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Research article

Assessing the effects of meteorological factors on daily children's respiratory disease hospitalizations: A retrospective study

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ABSTRACT

Respiratory disease symptoms in children are aggravated by frequent changes in meteorological conditions. The net effective temperature (NET) integrates temperature, relative humidity, and wind speed as a cooling indicator. This study aims to assess the effect of daily changes in meteorological factors and corresponding NET data on children's hospitalizations for different ages, genders and subtypes of respiratory infections in Baotou, China. Distributed lag non-linear models were constructed to simultaneously assess the exposure–response associations between daily admission counts of children with respiratory diseases and daily NET and other meteorological factors, as well as their lag dependencies. As air pollution significantly affects the respiratory tract, it was considered as confounding factor. In general, the cumulative meteorological factors had greater effects on lower respiratory tract infections than upper respiratory tract infections (RR: temperature [5.21 vs. 2.33], wind speed [4.89 vs. 3.12], and humidity [1.77 vs. 0.97]). The effects of cumulative meteorological factors on female children were greater than those on male children (RR: temperature [2.14 vs. 1.82], wind speed [5.46 vs. 1.90], and humidity [1.60 vs. 1.55]). Temperature and wind speed showed an influence on 4–7-year-old children, but these factors had no influence on other age groups; humidity only showed an influence on the 0–3-year-old group. The NET value had a large effect on lower respiratory infections, in the 4–7-year-old group and female children. In conclusion, a complex non-linear relationship exists between climate variability and children's respiratory diseases. The results of the study can be used to support the development of important meteorological information tools for early warnings of respiratory disease events in children. Concurrently, the NET values can be used for comprehensive assessments of climate change in the future, which will help the government and health authorities better minimize the impacts of children's respiratory diseases.

1. Introduction

Respiratory disease is one of the most common types of diseases in children and can be affected by complex meteorological factors. Previous studies revealed that a relationship exists between children's respiratory diseases and meteorological factors, including temperature, humidity, wind speed, and atmospheric pressure [1, 2, 3]. However, the results and conclusions still contain some irregularities. Some studies suggest that the effects of cold spells on human health might be mainly due to the daily temperature fluctuations, as well as the persistent and extreme climate change [4, 5]. Temperature changes increase the rates of medical service utilization in terms of emergency department visits [6] and hospital admissions [7]. A meta-analysis in previous work showed that comprehensive evaluations of temperature, humidity, and wind speed on disease incidence have better results than that of a single evaluation of temperature [4]. This was not an unexpected discovery because high winds can aggravate the physiological effects of cold temperatures and a dry environment can stimulate the production of additional external dust and other substances, which have negative effects on the respiratory system. Because of the complicated patterns in the association of health outcomes with seasonal characteristics, several studies have evaluated the health effects of different air characteristics while integrating climatic conditions in the analysis [8, 9, 10]. The net effective temperature (NET) integrates temperature, relative humidity, and wind speed as a

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cooling indicator; NET is known to increase with rising temperature and relative humidity and decrease with strong winds [11]. Respiratory diseases are related to a variety of outdoor environments. Notably, respiratory disease symptoms in children are aggravated by frequent changes in meteorological conditions [12]. Children are particularly vulnerable to environmental hazards because of their less developed immune systems, compared to adults, but only few studies have examined the relationship between climate and morbidity among children [2]. Children have fewer and immature bronchial smooth muscles, a low proportion of anti-fatigue diaphragm fiber, and immature immune systems [13]. Thus, they encounter respiratory diseases more frequently.

This study aims to explore the relationship between the daily changes in average temperature, average humidity, wind speed, and NET and respiratory disease hospitalizations (RDHs) in children of different ages and genders in the Baotou area.

Baotou City, China, is located in the southern part of the Mongolian Plateau; the Yinshan Mountains run through the northern part of the study area, and the Yellow River is close to the southern part. The complex geographical forms in this area have contributed to its complex climate characteristics and relatively distinct seasonal characteristics with temperature variations. Climate change will also significantly increase the incidence of respiratory diseases, such as seasonal flu, asthma, and pneumonia, by affecting viral activity and transmission, changing the immune responses of vectors and hosts, and facilitating the distribution of allergens [3, 14, 15]. This is the first comprehensive study to evaluate and compare the impacts of meteorological factors on the risk of children's RDHs in China. Our study not only fills in an important research gap for this geographical location in terms of worldwide knowledge on such issues, but it also provides integrated data for other researchers to comprehensively evaluate the impacts of climate on diseases.

2. Methods

2.1. Data sources

This study was conducted in Baotou (109°14′ E to 110°52′ E; 40°23′ N to 41°07′ N), which is located in the central part of Inner Mongolia, China, specifically in the southern part of the Mongolian Plateau. Baotou is a typical temperate continental climate zone, with four distinct seasons. The average annual precipitation is 240–400 mm which mainly occurs from July to September. Northwest wind prevails in winter and southeast wind prevails in spring and summer. Frequent dust storms occur from March to May [16]. The complex geographical characteristics of the city contribute to its complex and changeable meteorological environment. People living in such an environment, especially children, are vulnerable to the impacts of meteorological changes. Baotou is the largest city in Inner Mongolia and covers an area of 1785 km^2, with permanent population of 2.1039 million in 2018 and population density of 1178 persons/km^2 [17].

Data on children's RDHs in this study were sourced from the following three major hospitals in Baotou: The First Affiliated Hospital of Baotou Medical College, Inner Mongolia Baotou City Central Hospital, and Zhong Meng Hospital of Baotou City. The three hospitals are located in the eastern (Kunqu District), the western (Donghe District) and the central region (Jiuyuan District), respectively, The population coverage of the three hospitals is approximately 85%. Our target population was aged less than 18 years and had been hospitalized for a natural respiratory disease between January 1, 2014, and December 31, 2018. We screened the admission registration information records from the electronic databases. The inclusion criteria for hospital admissions were met if the data comprised primary and discharge diagnoses, dates of admission and discharge, age, sex, and residential location of the individual patients. We excluded patients who were not residents of Baotou city. The hospitalization data consisted of daily admissions due to respiratory diseases (according to ICD-10, J00-99, and excluding lung diseases due to external agents). Then, we calculated the number of children's respiratory admission cases per day. According to the school age of Chinese children, we divided the ages into the early childhood stage (0–3 years old), kindergarten stage (4–7 years old), and primary school and above stage (>7 years old).

The meteorological data were obtained from electronic databases containing routine meteorological observations collected at a ground observation station by the Baotou Meteorological Administration from January 1, 2014, to December 31, 2018; the data included the average temperature, average wind, relative humidity, and pressure. Data on air pollutants, including 24-hour mean particulate matter ≤2.5 μm (PM2.5), particulate matter ≤10 μm (PM10), sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) were obtained from all of the ambient monitoring stations operated by the Pollution Control Department located in the study area.

2.2. Definition of the NET

The NET is an index that integrates the effects of temperature, humidity, and wind speed to evaluate weather stress [11]. The formula for calculating the NET is expressed as follows:

$$\mathrm{NET} = 37 - \frac{37 - \mathrm{T}}{0.68 - 0.0014\mathrm{H} + \left(1.76 + 1.4\mathrm{V}^{0.75}\right)^{-1}} - 0.29\mathrm{T}(1 - 0.01\mathrm{H}),$$

where T is the ambient temperature (°C), V refers to the wind speed (m/s), and H is the relative humidity (%). A large positive NET value implies an exceptionally high heat load, while a large negative value represents large heat loss. In hot weather, the NET value increases with an increase in temperature and/or relative humidity, but it decreases with an increase in wind speed. In cold weather, the NET value decreases with a decrease in temperature and with an increase in relative humidity and wind speed [11].

2.3. Statistical analysis

As the daily count of children's RDHs typically followed a Poisson distribution, a statistical analysis using a Poisson distribution was carried out. Meanwhile, previous studies have shown that the association between meteorological factors and incidence is non-linear and changes in meteorological factors can have lagged effects on respiratory illness [18]. Therefore, quasi-Poisson regressions with distributed lag non-linear models (DLNMs) were applied to explore the impacts of meteorological factors on hospital visits for respiratory diseases of children. The models were formulated as follows:

$$\begin{aligned}&\mathrm{Log}(\mathrm{E}(\mathrm{Y})) = \alpha + \beta(\text{Meteorological factors}, \mathrm{Lag} = 21) + \mathrm{ns}(\mathrm{time}, 4\mathrm{df}/\mathrm{year}) +\\ &\mathrm{ns}(\mathrm{PM2.5}, 3\mathrm{df}) + \mathrm{ns}(\mathrm{PM10}, 3\mathrm{df}) + \mathrm{ns}(\mathrm{SO}_2, 3\mathrm{df}) + \mathrm{ns}(\mathrm{NO}_2, 3\mathrm{df}) + \eta\mathrm{Holiday} + \delta\mathrm{Dowt},\end{aligned}$$

where E(Y) is the expected number of daily hospital visits of children due to respiratory diseases. The meteorological factors included the daily mean temperature, humidity, wind speed, and NET. β is the regression coefficient and ns is the natural spline-smoothing function. Holiday denotes the number of public holidays, and Dow_t is the categorical day of the week. Pressure was excluded in our final model, as this factor was strongly associated with the mean temperature. The df for time and NET were 20 and 3, respectively, and the df were 5 for temperature, humidity, and wind speed. The preliminary analysis shows that the effects of meteorological factors on hospital admissions persisted for 21 days. We then examined the cumulative effects of meteorological factors on hospital admissions up to 21 days (cumulative lag 0–lag 21 days).

The Akaike information criterion (AIC) was used to select the model. All associations were reported as the relative risk (RR) with the corresponding 95% confidence interval (CI), compared to the defined reference value. All of the statistical analyses were conducted by using R3.6.1.

3. Results

RDHs of 30,486 children were recorded among children during the entire study period. Table 1 shows the summary statistics for mean temperature, relative humidity, daily barometric pressure, wind speed, and air pollutants, as well as the cause-, age-, and gender-specific pediatric children's RDHs. The average mean temperature, average relative humidity, average wind speed, and average barometric pressure were 8.3 °C (range: -19.7–30.0 °C), 54.8% (11.5%–97.0%), 2.9 m/s (0.9–7.8 m/s) and 902.2 Pa (885.0–924.7 Pa), respectively. The 24-hour mean values of $PM_{2.5}$, PM_{10}, SO_2 and NO_2 were 44.5 μg/m^3 (0.0–388.3 μg/m^3), 103.2 μg/m^3 (0.0–632.1 μg/m^3), 34.1 μg/m^3 (4.0–254.0 μg/m^3), and 40.9 μg/m^3 (9.0–99.0 μg/m^3), respectively. The daily number of children's RDHs was higher among children aged 0–3 years (median: 9) than among those 4–7 years (median: 4) and older than 7 years (median: 2). The daily number of RDHs was greater among male children (median: 9) than female children (median: 7). The daily number of children's RDHs was greater among patients with lower respiratory tract infections (median: 12) than those with upper respiratory tract infections (median: 5).

The spearman correlation coefficients between air pollutants and meteorological parameters are shown in Table 2. Each of the meteorological parameters was significantly correlated with the air pollutants. Further, temperature and pressure were significantly correlated with each other. These results indicated that the confounding effects of air pollutants and the effects of pressure should be controlled in models.

Figure 1 shows the cumulative effects (lag days: 0–21) of the different meteorological factors on the children's RDHs stratified by age, gender, and subtype. The relationship between temperature and children's RDHs had an inverted U-shape. The cumulative effects of daily average temperature on the children's RDHs increased as the temperature changed from cold to hot and decreased as it changed from hot to cold. Total RDHs, female children, and children with upper respiratory tract infections were more susceptible to temperatures ranging from 0 to 20 °C, whereas children with lower respiratory tract infections and those 4–7 years were more susceptible to temperatures ranging from -10 to 20 °C. Male children were more susceptible to temperatures ranging from 9 to 18 °C. Temperature variations did not exert much of an effect on hospital visits for children aged 0–3 years. Table 3 shows that the influence of temperature, wind speed, and NET on admissions for lower respiratory tract infections was greater than that for upper respiratory tract infections. Moreover, admissions of 4–7-year-old children were greater than those of other age groups, and admissions of female children were greater than those of male children. However, the influence of humidity on admissions of 0–3-year-old children was greater than that in the other age groups.

Figure 2 showed Cumulative effects of NET variables on children's RDHs. The cumulative effect of the NET on total children's RDHs increased for NET values from -10 to 20 and peaked at an NET value of -0.5 (RR: 1.91, 95% CI: 1.39–2.63). The cumulative effect of the NET on lower respiratory tract infections increased for NET values from -20.2 to 24 and peaked at an NET value of -7 (RR: 3.74, 95% CI: 1.86–7.54). The cumulative effect of the NET on upper respiratory tract infections increased for NET values from -8.2 to 18.8 and peaked at an NET value of -1.3 (RR: 2.25, 95% CI: 1.49–3.41). The cumulative effect of the NET on RDHs of patients 4–7 years increased for NET values from -13.8 to 24 and peaked at an NET value of -3.9 (RR: 7.67, 95% CI: 3.94–14.93). The cumulative effect of the NET on male children RDHs increased with NET values from -6.2 to 24 and peaked when the NET was 2.7 (RR: 1.75, 95% CI: 1.22–2.50). The cumulative effect of the NET on female children RDHs increased with NET values from -8.1 to 11.9 and peaked when the NET value was -2.1 (RR: 2.08, 95% CI: 1.31–3.31).

The RR value and 95% CIs of the effects of different indicators on the children's RDHs on the current day and lag days 1 through 21 can be found in Table 4. The influence of meteorological factors on the admissions of children with respiratory problems was mainly concentrated on the lags of 7 and 14 days. Meanwhile, no statistical significance was detected for the lag of 21 days.

4. Discussion

Our study assessed the relationship between meteorological factors and children's RDHs. The meteorological factors in region were found to be significantly associated with children's RDHs after adjusting for

Table 1. Descriptive summary for children hospitalizations of respiratory disease and meteorological factors in Baotou, China (2014–2018).

	Min.	P (1th)	Median	Mean	P (99th)	Max.
Total respiratory (n = 30486)	1	3	16	17	39	70
Lower respiratory infection (n = 23443)	0	1	12	12	33	67
Upper respiratory infection (n = 7043)	0	0	5	5	15	34
0-3-years-old group (n = 18041)	0	1	9	10	25	49
4–7 years old group (n = 8179)	0	0	4	4	14	21
>7 years old group (4266)	0	0	2	2	9	13
male (n = 16772)	0	1	9	9	22	62
female (n = 13714)	0	1	7	7	19	42
Meteorological variables						
Mean temperature (°C)	-19.7	-15.6	10.1	8.3	27.3	30.0
Relative humidity (%)	11.5	21.0	55.3	54.8	90.5	97.0
Pressure (PA)	885.0	889.6	902.2	902.2	917.2	924.7
Wind speed (m/s)	0.9	1.1	2.7	2.9	6.9	7.8
PM2.5 (μg/m^3)	0.0	0.0	38.0	44.5	154.4	388.3
PM10 (μg/m^3)	0.0	0.0	89.5	103.2	371.4	632.1
SO_2 (μg/m^3)	4.0	6.0	27.0	34.1	119.7	254.0
NO_2 (μg/m^3)	9.0	11.0	39.0	40.9	82.7	99.0
NET	-34.5	-26.2	3.0	0.8	21.6	24.0

Table 2. Spearman correlation coefficients between air pollutants and meteorological parameters.

	Temperature	Pressure	Humidity	Wind	PM2.5	PM10	SO2	NO2
Temperature	1.000							
Pressure	-.817**	1.000						
Humidity	0.002	0.031	1.000					
Wind	.104**	-.112**	-.166**	1.000				
PM2.5	-.306**	.127**	.265**	-.140**	1.000			
PM10	-.215**	0.037	-0.007	-0.038	.867**	1.000		
SO_2	-.520**	.322**	.082**	-.207**	.735**	.674**	1.000	
NO_2	-.295**	.158**	.233**	-.351**	.738**	.631**	.784**	1.000

**p < 0.01.

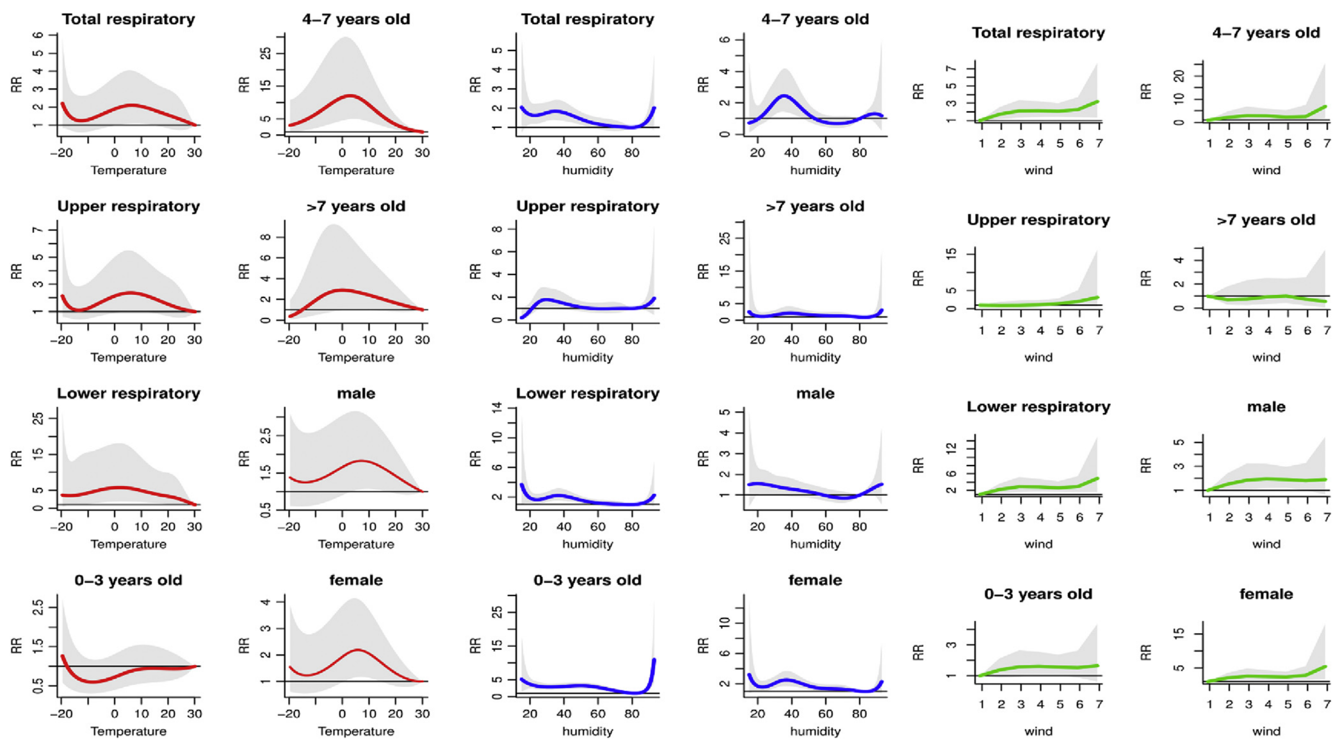

Figure 1. Cumulative effects of meteorological factors on respiratory hospitalizations stratified by age, gender, and respiratory subtypes.

Table 3. Cumulative relative risk of meteorological factors in different respiratory subgroups.

Indicators	Cumulative RR (95CI) in respiratory subgroups							
	Total respiratory	Lower respiratory infection	Upper respiratory infection	0–3 years	4–7 years	>7 years	Male	Female
Temperature (8.3 vs 30 °C)	**2.08 (1.09–3.96)**	**5.21 (1.76–15.47)**	**2.33 (1.03–5.30)**	0.87 (0.39–1.93)	**10.32 (4.54–23.45)**	2.53 (0.98–6.51)	**1.82 (1.07–3.09)**	**2.14 (1.16–3.93)**
Humidity (21 vs 80.1%)	**1.64 (1.19–2.26)**	**1.77 (1.17–2.65)**	0.97 (0.54–1.75)	**3.50 (2.38–5.13)**	1.04 (0.58–1.87)	1.21 (0.57–2.57)	**1.55 (1.05–2.28)**	**1.60 (1.03–2.49)**
Wind speed (6.9 vs 0.9 m/s)	**3.19 (1.32–7.70)**	**4.89 (1.59–15.00)**	3.12 (0.60–16.27)	1.65 (0.62–4.37)	**6.91 (1.85–25.77)**	0.78 (0.08–7.48)	1.90 (0.66–5.48)	**5.46 (1.65–18.07)**
NET (peaks vs 24)	**1.91 (1.39-2.63)**[a]	**3.74 (1.86-7.54)**[b]	**2.25 (1.49-3.41)**[c]	1.25 (0.90–1.72)[d]	**7.67 (3.94-14.93)**[e]	2.23 (0.89–5.53)[f]	**1.75 (1.22-2.50)**[g]	**2.08 (1.31-3.31)**[h]

The bold values are represents the P value of confifidence interval < 0.05.
[a] peaking at -0.5 of NET values.
[b] peaking at -7 of NET values.
[c] peaking at -1.3 of NET values.
[d] peaking at 6.4 of NET values.
[e] peaking at -3.9 of NET values.
[f] peaking at -7.6 of NET values.
[g] peaking at 2.7 of NET values.
[h] peaking at -2.1 of NET values.

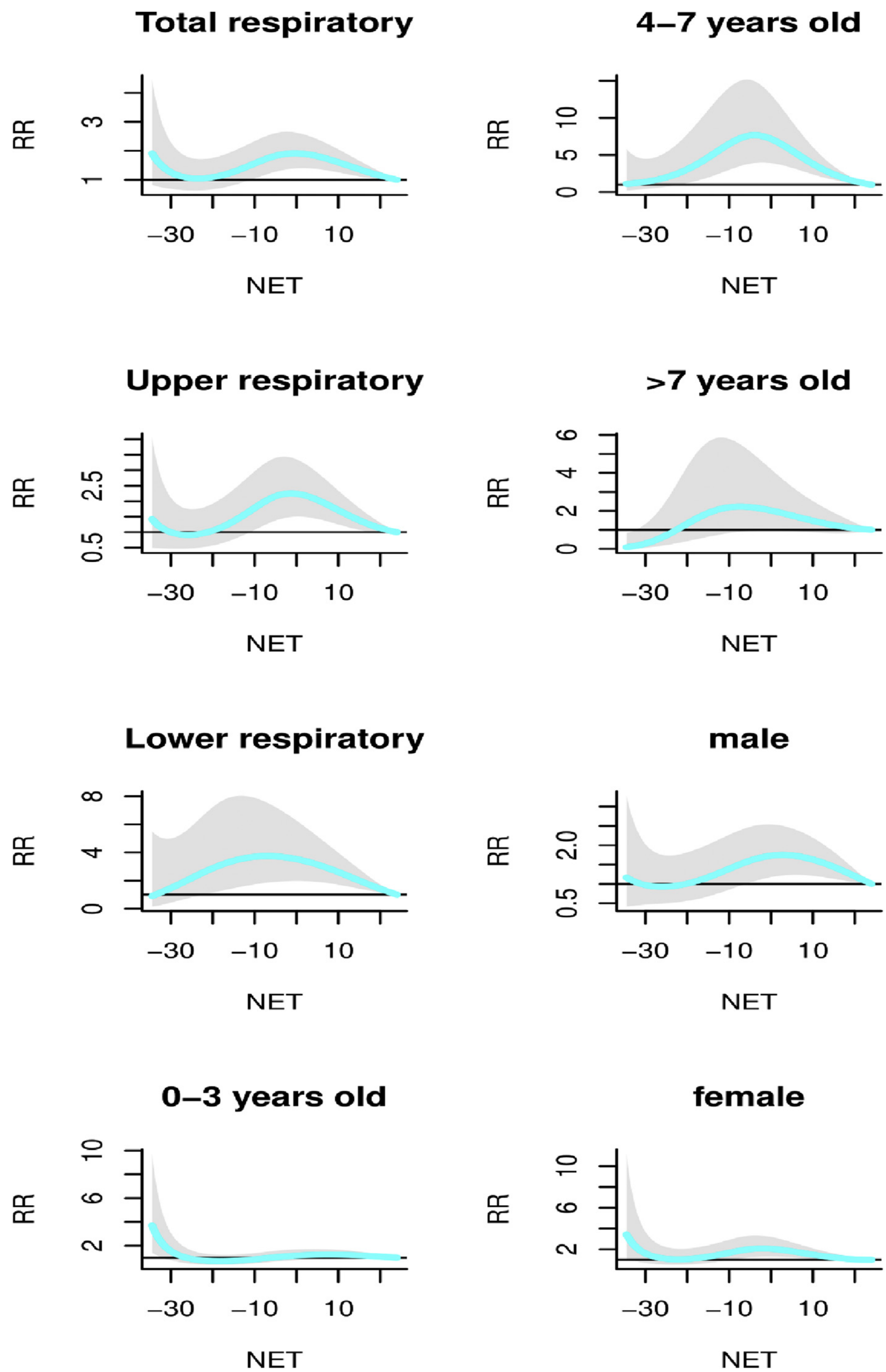

Figure 2. Cumulative effects of NET variables on children's RDHs.

confounding effects of air pollutants. However, the effects of each factor were different for various ages, genders, and respiratory infection subtypes. The relationship between temperature and children's RDHs had an inverted U-shape. The extreme cold and hot temperatures had no effects on children's hospitalizations for respiratory diseases. The impact of temperature on children's RDHs was realized when the temperature changed from cold to hot or vice versa. This type of temperature change mainly occurs in spring and autumn in Baotou. Humidity showed negative effects on 0–3-year-old patients. Greater wind speeds were associated with greater risks of hospitalization for the 4–7-year-old group and female children. In general, the cumulative meteorological factors showed greater effects on lower respiratory tract infections than upper respiratory tract infections; the effects on 4–7-year-old group were greater than those on 0–3-yea-old group; and the effects on female children were greater than those on male children. However, some differences were observed between groups with regard to the effect of humidity. Hence, the NET value was calculated by using comprehensive data on meteorological factors, and the influence range value and peak value of each group were determined.

As per the current research findings, most studies point to the impacts of extremely cold and hot environments on respiratory diseases [1, 3, 9, 10, 18, 19, 20, 21, 22]. A time series analysis of asthma cases in Shenyang showed that children's asthma risk increases with a decrease in temperature [3]. A study of the effects of temperature on respiratory diseases in

Table 4. The RRs with 95%CI of NET on hospital admissions in children by time lag.

	lag 1	lag 7	lag 14	lag 21
temperature				
total	0.96 (0.85–1.07)	1.04 (0.98–1.09)	**1.07 (1.02–1.26)**	1.04 (0.93–1.17)
Lower	**1.35 (1.11–1.62)**	0.98 (0.91–1.07)	1.04 (0.96–1.12)	1.15 (0.95–1.38)
Upper	0.92 (0.79–1.06)	**1.08 (1.01–1.15)**	**1.11 (1.04–1.18)**	0.98 (0.85–1.35)
0–3 years	0.85 (0.74–0.97)	1.01 (0.94–1.08)	1.04 (0.98–1.10)	1.03 (0.89–1.18)
4–7 years	1.10 (0.96–1.27)	**1.11 (1.03–1.19)**	**1.12 (1.06–1.19)**	1.10 (0.96–1.26)
>7 years	1.03 (0.87–1.22)	**1.09 (1.01–1.18)**	1.05 (0.98–1.12)	0.95 (0.82–1.10)
male	0.93 (0.84–1.02)	1.03 (0.99–1.08)	**1.07 (1.03–1.11)**	1.05 (0.96–1.14)
female	0.97 (0.87–1.08)	**1.06 (1.01–1.12)**	**1.06 (1.02–1.11)**	0.99 (0.90–1.10)
humidity				
total	**1.06 (1.01–1.11)**	1.02 (0.99–1.04)	**1.01 (1.01–1.03)**	1.02 (0.97–1.07)
Lower	**1.09 (1.03–1.15)**	1.01 (0.98–1.04)	1.01 (0.98–1.04)	1.02 (0.97–1.09)
Upper	0.95 (0.87–1.04)	1.01 (0.97–1.06)	1.01 (0.97–1.05)	1.00 (0.92–1.09)
0–3 years	**1.15 (1.09–1.22)**	**1.04 (1.01–1.08)**	**1.04 (1.01–1.07)**	1.05 (0.98–1.11)
4–7 years	1.01 (0.93–1.20)	0.99 (0.95–1.04)	1.01 (0.96–1.05)	1.00 (0.92–1.09)
>7 years	1.08 (0.97–1.22)	0.99 (0.93–1.05)	0.98 (0.92–1.03)	1.03 (0.92–1.15)
male	1.03 (0.97–1.09)	**1.03 (1.00–1.06)**	1.02 (0.99–1.05)	0.99 (0.94–1.04)
female	**1.11 (1.04–1.18)**	0.99 (0.97–1.03)	0.99 (0.97–1.02)	1.04 (0.98–1.11)
wind				
total	1.08 (0.99–1.16)	**1.07 (1.01-1.13)**	**1.06 (1.00–1.11)**	1.00 (0.93–1.09)
Lower	1.10 (0.99–1.21)	**1.10 (1.03–1.17)**	**1.08 (1.01–1.16)**	1.00 (0.91–1.11)
Upper	1.10 (0.96–1.27)	1.07 (0.97–1.19)	1.02 (0.93–1.13)	1.01 (0.87–1.18)
0–3 years	1.04 (0.95–1.13)	1.02 (0.96–1.08)	1.03 (0.97–1.09)	1.01 (0.93–1.11)
4–7 years	1.11 (0.95–1.30)	**1.18 (1.06–1.32)**	**1.14 (1.03–1.27)**	1.06 (0.90–1.24)
>7 years	1.14 (0.94–1.39)	1.02 (0.89–1.17)	0.95 (0.83–1.09)	0.87 (0.71–1.06)
male	1.05 (0.96–1.15)	1.04 (0.98–1.11)	1.01 (0.95–1.07)	1.02 (0.92–1.12)
female	1.09 (0.98–1.20)	**1.09 (1.02–1.17)**	**1.11 (1.03–1.19)**	1.01 (0.90–1.13)
NET				
total	0.97 (0.91–1.04)	**1.04 (1.00–1.07)**	**1.06 (1.03–1.09)**	1.02 (0.96–1.10)
Lower	1.05 (0.93–1.18)	1.06 (0.99–1.12)	**1.07 (1.01–1.13)**	1.08 (0.96–1.21)
Upper	0.98 (0.90–1.07)	**1.06 (1.02–1.11)**	**1.06 (1.02–1.10)**	1.00 (0.92–1.10)
0–3 years	0.93 (0.86–1.01)	1.00 (0.97–1.05)	**1.05 (1.01–1.09)**	1.03 (0.95–1.12)
4–7 years	1.08 (0.95–1.23)	**1.10 (1.03–1.17)**	**1.10 (1.04–1.17)**	1.10 (0.97–1.25)
>7 years	0.99 (0.85–1.18)	1.08 (0.99–1.16)	1.05 (0.97–1.12)	0.98 (0.84–1.14)
male	0.96 (0.88–1.04)	1.03 (0.99–1.07)	**1.05 (1.02–1.09)**	1.03 (0.95–1.12)
female	0.98 (0.89–1.09)	**1.06 (1.01–1.11)**	**1.06 (1.02–1.11)**	0.99 (0.90–1.10)

The bold values are represents the P value of confifidence interval < 0.05.

Lanzhou, China, showed that the peak period of respiratory diseases ranged from November to March of the next year. Both low and high temperatures increase the risk of hospitalization for respiratory disease [18]. Moreover, the risk of children suffering from respiratory diseases in other environments has been reported. A study in Beijing showed that the incidence of respiratory diseases in children infected with adenovirus was positively correlated with the average monthly temperature and negatively correlated with the wind speed [14]. A study in Seoul, Korea, found that the impact of the dry season on children's respiratory health was strongest in spring for those aged 0–4 years, while the impact of the moist season on children's respiratory health was strongest for ages 5–9 years [13]. In terms of temperature, the utilization rate of medical services for respiratory diseases in 5–9 year old children increased significantly in moderate temperature environments [13]. Another study employing stratified analysis by season in Seoul found that the strongest effect on allergic rhinitis occurred in autumn (September–November) [15].

According to the results of a comparative study of the current literature, many works have focused on children's respiratory diseases in extremely cold and hot environments, but some of these supported our findings, i.e., children were more susceptible to respiratory diseases in relatively mild environments than in extremely cold and hot environments. The following have been proposed as the possible reasons for this finding. The biological mechanism of the relationship between relatively mild environments and children's respiratory diseases might be related to the effect of allergen (e.g., mites and pollen) growth. Asian dust storms were also associated with hospital admissions for respiratory diseases [23, 24]. These meteorological factors usually appear in spring and autumn in Baotou; compared with winter, the temperature is warmer, the humidity is lower, and the wind speed is higher at these times of the year. Another reason for this finding was that lower respiratory tract infections can be caused by several pathogens, but respiratory viruses are the most common cause for lower respiratory tract infections in children. Geographical and meteorological factors significantly affect the etiology of respiratory virus infections, which is reflected in the regional and seasonal changes of respiratory virus circulation. For instance, the respiratory syncytial virus exhibits notable seasonal distributions, namely, beginning in early autumn, peaking at the end of November or in early December, and gradually decreasing in spring. However, adenovirus, influenza, and human parainfluenza virus were more frequently detected in the spring and summer months, between March and August [25, 26]. A study on the admission of children with respiratory diseases in Beijing showed that the most common diagnosis (86.11%) in the adenovirus-positive cases was pneumonia, which was accompanied by common signs and symptoms of fever and cough [14]. In addition, differences among populations, as well as varying local climates, socio-economic conditions, demographic factors, and degrees of adaptation to the local environment, were factors that influenced the relationship between meteorological factors and respiratory diseases.

Our results showed that the influence of meteorological factors on lower respiratory tract diseases was greater than that on upper respiratory tract diseases. Respiratory diseases could be acute or chronic. The former type was responsible for the majority of the hospitalization cases in children. Acute respiratory infections caused by viruses or bacteria could affect either the lower respiratory tract (below the vocal cords) or the upper respiratory tract. The most common (upper respiratory tract) infections were colds, acute sinusitis, acute pharyngitis, and acute tonsillitis. Lower respiratory diseases included pneumonia, bronchopneumonia, acute bronchitis, and bronchiolitis, which were less common than the upper respiratory tract infections, but were usually more severe and had a higher incidence of hospitalization [27]. Another finding of our study was that the effects of meteorological factors on respiratory diseases in patients older than 4 years were greater than those on these diseases in patients aged 0–3 years. Additionally, the effects of meteorological factors on respiratory diseases in female children were greater than those in male children. Children older than 4 years may play outdoors more often than younger children, which may increase their exposure to the external environment [2]. The development process of older female children differs considerably from that of male children. For example, the increase in estrogen may affect their thermoregulation functions, thus making female children more vulnerable to the influence of relatively low temperatures than male children [28].

To assess the delayed effect between exposure and health outcomes, we estimated the delayed effect for 21 days, including the day of hospitalization for respiratory tract diseases. Various delayed effects of respiratory diseases related to meteorological factors (temperature, humidity, and wind speed) have been confirmed in some studies to last from 2–3 days to several weeks [3, 13]. In our study, the utilization of pediatric medical services in response to respiratory diseases was considered as the research object, and it was found that children showed relatively immediate response compared with adults. In fact, while assessing the impact of meteorological changes on the health of respiratory tract diseases in children, it was observed that children's delayed impact occurred within a week or a little more than a week, a timeline that may be more sensitive to meteorological factors due to the children's less developed immune systems, special physiques, and still-maturing respiratory systems [2].

Our study used the NET, which integrates temperature, relative humidity, and wind speed as a cooling indicator, to evaluate the impacts of climate on hospitalizations for children's respiratory diseases. Based on the NET values, the influence range and peak value of each group were determined. The results showed that the influence range for lower respiratory tract infections was extended to slightly cold ranges compared to the case for upper respiratory tract infections. Compared with male children, the sensitive peak for female children was colder, and those over the age of 4–7 years were more inclined to exhibit a colder sensitive peak value than those 0–3 years. Overall, we found that this comprehensive evaluation index could be used to accurately evaluate the impacts of meteorological factors on different groups in terms of hospitalizations for respiratory disease; thus, it would be prudent to take different measures to protect children to reduce their exposure under sensitive meteorological conditions.

This study suffers from some limitations. First, this work can be described as an ecological study. The study lacked data related to exposures for individuals and could not ascertain the impact of an individual's activity patterns. Additionally, our data only included severely affected patients at three large hospitals and excluded outpatients and emergency patients. Therefore, the impacts of meteorological factors on children with mild and severe respiratory diseases at the present time for this region cannot be comprehensively summarized.

5. Conclusion

The study found complex non-linear relationships between climate variability and children's RDHs with different risk windows by type in temperate continental China. The findings may provide important information for the development of early warning systems based on climate factors for children's RDHs. The findings also suggest that it may be possible to use the NET to evaluate climate change comprehensively in the future in such a way as to facilitate government and health authorities in their efforts to better minimize the impacts on children's RDHs.

Declarations

Author contribution statement

W. Guo and M. Li: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

L. Yi: Analyzed and interpreted the data; Wrote the paper.

P. Wang and B. Wang: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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