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Association between air temperature exposure and childhood rhinitis risk, and the mediating role of ambient O_3: A multi-city study of 40,103 Chinese preschool children

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ABSTRACT

Higher air temperature and increased ambient ozone (O_3) concentration have been associated with childhood rhinitis risk. However, the potential mediating role of elevated O_3 in the increased childhood rhinitis risk due to higher air temperature exposure has not been examined. This large-scale cross-sectional study included 40,103 preschool children from 7 Chinese capital cities. Information on ever-rhinitis, current-rhinitis, and doctor-diagnosed allergic rhinitis (AR) was collected using a standardized questionnaire. Average air temperature (TEMavg) and O_3 concentration in the whole year, warm season, and cold season were estimated at 1 km spatial resolution. The findings revealed that exposure to higher air temperature (annual TEMavg, warm season TEMavg, and cold season TEMavg) and ambient O_3 (annual O_3, and warm season O_3) were associated with an elevated risk of ever-rhinitis, current-rhinitis, and doctor-diagnosed AR. Moreover, elevated O_3 concentration played important mediation effects on the relationships between higher air temperature and childhood rhinitis risk, with the mediated proportions ranging from 19.92% to 35.14% for the whole year, 18.62% to 32.82% for the warm season, and 3.85% to 13.32% for the cold season. Our study highlighted that controlling O_3 pollution may be an effective approach to mitigate the increasing childhood rhinitis risk due to global warming.

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1. Introduction

Rhinitis, characterized by nasal congestion, sneezing, itching, and a runny nose, is a predominant respiratory disease affecting around 40% of children (Li et al., 2024) and causes great disability and burden of diseases worldwide (Vandenplas et al., 2018). In recent years, the prevalence of childhood rhinitis has continued to rise in both developing and developed countries (Chen et al., 2022; Genuneit et al., 2017; Wang et al., 2016; Wang et al., 2020). According to the China, Children, Homes, Health (CCHH) study, the prevalence of self-reported doctor-diagnosed allergic rhinitis (AR) among Chinese preschool children was 8.8% in 2011 (Chen et al., 2022), whereas this rate increased to 12.5% in 2019 (Li et al., 2024). Numerous studies indicated that childhood rhinitis is influenced by a combination of genetic and environmental factors (Acevedo et al., 2021). The slow process of genetic evolution alone may be insufficient to account for the rapid rise in the prevalence of rhinitis, with the rapidly changing environment considered a more substantial factor contributing to the escalating prevalence of this condition (Cai et al., 2019; Chen et al., 2022; Deng et al., 2016).

Global warming, characterized by increasing air temperature worldwide, has become a prominent global public health issue with potentially detrimental effects on the human respiratory system (Shan et al., 2024), particularly among vulnerable populations such as children (D'Amato et al., 2020; Pacheco et al., 2021). As global warming intensifies, the frequency and duration of heatwaves and extreme heat events (EHE) have significantly increased (Sahani et al., 2024; Wang et al., 2024), causing damage to the respiratory system (Çelebi Sözener et al., 2023; Shan et al., 2024). Moreover, rising air temperatures and changing climate patterns may lead to longer pollen seasons, higher pollen concentrations, and increased air pollutants, all of which can trigger or worsen rhinitis symptoms (Shan et al., 2024; Zhaobin et al., 2024). However, the number of studies on the relationships between air temperature and childhood rhinitis risk was limited (Hu et al., 2020; Lee et al., 2003; Wang et al., 2016b; Wang et al., 2021, 2020), and the results were inconsistent. For example, the CCHH 2011 study reported no significant association between air temperature and rhinitis risk among preschool children (Wang et al., 2019). Another study of middle-school students in Taiwan, China, found that exposure to higher air temperature during non-summer periods was related to increased physician-diagnosed AR risk. However, no significant findings were noted for the relationships between summer temperature and physician-diagnosed AR, as well as the relationships between self-reported AR and air temperature during summer and non-summer periods (Lee et al., 2003). Moreover, the air temperature data in those studies was obtained from meteorological monitoring stations, which might introduce significant biases compared to actual individual exposure (Hu et al., 2020). In recent years, with the advancement of satellite remote sensing and artificial intelligence technologies, high spatial resolution air temperature datasets have been developed (Bai et al., 2024; Zhang et al., 2023; Zhang et al., 2022; Zhao & Zhu, 2022). Further research using high-resolution air temperature data is warranted to provide more precise epidemiological evidence for the prevention and management of childhood rhinitis. Furthermore, China has undergone rapid urbanization in the past decades (Jiang et al., 2023; Liu et al., 2024). Rapid urbanization has exacerbated the increase in air temperatures and the frequency and duration of EHE in densely populated urban areas (Cheng & Sha, 2024; Wang et al., 2024; Xie et al., 2024; Zhang et al., 2024), resulting in significant health risks to children's respiratory health. Further studies are warranted to re-examine the relationship between exposure to higher air temperatures and rhinitis risk in Chinese children amidst global warming and repaid urbanization, providing updated evidence for reducing childhood asthma risk in China.

Air pollution represents another significant environmental challenge during the global warming process, resulting in further health risks to populations (Jiang et al., 2023; Q. Liu et al., 2024). Ozone (O_3) pollution is an environmental factor that cannot be overlooked in the process of global warming and the increasing prevalence of childhood rhinitis. As a secondary pollutant originating from nitrogen oxides (NOx) and volatile organic compounds (VOCs), O_3 formation was indicated to be strongly influenced by air temperature (Ding et al., 2024; Liu et al., 2023). For instance, a study of the spatiotemporal patterns of O_3 pollution in China from 1980 to 2021 found a strong positive correlation between air temperature and O_3 concentrations and indicated that enhancement of photochemical reactions and the increased emissions of biogenic VOCs at higher air temperature were crucial contributors for the O_3 concentration increase (Ding et al., 2024). Jiang et al. investigated the relationships between land surface temperature and air pollution in the Yangtze River Delta Urban Agglomeration, China, and indicated that both daytime and nighttime land surface temperatures were positively correlated with the concentration of O_3 (Jiang et al., 2023). Wang et al. investigated the impact of weather-induced natural processes on O_3 pollution and indicated high air temperature contributed 43.1% to the production of ambient O_3 (Wang et al., 2024). Meanwhile, with the severe O_3 pollution challenge in China in recent years (Wang et al., 2022), the impact of O_3 on rhinitis has begun to attract the attention of some studies (Hu et al., 2020; Na et al., 2024; Zhou et al., 2021). For example, a time-series study conducted in Shanghai indicated that each 10 $\mu g/m^3$ increase in O_3 exposure was related to a 0.65% (95%CI: 0.43%, 0.87%) increase in AR outpatient visits (Na et al., 2024). Based on the findings above, it is reasonable to hypothesize that the increase in ambient O_3 concentrations possibly serves as an important mediating factor in the elevated childhood rhinitis risk in its association with higher air temperature. However, to our knowledge, whether ambient O_3 plays a mediating role in the relationship between air temperature exposure and childhood rhinitis risk has not been reported. Further research comprehensively examining the potential mediation role of O_3 on the relationship between air temperature and childhood rhinitis risk is warranted to provide new epidemiological evidence on the impact of global warming on childhood rhinitis and its mechanisms.

In this multi-city, large-scale study of Chinese preschool children, we aimed to comprehensively examine the impacts of exposure to air temperature and ambient O_3 on childhood rhinitis risk, as well as the mediating effect of ambient O_3 on the relationship between air temperature exposure and childhood rhinitis risk. Air temperature and ambient O_3 concentration in different seasons (whole year, warm season, and cold season) were assessed at 1 km gridded spatial resolution, as well as different types of rhinitis outcomes (ever-rhinitis, current-rhinitis, and doctor-diagnosed AR).

2. Methods

2.1. Study population

A multi-city, large-scale cross-sectional study was conducted among Chinese preschool children in the CCHH 2019 study. In brief, the CCHH 2019 employed a muti-stage random cluster sample method to recruit preschool children aged from 3 to 6 years from 318 kindergartens in seven major provincial capital cities (Shanghai, Nanjing, Wuhan, Changsha, Chongqing, Taiyuan, and Urumqi) across different geographic regions of China. A standardized questionnaire developed based on the International Study of Asthma and Allergies in Childhood (ISAAC) (Asher et al., 1995; Savoure et al., 2023) and the Dampness in Building and Health (DBH) study (Wang et al., 2019) was filled out by the legal guardians of the children to investigate the potential impact of indoor and outdoor environmental exposure on rhinitis, asthma and eczema in Chinese preschool children. More information regarding the CCHH study was previously reported in published literature (Chen et al., 2024; Wu et al., 2022; Zhang et al., 2022). In this survey of the CCHH study, a total of 52,182 children were enrolled, and the survey was completed by 46,502 participants (response rate: 88.05%). After excluding children with missing current address information, aged below three or above 7, missing rhinitis information, and missing temperature and O_3 exposure data, we finally included 40,103 preschool children in this study (**Figure S1**).

The CCHH 2019 study was approved by the Institutional Review Board of the School of Public Health, Fudan University (IRB#2019–09–0778). Informed consent forms were signed by the legal guardians of all children participating in the survey.

2.2. Definitions of rhinitis

Three rhinitis symptoms were analyzed in this study, including ever-rhinitis, current-rhinitis, and doctor-diagnosed AR. Ever-rhinitis and current rhinitis were defined using the standardized questions recommended by the ISAAC (Asher et al., 1995; Garcia-Marcos et al., 2022; Savoure et al., 2023), which have been extensively employed in epidemiological research on childhood rhinitis in China (Chen et al., 2024; Chen et al., 2022; Liu et al., 2020). Ever-rhinitis was defined by a positive answer to the question "Has your child experienced symptoms of sneezing, runny nose, or nasal congestion when they did not have a cold or the flu?". Current-rhinitis was defined by a positive answer to the question "In the past 12 months, has your child experienced symptoms of sneezing, runny nose, or nasal congestion when they did not have a cold or the flu?". Finally, clinically diagnosed rhinitis was included in this study. Children were considered as having doctor-diagnosed AR if their parents reported positive answers to the question "Has your child ever been diagnosed by a doctor with hay fever or allergic rhinitis?".

2.3. Air temperature, ambient O_3 assessments

Daily average air temperature (TEMavg), and maximum 8-hour average O_3 concentrations for each child were assessed over the past year according to their residential address at 1 km gridded spatial resolution using the ChinaHighAirPollutants (CHAP) dataset, which contained a series of high-resolution data of ground-level air pollution and meteorological factors (such as air temperature) in China. In brief, ground-based measurement data, satellite remote sensing data, and atmospheric reanalysis data were incorporated into the four-dimensional spatiotemporal deep forest model to estimate the ground-level air temperature and O_3 across China. Detailed information for the CHAP dataset could be obtained from the CHAP website and relevant studies (Wang et al., 2024; Wei et al., 2022; Yang et al., 2025). The annual TEMavg and O_3 concentrations were calculated using the average of daily data. Furthermore, the warm season (April to September) and cold season (October to March) TEMavg and ambient O_3 concentrations were calculated to distinguish the potential heterogeneity of different seasons (Liu et al., 2023; Luo et al., 2023; Zhu et al., 2024).

2.4. Covariates

Based on the literature review of the previous CCHH studies (Cai et al., 2019; Chen et al., 2022; Norback et al., 2018; Wang et al., 2021), a series of potential confounding factors were included as covariates in the current study. These covariates included: (1) sociodemographic characteristics: age (years), sex ("male" or "female"), residence ("Rural", "Suburb" or "Urban"); (2) socioeconomic characteristics: parental annual income ("Less than 50,000 CNY", "50,000100,000 CNY", "100, 000–200,000 CNY" or "More than 200,000 CNY"), maternal education level ("Technical secondary school or below", "College or university graduate", or "Master's degree or above"), and paternal education level ("Technical secondary school or below", "College or university graduate", or "Master's degree or above") (Norback et al., 2018); (3) delivery situation and breastfeeding: delivery mode ("Natural birth", or "Cesarean delivery"), premature birth ("No" or "Yes"), and breastfeeding duration ("<6 months", "6–12 months", or "> 12 months"); (4) family history of rhinitis: maternal rhinitis history ("No" or "Yes") and paternal rhinitis history ("No" or "Yes"); (5) indoor environmental factors exposure: cooking fuel use ("Clean fuel" or "Solid fuel") (Han et al., 2022), secondhand smoke exposure ("No" or "Yes"), and indoor dampness and mold ("No" or "Yes")(Cai et al., 2019); (6) outdoor air pollution exposure: annual particulate matter with a diameter $\leq$2.5 μm ($PM_{2.5}$), warm season $PM_{2.5}$, and cold season $PM_{2.5}$. The estimation of ambient $PM_{2.5}$ was also based on the CHAP dataset at 1 km gridded spatial resolution (Wei et al., 2020, 2021), while other covariate information was collected using standardized questionnaires.

2.5. Statistical analysis

Descriptive statistics were performed on the characteristics of study participants, TEMavg, and ambient O_3. For study participants' characteristics, continuous variables were presented as mean $\pm$ standard deviation (SD), while categorical variables were described using frequencies and percentages (%). Student *t*-test was utilized to compare differences in continuous variables, while Chi-square test was performed to compare differences in categorical variables between children with and without rhinitis. Mean $\pm$ SD, percentiles (P25, P50, and P75), and interquartile range (IQR) were utilized to assess the distribution of TEMavg and ambient O_3, and the Student *t*-test was utilized to compare the differences in TEMavg and O_3 exposure between children with and without rhinitis.

Four-stage statistical analysis was performed to investigate the relationships of TEMavg, $O_{3,}$ and childhood rhinitis risk and assess the mediation effects of O_3 on the relationships of TEMavg with childhood rhinitis risk. In the first stage, a multi-variable generalized linear model (GLM) was performed to examine the associations between TEMavg (annual TEMavg, warm season TEMavg, and cold season TEMavg) and rhinitis risk, and the exposure-outcome (E-R) relationships between TEMavg and rhinitis risk were established using restricted cubic splines (RCS) curves with 3 knots. In the second stage, the associations between ambient O_3 (annual O_3, warm season O_3, and cold season O_3) and rhinitis risk were examined using GLM, and the E-R relationships were assessed using RCS curves. In the third stage, we utilized the GLM model to examine the relationships between TEMavg and ambient O_3 during the whole year, warm season, and cold season. In the fourth stage, the causal mediation effect model with consideration of the potential interaction effect between the exposure factor and the mediator was performed to calculate the mediated proportion (%) of O_3 on the relationships between TEMavg and childhood rhinitis risk (Niu et al., 2024).

Given that pollen has been identified as a significant environmental factor contributing to the occurrence of rhinitis (Lindqvist et al., 2024), we conducted a sensitivity analysis to investigate the relationships between air temperature, $O_{3,}$ and rhinitis risk, as well as the mediating effect of O_3 in these relationships during the pollen season and non-pollen season. We utilized the Meteorological index of pollen allergy (QX/T 324–2016) released by the China Meteorological Administration as the criteria for distinguishing between the pollen season and non-pollen season, and months with an allergy index $\geq$ 4 were defined as the pollen season.

The statistical analyses were carried out using R software (version 4.4.1). The RCS curves were analyzed using the "plotRCS" package, and the causal mediation effect model was conducted utilizing the "mediation" package. A significance level of 0.05 was used to determine statistical significance in two-sided tests.

3. Results

3.1. Demographic characteristics of study participants

The characteristics of 40,013 preschool children are presented in Table 1 and **Table S1**. The average age of the included preschool children was 4.90 $\pm$ 0.98 years, and 51.98% of included childhood were male. A total of 15,335 (38.33%) children reported ever-rhinitis and

13,170 (32.91%) children reported current rhinitis, 4880 (12.20%) children reported having doctor-diagnosed AR. The prevalence of ever-rhinitis, current rhinitis, and doctor-diagnosed AR was significantly higher among boys, children from urban areas, children with maternal or parental rhinitis history, and children born through cesarean delivery. Moreover, children who were breastfed for less than 6 months, exposed to secondhand smoke, and exposed to indoor dampness and mold had significantly increased prevalence of rhinitis.

3.2. The distributions of air temperature and ambient O_3 exposure

Fig. 1 shows the geographic distribution of study subjects and the annual average air temperature in mainland China in 2019. The seven cities included in this study were located in different regions of China, including the southeast (Shanghai, Nanjing), central (Wuhan, Changsha), southwest (Chongqing), north (Taiyuan), and northwest (Urumqi), where there were some variations in the annual TEMavg. The distributions of air temperature and ambient O_3 are summarized in Table 2. The annual TEMavg and O_3 were 15.75 ± 3.66 °C and 101.59 ± 10.76 μg/m^3, respectively. In warm season, TEMavg, O_3 and $PM_{2.5}$ were 23.89 ± 1.93 °C and 135.07 ± 13.56 μg/m^3. In the cold season, TEMavg and O_3 were 7.61 ± 5.56 °C and 68.11 ± 12.69 μg/m^3, respectively. The comparison of air temperature and ambient O_3 exposure in children with and without ever-rhinitis, current-rhinitis, or doctor-diagnosed AR is shown in **Table S2**. Compared to those without rhinitis, children with rhinitis were exposed to higher air temperature and O_3 levels throughout the whole year, as well as during the warm and cold seasons.

3.3. Associations between air temperature exposure and childhood rhinitis risk

The relationships between air temperature and childhood rhinitis risk are presented in Fig. 2. We observed that both in crude and adjusted models, higher TEMavg exposure was significantly linked to an elevated risk of childhood rhinitis. For each IQR increase in annual TEMavg (5.97 °C), warm season TEMavg (3.94 °C) and cold season TEMavg (8.04 °C), the OR values of ever-rhinitis were 1.27 (95%CI: 1.19, 1.36), 1.21 (95% CI: 1.14, 1.28), and 1.39 (95%CI: 1.28, 1.50) in fully-adjusted models (Model 4), respectively. For current-rhinitis, each IQR increase in annual TEMavg, warm season TEMavg, and cold season TEMavg was associated with the OR values of 1.20 (95%CI: 1.12, 1.29), 1.17 (95%CI: 1.11, 1.24), and 1.31 (95%CI: 1.20, 1.42), respectively. For doctor-diagnosed AR, when the annual TEMavg, warm season TEMavg and cold season TEMavg increased by one IQR, the OR values of values were 2.16 (95% CI: 1.94, 2.41), 1.95 (95%CI: 1.78, 2.14), and 2.49 (95%CI: 2.19, 2.83), respectively.

Fig. 3 displays the E-R relationships of the annual TEMavg, warm season TEMavg, and cold season TEMavg with childhood rhinitis risk. The E-R curve showed that the OR of ever-rhinitis, current-rhinitis, and doctor-diagnosed AR had significant upward trends with the air temperature (annual TEMavg, warm season TEMavg, and cold season TEMavg) increase (*P for overall* <0.001). Regarding the shapes of the E-R curve, the annual TEMavg and cold season TEMavg showed inverted J-shaped relationships with childhood rhinitis risk (*P for nonlinear* <0.001). The warm season TEMavg E-R curve showed a J-shaped trend for ever-rhinitis (*P for nonlinear* =0.014) and near linear increase trends for current-rhinitis and doctor-diagnosed AR (*P for nonlinear >0.05*).

3.4. Association between ambient O_3 exposure and childhood rhinitis risk

Fig. 4 presents the relationships between ambient O_3 concentration and childhood rhinitis risk. We observed positive and robust relationships between childhood rhinitis risks (ever-rhinitis, current-rhinitis, and doctor-diagnosed AR) with annual O_3 and warm season O_3 exposure, as well as the association between cold season O_3 exposure and current-rhinitis. For each IQR increase in annual O_3 (14.68 μg/m^3) and

Table 1
Basic characteristics of study participants.

Variable	All (*n* = 40,013)	Never-rhinitis (*n* = 24,678)	Ever-rhinitis (*n* = 15,335)	*P-value*
Age (years)	4.90 ± 0.98	4.88 ± 0.99	4.92 ± 0.98	<0.001 ***
Sex #				<0.001 ***
Male	20,798 (51.98%)	12,317 (49.91%)	8481 (55.32%)	
Female	19,159 (47.88%)	12,321 (49.93%)	6838 (44.59%)	
Residence #				<0.001 ***
Rural areas	1353 (3.38%)	1031 (4.18%)	322 (2.10%)	
Suburb areas	6820 (17.04%)	4424 (17.93%)	2396 (15.62%)	
Urban areas	31,654 (79.11%)	19,087 (77.34%)	12,567 (81.95%)	
Maternal education level #				<0.001 ***
Technical secondary school or below	11,018 (27.54%)	7466 (30.25%)	3552 (23.16%)	
College or university graduate	25,131 (62.81%)	15,049 (60.98%)	10,082 (65.75%)	
Master's degree or above	3825 (9.56%)	2134 (8.65%)	1691 (11.03%)	
Paternal education level #				<0.001 ***
Technical secondary school or below	11,161 (27.89%)	7592 (30.76%)	2837 (18.50%)	
College or university graduate	24,154 (60.37%)	14,491 (58.72%)	8015 (52.27%)	
Master's degree or above	4631 (11.57%)	2547 (10.32%)	1760 (11.48%)	
Parental annual income				<0.001 ***
Less than 50,000 CNY	5150 (12.87%)	3131 (12.69%)	2019 (13.17%)	
50,000–100,000 CNY	22,744 (56.84%)	13,488 (54.66%)	9256 (60.36%)	
100,000–200,000 CNY	1043 (2.61%)	605 (2.45%)	438 (2.86%)	
More than 200,000 CNY	158 (0.39%)	85 (0.34%)	73 (0.48%)	
Maternal rhinitis history				<0.001 ***
No	33,533 (83.81%)	22,065 (89.41%)	11,468 (74.78%)	
Yes	6480 (16.19%)	2613 (10.59%)	3867 (25.22%)	
Paternal rhinitis history				<0.001 ***
No	32,254 (80.61%)	21,385 (86.66%)	10,869 (70.88%)	
Yes	7759 (19.39%)	3293 (13.34%)	4466 (29.12%)	
Delivery mode #				<0.001 ***
Natural birth	20,243 (50.59%)	12,741 (51.63%)	7502 (48.92%)	
Cesarean delivery	19,331 (48.31%)	11,638 (47.16%)	7693 (50.17%)	
Premature birth				0.095
No	38,628 (96.54%)	23,854 (96.66%)	14,774 (96.34%)	
Yes	1385 (3.46%)	824 (3.34%)	561 (3.66%)	
Breastfeeding duration #				<0.001 ***
<6 months	15,082 (37.69%)	8945 (36.25%)	6137 (40.02%)	
6–12 months	12,881 (32.19%)	8133 (32.96%)	4748 (30.96%)	

(*continued on next page*)

Table 1 (*continued*)

Variable	All (n = 40,013)	Never-rhinitis (n = 24,678)	Ever-rhinitis (n = 15,335)	*P-value*
> 12 months	12,003 (30.00%)	7564 (30.65%)	4439 (28.95%)	
Cooking fuel use				1.000
Clean fuel	39,173 (97.90%)	24,160 (97.90%)	15,013 (97.90%)	
Solid fuel	840 (2.10%)	518 (2.10%)	322 (2.10%)	
Second-hand smoke exposure				<0.001 ***
Yes	13,878 (34.68%)	8218 (33.30%)	5660 (36.91%)	
No	25,985 (64.94%)	16,360 (66.29%)	9625 (62.76%)	
Indoor dampness and mold				
No	34,509 (86.24%)	21,756 (88.16%)	12,753 (83.16%)	<0.001 ***
Yes	5504 (13.76%)	2922 (11.84%)	2582 (16.84%)	
Ambient $PM_{2.5}$ (μg/m^3)				
Annual $PM_{2.5}$	46.25 ± 8.69	46.46 ± 8.85	45.92 ± 8.41	<0.001 ***
Warm season $PM_{2.5}$	28.40 ± 5.10	28.33 ± 5.21	28.51 ± 4.90	<0.001 ***
Cold season $PM_{2.5}$	64.11 ± 18.66	64.60 ± 19.02	63.32 ± 18.04	<0.001 ***

Notes: * *P-value* <0.05; ** *P-value* <0.01;.
*** P-value <0.001.
# Missing data existed.

warm season O_3 (24.70 μg/m^3), the OR values of ever-rhinitis were 1.31 (95%CI: 1.22, 1.40), 1.59 (95%CI: 1.47, 1.73), respectively. For current-rhinitis, each IQR increase in annual O_3, warm season O_3, and cold season O_3 (8.52 μg/m^3) was associated with the OR values of 1.38 (95% CI: 1.29, 1.48), 1.63 (95%CI: 1.50, 1.78), and 1.04 (95%CI: 1.01, 1.06), respectively. For doctor-diagnosed AR, each IQR increase in annual O_3 and warm season O_3 exposure was related to the OR values of 1.30 (95% CI: 1.17, 1.44), and 1.68 (95%CI: 1.49, 1.90), respectively.

Fig. 5 displays the E-R relationships between ambient O_3 exposure and rhinitis risk. For ever-rhinitis, we found that the risk of rhinitis increased consistently with the rise in annual O_3, warm season O_3, and cold season O_3 exposure (*P for overall* <0.01). In terms of the shapes of the E-R curve, the annual O_3, warm season O_3, and cold season O_3 exposure showed J-shaped, inverted J-shaped, and near-linear relationships, respectively. Consistent with ever-rhinitis, the E-R

Table 2
Descriptive statistics of air temperature and ambient O_3.

Exposure	Mean ± SD	P25	P50	P75	IQR
Air temperature (°C)					
Annual TEMavg	15.75 ± 3.66	12.08	17.81	18.05	5.97
Warm season TEMavg	23.89 ± 1.93	21.56	24.65	25.49	3.94
Cold season TEMavg	7.61 ± 5.56	3.01	10.39	11.05	8.04
Ambient O_3 (μg/m^3)					
Annual O_3	101.59 ± 10.76	94.47	104.95	109.15	14.68
Warm season O_3	135.07 ± 13.56	122.66	133.95	147.37	24.70
Cold season O_3	68.11 ± 12.69	64.05	69.27	72.57	8.52

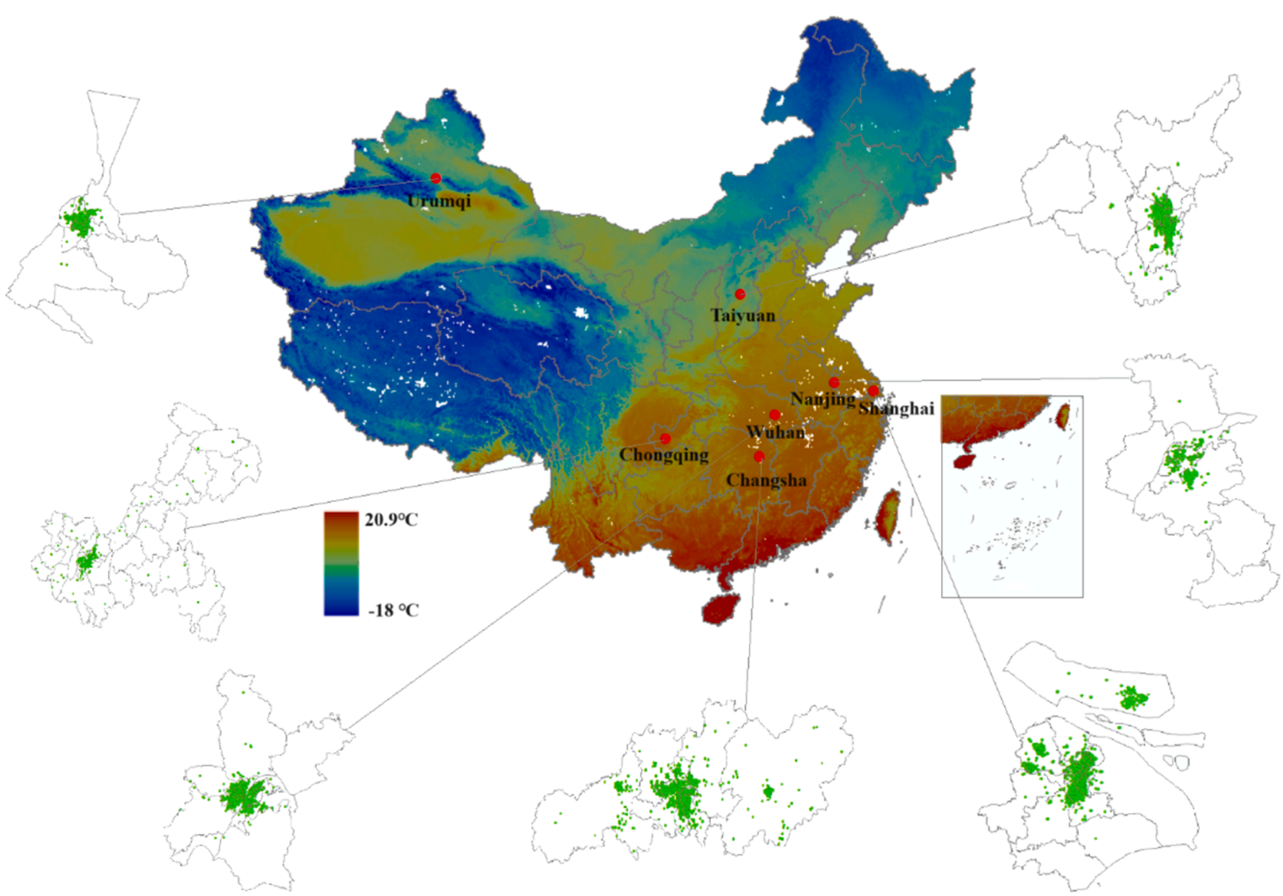

Fig. 1. Geographic distribution of study subjects and annual average air temperature in mainland China in 2019.
Notes: The green dots in the map represent the geographical distribution of each child's home address.

	Model 1	Model 2	Model 3	Model 4
Ever−rhinitis				
Annual TEMavg	1.20 (1.17, 1.25)***	1.17 (1.12, 1.22)***	1.13 (1.08, 1.19)***	1.27 (1.19, 1.36)***
Warm season TEMav	1.32 (1.26, 1.37)***	1.25 (1.19, 1.32)***	1.21 (1.14, 1.28)***	1.21 (1.14, 1.28)***
Cold season TEMavg	1.16 (1.13, 1.20)***	1.13 (1.08, 1.18)***	1.10 (1.05, 1.14)***	1.39 (1.28, 1.50)***
Current−rhinitis				
Annual TEMavg	1.25 (1.20, 1.29)***	1.16 (1.11, 1.22)***	1.12 (1.07, 1.18)***	1.20 (1.12, 1.29)***
Warm season TEMavg	1.35 (1.30, 1.41)***	1.22 (1.16, 1.30)***	1.18 (1.11, 1.25)***	1.17 (1.11, 1.24)***
Cold season TEMavg	1.20 (1.16, 1.24)***	1.13 (1.08, 1.18)***	1.09 (1.05, 1.14)***	1.31 (1.20, 1.42)***
Doctor−dianosed rhinitis				
Annual TEMavg	1.67 (1.58, 1.78)***	1.73 (1.60, 1.87)***	1.68 (1.55, 1.81)***	2.16 (1.94, 2.41)***
Warm season TEMavg	2.03 (1.89, 2.17)***	2.03 (1.85, 2.23)***	1.96 (1.79, 2.16)***	1.95 (1.78, 2.14)***
Cold season TEMavg	1.52 (1.45, 1.60)***	1.55 (1.45, 1.66)***	1.51 (1.41, 1.62)	2.49 (2.19, 2.83)***

OR: 1.5, 2.0

Fig. 2. Odds ratios (OR) of rhinitis outcomes associated with per IQR increase in air temperature among preschool children.
Notes: The IQR values of annual TEMavg, warm season TEMavg, and cold season TEMavg were 5.97 °C, 3.94 °C, and 8.04 °C, respectively; Model 1, crude model; Model 2, adjusted for age, sex, residence, parental annual income, maternal education level, paternal education level, delivery mode, breastfeeding duration and family history of rhinitis; Model 3, additionally adjusted for cooking fuel use, second-hand smoke exposure and indoor dampness and mold; Model 4, additionally adjusted for ambient $PM_{2.5}$ exposure;* *P-value* <0.05; ** *P-value* <0.01; *** *P-value* <0.001.

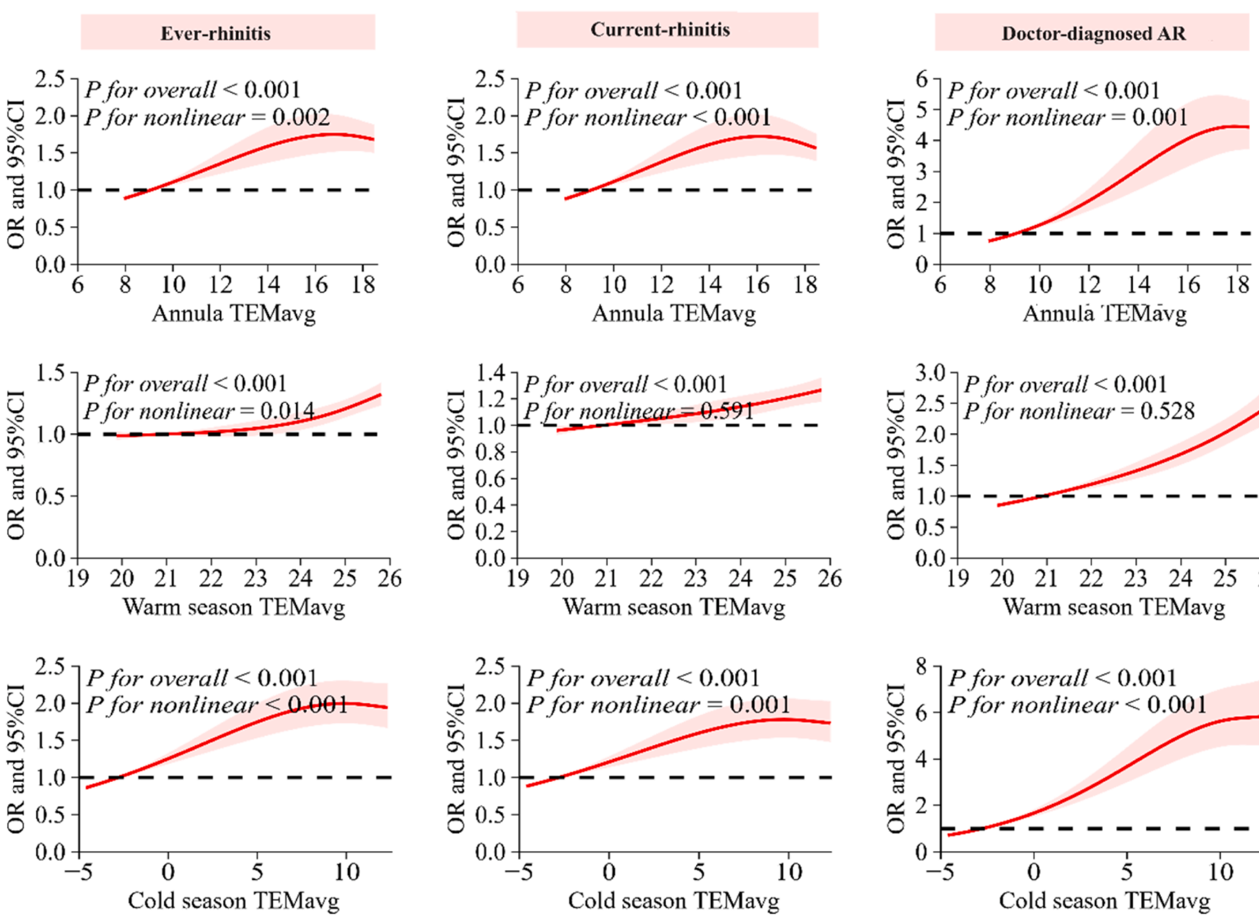

Fig. 3. Exposure-response (E-R) relationships of air temperature exposure and rhinitis risk among preschool children.
Notes: To minimize the influence of outliers on the E-R curve, study subjects with TEMavg exposure in the lowest and highest 1 % were excluded; Age, sex, residence, parental annual income, maternal education level, paternal education level, delivery mode, breastfeeding duration, family history of rhinitis, cooking fuel use, second-hand smoke exposure, indoor dampness and mold, and ambient $PM_{2.5}$ were adjusted.

relationships of current-rhinitis with annual O_3, warm season O_3, and cold season O_3 exposure also demonstrated consistent upward trends and similar E-R shapes. For the doctor-diagnosed AR, the E-R curve showed J-shaped increasing trends for the OR value of doctor-diagnosed AR with the increase of annual O_3 exposure (*P for overall* <0.001, *P for nonlinear* <0.001). When the concentrations of warm season O_3 were below 140 μg/m^3, the OR of doctor-diagnosed AR showed an increasing trend with the rise in O_3 concentrations. However, the OR value

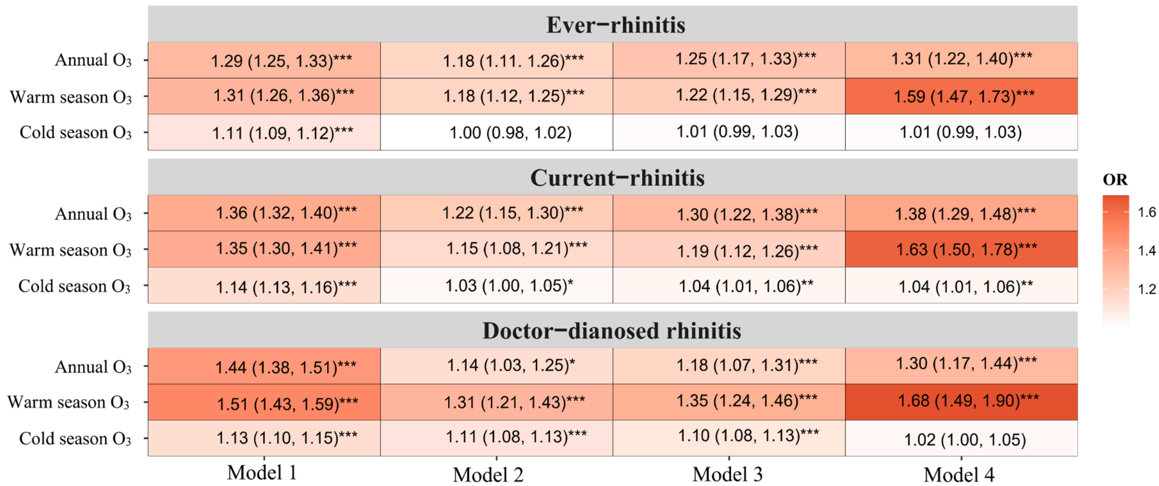

Fig. 4. Odds ratios (OR) of rhinitis outcomes associated with per IQR increase in ambient O_3 among preschool children.
Notes: The IQR values of annual O_3, warm season O_3 and cold season O_3 were 14.68 μg/m^3, 24.70 μg/m^3, and 8.52 μg/m^3, respectively; Model 1, crude model; Model 2, adjusted for age, sex, residence, parental annual income, maternal education level, paternal education level, delivery mode, breastfeeding duration and family history of rhinitis; Model 3, additionally adjusted for cooking fuel use, second-hand smoke exposure and indoor dampness and mold; Model 4, additionally adjusted for ambient $PM_{2.5}$ exposure;* *P-value* <0.05; ** *P-value* <0.01; *** *P-value* <0.001.

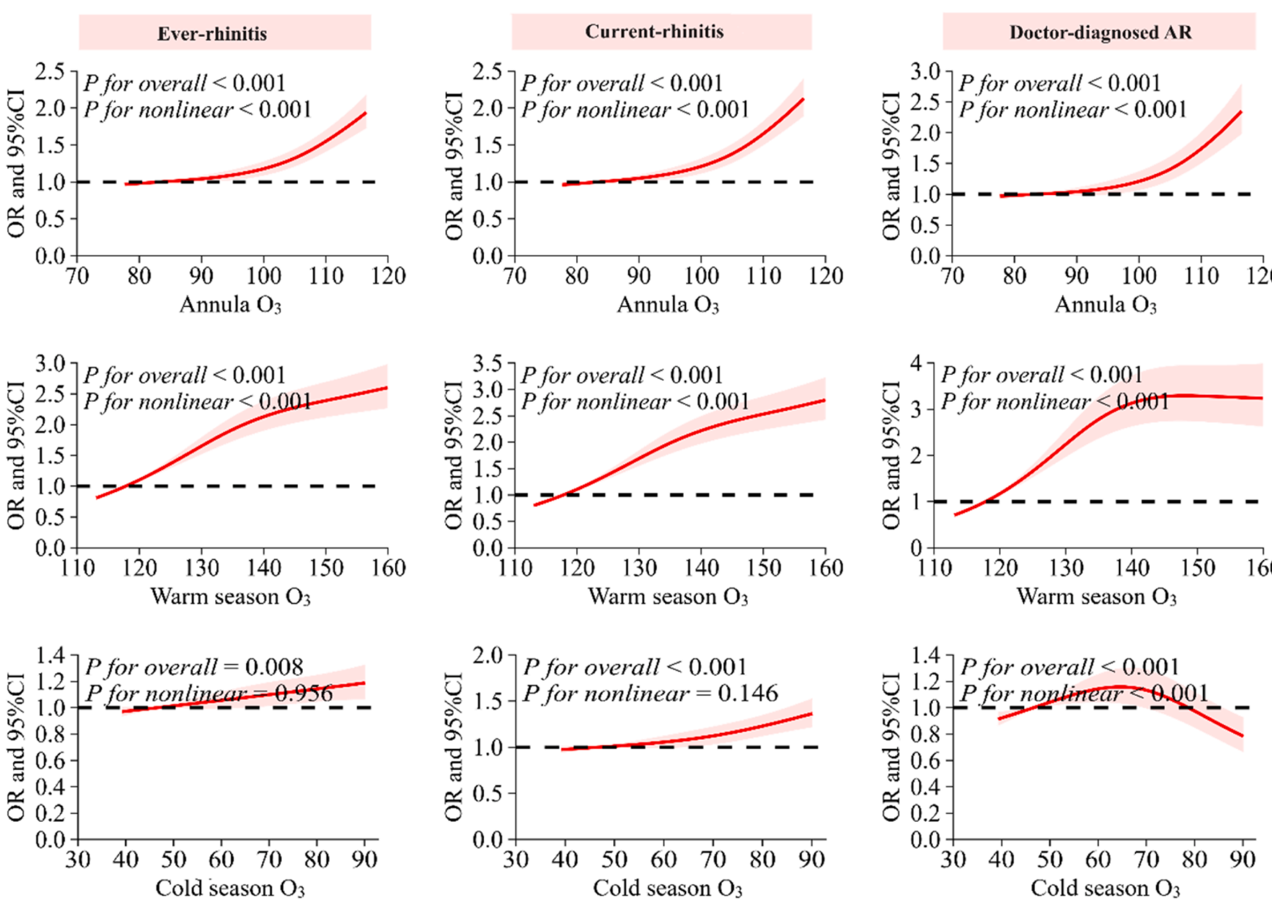

Fig. 5. Exposure-response (E-R) relationships of ambient O_3 exposure and rhinitis risk among preschool children.
Notes: To minimize the influence of outliers on the E-R curve, study subjects with O_3 exposure in the lowest and highest 1 % were excluded; Age, sex, residence, parental annual income, maternal education level, paternal education level, delivery mode, breastfeeding duration, family history of rhinitis, cooking fuel use, second-hand smoke exposure, indoor dampness and mold, and ambient $PM_{2.5}$ were adjusted.

appeared to have no significant increase beyond the breakpoints of approximately 140 μg/m^3 for O_3 concentration (*P for overall* <0.001, *P for nonlinear* <0.001).

3.5. Association between air temperature and O_3 concentration

Table 3 presents the associations between air temperature and O_3 concentration. Each IQR increase in annual TEMavg (5.97 °C) was

Table 3
Association between air temperature and ambient O_3 concentration.

Exposure	Annual O_3		Warm season O_3		Cold season O_3	
	β and 95%CI	*P-value*	β and 95%CI	*P-value*	β and 95%CI	*P-value*
Air temperature (°C)	6.07 (5.91, 6.23)	<0.001 ***	6.04 (5.78, 6.30)	<0.001 ***	3.39 (6.22, 6.56)	<0.001 ***

Notes: The results were presented as the change in O_3 concentration for each IQR (annual: 5.97 °C; warm season: 3.94 °C; cold season: 8.04 °C) increase in air temperature; * *P-value* <0.05; ** *P-value* <0.01;.
*** P-value <0.001.

associated with a 6.07 μg/m^3 (95%CI: 5.91, 6.23) increase in annual O_3. For each IQR increase in warm season TEMavg (3.94 °C), the warm season O_3 concentration increased by 6.04 μg/m^3 (95%CI: 5.78, 6.30). For each IQR increase in cold season TEMavg (8.04 °C), the cold season O_3 concentration increased by 3.39 μg/m^3 (95%CI: 6.22, 6.56).

3.6. The mediation effect of O_3 concentration in the association between temperature exposure and childhood rhinitis

Fig. 6 presents the mediation effects of O_3 on the relationships between air temperature and childhood rhinitis. We found that the increase in ambient O_3 concentration significantly mediated the association between higher temperature exposure and increased risk of childhood rhinitis. The mediated proportion of annual O_3 exposure in the relationships of annual TEMavg with the risks of ever-rhinitis, current-rhinitis, and doctor-diagnosed AR were 30.16% (95%CI: 25.29%, 34.87%), 35.14% (95%CI: 30.16%, 42.59%) and 19.92% (95%CI: 16.05%, 22.37%), respectively. In the warm season, the mediated proportion of O_3 concentration was 30.55% (95%CI: 27.35%, 34.12%) for ever-rhinitis, 32.82% (95%CI: 29.30%, 38.95%) for current-rhinitis, and 18.62% (95%CI: 16.27%, 21.35%) for doctor-diagnosed AR, respectively. In cold season, lower mediation effects of the O_3 concentration were observed for the relationships between air temperature exposure and rhinitis risk, with the mediated proportions of 9.88% (95%CI: 6.13%, 12.29%) for ever-rhinitis, 13.32% (95%CI: 9.55%, 16.71%) for current-rhinitis, and 3.85% (95%CI: 1.55%, 7.24%) for doctor-diagnosed AR, respectively.

3.7. Sensitivity analysis

Sensitivity analysis was conducted to investigate the relationships between air temperature, O_3, and rhinitis risk, as well as the mediating effect of O_3 in these relationships during the pollen season and non-pollen season. We found that exposure to higher air temperature and O_3 during the pollen season and the non-pollen season were all associated with an elevated risk of rhinitis, except for the relationship between non-pollen season O_3 and doctor-diagnosed rhinitis **(Table S3)**. Mediation effect analysis found that both pollen season and non-pollen season O_3 exposure significantly mediated the relationships between air temperature exposure and rhinitis risk, with a higher mediated proportion for pollen season **(Table S4)**.

4. Discussion

4.1. Key findings

In this multi-city study of 40,013 Chinese preschool children, we found that higher air temperature (annual TEMavg, warm season TEMavg, and cold season TEMavg) and ambient O_3 (annual O_3 and warm season O_3) exposure were significantly associated with increased risk of childhood rhinitis, and E-R curves indicated consistent results. Moreover, we found that elevated O_3 concentration played significant mediation effects on the relationships between higher air temperature and childhood rhinitis risk, with the mediated proportions ranging from 19.92% to 35.14% for the whole year, 18.62% to 32.82% for the warm season, and 3.85% to 13.32% for the cold season. To our knowledge, this study is the first study that reported the significant mediation effects of elevation of ambient O_3 concentration on the relationships between exposure to higher air temperature and increased childhood rhinitis, which could provide new insights into the adverse impacts of gradually increasing air temperature on childhood rhinitis in the context of global warming.

4.2. Comparison with other studies and interpretations

With the intensification of global warming trends, rapidly rising air temperatures are leading to increasingly frequent occurrences of EHE and substantial alterations in the ecological environment. Previous studies indicated that over the past 20 years, the population exposed to extreme high temperatures in Chinese cities has increased by approximately 115 million, primarily concentrated in densely populated and more developed urban areas and regions (Wang et al., 2024). These changes would increase the risk and severity of respiratory diseases, with preschool children being more susceptible due to their vulnerable respiratory systems. In this study, we revealed that higher air temperature exposure was associated with elevated childhood rhinitis risk. Each IQR increase in annual TEMavg (5.97 °C) was related to the OR values of 1.38 (95%CI: 1.28, 1.48), 1.20 (95%CI: 1.12, 1.29) and 2.16 (95%CI: 1.94, 2.41) for ever-rhinitis, current-rhinitis and doctor-diagnosed AR, respectively. Despite the limited study in children, our results could be corroborated by several previous studies. Firstly, the rapidly rising air temperature during global warming could significantly increase the frequency and duration of EHE, which has been indicated to directly cause rhinitis, and elevate rhinitis risk by creating a more favorable environment for the proliferation of allergens and pollutants (Çelebi Sözener et al., 2023). For example, a national study of 505,386 US adults based on the National Health Interview Survey found that comparing with the US adults exposed to the lowest quartile of EHE, those exposed to the highest quartile of EHE had an increased risk of hay fever (OR=1.07, 95%CI: 1.02, 1.11), which was also known as seasonal AR (Upperman et al., 2017). Secondly, increasing air temperature can alter vegetation patterns and extend the pollen season, exposing individuals to higher levels of allergens for longer periods, further exacerbating the risk of rhinitis development (Lake et al., 2017; Ziska et al., 2019). For instance, an ecological study on airborne pollen dispersion in Europe, Asia, and North America over the past 20 years found that rising air temperature was significantly associated with elevated pollen load and pollen season duration (Ziska et al., 2019). Thirdly, gradually increasing temperatures can lead to mutations in fungi, resulting in the production of more toxic fungal pathogens, ultimately increasing the risk of developing rhinitis and worsening symptoms (Huang et al., 2024). Finally, previous studies indicated that higher air temperature could lead to higher levels of air pollutants such as O_3, which have been associated with childhood rhinitis risk. Consistent positive associations were observed in our study. We found that each IQR increase in annual TEMavg (5.97 °C), warm season TEMavg (3.94 °C) and cold season TEMavg (8.04 °C) was related to 6.07 μg/m^3 (95%CI: 5.91, 6.23), 6.04 μg/m^3 (95%CI: 5.78, 6.30) and 3.39 μg/m^3 (95%CI: 6.22, 6.56) increase in O_3 concentrations, respectively.

After the enactment of the Air Pollution Prevention and Control Action Plan (APPCAP) in 2013, China has effectively mitigated the concentration of particulate matter. However, the increasing O_3

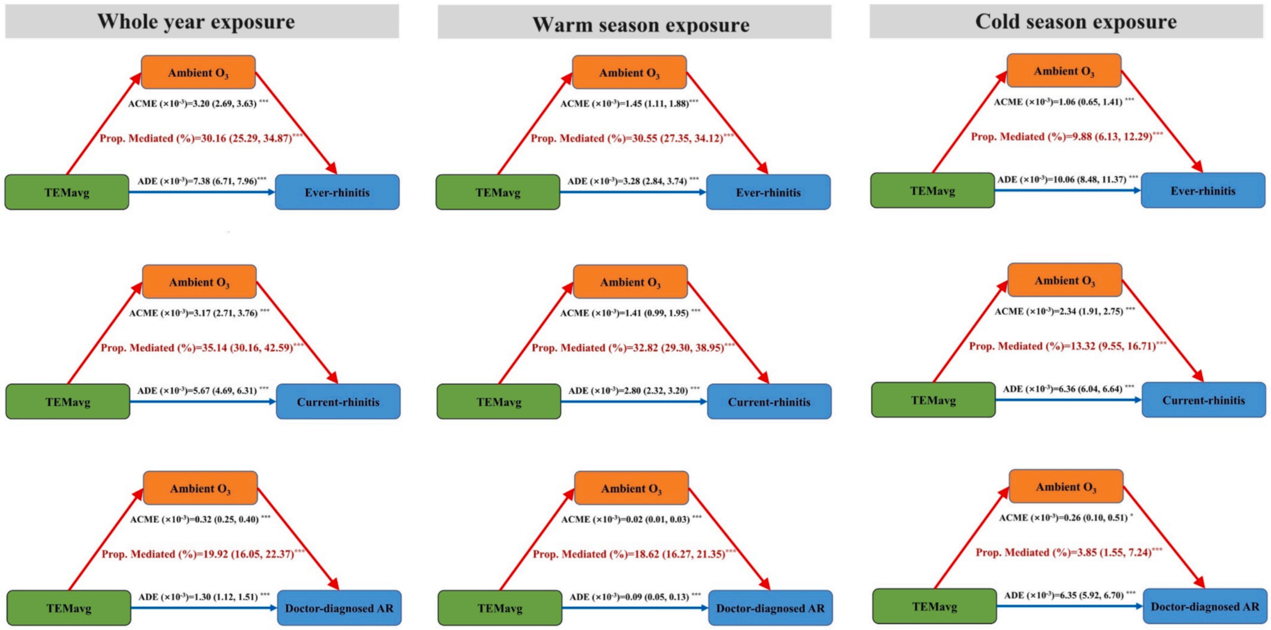

Fig. 6. The mediation effects of O_3 in the associations of air temperature with rhinitis risk.
Notes: ACME, average causal mediation effects (indirect effect); ADE, average direct effects; Prop. Mediated (%), the mediated proportion (%) of O_3 on the relationships between TEMavg and childhood rhinitis risk; TEMavg, average air temperature; * *P-value* <0.05; ** *P-value* <0.01; *** *P-value* <0.001.

concentration has become a major problem that affects human health (Chen et al., 2024; Niu et al., 2022). In this study, we observed that elevated exposure to O_3 concentration was linked to an increased risk of childhood rhinitis. Each IQR increase in annual O_3 concentration was related to the OR values of 1.31 (95%CI: 1.22, 1.40), 1.30 (95%CI: 1.22, 1.38), and 1.30 (95%CI: 1.17, 1.44) for ever-rhinitis, current-rhinitis and doctor-diagnosed AR, respectively. Our findings could be supported by both epidemiological studies and experimental studies (Maio et al., 2023; Na et al., 2024). For instance, a time-series study carried out in Shanghai demonstrated that for every 10 $\mu g/m^3$ rise in O_3 exposure, there was a 0.65% (95%CI: 0.43%, 0.87%) increase in outpatient visits for allergic rhinitis (Na et al., 2024). Studies conducted on animals have revealed that exposure to O_3 can induce epigenetic alterations (Tovar et al., 2020), induce migration of neutrophils, increase inflammatory cytokines, activate transient receptor potential vanilloid (TRPV) 1 channel, cause epithelial barrier damage, and elevate the risk of respiratory diseases such as rhinitis (Müller et al., 2022; Mumby et al., 2019). More importantly, we established the E-R relationships between the risks of different rhinitis types (ever-rhinitis, current-rhinitis, and doctor-diagnosed AR) and O_3 concentration during the whole year and different seasons. The consistent J-shaped E-R relationships between annual O_3 and different rhinitis types and slight inverted J-shaped relationships between warm season O_3 concentrations and different rhinitis types were observed. To our knowledge, this study may be the first to report the E-R relationships between chronic exposure to O_3 and childhood rhinitis risk. Overall, our study could provide new epidemiological evidence on the adverse impacts of O_3 exposure on childhood rhinitis risk and emphasize the need to pay special attention to the elevated childhood rhinitis risks associated with warm season O_3 exposure.

A noteworthy contribution of our study was the first identification of a significant mediation effect of elevated O_3 concentration on the associations between exposure to higher air temperature and increased childhood rhinitis risk. We found that annual O_3 exposure significantly mediated 26.94%, 35.14%, and 19.92% of the relationships of annual TEMavg with the risks of ever-rhinitis, current-rhinitis, and doctor-diagnosed AR, respectively. Despite no similar findings having been reported previously, we noticed that several previous studies could support this finding. Firstly, previous studies confirmed that higher air temperature could affect the formation and reaction rates of VOC and NOx, and then accelerate the production of O_3 (Ding et al., 2024; Fu & Tai, 2015; Huang et al., 2023; Liu et al., 2023; Wu et al., 2024). For example, a study conducted in the Beijing-Tianjin-Hebei region during the summer of 2017 demonstrated that air temperature could significantly influence the emissions of anthropogenic VOCs and exacerbate O_3 pollution issues (Wu et al., 2024). A study in East Asia indicated that global warming led to elevated O_3 concentration, and revealed that each 1 °C increase in air temperature was related to a 0.4 $\mu g/m^3$ to 4 $\mu g/m^3$ increase in O_3 concentration in urban areas and their surroundings (Fu & Tai, 2015). Considering the evidence of positive associations between higher air temperature (Çelebi Sözener et al., 2023; Upperman et al., 2017) and O_3 exposure (Maio et al., 2023; Na et al., 2024) with increased rhinitis risks, it might be reasonable to hypothesize that the rise in temperature leads to an elevation in O_3 production, consequently contributing to the occurrence of rhinitis. Secondly, it was worth noting that the mediated proportions of O_3 exposure on the relationships between air temperature and childhood rhinitis risk during the warm season were significantly higher than those of the cold season O_3 exposure (warm season: 18.62% to 32.82%; cold season: 3.85% to 13.32%), which was consistent with previous studies reporting the co-occurrence of high air temperature and high O_3 pollution during warm seasons in the Chinese region (Lu et al., 2018; Xu et al., 2024). Finally, the mediation effect of ambient O_3 was examined using causal mediation analysis, which could combine the advantages of mediation analysis and causal inference (Li et al., 2023; Valente et al., 2020) and control the potential moderating effect of ambient O_3 in the relationships between air temperature exposure and childhood rhinitis (Robins & Greenland, 1992) **(Table S5)**. In this study, the robust causal mediation effect of ambient O_3 in the relationships of higher air temperature exposure with childhood rhinitis may provide new perspectives for potential mechanisms of increased childhood rhinitis in the context of exacerbated global warming.

4.3. Potential mechanisms linking air temperature, ambient O_3, and childhood rhinitis risk

While the mechanisms underlying the adverse impact of higher air temperature on the elevation of childhood rhinitis risk are still unclear, several potential explanations have been proposed to elucidate this relationship (Çelebi Sözener et al., 2023; S.E. Pacheco et al., 2021). Firstly, exposure to extremely high air temperatures could result in direct damage to the respiratory epithelial barrier. Extreme air temperature impacts the thermoregulatory system, resulting in elevated tidal volume and respiratory rate, which subsequently leads to reflex bronchoconstriction and specific airway resistance mediated by the activation of bronchopulmonary vagal C fibers and the increased expression of TRPV1 and TRPV4 (Deng et al., 2020; Han et al., 2023). Heat stress can potentially trigger heat shock proteins, causing epithelial barrier dysfunction and airway inflammation, ultimately worsening the frequency and intensity of rhinitis (Bouchama et al., 2017). Secondly, the rapid increase in air temperature can lead to elevated levels of mold, pollen, dust mites, and air pollution, while enhancing the permeability of these allergens into the respiratory tract, ultimately resulting in rhinitis. Previous studies indicated that the rapid elevation in air temperature can result in heightened levels of mold, pollen, dust mites, and air pollution, disrupting the epithelial barrier integrity and triggering allergic inflammation and ultimately leading to rhinitis (Gaspar et al., 2020). Moreover, the rise in air temperature could lead to an escalation of heavy rainfall and floods, creating a hot and humid environment conducive to increased mold proliferation, and inducing respiratory epithelial barrier damage and inflammation in the airways (Çelebi Sözener et al., 2023; Du et al., 2021). Finally, as indicated in this study, ambient O_3 plays a crucial mediating role in the increased risk of rhinitis due to higher air temperature exposure. Higher temperatures accelerate photochemical reactions, enriching the atmosphere with reactive species that facilitate ozone formation, while also enhancing the emission of VOCs that act as ozone precursors, collectively escalating ozone production (Jiang et al., 2023). The elevated levels of ozone can lead to structural damage in respiratory epithelial tissues, stimulate cytokine production, activate the TRPV1 channel (Müller et al., 2022), and trigger an increase in eosinophils and an imbalance in Th1/Th2 cytokines, exacerbating rhinitis symptoms (Sun et al., 2021).

4.4. Implications of findings for sustainable urban planning and public health

With the acceleration of global warming and rapid urbanization (Wang et al., 2024; Xie et al., 2024), the gradually rising air temperatures and increasing O_3 concentration have become significant risk factors for children's respiratory health (Shan et al., 2024). Our study suggested that exposure to higher air temperatures and ambient O_3 concentration can significantly increase the risk of childhood rhinitis, underscoring the importance of taking measures to mitigate the global warming process and reducing high air temperatures and O_3 concentration exposure in controlling childhood rhinitis risk. Moreover, we found that elevated O_3 concentration played a crucial mediation effect on the relationship between higher air temperature and childhood rhinitis risk. Compared to prior studies that predominantly assessed the individual impacts of air temperature and O_3 exposure, or the interaction effects of air temperature and O_3 exposure on childhood rhinitis risk, our study provided new epidemiological evidence and insights into the adverse impact and mechanisms of higher air temperature exposure on childhood rhinitis risk. It highlighted that controlling O_3 pollution may be an effective approach to mitigate the increasing childhood rhinitis risk due to higher air temperature exposure, especially during the warm season.

4.5. Strengths and limitations

Our study may have some strengths. Firstly, this study is the first to observe the significant mediating role of elevated ambient O_3 in the relationships between higher air temperature and increased childhood rhinitis. Our study will provide new mechanistic insights into the increased risk of childhood rhinitis related to higher air temperature exposure in the context of global warming. Secondly, the E-R relationships between air temperature, O_3, and childhood rhinitis risk were established in our study for the first time. Except for the relationship between cold season O_3 exposure and childhood rhinitis risk, the consistent upward trend of E-R relationships between air temperature, O_3, and childhood rhinitis risk provided more detailed epidemiological evidence for the adverse impacts of higher air temperature and O_3 exposure on childhood rhinitis risk. Thirdly, in contrast to previous studies that mainly relied on ground monitoring stations for air temperature and O_3 exposure assessment (Bai et al., 2024), this study utilized high-resolution air temperature and ambient O_3 concentration (1 km gridded spatial resolution) datasets in exposure assessments, which could significantly reduce the error in exposure estimation compared to previously used meteorological monitoring station data (Zhang et al., 2021). Finally, the impacts of air temperature and O_3 on childhood rhinitis during different seasons (whole year, warm season, and cold season), and included three types of rhinitis as health outcomes (ever-rhinitis, current-rhinitis, and doctor-diagnosed AR) were investigated in this study, which may provide a more comprehensive understanding of air temperature and O_3 exposure on childhood rhinitis risk.

Several limitations need to be noted in this study. Firstly, the cross-sectional design of the CCHH study restricted the ability to establish causal relationships between air temperature, O_3 exposure, and childhood rhinitis risk. Further longitudinal research is essential to validate our findings (Chen et al., 2024). Secondly, data on rhinitis-related information and covariates were collected using a standardized questionnaire, which may introduce recall and reporting bias in the study (Zhang et al., 2021). However, the questionnaire items for rhinitis were utilized the ISAAC questionnaires, which have been validated by numerous studies (Asher et al., 2006; García-Marcos et al., 2022; Savoure et al., 2023; Sigurdardottir et al., 2021). Moreover, three rhinitis outcomes (ever-rhinitis, current-rhinitis, and doctor-diagnosed AR) were included, and the consistent results across different types of rhinitis may support the robustness of our findings. Thirdly, the emissions of greenhouse gases, such as CO_2 and CH_4, play a crucial role in global warming and air temperature rise (Bao et al., 2023). The absence of high-resolution greenhouse gas emission data limited our ability to examine how greenhouse gas emissions affect air temperature, consequently leading to an increased risk of childhood rhinitis. Further research incorporating high-resolution greenhouse gas emission data is warranted to enhance our understanding of the relationship between greenhouse gas emissions, air temperature changes, and childhood rhinitis risk. Fourthly, although the significant causal mediation effect of O_3 was found for the elevated risk of childhood rhinitis associated with higher air temperature exposure, it should be acknowledged that the generation of O_3 could be also influenced by other environmental factors, such as the concentrations of NOx, VOC precursors, atmospheric dynamics and ultraviolet radiation (Liu et al., 2023). The absence of information on these variables in our study highlighted the necessity for future research to consider incorporating these factors into the analysis to provide a more comprehensive understanding of the relationship between O_3, air temperature, and childhood rhinitis risk. Finally, while multiple potential confounding factors were controlled for in this study, it should be acknowledged that there may be other unaccounted confounding factors that could influence our results. Future research should consider a broader range of potential confounders to more accurately assess the relationship between air temperature, O_3 exposure, and childhood rhinitis.

5. Conclusion

In conclusion, this multi-city study of Chinese preschool children indicated that higher air temperature and ambient O_3 exposure were significantly associated with childhood rhinitis risk and first found that elevated O_3 concentration played a crucial mediation effect on the relationship between higher air temperature and childhood rhinitis risk. Given the rapid global warming, severe O_3 pollution, and high prevalence of childhood rhinitis risk, our study provided new epidemiological insight into the adverse impact and mechanisms of higher air temperature exposure on childhood rhinitis risk. These findings highlighted that controlling O_3 pollution may be an effective approach to mitigate the increasing childhood rhinitis risk due to higher air temperature exposure, especially during the warm season. Further studies incorporating high-resolution emission data on greenhouse gas and O_3 precursors could be conducted to enhance our understanding of the relationship among air temperature, ambient O_3, and childhood rhinitis risk.

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Declaration of generative AI in scientific writing

None.

CRediT authorship contribution statement

Zhiping Niu: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ling Zhang:** Methodology, Investigation, Data curation. **Xin Zhang:** Methodology, Investigation, Data curation. **Chan Lu:** Methodology, Investigation, Data curation. **Tingting Wang:** Methodology, Investigation, Data curation. **Xiaohong Zheng:** Methodology, Conceptualization. **Dan Norback:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Juan Wang:** Conceptualization, Methodology, Supervision. **Yanyi Xu:** Writing – review & editing, Methodology. **Jing Wei:** Methodology, Data curation. **Feng Li:** Writing – review & editing, Conceptualization. **Li Peng:** Conceptualization. **Zhenhua Zhang:** Writing – original draft, Conceptualization. **Tippawan Prapamontol:** Writing – review & editing, Methodology, Conceptualization. **Wei Yu:** Methodology, Data curation, Conceptualization. **Qihong Deng:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zhuohui Zhao:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

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

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2024.106122.

Data availability

Data will be made available on request.

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