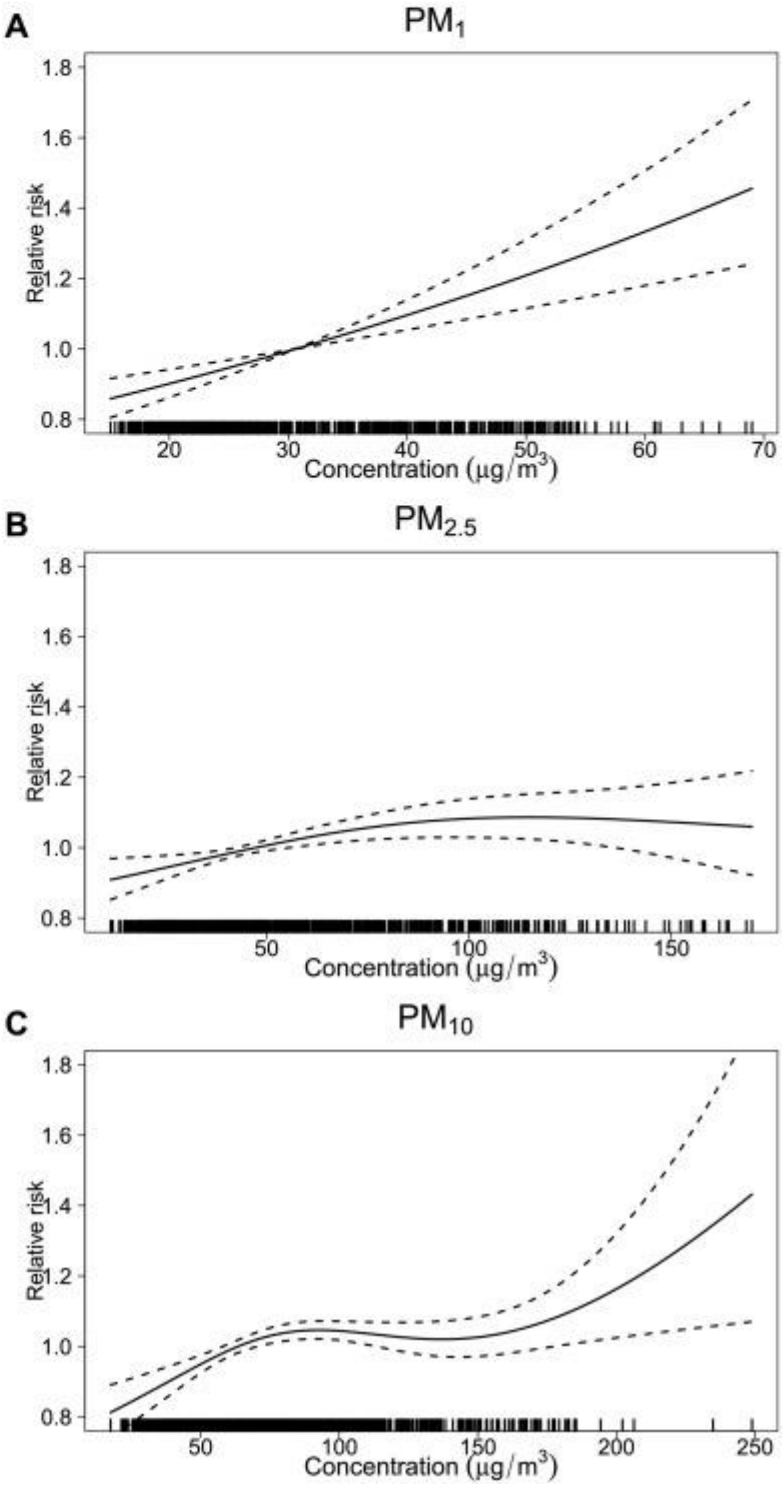

Fig. 3. Exposure-response curves for the associations of childhood pneumonia hospitalizations with PM1, PM2.5, and PM10 concentrations. Solid lines indicate the relative risk and dashed lines are the corresponding 95% confidence interval.

We performed three sensitivity analyses by running two-pollutant models (Table S2), replacing Poisson models with quasi-Poisson models (Table S3), adopting different strategies to adjust for long-term trend and seasonality (Table S4), and adjusting for wind speed and air pressure (Table S5). These sensitivity analyses in general generated similar results, suggesting the robustness of our findings. For example, before and after controlling for O3, each 10 μg/m3 increase in PM1 concentration was associated with 10.28% (95%CI: 5.88%–14.87%) and 10.77% (95%CI: 6.15%–15.58%) increase in the risk of childhood pneumonia hospitalizations (Table S2). Although PM1 effect was reduced after using a natural cubic spline for time with six to eight degrees of freedom per year to adjust for long-term trend and seasonality, the effect difference was not statistically significant (p-value>0.05) (Table S4).

4. Discussion

This study investigated the role of PM sizes (PM1, PM2.5, and PM10) in influencing childhood pneumonia hospitalizations. This study yielded some interesting findings. First, we found positive associations of childhood pneumonia hospitalizations with 3 PM examined. PM1 had the largest impact on pneumonia hospitalizations, followed by PM2.5, and PM10. Second, stratified analyses by sex, age, and season not only verified the greater effects of PM1 but also revealed detrimental PM1 effects in more subgroups and seasons. Third, the shape of exposure-response curve for PM1 and pneumonia hospitalization is approximately linear, suggesting no threshold for the adverse PM1 effects on pneumonia.

The results regarding short-term effects of PM2.5 and PM10 on pneumonia hospitalizations are somewhat consistent with previous studies (Barnett et al., 2005; Cheng et al., 2019a; Li et al., 2018; Tian et al., 2019). For example, Tian et al. (2019) conducted a nationwide study in mainland China. This study reported a positive association between PM and pneumonia hospitalizations. Specifically, a 10 μg/m3 increase in 3-day moving average of PM2.5 and PM10 concentrations were associated with 0.31% and 0.19% increase in adult pneumonia hospitalizations, respectively (Tian et al., 2019). Comparatively, a study in Ningbo, China (Li et al., 2018) and the present study found larger PM2.5 and PM10 effects on childhood pneumonia hospitalizations. Researchers also found harmful effects of PM2.5 and PM10 air pollution on childhood pneumonia in many regions such as Taiwan, China, Australia and New Zealand (Cheng et al., 2019a; Barnett et al., 2005). Meanwhile, these studies suggested that PM2.5 had a slightly larger pneumonia effect than did PM10. However, none of previous studies have investigated the effect of smaller PM such as PM1 on pneumonia occurrence in children.

Specifically, one key finding of this study is that PM1 was found to pose a greater short-term impact on childhood pneumonia hospitalizations than did PM2.5 and PM10. As stated above, there was a lack of studies with similar research context. Therefore, it is difficult to directly compare our findings with previous research. Although short-term relationship between PM1 and childhood pneumonia occurrence is underestimated to date, a recent study has found a greater impact of PM1 than PM2.5 on pneumonia hospitalizations for all ages (Zhang et al., 2020a), which could somewhat support our hypotheses and findings. Several studies also documented greater short-term effects of PM1 than larger sizes PM (PM2.5 and PM10) on all-cause total, cardiovascular and respiratory mortality/morbidity (Chen et al., 2017b; Yin et al., 2020; Zhang et al., 2020a).

In term of toxicology, the impact of PM1 is hard to determine simply based on our statistical analysis. However, several studies (Sun et al., 2013; Niu et al., 2020) documented that PM1 was mainly formed by organic aerosol (OA), In particularly, PM1 related OA could be mainly contributed from primary OA such as hydrocarbon-like OA, cooking OA, coal combustion OA (Křůmal et al., 2013). For example, a study in Beijing found that primary OA dominates PM1-related OA during wintertime (69%) (Sun et al., 2013). As a major component of PM1, long-term exposure to polycyclic aromatic hydrocarbons (PAHs) with high molecular weight could be associated with respiratory diseases, bronchitis and pneumonia, especially to carcinogenic PAHs such Ind, BbkF, DahA, BaP, and BghiP (Agudelo-Castañeda et al., 2017). These may be the factors causing short-term effects of oxidative stress as well as inflammation and resulting childhood pneumonia, while more studies regarding the environmental-health mechanism should be further investigated.

Regarding the impact of different PM on childhood pneumonia hospitalizations in subgroups by sex and age, we also observed a larger increase in hospitalizations due to PM1 in all subgroups in comparison to PM2.5 and PM10. Likewise, previous studies showed a slightly higher risk of total respiratory disease and asthma associated with PM1 than PM2.5 in different sex and age groups (Zhang et al., 2020a; Yang et al., 2018a). Besides, PM1 in this study was found to affect boys and girls as well as age groups of <12 months and 1–4 years. However, PM2.5 and PM10 seemed to affect only boys and 1–4-year-old children. One potential reason for the age and sex differences in PM2.5 and PM10 effects may be related to different behaviors. In general, older children and boys are more active and play more time outdoors, thereby increasing their exposure to PM. Infants or children younger than 12 months in China tend to be kept more time indoors by parents or guardians. Meanwhile, breastfeeding could protect infants from being less affected by PM2.5 and PM10 (Dong et al., 2013). The difference of the results from various PM highlighted that girls and age groups of

<12 months should also be protected in order to minimize the adverse effects on respiratory health across the study area. While the consequences of the effect of PM1 could not clearly been shown from our analysis, one of the possible assumptions could be the toxic composition of PM1, which might be more sensitive to newborn baby with a weak lung. Particularly, younger children (age < 4 years) should have spent more time to stay at home. Therefore, they could have a high chance to be exposed to cooking OA and coal combustion OA. Considering that PM pollution is a ubiquitous threat to childhood respiratory health around the world, more investigations on ultra-fine PM and pneumonia including the mechanism behind the PM-health relationship are needed in other settings. This is because the results might be influenced by geographical disparities of background pollution level and socioeconomic status, therefore, resulting in a variation of sex- and age-specific effects of PM on childhood pneumonia across regions (Li et al., 2018; Qiu et al., 2014; Zhang et al., 2020a).

Partly due to the varying levels, sources, and chemical compositions of PM pollution in different seasons, PM effects on respiratory diseases have been reported to be greater in cold season than in warm season (Li et al., 2018; Zhang et al., 2020a). In the present study, we further divided a year into four seasons and found harmful PM1 effects on childhood pneumonia in both autumn and winter, whereas harmful PM2.5 and PM10 effects were evident only in autumn. In spite of the highest pollution level of PM in winter, local people in China have had an awareness of adverse health effects of particulate matter and take active protective measures such as wearing masks and stay at home in highly polluted days in winter, which could largely reduce or avoid the exposure to PM2.5 and PM10. However, the adverse health effects of PM1 have not been well perceived by people because there were a lack of relevant health research and no real-time reporting platform for PM1 air pollution. Therefore, these preventive measures for PM2.5 and PM10 might not be relevant to PM1. Based on the evidence from the studies of source appointment and chemical compositions (Sun et al., 2013; Niu et al., 2020), staying at home might actually induce a higher risk of PM1 because of coal combustions for heat as well as cooking. Compared with PM2.5 and PM10, there may be a much easier migration of PM1 from the ambient air into the interior space, increasing the exposure frequency to PM1. Conversely, the temperature in autumn is more comfortable than in winter, which motivates children to spend more time outside and expose themselves more frequently and longer to PM air pollution. As a negative health consequence, the risk of childhood pneumonia would be much higher in autumn than winter, as shown in this study. It is also possible that the sources for PM1, PM2.5, and PM10 are different between autumn and winter, leading to inconsistent effects of particulate matter on childhood pneumonia hospitalizations. However, this hypothesis needs to be tested in future investigations.

We also observed an approximately linear relationship between PM1 concentration and childhood pneumonia hospitalizations. This finding implies that childhood pneumonia can be affected by PM1 not only at high concentrations but also at low concentrations. In reality, the distribution of daily PM1 concentration is left skewed, suggesting there are more days with low PM1 concentration than days with high PM1 concentration. Therefore, it is necessary to take proactive measures to protect children's respiratory health even in low-level PM1 polluted days. Particularly, a previous study has found that even a low level of PM1 related carcinogenic PAHs (BaP and DahA) could result in long-term respiratory risk (Agudelo-Castañeda et al., 2017). This further implies the need of protecting short-term risk of respiratory health among children from days with low-level of PM1. In China, the government has already enacted air quality standards for PM2.5 and PM10 pollution and undertaken a series of measures (e.g. 2013 Air Pollution Prevention and Control Action Plan) to improve air quality, which plays an important role in lowering PM2.5 and PM10 concentration and mitigating associated health effects (Huang et al., 2018; Tian et al., 2019). Additionally, the China Atmosphere Watch Network (CAWNET) has established a routine monitoring network for PM1 pollution across China. Based on this foundation, air quality standards as well as warning system could be set up based on the retrieved information from CAWNET in order to develop further action plans to improve air quality. Establishment of warning systems and air quality standards could also be based on accumulating evidence of deleterious PM1 effects on respiratory health (e.g., pneumonia and asthma) and other health outcomes (e.g. emergency department visits, cardiorespiratory mortality) (Zhang et al., 2020a, Zhang et al., 2020b; Yin et al., 2020).

Unlike the linear expose-response association between PM1 and childhood pneumonia hospitalizations, the observed associations for PM2.5 and PM10 are somewhat non-linear. The reasons behind this heterogeneity may be multifaceted including but not limited to the differences in the population awareness or behaviors of protecting themselves in days polluted by different particulate matter, exposure level, and sources and toxicity of different particulate matters. In the case of the association of childhood pneumonia hospitalizations with PM10, a similar exposure-response association shape was also found in a nationwide investigation of PM10 and adult pneumonia hospitalizations in China (Tian et al., 2019). We hypothesized that the increasing trend of PM10 effects at relatively low concentrations could be a result that people did not perceive the risk of low-level of PM10 concentration. Before the PM10 concentration rose up to around 150 μg/m3, PM10 effects were stable, which may be due to a series of protection measures such as wearing masks and house ventilation. The rebound of PM10 effects (increasing trend) seemed to be related to the sporadic occurrence of heavily polluted days by PM10 (above 150 μg/m3) as shown in Fig. 1. The sudden occurrence of heavily polluted days by PM10 did not leave people enough time to take timely response actions, consequently contributing to increased risk of childhood pneumonia.

This study has several limitations. First, this is a single city research, which limits the extrapolation of our findings to other cities/regions with different characteristics. For instance, previous investigations revealed varied short-term PM effects on pneumonia hospitalizations by regional characteristics such as the background pollution level, economic and demographic patterns, and weather conditions (Tian et al., 2019). Second, as with many previous time-series studies, the ecological study design cannot prove the causal association between particulate matters and pneumonia hospitalizations (Tian et al., 2019; Xu et al., 2014). Third, we used air pollution data from fixed air pollution monitors and geographical interpolation technique to measure exposure level at the city-level, which may not be able to reflect PM exposure at individual-level. Thus, uncertainty of the exposure measurement cannot be excluded. Meanwhile, different data sources for PM1, PM2.5, and PM10 may have caused uncertainties in comparing the effects of different PM fractions. More reliable comparison results could be achieved if data on PM1, PM2.5, and PM10 could be from the same source such as the National Urban Air Quality Real-time Publishing Platform. Fourth, due to the issue of data availability, we were unable to examine the effects of chemical compositions of particulate matters, which warrants further investigation. Fifth, we only considered a limited number of confounders in regression model. Several potential confounders such as the influenza epidemics could be risk factors of pneumonia (Shrestha et al., 2015). The results of this study may be influenced after taking into account more confounders in the model. Sixth, due to the issue of data availability, we only collected data from one hospital. Future studies are needed to prove our findings using data from more hospitals.

5. Conclusion

Overall, this study suggests a larger impact of PM1 on childhood pneumonia than PM2.5 and PM10. In addition, compared with PM2.5 and PM10 effects, PM1 effects appeared to be evident in more subgroups including boys and girls, children aged 4 years or younger as well as in more months within a year including autumn and winter. In view of persistent high or increasing level of PM pollution in China and many other rapid developing countries, it is necessary to further examine the effects of different PM, particularly the ultra-fine PM such as PM1 on childhood pneumonia.

References

D.M. Agudelo-Castañeda, E.C. Teixeira, I.L. Schneider, S.R. Lara, L.F.O. Silva. Exposure to polycyclic aromatic hydrocarbons in atmospheric PM1.0 of urban environments: carcinogenic and mutagenic respiratory health risk by age groups. Environ. Pollut., 224 (2017), pp. 158-170

A.J. Badyda, J. Grellier, P. Dąbrowiecki. Ambient PM2.5 exposure and mortality due to lung cancer and cardiopulmonary diseases in Polish cities. Adv. Exp. Med. Biol., 944 (2017), pp. 9-17

A.G. Barnett, G.M. Williams, J. Schwartz, *et al.* Air pollution and child respiratory health: a case-crossover study in Australia and New Zealand. Am. J. Respir. Crit. Care Med., 171 (11) (2005), pp. 1272-1278

R. Chen, P. Yin, X. Meng, *et al.* Fine particulate air pollution and daily mortality. A nationwide analysis in 272 Chinese cities. Am. J. Respir. Crit. Care Med., 196 (1) (2017), pp. 73-81

G. Chen, S. Li, Y. Zhang, *et al.* Effects of ambient PM1 air pollution on daily emergency hospital visits in China: an epidemiological study. Lancet Planet Health., 1 (6) (2017), pp. e221-e229

G. Chen, Z. Jin, S. Li, *et al.* Early life exposure to particulate matter air pollution (PM1, PM2.5 and PM10) and autism in Shanghai, China: a case-control study. Environ. Int., 121 (Pt 2) (2018), pp. 1121-1127

C.Y. Cheng, S.Y. Cheng, C.C. Chen, H.Y. Pan, K.H. Wu, F.J. Cheng. Ambient air pollution is associated with pediatric pneumonia: a time-stratified case-crossover study in an urban area. Environ. Health, 18 (1) (2019), p. 77

J. Cheng, Z. Xu, X. Zhang, H. Zhao, W. Hu. Estimating cardiovascular hospitalizations and associated expenses attributable to ambient carbon monoxide in Lanzhou, China: scientific evidence for policy making. Sci Total Environ., 682 (2019), pp. 514-522

G.H. Dong, Z.M. Qian, M.M. Liu, D. Wang, W.H. Ren, S. Bawa, J. Fu, J. Wang, R. Lewis, A . Zelicoff, M. Simckes, E. Trevathan. Breastfeeding as a modifier of the respiratory effects of air pollution in children. Epidemiology., 24 (3) (2013), pp. 387-394

J. Gao, H. Tian, K. Cheng, *et al.* The variation of chemical characteristics of PM2. 5 and PM10 and formation causes during two haze pollution events in urban Beijing, China. Atmos. Environ., 107 (2015), pp. 1-8

N. Gouveia, T. Fletcher. Respiratory diseases in children and outdoor air pollution in São Paulo, Brazil: a time series analysis. Occup. Environ. Med., 57 (7) (2000), pp. 477-483

M. Hadei, A. Shahsavani, M. Krzyzanowski, *et al.* Burden of mortality attributed to PM2.5 exposure in cities of Iran; contribution of short-term pollution peaks. Atmos. Environ., 224 (2020), pp. 1352-2310

J. Huang, X. Pan, X. Guo, G. Li. Health impact of China's air pollution prevention and control action plan: an analysis of national air quality monitoring and mortality data. Lancet Planet Health., 2 (7) (2018), pp. e313-e323

K. Křůmal, P. Mikuška, Z. Večeřa. Polycyclic aromatic hydrocarbons and hopanes in PM1 aerosols in urban areas. Atmos. Environ., 67 (2013), pp. 27-37

D. Li, J.B. Wang, Z.Y. Zhang, *et al.* Effects of air pollution on hospital visits for pneumonia in children: a two-year analysis from China. Environ. Sci. Pollut. Res. Int., 25 (10) (2018), pp. 10049-10057

N. Li, G. Chen, F. Liu, *et al.* Associations of long-term exposure to ambient PM1 with hypertension and blood pressure in rural Chinese population: the Henan rural cohort study. Environ. Int., 128 (2019), pp. 95-102

H. Lin, J. Tao, Y. Du, *et al.* Particle size and chemical constituents of ambient particulate pollution associated with cardiovascular mortality in Guangzhou, China. Environ Pollut., 208 (Pt B) (2016), pp. 758-766

N.T.T. Nhung, H. Amini, C. Schindler, *et al.* Short-term association between ambient air pollution and pneumonia in children: a systematic review and meta-analysis of time-series and case-crossover studies. Environ. Pollut., 230 (2017), pp. 1000-1008

N.T.T. Nhung, C. Schindler, T.M. Dien, N. Probst-Hensch, L. Perez, N. Künzli. Acute effects of ambient air pollution on lower respiratory infections in Hanoi children: an eight-year time series study. Environ. Int., 110 (2018), pp. 139-148

X. Niu, Y. Wang, S.S.H. Ho, *et al.* Characterization of organic aerosols in PM1 and their cytotoxicity in an urban roadside area in Hong Kong. Chemosphere., 263 (2020), p. 128239

R. Pan, J. Gao, X. Wang, *et al.* Impacts of exposure to humidex on the risk of childhood asthma hospitalizations in Hefei, China: effect modification by gender and age. Sci Total Environ., 691 (2019), pp. 296-305

H. Qiu, L.W. Tian, V.C. Pun, K.F. Ho, T.W. Wong, I.T. Yu. Coarse particulate matter associated with increased risk of emergency hospital admissions for pneumonia in Hong Kong. Thorax., 69 (11) (2014), pp. 1027-1033

S. Shrestha, B. Foxman, J. Berus, *et al.*The role of influenza in the epidemiology of pneumonia. Sci. Rep., 5 (2015), p. 15314

Y.L. Sun, Z.F. Wang, P.Q. Fu, *et al.* Aerosol composition, sources and processes during wintertime in Beijing, China. Atmos. Chem. Phys., 13 (9) (2013), pp. 4577-4592

Y. Tian, H. Liu, Y. Wu, *et al.* Ambient particulate matter pollution and adult hospital admissions for pneumonia in urban China: a national time series analysis for 2014 through 2017. PLoS Med., 16 (12) (2019), Article e1003010

C.L.F. Walker, I. Rudan, L. Liu, *et al.* Global burden of childhood pneumonia and diarrhoea. Lancet., 381 (9875) (2013), pp. 1405-1416

J. Wei, Z. Li, J. Guo, *et al.* Satellite-derived 1-km-resolution PM1 concentrations from 2014 to 2018 across China. Environ Sci Technol., 53 (22) (2019), pp. 13265-13274

J. Wei, Z. Li, A. Lyapustin, *et al.* Reconstructing 1-km-resolution high-quality PM2.5 data records from 2000 to 2018 in China: spatiotemporal variations and policy implications. Remote Sens. Environ., 252 (112136) (2021), [10.1016/j.rse.2020.112136](10.1016/j.rse.2020.112136)

World Health Organization. Regional Office for Europe & European Centre for Environment and Health. Effects of Air Pollution on Children's Health and Development: A Review of the Evidence. WHO Regional Office for Europe, Copenhagen (2005). https://apps.who.int/iris/handle/10665/107652 (accessed 10 December 2020)

J. Xie, J. Teng, Y. Fan, R. Xie, A. Shen. The short-term effects of air pollutants on hospitalizations for respiratory disease in Hefei, China. Int. J. Biometeorol., 63 (3) (2019), pp. 315-326

Z. Xu, Y. Liu, Z. Ma, S. Li, W. Hu, S. Tong. Impact of temperature on childhood pneumonia estimated from satellite remote sensing. Environ. Res., 132 (2014), pp. 334-341

M. Yang, C. Chu, M.S. Bloom, *et al.* Is smaller worse? New insights about associations of PM1 and respiratory health in children and adolescents. Environ. Int., 120 (2018), pp. 516-524

B.Y. Yang, Z.M. Qian, S. Li, *et al.* Long-term exposure to ambient air pollution (including PM1) and metabolic syndrome: the 33 Communities Chinese Health Study (33CCHS). Environ. Res., 164 (2018), pp. 204-211

BY Yang, Y Guo, L Morawska, M.S. Bloom, I Markevych, J Heinrich, ..., G Chen. Ambient PM1 air pollution and cardiovascular disease prevalence: Insights from the 33 Communities Chinese Health Study. Environ Int., 123 (2019), pp. 310-317

P. Yin, J. Guo, L. Wang, W. Fan, F. Lu, M. Guo, S.B.R. Moreno, Y. Wang, H. Wang, M. Zhou, Z. Dong. Higher risk of cardiovascular disease associated with smaller size-fractioned particulate matter. Environ Sci Technol Lett., 7 (2020), pp. 95-101

Y. Zhang, J. Lang, S. Cheng, *et al.* Chemical composition and sources of PM1 and PM2.5 in Beijing in autumn. Sci. Total Environ., 630 (2018), pp. 72-82

Y. Zhang, H. Ni, L. Bai, *et al.* The short-term association between air pollution and childhood asthma hospital admissions in urban areas of Hefei City in China: a time-series study. Environ. Res., 169 (2019), pp. 510-516

Y. Zhang, Z. Ding, Q. Xiang, W. Wang, L. Huang, F. Mao. Short-term effects of ambient PM1 and PM2.5 air pollution on hospital admission for respiratory diseases: case-crossover evidence from Shenzhen, China. Int J Hyg Environ Health, 224 (2020), Article 113418

Y. Zhang, J. Fang, F. Mao, Z. Ding, Q. Xiang, W. Wang. Age- and season-specific effects of ambient particles (PM1, PM2.5, and PM10) on daily emergency department visits among two Chinese metropolitan populations. Chemosphere, 246 (2020), Article 125723