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RESEARCH ARTICLE

Exposure–response relationship between temperature, relative humidity, and varicella: a multicity study in South China

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Abstract
Varicella is a rising public health issue. Several studies have tried to quantify the relationships between meteorological factors and varicella incidence but with inconsistent results. We aim to investigate the impact of temperature and relative humidity on varicella, and to further explore the effect modification of these relationships. In this study, the data of varicella and meteorological factors from 2011 to 2019 in 21 cities of Guangdong Province, China were collected. Distributed lag nonlinear models (DLNM) were constructed to explore the relationship between meteorological factors (temperature and relative humidity) and varicella in each city, controlling in school terms, holidays, seasonality, long-term trends, and day of week. Multivariate meta-analysis was applied to pool the city-specific estimations. And the meta-regression was used to explore the effect modification for the spatial heterogeneity of city-specific meteorological factors and social factors (such as disposable income per capita, vaccination coverage, and so on) on varicella. The results indicated that the relationship between temperature and varicella in 21 cities appeared nonlinear with an inverted S-shaped. The relative risk peaked at 20.8 ℃ (RR = 1.42, 95% CI: 1.22, 1.65). The relative humidity-varicella relationship was approximately L-shaped, with a peaking risk at 69.5% relative humidity (RR = 1.25, 95% CI: 1.04, 1.50). The spatial heterogeneity of temperature-varicella relationships may be caused by income or varicella vaccination coverage. And varicella vaccination coverage may contribute to the spatial heterogeneity of the relative humidity-varicella relationship. The findings can help us deepen the understanding of the meteorological factors-varicella association and provide evidence for developing prevention strategy for varicella epidemic.

Keywords Varicella · Infectious disease · Temperature · Relative humidity · Exposure–response relationship · Modification effect

Introduction

Varicella (or chickenpox) is an extremely contagious infectious disease, which is mainly caused in infants and children by the first infection of the ubiquitous varicella-zoster virus. Varicella is an important public health concern worldwide. The World Health Organization (WHO) estimated approximately 4.2 million varicella cases with severe complications in 2014, and approximately 4200 related deaths occurring per year in the world (WHO 2014). In China, the incidence and outbreak events of varicella have increased significantly in recent years, with an incidence of 70.14 per 100,000 people in 2019 (Dong et al. 2020).

Many factors may influence the varicella epidemics, such as vaccination (Pan et al. 2021) and personal contact (Marziano et al. 2018). And several studies have investigated the

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possible association between the occurrence of varicella infection and meteorological factors such as relative humidity and temperature (Critselis et al. 2012; Lu et al. 2020; Wang et al. 2018). Some studies have suggested that relative humidity is associated with varicella (Chan et al. 2014; Yang et al. 2016), whereas another study showed a weak link between relative humidity and varicella (Chen et al. 2017). It has been reported that the mean temperature has a considerable influence on the incidence of varicella and is closely related to the transition of varicella patterns (Sumi 2018). However, the results of different studies have been inconsistent. For instance, a study conducted in Lanzhou, China (Wang et al. 2018) demonstrated an approximately M-shaped nonlinear relationship between temperature and varicella; meanwhile, a study in Guangzhou, China, reported an inverted U-shaped nonlinear relationship between temperature and varicella (Lu et al. 2020).

Some infectious diseases, including malaria, measles, Japanese encephalitis, and mumps, exhibit heterogeneity in their spatial and temporal distributions (Tang et al. 2017; Wang et al. 2014; Yu et al. 2018; Zhang et al. 2012). Previous studies have reported that the transmission of varicella is affected by different geographic regions, climatic belts, population densities, and socio-economic statuses (such as vaccination coverage) (Daulagala and Noordeen 2018, Toi and Dwyer 2010, WHO 2016), and that these characteristics may contribute to the spatial heterogeneity of the effect of meteorological factors on varicella incidence. However, the heterogeneity of meteorological factors on varicella remains to be further explored. Previous studies have primarily been conducted in one city (Lu et al. 2020; Wang et al. 2018), which prevents the modeling and quantitative assessment of heterogeneous relationships. Thus, it is necessary to investigate the effect of spatial heterogeneity of meteorological factors on varicella and explore the effects of modification factors on heterogeneity.

In this study, based on the data from 21 cities in Guangdong Province in south China, we investigated the impact of temperature and relative humidity on varicella and further explored the effect modification for its spatial heterogeneity. The aim of the study was to provide results that would identify the potential predictive factors for the varicella epidemic, and therefore provided information to aid public health authorities.

Materials and methods

Study sites

Guangdong Province is located at the southern tip of the Chinese mainland coast. It ranges from 109° 39′ to 117° 19′ E longitude and 20° 13′ to 25° 31′ N latitude, comprising a total of 21 prefecture-level cities and an extremely high population of 126 million people as of 2020 (Guangdong Bureau of Statistics 2021). Socio-economic conditions vary among cities (Guangdong Bureau of Statistics 2021). Significant differences were observed in indicators such as the population density, disposable income per capita, and medical institutions. For example, the disposable income per capita of Shenzhen is 64,878 Chinese Yuan (CNY), which is approximately 2.8 times of Jieyang (21,821 CNY). Guangdong is located in a typical monsoon-influenced climate area, with a wet hot summer and a dry cold winter. The number of varicella cases in Guangdong ranks among the top three in China (Dong et al. 2020). Therefore, Guangdong is an ideal site to study the relationship between varicella and meteorological factors.

Varicella is not a notifiable infectious disease in China, but it was categorized as a surveillance infectious disease by the Guangdong Department of Health in 2005. Subsequently, all medical practitioners in both public and private sectors in Guangdong were required to report varicella cases online to the National Notifiable Infectious Diseases Reporting Information System (NNIDRIS), using a standardized form. The varicella vaccine is a voluntarily self-funded vaccine that has not been included in Expanded Program on Immunization in Guangdong Province. Various cities in the province have considerably different levels of varicella immunization (Zhu et al. 2016).

Based on the school calendar provided by the Department of Education of Guangdong Province and Guangzhou Municipality, schools are opened during autumn and spring, and closed during winter and summer. The summer vacation lasts from July to August for approximately seven weeks, while the winter vacation begins in February or March for about four weeks.

Data collection

Data of varicella and meteorological variables

Daily data series of varicella cases from January 1, 2011, to December 31, 2019, were collected from NNIDRIS. A clinical case of varicella should be reported to NNIDRIS within 24 h of diagnosis, using a standardized form. For this study, these daily counts of varicella clinical cases based on the date of symptom onset were then aggregated for each of the 21 cities in Guangdong.

Daily monitoring data of meteorological factors, including mean temperature, mean relative humidity, accumulated precipitation, and wind speed for the 21 selected cities from January 1, 2011, to December 31, 2019, were collected from the China Meteorological Data Sharing Service System (http://www.cma.gov.cn/), which was constructed by the Chinese National Meteorological Information Centre. The daily meteorological data for each city was calculated as the average of the monitoring stations in counties within the city administrative boundaries.

For incomplete data, the missing values were imputed with the mean of the values before and after each missing value; meanwhile, the abnormal values of the meteorological variables were handled in the same way for the missing value. However, this was negligible due to the very small proportion of missing values (no meteorological variables with more than 0.4% missing values) and the high quality of monitoring data. For cities with no meteorological monitoring stations within their administrative boundaries, data from stations in adjacent cities closest to the city center was used (Luo et al. 2020).

City-specific characteristics

The climatic and social characteristics of each of the 21 cities in Guangdong Province were collected. The annual mean of the daily monitoring data of meteorological factors at each city/station was calculated to represent the climatic differences including temperature, relative humidity, precipitation, and wind speed. City-specific social characteristics were collected from the China City Statistical Yearbook, including geographical variables (latitude), demographic variables (population density), and socioeconomic variables, such as disposable income per capita, vaccination coverage, and medical institutions per 10,000 people.

Statistical analysis

We first fitted a DLNM for each of the 21 cities to explore the exposure–response relationship between meteorological factors and varicella incidence. Then, the single exposure–response relationships were pooled to determine the overall cumulative exposure–response using multivariate meta-analysis. Finally, meta-regression analysis was applied to explore the effect of medication factors on the spatial heterogeneity of the exposure–response relationship.

City-specific analysis

Given that multiple previous studies have suggested that the meteorological factors-varicella relationship can be delayed (Gao et al. 2020; Wu et al. 2016), a DLNM was incorporated. The DLNM was fitted to each of the 21 cities to relate the daily series of varicella counts to mean temperature or relative humidity.

The model for temperature or relative humidity can be specified as:

$$
\begin{aligned}
Log(\mu_t) = {} & \beta_0 + \beta_1 Exposure_{t,l} \\
& + ns(Relative\ humidity\ or\ temperature, df) \\
& + \beta_2 Term_t + \beta_3 Holiday_t + ns(Time, df) + \beta_4 DOW_t
\end{aligned}
$$

where μ_t is the expected number of varicella on date t; β_0 is the intercept; $Exposure_{t,l}$ is the cross-basis exposure (temperature or relative humidity) matrix of lag, varicella, and temperature (or relative humidity); *ns* indicates a smoother base on natural cubic splines; *df* is the degree of freedom; *DOW* is an indicator for day of week; *Holiday* is a binary variable for the public holiday; *Time* is an indicator for calendar time; *Term* was introduced as a binary variable for the school term; and β is the regression coefficient.

A quasi-Poisson regression model was adopted to allow for overdispersion. The bi-dimensional exposure-lag-response relationship between meteorological factors (temperature or relative humidity) and varicella was described through a cross-basis function (Gasparrini et al. 2010) using natural cubic splines for the exposure–response and lag-response relationships. The lag interval was determined by the incubation period of varicella infections (21 days) (Ayoade and Kumar 2021). The pooled estimates of the temperature-varicella relationship returned to 1 on day 21 (Supplementary Fig. 1). To control for unmeasured time-varying confounding, we used natural cubic splines of *Time* to remove long-term trends and seasonality. The *df* value was set according to previous studies (Xiao et al. 2017; Yang et al. 2020). We either incorporated relative humidity in the same lag range of temperature, or incorporated temperature in the same lag range of relative humidity. We also adjusted for the effect of the day of week (DOW), holidays (including national public holidays), and school terms as indicator variables. Relative risk (RR) with its 95% confidence interval (CI) was used to estimate the risk of meteorological factors on varicella. Our preliminary exploration revealed that there was a nonlinear relationship between meteorological variables and varicella. According to the previous studies (Lam et al. 2018; Ma et al. 2015), the value of a meteorological variable corresponding to the minimum RR for varicella was set as the reference value when estimating the varicella risk. In this study, the exposure–response relationship between temperature and varicella showed that the extreme high temperature corresponded to the lowest RR value. Thus, we set the reference temperature at 31 °C which was at the 99th percentile of temperature distribution (defined as the extreme high temperature) referring to Fang and Lin et al.'s studies (Fang et al. 2021; Lin et al. 2017). For the relationship between relative humidity and varicella, the relative humidity value of 52.5% which corresponded to the minimum RR was set as a reference value.

Multivariate meta-analysis and meta-regression analysis

A multivariate meta-analysis was applied to pool the city-specific estimations following the method of previous studies (Gasparrini and Armstrong 2013) to examine the overall meteorological factor-varicella relationship, and a meta-regression analysis was used to capture the potential effect modifiers of the relationship. The estimated city-specific meteorological factor-varicella relationship, represented by RR, was pooled using a multivariate meta-analysis to estimate the overall nonlinear relationship between meteorological variables and varicella.

To identify the potential modification factors of significant heterogeneity, meta-regression analyses modeling city-specific characteristics were performed (Supplementary Table 1, Supplementary Table 2). These included independent variables such as latitude, population density, disposable income per capita, medical institutions per 10,000 people, and the annual average of meteorological factors. First, we fitted a multivariate meta-regression model with an intercept only, allowing for heterogeneity being modeled through random effects (denoted as the intercept-only model). We then ran a single meta-predictor analysis by incorporating city-specific characteristics into the model separately (denoted as single meta-predictor models) and compared it to the intercept-only model. For the second-stage analysis, we used the maximum likelihood estimation to obtain estimates, and a Wald test to test the significance of meta-predictors and differences between models. Residual heterogeneity was assessed using multivariate extension of I^2 statistics (Gasparrini et al. 2012).

The meta-predictor Wald test was selected for further exploration. The effect of these meta-predictors was displayed by predicting the averaged associations between meteorological factors and varicella for the 10th and 90th percentiles of their distribution, using the baseline reference of 31 °C for temperature and 52.5% for relative humidity.

The indicator of cities with $P < 0.05$, which are considered statistically significant for the Wald test, is a categorized proxy variable of potential effect modifiers that had the largest impact in their category and a more sensible interpretation.

Sensitivity analysis

To check the robustness of our estimates, sensitivity analyses were conducted by changing the meta-regression method, where the REML model and fixed-effect model were fitted (Supplementary Fig. 2).

All the implementations were accomplished using R software version 4.0.2. Specifically, exposure–response analysis, meta-analysis, meta-regression, and accompanying graphical presentation were carried out with *dlnm* (Gasparrini 2011), *mvmeta* (Gasparrini et al. 2012), and *metafor* packages. Statistical significance was set at $P < 0.05$, and all P values were 2-sided.

Results

From 2011 to 2019, 617,898 varicella cases were reported in the 21 cities in Guangdong, with an annual average incidence of 6.33 per 10,000. Varicella incidence varies geographically, with most cases occurring in densely populated cities (Fig. 1a). The cities in the Pearl River Delta such as Shenzhen, Guangzhou, Foshan and Zhongshan had higher prevalence than that in other cities in Guangdong; that is, their respective incidences per 10,000 were 15.98, 13.85, 9.77, and 9.27 (Fig. 1b).

Figure 2 depicts the time series of daily varicella counts and weather conditions in Guangdong from 2011 to 2019. There was obvious seasonality of a bimodal pattern for varicella occurrence, especially during 2017–2019, with the first peak from April to June, and the second peak from November to January of the following year. We observed that high varicella incidence seems to be related to temperate temperatures and higher humidity (for instance, in April) and low temperature and low humidity (for instance, in December) (Fig. 2).

Figure 3 shows the exposure–response relationship between meteorological factors (temperature and relative humidity) and varicella. The overall pooled estimates suggested a nonlinear relationship between temperature and varicella, with an approximately inverted S-shape (Fig. 3a). We found the relative risk of varicella peaked at 20.8 °C (RR = 1.42, 95% CI: 1.22,1.65), with reference to the 99th percentile of temperature distribution. For relative humidity, the overall pooled estimates suggested a nonlinear relationship between relative humidity and varicella, with an approximately L-shaped upturned tail (Fig. 3b). The threshold relative humidity was found to be approximately 52.5%. The RR of relative humidity on varicella was 1.25 (95% CI: 1.04,1.50) when comparing 69.5% (corresponding to the maximum RR with significance) with 52.5% (Supplementary Table 3). The meteorological factor-varicella relationship curves differed across the 21 cities (Fig. 3).

Table 1 summarizes the results of the heterogeneity analysis. For temperature, the single meta-predictor models showed that disposable income per capita and varicella vaccination coverage could partially explain the heterogeneity. Similar modification effect was found between varicella vaccination coverage and relative humidity. We also found a borderline impact of medical institutions and annual average temperature. The modification effect of these characteristics on temperature was negligible compared to that of disposable income per capita, or varicella vaccination coverage. Demographic, socioeconomic (excluding vaccination coverage), and meteorological characteristics were not significant in explaining the heterogeneity of relative humidity.

We only displayed the modification effects of disposable income per capita and varicella vaccination coverage (p value of Wald test < 0.05) for temperature and varicella vaccination coverage for relative humidity (p value < 0.05) because they had the largest impact and had a more sensible interpretation. Disposable income per capita had the best ability to explain heterogeneity, with

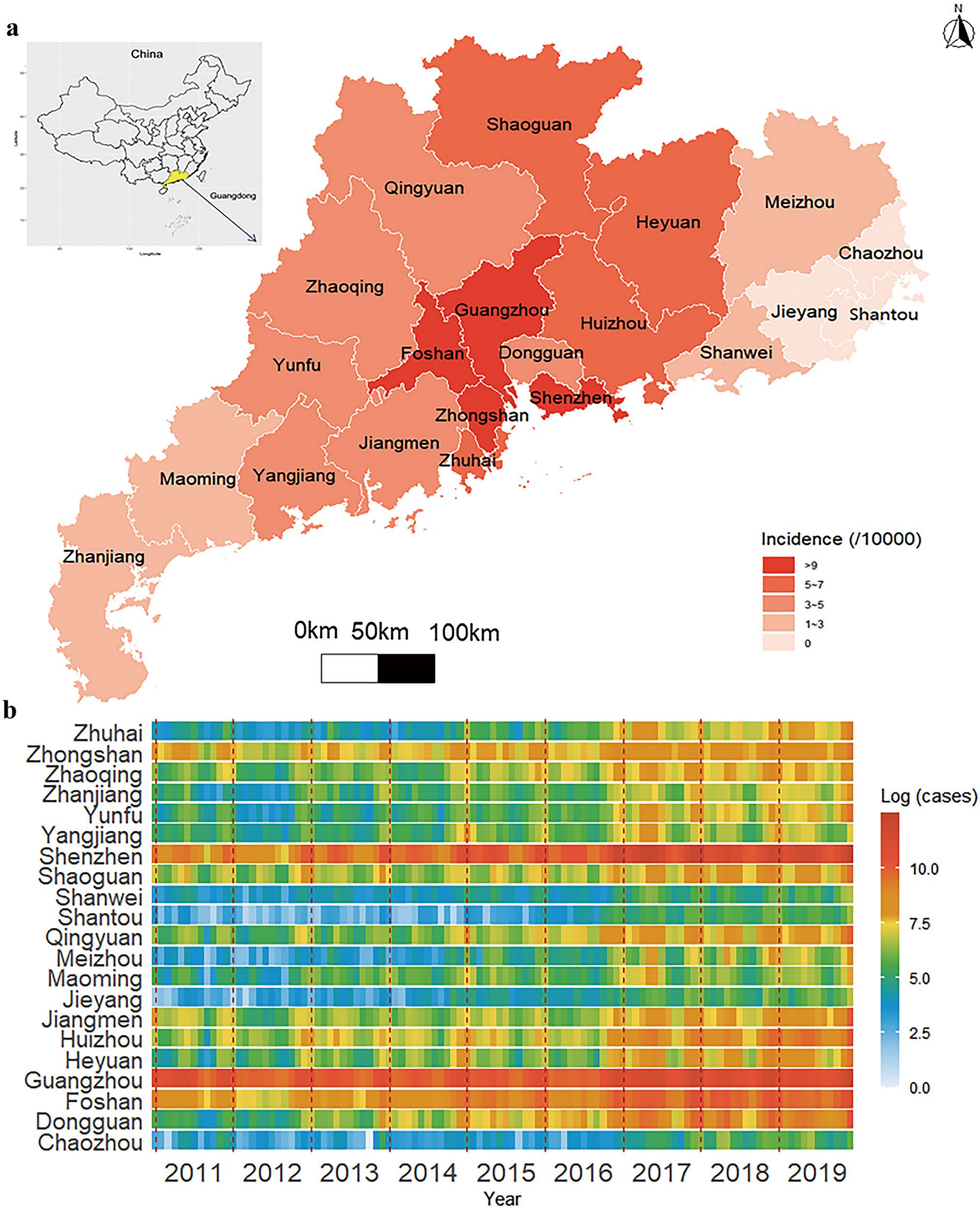

Fig. 1 The spatial distribution of the annual average incidence of varicella (**a**) and the heat map of monthly varicella cases (**b**) in 21 cities of Guangdong Province, China, 2011–2019

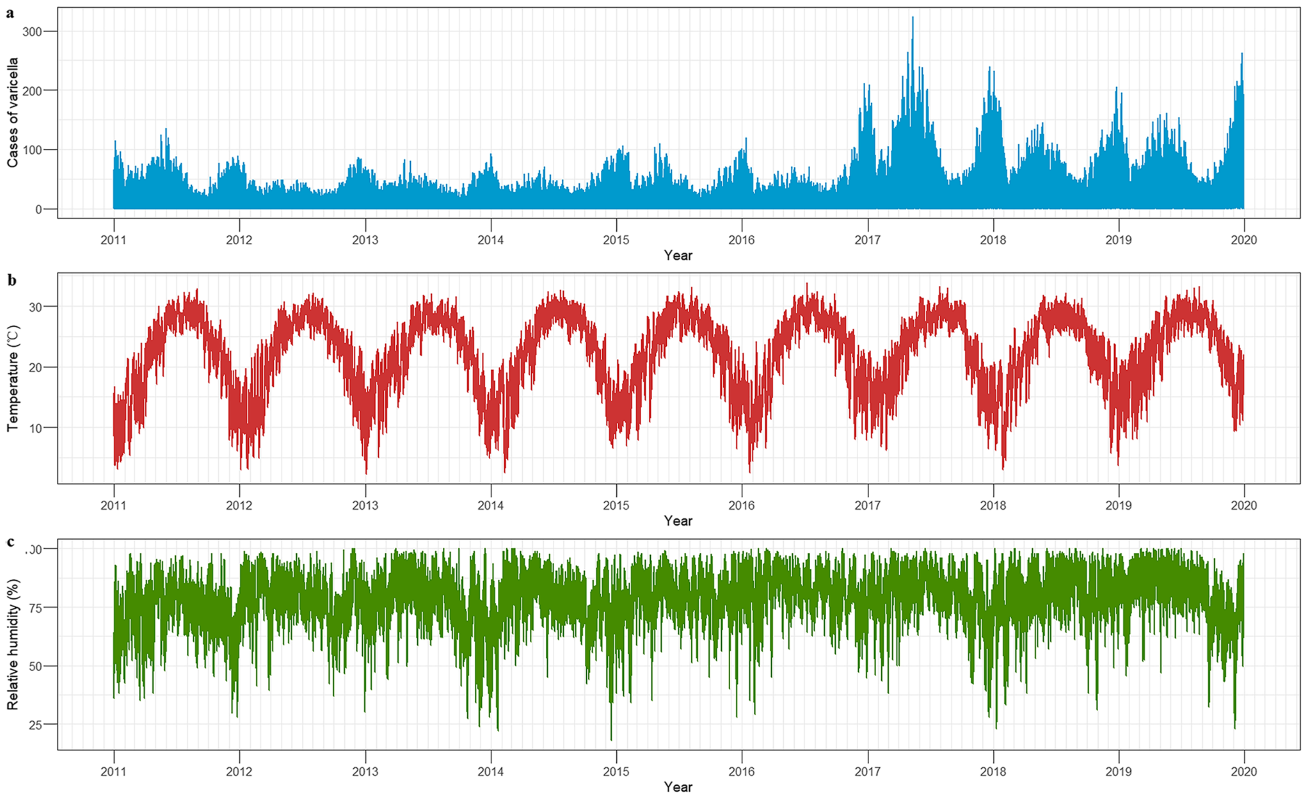

Fig. 2 The time series of daily varicella cases (**a**), temperature (**b**), and relative humidity (**c**) in Guangdong Province, China, 2011–2019

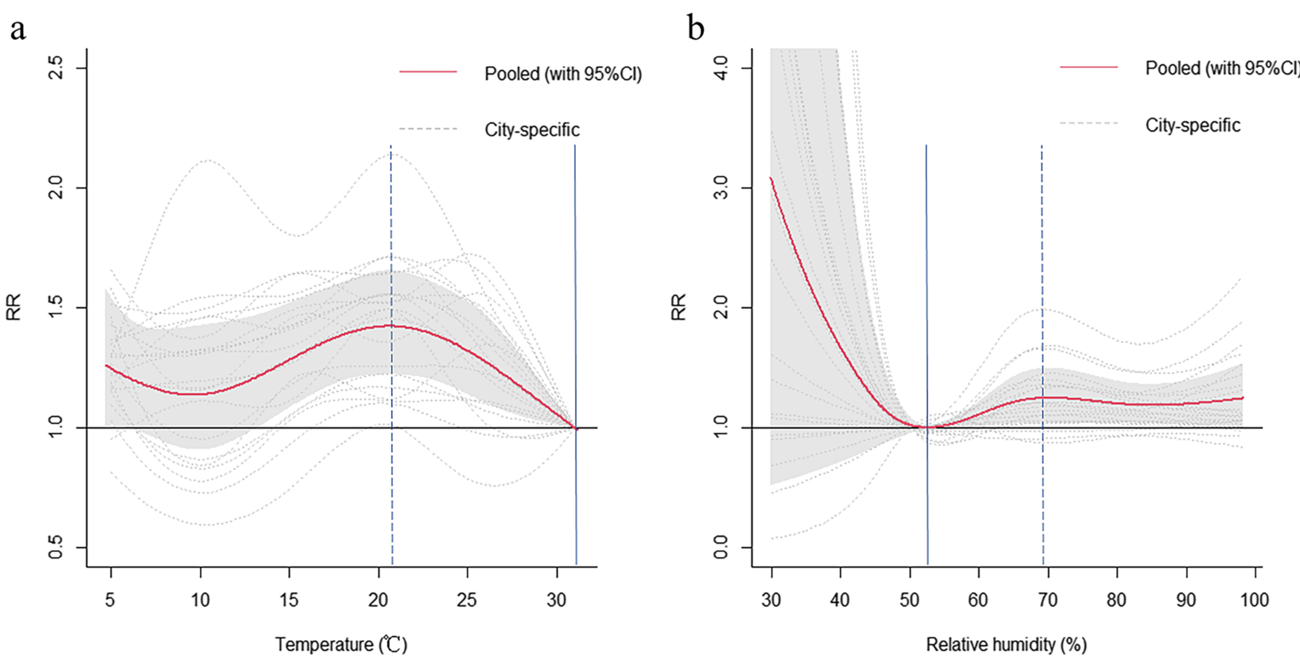

Fig. 3 Pooled overall curves of temperature-varicella relationship (**a**) and relative humidity-varicella relationship (**b**) based on 21 cities in Guangdong Province, China, 2011–2019 (solid blue lines are the reference value, the dotted blue lines are the value corresponded to the maximum relative risk (RR) with statistically significance)

the related I^2 statistic dropping from 39.6% (intercept-only model) to 36.4% (Table 1). We found that higher disposable income per capita and varicella vaccination coverage could elevate the risk of temperature or relative humidity on varicella (Fig. 4a, b). We found that the risk of relative humidity on varicella was higher in regions with higher vaccination coverage (Fig. 4c).

From the results of the sensitivity analysis, we observed that the results based on the REML model and fixed-effect model were similar, and the exposure–response curve showed no significant change (Supplementary Fig. 1).

Discussion

Based on data from 21 cities in South China, we conducted a two-stage analysis to investigate the exposure–response relationship between temperature, relative humidity, and varicella, and further explored the spatial heterogeneity of the relationship. We observed a nonlinear exposure–response relationship between temperature, relative humidity, and varicella incidence. These relationships may be modified by socioeconomic factors such as income and vaccination coverage. To the best of our knowledge, this is the first study to explore the modification effect of the relationship between meteorological factors and varicella incidence.

We found a nonlinear relationship between temperature and varicella, which is approximately inverted S-shaped, with the highest RR being observed at around 21 °C and low RR at cold or high temperatures. This result is similar to that of studies conducted in Lanzhou (Wang et al. 2018) and Guangzhou (Lu et al. 2020). The authors reported a nonlinear temperature-varicella association of approximately M-shape or inverted U-shape. The mechanism underlying the relationship between temperature and varicella is not fully understood. One possible reason is that temperature affects both varicella-zoster viruses (VZV) in titer and in vivo activity because of the heat sensitivity of VZV (WHO 2016), and the virus may be affected at higher temperatures (Halloran et al. 2012). Another reason may be related to the school calendar (Bakker et al. 2021). In China, students would take summer and winter vacations when suffering from extremely hot and cold temperatures, which significantly decreases the exposure between those students, corresponding to fewer opportunities to be affected (Marziano et al. 2018). Nevertheless, the inverted S-shaped curve for temperature and varicella would be helpful for further exploration in the prediction of varicella outbreaks.

A nonlinear relationship between relative humidity and varicella was observed in this study. The relative risk of varicella increased when the relative humidity was > 52.5%. Several studies have demonstrated that relative humidity is positively associated with infectious diseases such as hand-foot-mouth disease (HFMD), which is partly similar to our findings (Bo et al. 2020; Wu et al. 2014). Both varicella and HFMD can be transmitted through close contact and mainly affect infants and children. The exact mechanism underlying the potential association between relative humidity and varicella and transmission is unknown. One hypothesis is that during days of higher humidity, children tend to stay indoors with air conditioning; this increases the chance for close contact with others, thus facilitating varicella transmission (Sun et al. 2011; Ueshiba et al. 2013). It is necessary

Table 1 Multivariate meta-regression analyses for the potential source of spatial heterogeneity for the meteorological factors-varicella relationship in Guangdong Province, China

Variables	Temperature				Relative humidity			
	I^2		Wald test		I^2		Wald test	
	%	ΔI^2	*Stat*	*P*	%	ΔI^2	*Stat*	*P*
Intercept only	39.6	—	—	—	54.3	—	——	——
Latitude (°N)	37.7	1.9	4.6	0.098	53.4	0.9	3.8	0.15
Population density (per km^2)	37.6	2.0	4.7	0.095	53.2	1.1	2.9	0.23
Disposable income per capita (CNY)	36.4	3.2	10.0	0.007	55.4	−1.1	2.0	0.37
Vaccination coverage (dose per 1000 persons)	38.7	0.9	8.4	0.015	53.5	0.8	6.0	0.05
Medical institutions (per 10,000 persons)	38.3	1.3	5.4	0.066	52.5	1.8	2.9	0.24
Temperature (°C)	37.0	2.6	5.4	0.067	55.6	−1.3	2.4	0.30
Precipitation (mm)	41.4	−1.8	5.1	0.079	54.0	0.3	3.3	0.19
Relative humidity (%)	37.5	2.1	4.0	0.140	52.3	2.0	4.3	0.12
Wind speed (m/s)	39.2	0.4	2.8	0.240	53.9	0.4	2.7	0.26
Multiple meta-predictors model								
Vaccination coverage + disposable income per capita	37.4	2.2	4.7	0.096	-	-	-	-

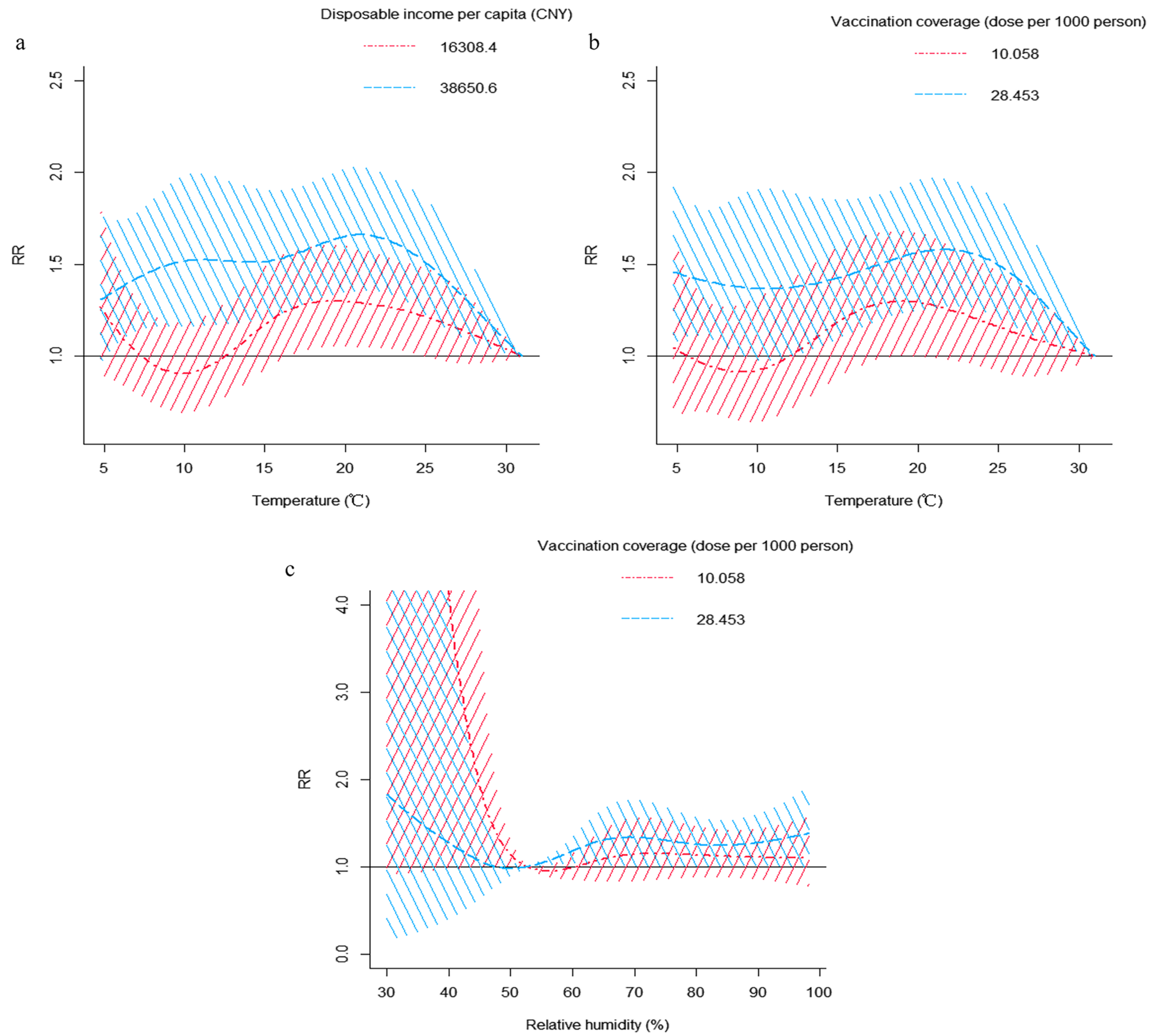

Fig. 4 The modification of disposable income per capita and vaccination coverage on the temperature-varicella relationship (**a**, **b**) and vaccination coverage on relative humidity-varicella relationship (**c**). Predictions for the 10th (red dot-dashed line) and 90th (blue dashed line) percentiles of disposable income per capita and vaccination coverage of cities. Reference at 31 °C for temperature and 52.5% for relative humidity, respectively. The 95% CI of RR are reported as shaded area

to strictly implement a school registration system for absenteeism due to illness as well as conduct morning checks of students' basic health conditions, including basic visible symptoms such as fever and pox rash, to aid the early detection of physical abnormalities and prevent disease spread.

Our study indicated that a high disposable income per capita could elevate the association between temperature and varicella. The modification effects of disposable income per capita may be attributed to its association with population density and socioeconomic development. Guangdong is a province with a large population, high population density, and high disposable income per capita, particularly in cities located in the Pearl River Delta. Previous studies have found that factors such as population density, nursery attendance, and socioeconomic development may also influence the epidemiology of VZV in areas where universal vaccination has not yet been implemented (Arat et al. 2019; Chan et al. 2018). Changes in the epidemiology of varicella infection, particularly in tropical regions, have been attributed to demographic changes, including increased population density and urbanization (Daulagala et al. 2017; Neiderud 2015). Seroprevalence rates of varicella infection have been observed to be higher among urban populations, regardless of age distribution (Li et al. 2019; Liyanage et al. 2007). Specifically, urban settings may enable enhanced social interaction and population mobility within and between communities, thus facilitating viral transmission. Such evidence was corroborated by findings and indicated that children with enhanced social interaction, such as those attending to nurseries, are more likely to contract varicella infections (Santermans et al. 2015). This shows the importance and difficulty of preventing the spread of the virus, as social interaction and population mobility are inevitable. To block the varicella epidemic and limit the size of outbreaks, pre-outbreak and post-outbreak varicella vaccination should be prioritized, along with self-home quarantine for the infected.

Districts with higher varicella vaccination coverage were associated with a higher RR, either in the temperature-varicella relationship or the relative humidity-varicella relationship. The mechanism underlying this phenomenon remains unknown. One possible reason might be the high population density. The Pearl River Delta region, which has a high level of varicella immunization, is the most economically developed and densely populated area in Guangdong Province. A high population density could facilitate the spread of varicella (Daulagala et al. 2017) because the residents living in dense areas have a higher probability of getting into close contact with others. Another reason might be that the vaccination coverage of varicella (Ni et al. 2018) has not reached the standard recommended by the WHO (WHO 2016). Vaccine coverage that remains < 80% over the long term is expected to shift varicella infections to the older age group of children in some settings, which may increase morbidity and mortality, despite a reduction in the total number of cases (WHO 2016). This suggests that more attention should be paid to varicella vaccination uptake to establish an immune barrier.

This study has a few limitations. First, being an observational ecological study, results should be interpreted at the population level and cannot be read as causal associations. Second, multiple factors may influence varicella epidemics, such as meteorological factors, vaccination coverage, socioeconomic factors, and host susceptibility (Lu et al. 2020). We were unable to account for all confounding factors, and the important confounder of vaccine coverage was only considered in the multivariate regression analysis and not in the model. These factors may have influenced our results to some extent. Third, vaccination policies and coverage varied across the 21 cities, which could have influenced the results.

Conclusion

Our study showed that there is a nonlinear relationship between temperature, relative humidity, and varicella. Medium temperature and high relative humidity would elevate the risk of varicella infection in South China. Disposable income per capita and varicella vaccination coverage may modify the relationship between meteorological factors and varicella. Our findings can help deepen our understanding of how meteorological factors impact varicella epidemics. Furthermore, this evidence can provide implications for related public health decisions, such as varicella prediction, based on meteorological factors.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-22711-8.

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Author contribution All authors contributed to the study conception and design. Conceived and designed the experiments: Limei Sun, Jianpeng Xiao. Analyzed the data: Yihan Li, Jianpeng Xiao. Contributed reagents/materials/analysis tools: Yihan Li, Jialing Li, Zhihua Zhu, Weilin Zeng, Qi Zhu, Zuhua Rong, Jianxiong Hu, Xing Li, Guanhao He, Jianguo Zhao, Lihua Yin, Yi Quan, Qian Zhang, Manman Li, Li Zhang, Yan Zhou, Tao Liu, Wenjun Ma, Siqing Zeng, Qing Chen, Limei Sun, Jianpeng Xiao. Wrote the paper: Yihan Li, Jianpeng Xiao, Weilin Zeng. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The data of daily meteorological variables from 2011 to 2019 can be accessed from the China Meteorological Data Sharing Service System (http://www.cma.gov.cn/), and city-specific socioeconomic characteristics for 21 cities in Guangdong can be accessed from the official website of Guangdong Provincial Bureau of Statistics (http://stats.gd.gov.cn/gdtjnj/). The data of detailed surveillance generated during and/or analyzed during the current study are not publicly available due to the data management requirements but are available from the corresponding author on reasonable request.

Declarations

Ethical approval The study was approved by the ethics committee of Guangdong Provincial Center for Disease Control and Prevention (No. W96-027E-201925).

Consent to participate Not applicable.

Consent for publication The authors have provided consent to publish this work.

Conflict of interest The authors declare no competing interests.

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