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Effect of meteorological factors on the activity of influenza in Chongqing, China, 2012–2019

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Abstract

Background: The effects of multiple meteorological factors on influenza activity remain unclear in Chongqing, the largest municipality in China. We aimed to fix this gap in this study.

Methods: Weekly meteorological data and influenza surveillance data in Chongqing were collected from 2012 to 2019. Distributed lag nonlinear models (DLNMs) were conducted to estimate the effects of multiple meteorological factors on influenza activity.

Results: Inverted J-shaped nonlinear associations between mean temperature, wind speed, sunshine and influenza activity were found. The relative risks (RRs) of influenza activity increased as weekly average mean temperature fell below 18.18℃, average wind speed fell below 1.55 m/s and average sunshine fell below 2.36 hours. Taking the median values as the references, lower temperature and windless could significantly increase the risks of influenza activity and last for 4 weeks. A J-shaped nonlinear association was observed between relative humidity and influenza activity; the risk of influenza activity increased with rising relative humidity with 78.26% as the break point. Taking the median value as the reference, high relative humidity could increase the risk of influenza activity and last for 3 weeks. In addition, we found the relationship between aggregate rainfall and influenza activity could be described with a U-shaped curve. Rainfall effect has significantly higher RR than rainless effect.

Conclusions: Our study shows that multiple meteorological factors have strong associations with influenza activity in Chongqing, providing evidence for developing a meteorology-based early warning system for influenza to facilitate timely response to upsurge of influenza activity.

Background

Influenza has significant clinical and economic impacts each year. World Health Organization estimated that seasonal epidemics of influenza result in approximately 3-5 million severe illness and 290,000 to 650, 000 deaths worldwide each year [1]. China, the largest developing country in the world, has approximately 3.4 million influenza-associated outpatients and 88,100 influenza-associated excess respiratory deaths per year [2]. Understanding the epidemiology of influenza is critical for optimizing vaccination and other control measures. The influenza seasonal pattern is likely to be the outcome of complex interactions among survival and transmission of influenza virus, meteorological factors, and human behavior. Among which meteorological factors appear to be one of the most important. The association between weather conditions and influenza activity varied across regions and the transmission patterns of seasonal influenza were diverse even in neighboring regions sharing similar climate [3]. Therefore, it is critical to specially assess the response of influenza to meteorological factors on the local basis.

With the latitude of 29.6°N and a subtropical climate with four distinct seasons, Chongqing is the largest municipality with over 30 million registered inhabitants in China. Our previous studies demonstrated a substantial influenza mortality burden in Chongqing [4], and absolute humidity has a significant impact on influenza and pneumonia mortality among elderly people [5]. However, it remains unclear whether other meteorological factors such as temperature, relative humidity, precipitation, wind speed and sunshine affect the activity of influenza. In this study, we aimed at examining the relationships between multiple meteorological factors and influenza activity in Chongqing. This result will contribute to a better understanding of the health impacts of meteorological factors on influenza and provide more evidence for developing public health strategies and measures to reduce the high burden of influenza in Chongqing.

Materials And Methods

Study Area

This study is conducted in Chongqing, which covers an area of 82,400 km^2 in Southwestern China and has approximately 33 million registered residents in 2019 (Figure 1). It has a subtropical humid monsoon climate, a long and hot summer, and a short and warm winter.

Influenza Surveillance Data

The influenza-like-illness (ILI) was defined as patient who has acute respiratory infection with fever and at least one respiratory symptom (cough and/or sore throat). ILIs and influenza virus positive rates were obtained from sentinel influenza surveillance network in Chongqing, which have been stated in a previous study [6]. Briefly, seven sentinel hospitals were selected based on higher accessibility to patients, higher qualifications of medical staff, adequate specimen storage capacity, and the desire of the physicians and nurses to participate voluntarily in the surveillance program. At each sentinel hospital, trained nurses and clinicians collected data on the counts of visits and the total number of ILI to outpatient and/or emergency departments, and collected nasopharyngeal swabs specimens then tested influenza virus by reverse transcription-polymerase chain reaction.

In this study, the activity of influenza virus was represented by weekly confirmed influenza cases every ten thousand outpatient visits, which was calculated by multiplying the weekly positive rates of influenza by the weekly ILI counts, on the scale of every 10,000 of the outpatient visits, similar to a previous study [7].

Meteorological Data

We obtained simultaneous weekly meteorological data, including mean temperature (°C), relative humidity (%), atmospheric pressure (hPa), wind speed (m/s), sunshine (hours), as well as aggregate rainfall (mm), observed in 12 weather monitoring stations in Chongqing from the China Meteorological Data Sharing Service System (http://data.cma.cn/). The weather monitoring stations distribution in Chongqing was shown in Figure 1.

Statistical Analysis

The relationships between meteorological factors and the activity of influenza virus in the population are nonlinear and always lasting well beyond the exposure period. The weekly influenza activity, which was presented by weekly confirmed influenza cases every ten thousand outpatient visits, was modeled using a quasi-Poisson regression model combined with a distributed lag non-linear models (DLNM). The DLNM proposed by Gasparrini DLNMis a flexible model that estimated the nonlinearity and distributed lag effects of exposure-response relationships simultaneously [8].

In this study, we used DLNMs to explore the potential exposure-lag-response associations between multiple meteorological factors and influenza activity. We used the variance inflation factor (VIF) to assess the co-linearity. A VIF greater than 5 indicates multicollinearity [9]. The results showed that the VIFs of the mean temperature and atmospheric pressure are 8.39 and 5.70, which suggested that the two variables should not be included in the model simultaneously.

A Poisson regression with a quasi-Poisson function was established to test the over-dispersion in influenza activity, which was presented by weekly confirmed influenza cases every ten thousand outpatient visits. All models were adjusted with other explanatory variables of meteorological factors, seasonality and long-term trend, and school holiday etc. The model structure is stated as following:

$$\log[E(Y_t)] = \alpha + cb(\mathit{climate\ variables, lag, df}) + \sum ns(X_j, df) + ns(time, df*8) + factor\ (holiday)$$

Where *E(Yt)* is the expected weekly confirmed influenza cases every ten thousand outpatient visits on week t; α is the intercept; *cb( )* represents the cross-basis matrix of climate factors, including mean temperature, relative humidity, aggregate rainfall, wind speed and sunshine; df is the degree of freedom; X_j is the other explanatory variables of meteorological factors; time refers to duration of seasonality and long-term trend; holiday is an indicator variable which equals to 1 if week t is in school holidays and 0 otherwise. We used Akaike Information criterion (AIC) to choose the df, which was supported by other references [10-13]. The weeks of lag structure in the models were determined by incubation period and infectious period of influenza virus [14], the Akaike Information criteria and other references [10, 11]. We provided all AICs in the appendix (Supplementary Tab. S1).

We calculated the relative risk (RR) with corresponding 95% confidence interval (CI), relative to the reference levels. The reference levels were defined as the median values of mean temperature, relative humidity, wind speed, sunshine and aggregate rainfall. Moreover, we estimated the extreme effects by comparing the 97.5th percentiles and 2.5th percentiles to the median values. The RRs brought by high temperature (hot effect), high relative humidity (wet effect), high aggregate rainfall (rainy effect), high wind speed (windy effect), long sunshine (long-sunshine effect) were calculated by comparing the 97.5th percentiles to the median values. The RRs brought by low temperature (cold effect), low relative humidity (dry effect), low aggregate rainfall (rainless effect), low wind speed (windless effect), short sunshine (short-sunshine effect) were calculated comparing by the 2.5th percentiles to the median values.

Sensitivity analysis

To test the robustness of our results, sensitivity analyses were performed by changing (2-5) for climate variables and maximum lag weeks (2-4 weeks) in the model.

All statistical tests were two-sided, the *p*-value 0.05 was considered statistically significant. We performed all data analyses using R software version 3.4.2and used the “dlnm” package for the DLNMs.

Results

General characteristics

From January 1, 2012 to December 31, 2019, a total of 43664 specimens were tested in network laboratories and 18.16% (7928/43664) were positive for influenza virus. Figure 2 displayed the time-series distribution of the weekly meteorological factors and confirmed influenza cases every ten thousand outpatient visits during the study period. From top to bottom, the panels represent the distribution of weekly confirmed influenza cases every ten thousand outpatient visits, relative humidity, aggregate rainfall, sunshine, temperature and wind speed. We observed a significant seasonal variation for both influenza and meteorological factors. The weekly average mean temperature, average relative humidity, aggregate rainfall, average wind speed, and average sunshine were provided in Table 1.

Table 1 Descriptive statistics of meteorological factors and confirmed influenza cases every ten thousand outpatient visits in Chongqing, China, 2012-2019.

	Mean	SD	Min	P25	P50	P75	Max
Influenza	24.14	30.13	1.00	4.75	12.00	32.00	228.00
Tmean (°C)	17.19	7.49	3.55	10.11	17.14	22.98	31.84
RHmean (%)	77.78	7.06	57.07	73.65	78.30	82.95	90.63
Rainfall (mm)	3.17	3.27	0.00	0.63	2.00	4.89	14.72
WSmean (m/s)	1.56	0.27	0.83	1.37	1.54	1.75	2.52
APmean (hPa)	967.52	7.31	952.13	961.52	968.19	973.30	983.60
SUNmean (hour)	2.88	2.47	0.00	1.00	2.28	4.18	10.43

SD: standard deviation; Max: maximum; Min: minimum; Influenza: confirmed influenza cases every ten thousand outpatient visits; Tmean: mean temperature; RHmean: mean relative humidity; Rainfall: aggregate rainfall; WSmean: mean wind speed; SUNmean: mean sunshine. P25: the 25th percentile; P50: the 50th percentile; P75: the 75th percentile.

Spearman correlations (Table 2) revealed that the mean temperature, aggregate rainfall, wind speed and sunshine were negatively correlated with the activity of influenza in Chongqing. There was a strong correlation (r = −0.89, P0.01) between weekly average mean temperature and average atmospheric pressure. To avoid multicollinearity, mean temperature and atmospheric pressure were not included in the model simultaneously.

Table 2. Spearman's correlation results between weekly meteorological variables and confirmed influenza cases every ten thousand outpatient visits in Chongqing, China, 2012–2019.

	Influenza	Tmean	RHmean	Rainfall	WSmean	APmean	SUNmean
Influenza	1.000						
Tmean	-0.409**	1.000					
RHmean	0.072	-0.282**	1.000				
Rainfall	-0.295**	0.544**	0.257**	1.000			
WSmean	-0.126*	0.360**	-0.408**	0.235**	1.000		
APmean	0.280**	-0.887**	0.262**	-0.553**	-0.519**	1.000	
SUNmean	-0.254**	0.684**	-0.710**	0.121*	0.351**	-0.571**	1.000

*$P<0.05$; **$P<0.01$; Tmean: mean temperature; RHmean: mean relative humidity; Rainfall: aggregate rainfall; WSmean: mean wind speed; SUNmean: mean sunshine.

Associations between meteorological variables and influenza activity The three-dimensional plots in Figure 3 showed the relationship between the meteorological variables and influenza activity in Chongqing with various lag weeks. For a better interpretation, the relative risks (RRs) and 95% CIs of influenza were plotted against the risk at the reference levels for mean temperature, relative humidity, wind speed, sunshine and aggregate rainfall over the corresponding lag weeks in Figure 4. In general, multiple meteorological factors were associated with influenza activity. The RRs increased as weekly average mean temperature fell below 18.18°C, average wind speed fell below 1.55 m/s and average sunshine fell below 2.36 hours. The relationship between weekly aggregate rainfall and influenza activity could be described as a U-shaped curve. The RRs increased as aggregate rainfall was below 2.22 mm or above 7.47 mm per week. The risk of influenza activity increased with rising average relative humidity with 78.26% as the break point. More details were provided in Figure 4 and Table 3.

Table 3. The highest RRs for influenza activity and corresponding meteorological factors in Chongqing, China, 2012-2019.

Climate variables	Peak 1		Peak 2	
	Value	RR (95%CI)	Value	RR (95%CI)
Tmean	3.55℃	**22.02, 95%CI: 4.28-113.39**	NA	NA
RHmean	57.06%	1.19, 95%CI: 0.29-4.77	90.63%	**2.22, 95%CI: 1.31-3.77**
Rainfall	0mm	**2.61, 95%CI: 1.76-3.87**	15.02mm	**40.37, 95%CI: 7.13-228.56**
WSmean	0.83m/s	**5.93, 95%CI: 1.51-23.22**	NA	NA
SUNmean	0	1.72, 95%CI: 0.93-3.17	NA	NA

RR: relative risk; Tmean: mean temperature; RHmean: mean relative humidity; Rainfall: aggregate rainfall; WSmean: mean wind speed; SUNmean: mean sunshine. Bold numbers indicate effects of meteorological factors on influenza activity are significant on the 95% confidence limit.

To identify the extreme effects, the estimated effects of mean temperature, relative humidity, wind speed, sunshine and aggregate rainfall comparing the 95th percentiles to the median values and 5th percentiles to the median values were plotted in Figure 5(a) and Figure 5(b). A significant cold effect was observed along 0-4 lag weeks, and hot effect appeared within 1-4 lag weeks. The dry effect was not significant, whereas wet effect was observed at the current week. The rainless effect appeared within 0-3 lag weeks, and extreme rainfall effect was observed within 0.5-4 lag weeks. The windless effect was observed within 0.5-4 lag weeks, and windy effect was not significant. The short-sunshine effect was observed within 0.5-2 lag weeks, and long-sunshine effect was appeared with 1.5-4 lag weeks.

Sensitivity analyses were performed to check the robustness of our results. The residuals of the model for influenza were randomized distributed and independent over time (Supplementary Figure S1). We changed the lag weeks and the degrees of freedom for climatic variables, similar effects of meteorological factors on influenza activity were observed, indicating the robustness of our results (Supplementary Figure S2).

Discussion

Our study comprehensively explored the role of multiple meteorological factors on influenza activity in the largest municipality in China. The correlations between mean temperature, wind speed, sunshine and influenza activity were illustrated with inverted J-shaped curves. The relation between relative humidity and influenza activity was described as a J-shaped curve. The relationship between aggregate rainfall and influenza activity was illustrated with a U-shaped curve.

Consistent with previous studies [10-12, 15, 16], we found that the mean temperature was inversely associated with influenza activity. The influenza activity increased significantly with a lower temperature below 18℃. Laboratory studies showed that low temperature may promote the spread of influenza by lengthening the survival of influenza virus, enhancing the transmissibility of influenza virus, and increasing the host susceptibility [17, 18]. Moreover, people are likely to spend more time indoor under cold condition, so the indoor environment-virus-host interactions substantially increase the opportunity of influenza transmission [7, 19].

A significant wet effect on influenza activity was observed in Chongqing, which is consistent with previous studies [12, 20-23]. Experimental study has shown stronger infectivity of influenza virus in a high relative humidity [24]. High humidity may bring forth droplets that bind to influenza virus, increasing the concentration of virus in the air around the infection source [25]. However, many studies have demonstrated that “dry” condition played a critical role in influenza transmission [11, 16, 21, 26]. Laboratory study has shown that the influenza virus is active when relative humidity is below 50%, especially between 20% and 35% [27]. The lack of association between the “dry” condition with influenza activity in our study may be partly explained by the fact that no exposure to extremely dry condition of relative humidity below 50% was observed during the whole study period. The relative humidity was high all year around in Chongqing, with minimum weekly average relative humidity of 57.07% during 2012-2019. Our finding indicates that dehumidifying the indoor air on extreme moist days may be useful to reduce the spread of influenza in Chongqing.

Previous studies have inconsistent findings on the association between rainfall and influenza. Many studies reported increased influenza circulation during the rainy seasons [28, 29], while others reported no or contradicting effects of rainfall [11, 30]. The findings of our study agrees with the former. We found that extreme rainfall increased the risk of influenza activity with high relative risk of 40.37, which was much higher than rainless effect (relative risk was 2.61). Rainfall may lead to indoor crowding and consequently increase the probability for close contact which could speed the transmission of influenza virus [31]. Previous study also indicated that low level precipitation could increase the amount of virus particulate in the air and increased the risk of virus infection [32]. In the future, more studies are needed to fully solve the inconsistence in the association between rainfall and influenza.

The understanding of effects of sunshine and wind speed on influenza is still limited. We found that long sunshine decreases the risk of influenza activity. It has been proposed that sunshine could affect the influenza activity through the mediation effect of Vitamin D synthesis on individuals’ immune response to infection [33, 34], but remains unverified. In addition, our study showed that low wind speed increases the risk of influenza activity in Chongqing, which was consistent with previous study [35]. Future studies are needed to fully understand the roles of these meteorological factors on influenza activity and the potential mechanisms.

This study has several limitations. First, the meteorological data were taken from fixed monitoring sites rather than individual exposure measures, which may create measurement errors in the exposure. However, these errors are likely to be random. Second, due to data unavailability, we did not account for the effect of other factors such as socioeconomic condition, host susceptibility and vaccination status on the association between meteorological factors and influenza activity. Third, we didn't explore the effects of age and sex on the associations between meteorological factors and influenza activity. We plan to address this limitation in future work.

Conclusions

Our study provides evidence that multiple meteorological factors have strong associations with influenza activity in Chongqing. Accordingly, a meteorology-based early warning system for influenza should be developed and implemented to facilitate timely response to upsurge of influenza activity.

Declarations

Acknowledgments

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Authors' contributions

LQ, WGT, LZF and QYL designed the study. LQ, LZF, WGT, YG, QL and KS collected the data. LQ, LT, YG and DCT performed the statistical analysis. LQ, TL, WGT, LZF and QYL coordinated and drafted the manuscript. All the authors have read and approved the final manuscript.

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Availability of data and materials

The dataset used in the study is available from the corresponding author.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Figures

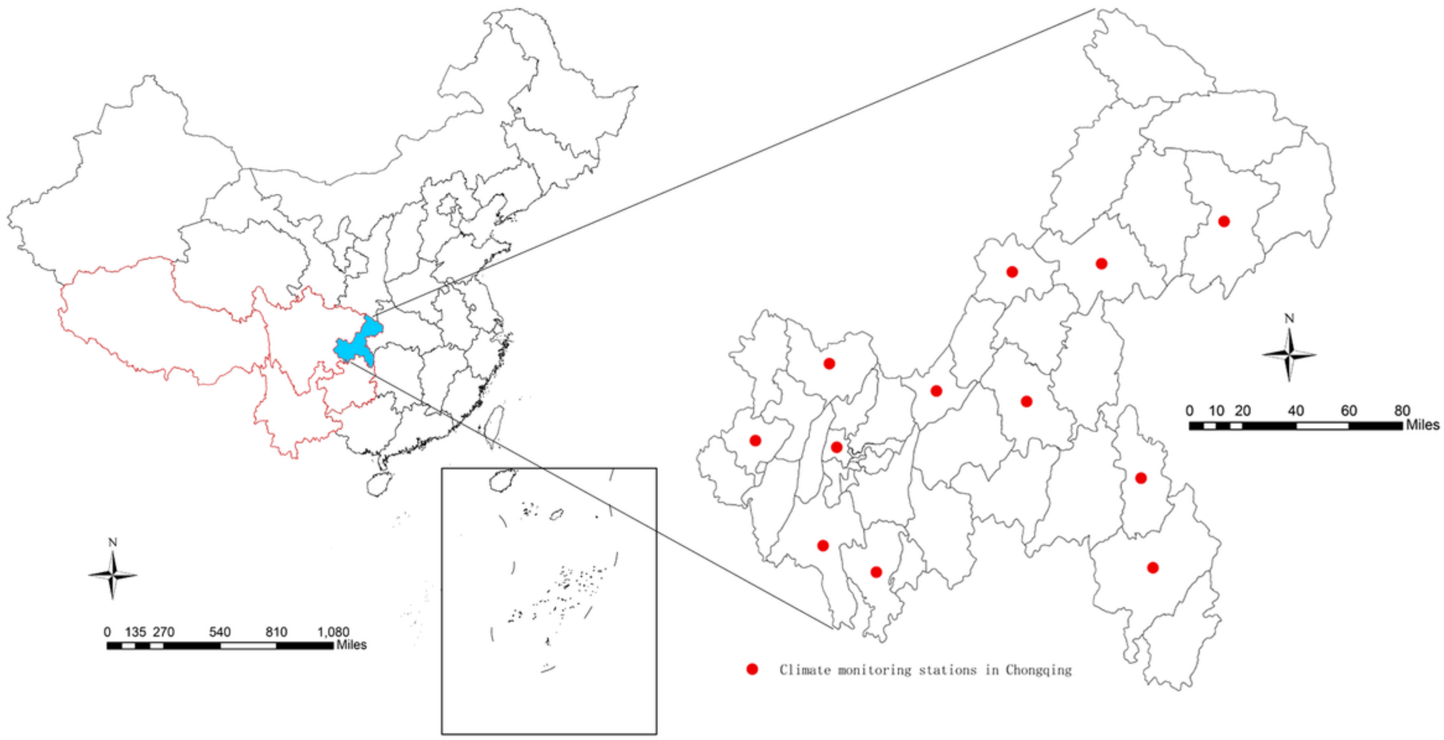

Figure 1

The geographical location and weather monitoring stations distribution of Chongqing, China. The red broadlines on the left map indicate the southwest of China and 12 red dots on the right map represent the 12 weather monitoring stations in Chongqing. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

The distribution of weekly confirmed influenza cases every ten thousand outpatient visits and meteorological variables in Chongqing, China, 2012–2019.

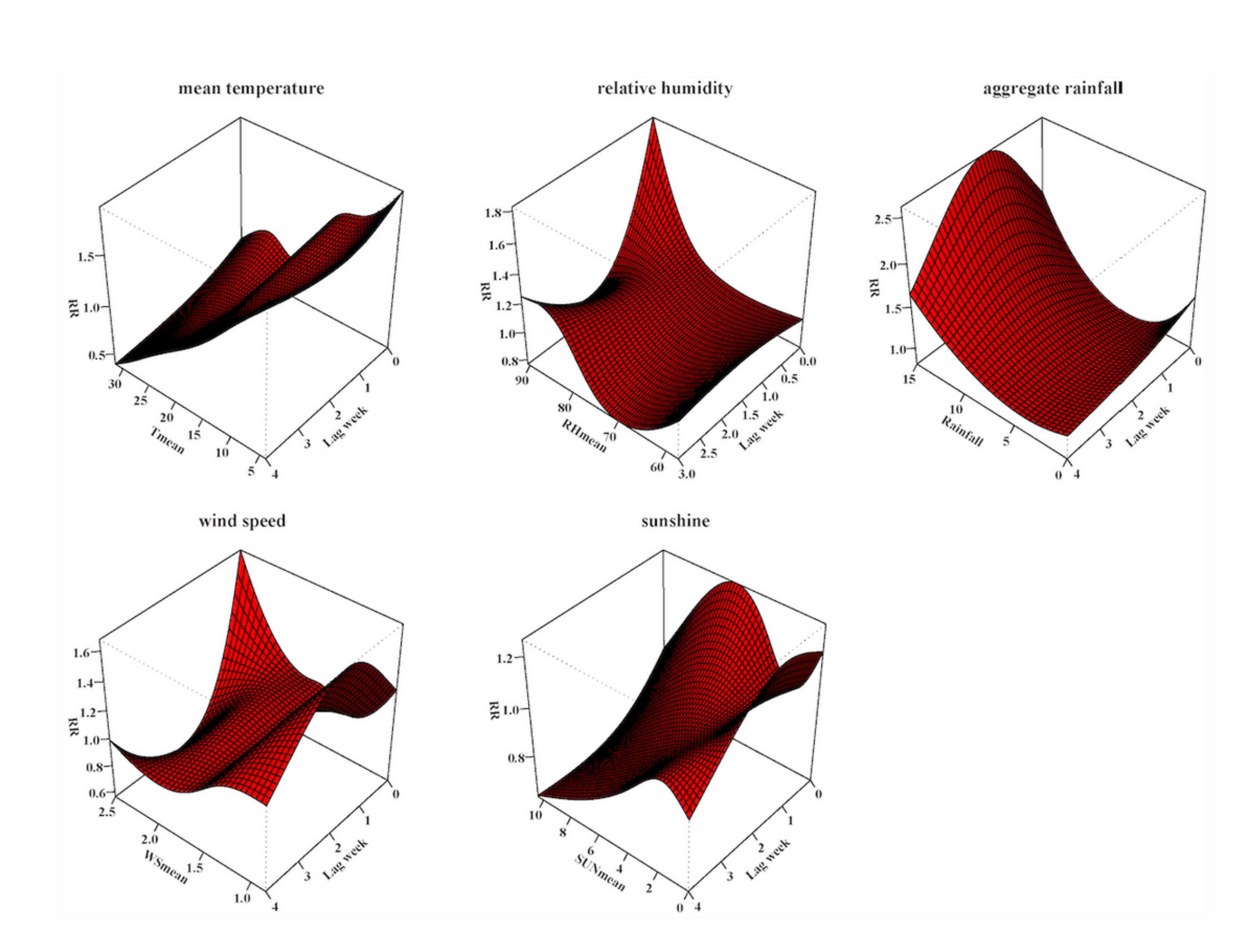

Figure 3

Plot of the relative risks of meteorological factors on influenza activity in Chongqing, China, 2012-2019.

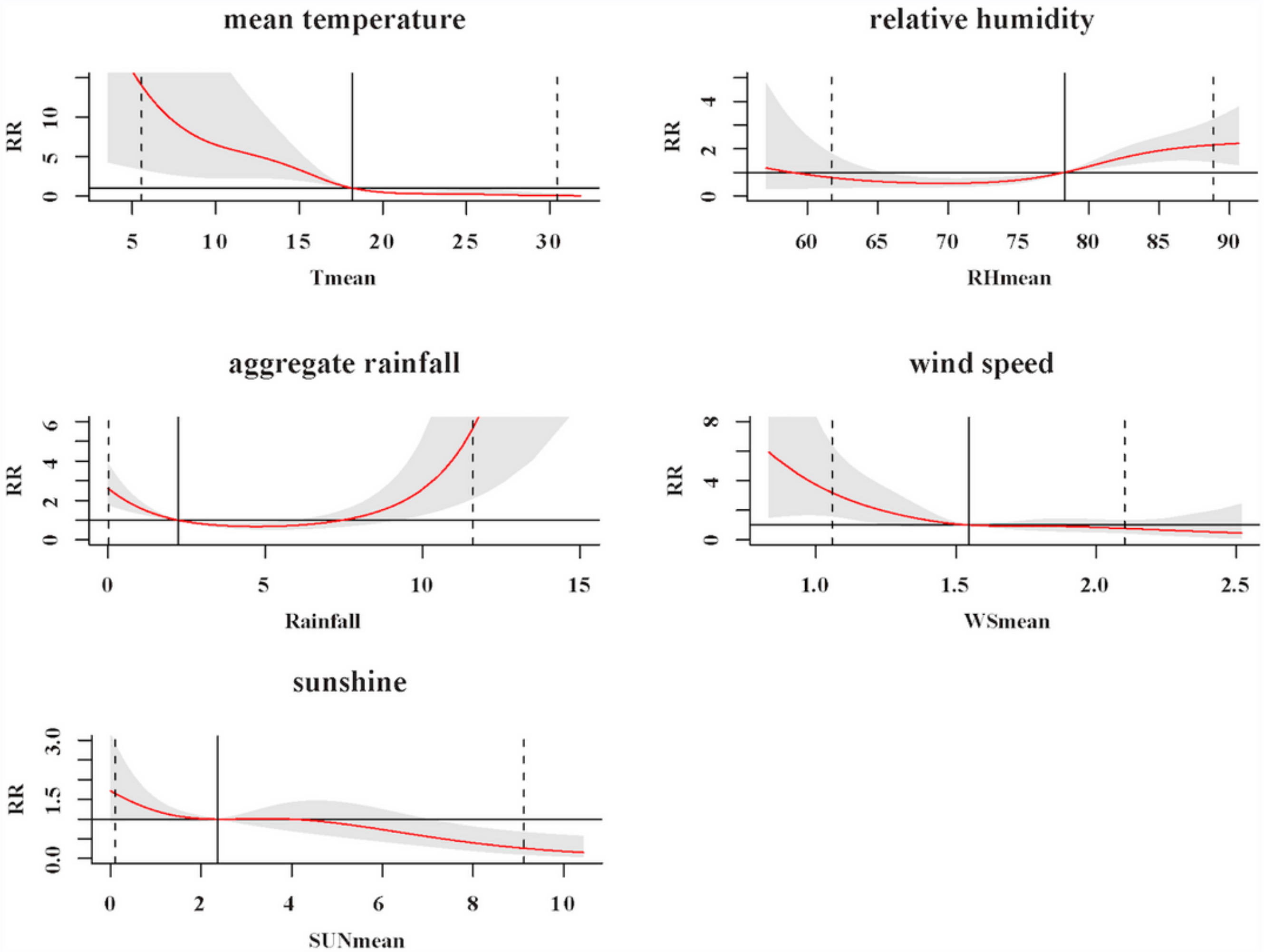

Figure 4

The estimated overall effects of mean temperature, relative humidity, aggregate rainfall, wind speed, and sunshine along corresponding lag days. In each panel, the y-axis represents the value of relative risk, and the x-axis represents the values of the corresponding relevant variable. The red line and grey region represent the relative risk and its 95% confidence interval, respectively. The black vertical line represents the median of the corresponding meteorological factor, and the two dashed lines represent the 2.5 percentile and the 97.5 percentile for the corresponding meteorological factor, respectively.

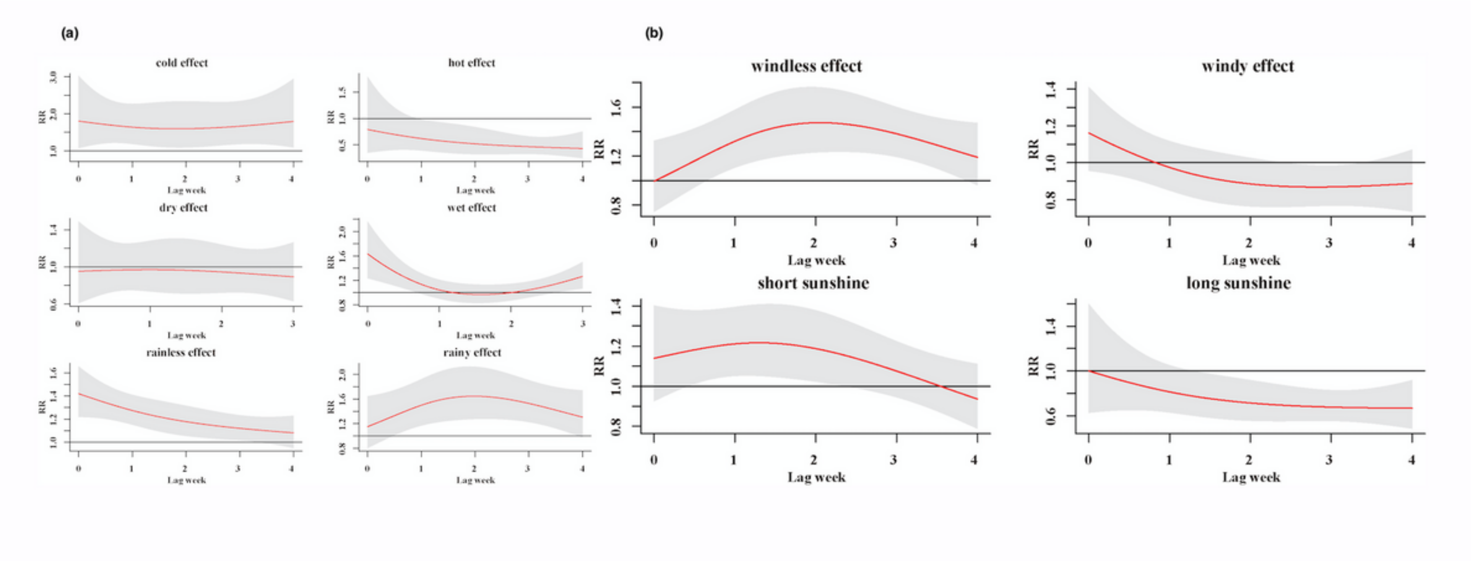

Figure 5

(a). The extreme effects of mean temperature, relative humidity, and aggregate rainfall with extreme high effects (97.5%) and extreme low effects (2.5%). In each panel, the y-axis represents the value of relative risk, and the x-axis represents the value of lag week. The red line represents mean relative risk and grey region represent 95% confidence interval. (b). The extreme effects of wind speed and sunshine duration with extreme high effects (97.5%) and extreme low effects (2.5%). In each panel, the y-axis represents the value of relative risk, and the x-axis represents the value of lag week. The red line represents mean relative risk and grey region represent 95% confidence interval.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Additionalfile1.docx
- Additionalfile2.tif
- Additionalfile3.tif