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 elusive 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°C, 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. The RR for rainfall effect was significantly higher 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 results in 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]. In China, the largest developing country in the world, there were 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 the survival and transmission of influenza virus, the environment, 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, the effects of multiple meteorological factors on the activity of influenza are elusive. 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 to develop public health strategies and measures to reduce the high risk of influenza in Chongqing.

Materials And Methods

Study Area

This study is conducted in Chongqing, which covers an area of 82,400 km^2 with approximately 33 million registered residents in 2019, and is located in Southwestern China (Fig. 1). It has a subtropical humid monsoon climate, a long and very 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]. In this study, the activity of influenza virus was represented by the way of multiplying the weekly positive rates of influenza by the weekly counts of ILIs, on the scale of every 10,000 of the outpatient visits, similar to previous study [7].

Meteorological Data

We obtained simultaneous weekly meteorological data, including mean temperature (°C), relative humidity (%), atmospheric pressure (hPa), wind velocity (m/s), sunshine (hours), as well as aggregate rainfall (mm) from the China Meteorological Data Sharing Service System (http://data.cma.cn/). The weather monitoring stations distribution of Chongqing was shown in Fig. 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. Gasparrini established a statistical framework named distributed lag non-linear models (DLNM) based on the cross-basis function to model the nonlinear exposure-response and the lag structure of the relationship simultaneously [8].

In this study, DLNMs were used 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. When only one of them was used with others predictor variables, the VIFs did not exceed 5 either.

A Poisson regression with a quasi-Poisson function was established to test the over-dispersion in the 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:

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

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, atmosphere pressure 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).

Moreover, 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, atmosphere pressure, wind speed, sunshine and aggregate rainfall.

Model Diagnostics And Sensitivity Analysis

To test the robustness of our results, sensitivity analyses were performed by changing df(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. All data analyses were conducted by using R software version 3.4.2.

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. The panels represent the distribution of influenza cases, relative humidity, atmosphere pressure, aggregate rainfall, sunshine, temperature and wind speed, from top to bottom. We observed a significant seasonal variation for both influenza and meteorological factors.

Table 1 showed weekly average mean temperature was 17.19 °C, average relative humidity was 77.78%, aggregate rainfall was 3.17 mm, average wind speed was 1.56 m/s, average atmosphere pressure was 967.52 hPa, and average sunshine was 2.88 hours, respectively.

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; Tmean: mean temperature; RHmean: mean relative humidity; Rainfall: aggregate rainfall; WSmean: mean wind speed; APmean: mean atmosphere pressure; 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. In contrast, atmosphere pressure was positively correlated with the activity of influenza. There was a strong correlation (r = − 0.89, $P < 0.01$) between weekly average mean temperature and average atmospheric pressure.

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; APmean: mean atmosphere pressure; SUNmean: mean sunshine.

Risk Respond To Climate Variability By Lag Using DLNMs

The three-dimensional plots in Fig. 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, atmosphere pressure, wind speed, sunshine and aggregate rainfall over the corresponding lag weeks in Fig. 4. In general, multiple meteorological factors were associated with influenza activity. The RRs 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. 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. The effect of atmosphere pressure on influenza activity was not significant. More details were provided in Fig. 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°C	**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	0 mm	**2.61, 95%CI: 1.76–3.87**	15.02 mm	**40.37, 95%CI: 7.13-228.56**
WSmean	0.83 m/s	**5.93, 95%CI: 1.51–23.22**	NA	NA
APmean	952.13 hPa	2.12, 95%CI: 0.44–10.32	971.41 hPa	1.36, 95%CI: 0.91–2.03
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; APmean: mean atmosphere pressure; 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, atmospheric pressure, wind speed, sunshine and aggregate rainfall comparing the 95th percentiles to the median values and 5th percentiles to the median values were plotted in Fig. 5(a) and Fig. 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. Both low-pressure and high-pressure effects were not observed. 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, and the effects of meteorological factors on influenza activity were similar, 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 curve. The relation between relative humidity and influenza activity was described as J-shaped curve. The relationship between aggregate rainfall and influenza activity was illustrated with U-shaped curve. No significant effect was observed for atmosphere pressure.

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 partly be 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 especially 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]. In general, 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, then 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, wind speed and atmosphere pressure on influenza is still limited. We found that long sunshine decrease 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 is 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]. Regarding atmosphere pressure, we did not find significant effect on influenza activity in Chongqing. Future studies are needed to fully understand the roles of these meteorological factors on influenza activity.

Several limitations exist in this study. 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, 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 because these data were not obtained. 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

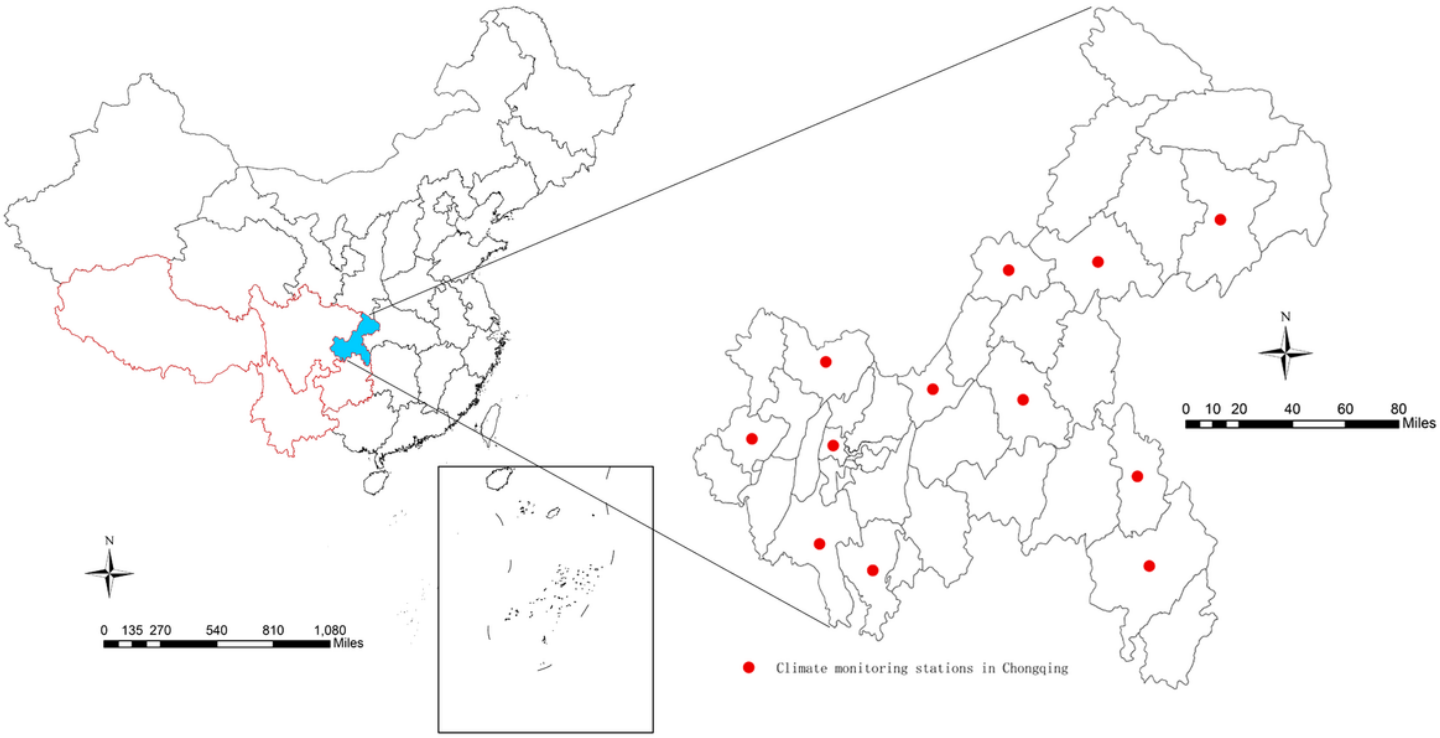

Figure 1

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.

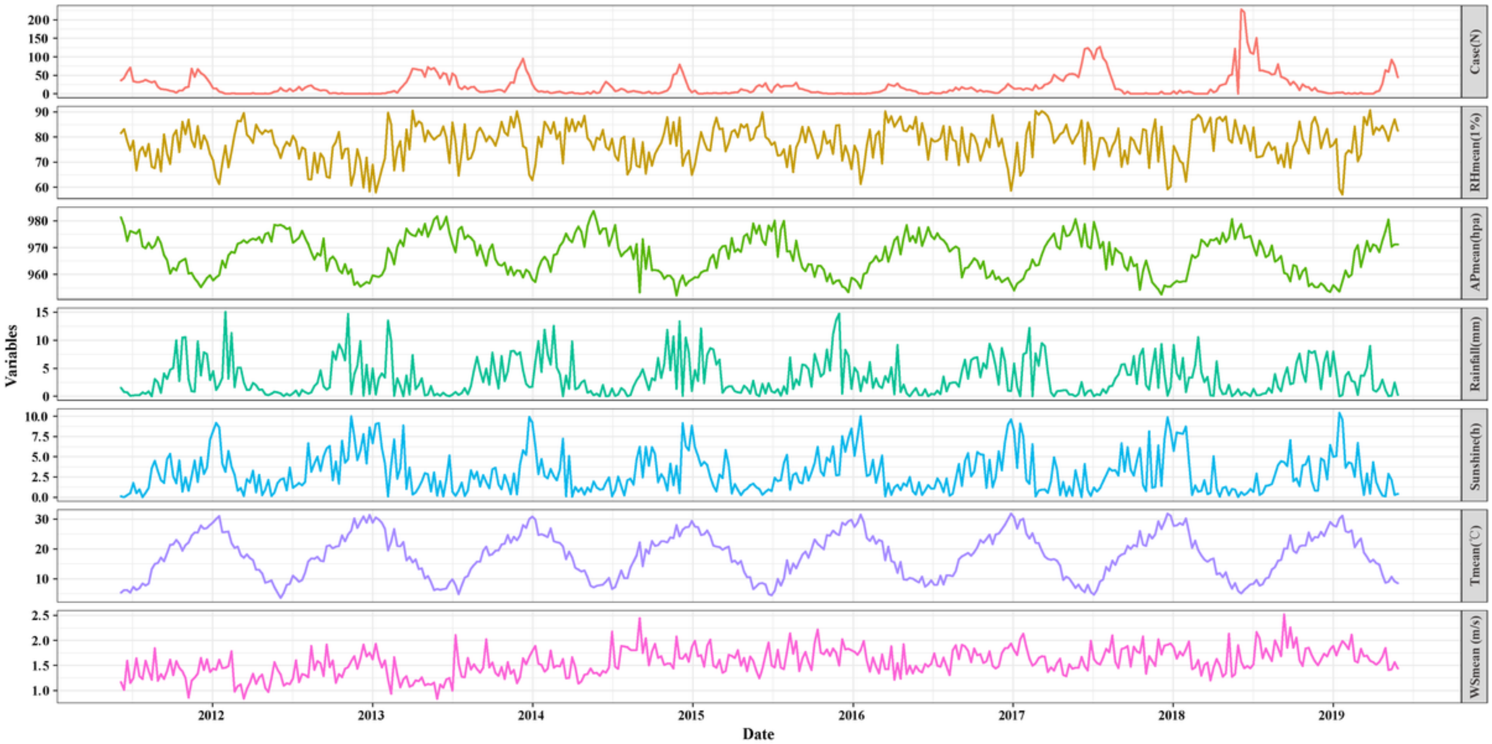

Figure 2

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

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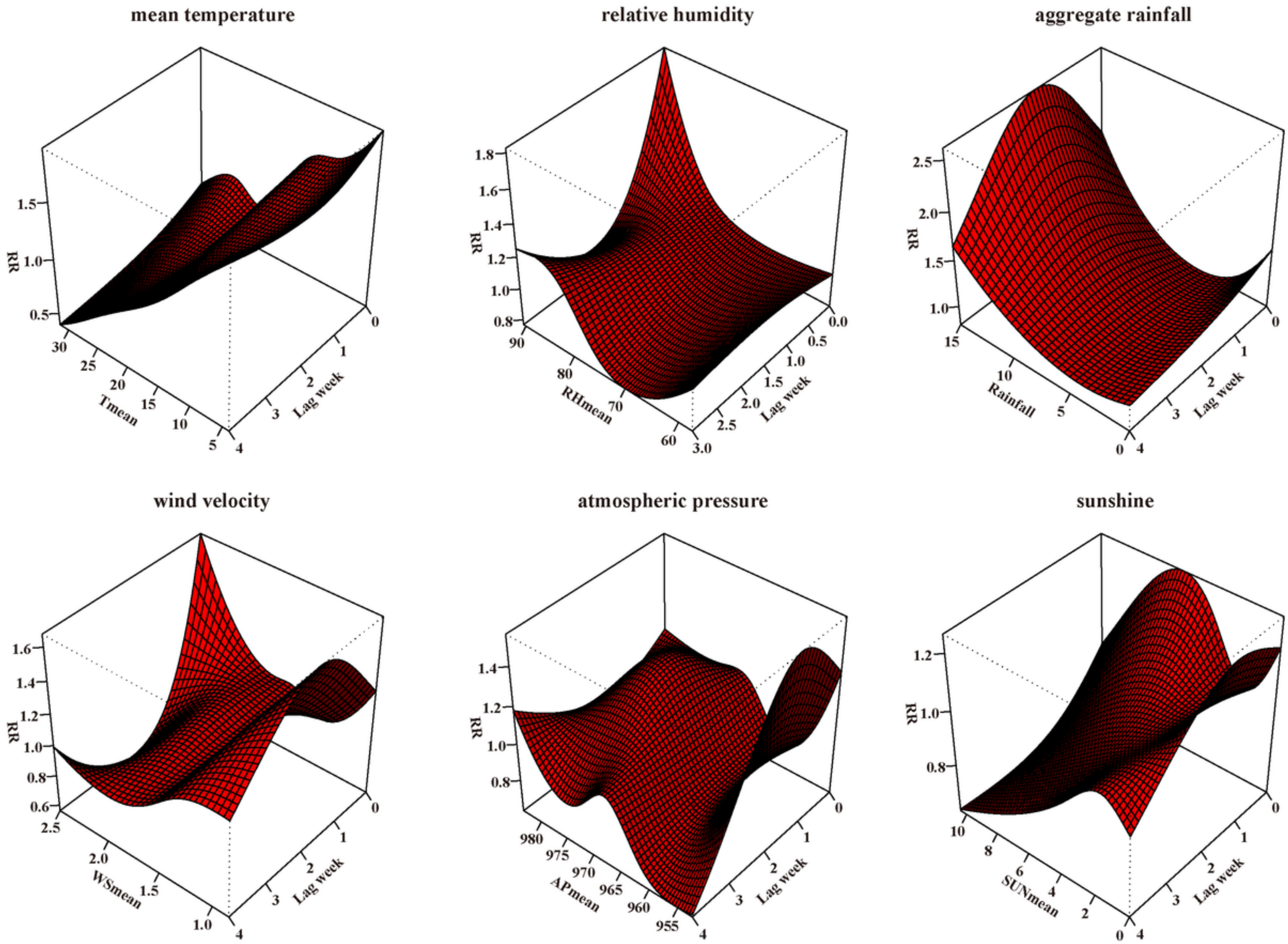

Figure 3

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

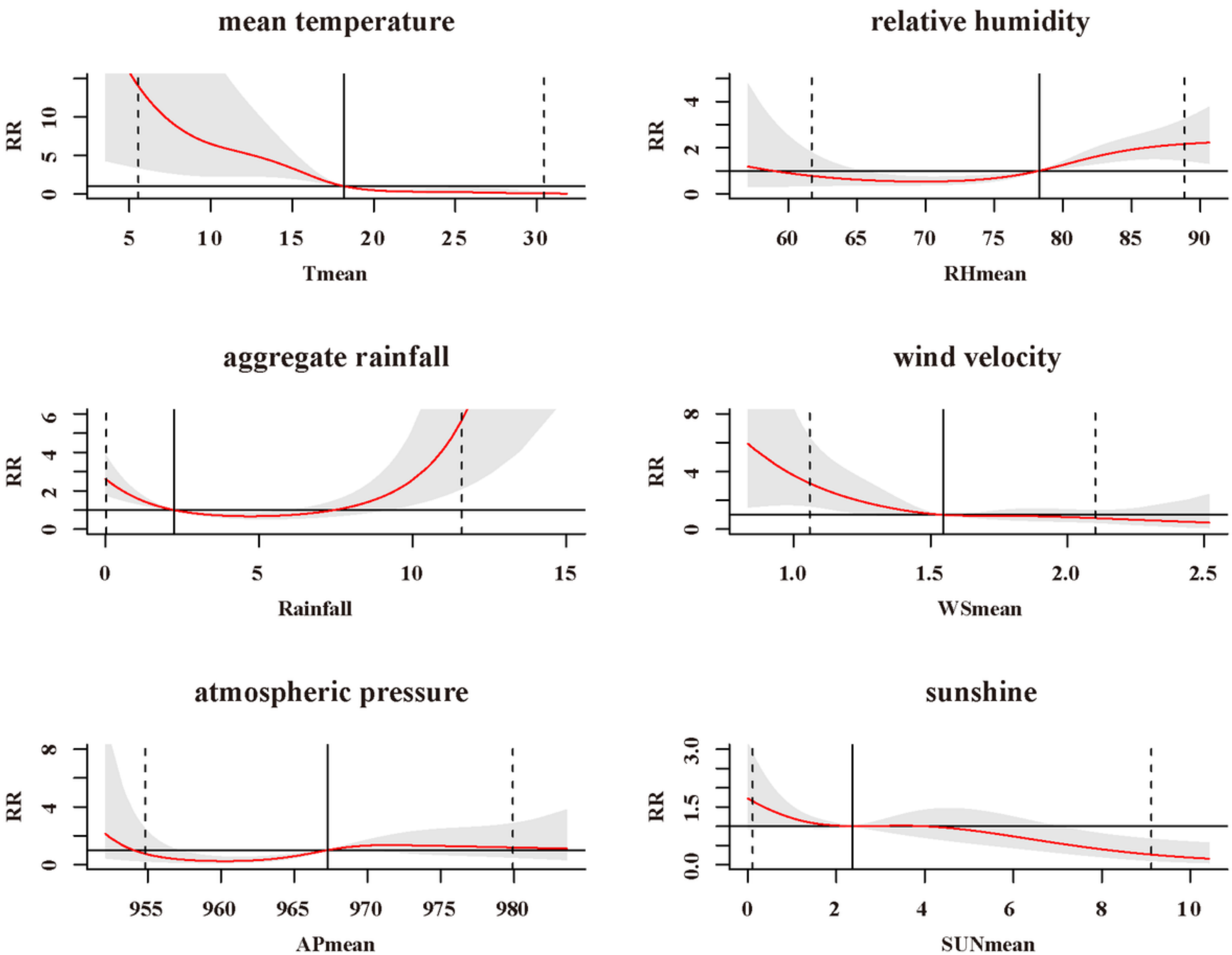

Figure 4

The estimated overall effects of mean temperature, relative humidity, aggregate rainfall, wind velocity, atmospheric pressure 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 dotted lines represent the 2.5 percentile and the 97.5 percentile for the corresponding meteorological factor, respectively.

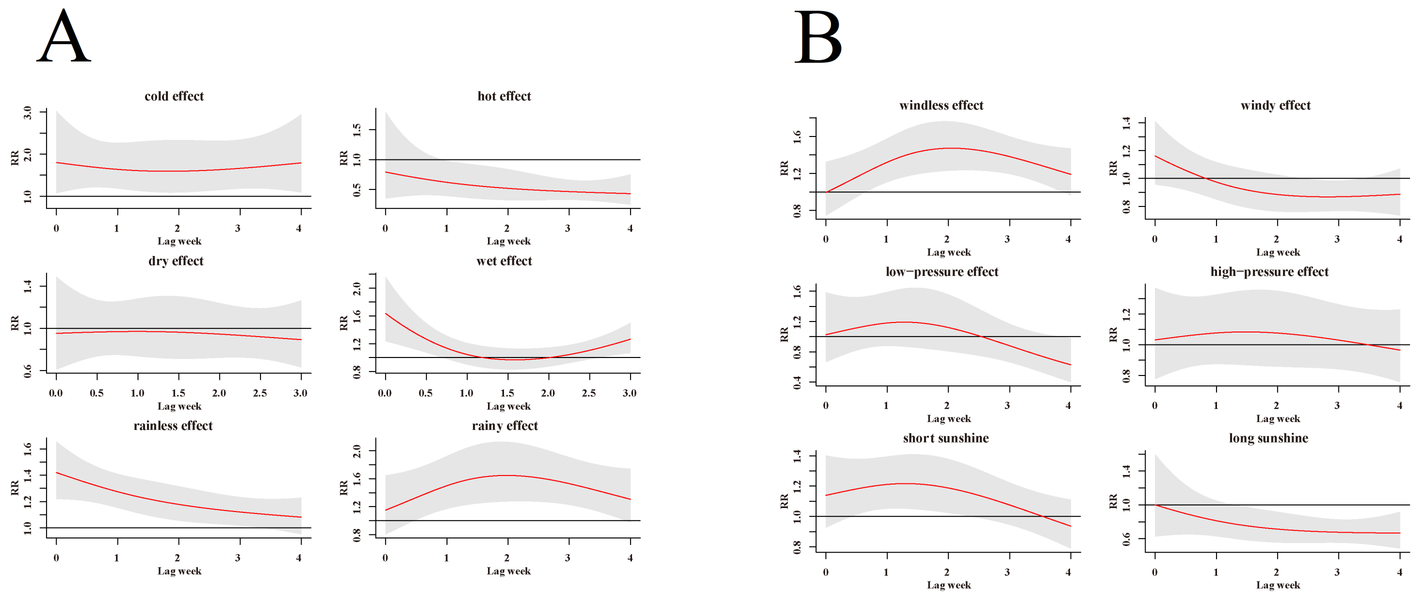

Figure 5

(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, atmosphere pressure 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