



COVID-19 transmission in Mainland China is associated with temperature and humidity: A time-series analysis

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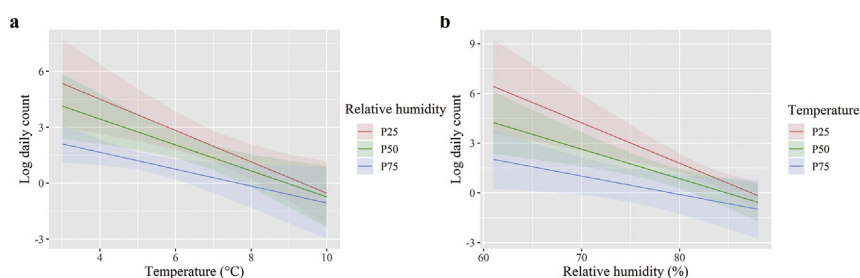
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HIGHLIGHTS

- Temperature and humidity showed negative associations with COVID-19.
- A significant interaction between temperature and humidity existed.
- Countries and regions with low temperature and humidity should pay more attention.

GRAPHICAL ABSTRACT



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ABSTRACT

COVID-19 has become a pandemic. The influence of meteorological factors on the transmission and spread of COVID-19 is of interest. This study sought to examine the associations of daily average temperature (AT) and relative humidity (ARH) with the daily counts of COVID-19 cases in 30 Chinese provinces (in Hubei from December 1, 2019 to February 11, 2020 and in other provinces from January 20, 2020 to February 11, 2020). A Generalized Additive Model (GAM) was fitted to quantify the province-specific associations between meteorological variables and the daily cases of COVID-19 during the study periods. In the model, the 14-day exponential moving averages (EMAs) of AT and ARH, and their interaction were included with time trend and health-seeking behavior adjusted. Their spatial distributions were visualized. AT and ARH showed significantly negative associations with COVID-19 with a significant interaction between them (0.04, 95% confidence interval: 0.004–0.07) in Hubei. Every 1 °C increase in the AT led to a decrease in the daily confirmed cases by 36% to 57% when ARH was in the range from 67% to 85.5%. Every 1% increase in ARH led to a decrease in the daily confirmed cases by 11% to 22% when AT was in the range from 5.04 °C to 8.2 °C. However, these associations were not consistent throughout Mainland China.

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1. Introduction

Starting in December 2019, the severe acute respiratory coronavirus 2 (SARS-CoV-2) identified in Wuhan, China, has caused an outbreak of a novel coronavirus disease (COVID-19) (Wu et al., 2020). Its typical clinical symptoms include fever, dry cough, myalgia, and pneumonia, and may cause progressive respiratory failure due to alveolar damage and death (Huang et al., 2020). As of March 23, 2020, a total of 81,603 confirmed cases (61.28% in Wuhan) and 3276 deaths have been reported in mainland China (China National Health Commission, 2020a). And now it is a pandemic (WHO, 2020).

Respiratory droplets and person-to-person contact are the major routes of transmission of the coronavirus (China National Health Commission, 2020b). Environmental factors such as temperature and relative humidity may influence the transmissions of coronavirus (Casanova et al., 2010) by affecting the survival of the virus in its transmission routes, there has evidence for severe acute respiratory coronavirus (SARS-CoV) (Cai et al., 2007; Tan et al., 2005) and Middle East respiratory syndrome coronavirus (MERS-CoV) (Altamimi and Ahmed, 2019; Gardner et al., 2019). Whether and how meteorological factors affecting the spread of COVID-19 has so far not been investigated. Using data of confirmed cases from all provinces in mainland China, we investigated the correlations between meteorological factors and the daily cases of COVID-19. The goal is to provide scientific evidence regarding the future progression of COVID-19 under the changing circumstances of climate factors.

2. Materials and methods

2.1. Study area and data

Daily counts of laboratory-confirmed cases in all provinces in China were collected from the official reports of the National Health Commission of People's Republic of China from December 1, 2019 to February 11, 2020 for Hubei province and from January 20, 2020 to February 11, 2020 for other provinces. Case definitions for suspected cases and laboratory-confirmed cases and the description of the surveillance system have been published online and reported elsewhere (China CDC, 2020; Li et al., 2020). Tibet was not included in the following model since only one case was reported during the 23-day period.

The meteorological data, including daily average temperature (AT) and daily average relative humidity (ARH) of each provincial capital, were retrieved from Weather Underground (<https://www.wunderground.com/>). The following keywords were applied in the Baidu index (<http://index.baidu.com/>), the largest search engine in China, using the keywords "novel coronavirus" OR "coronavirus disease 2019" OR "coronavirus disease-19" OR "2019 novel coronavirus" OR "2019-nCoV" OR "SARS-CoV-2" OR "COVID-19" OR "SARS-CoV-2" OR

"severe acute respiratory coronavirus 2". The province-based Baidu index with massive Internet behavior data recorded, including concerns for COVID-19, was used as a measure of health-seeking behavior that may affect the transmission of coronavirus (Du et al., 2017).

2.2. Statistical analysis

A generalized additive model (GAM) was applied to quantify the province-specific associations between meteorological variables and the daily cases of COVID-19 during the study periods, accounting for short-term temporal trend and health-seeking behavior through Baidu index.

The distribution of COVID-19 cases was assumed to be a negative binomial given that the variances of the daily counts were larger than their means. Considering the incubation period of COVID-19, the effects of AT, ARH, and covariates were modeled with a 14-day exponential moving average (EMA) to account of their potential lag effects and the interaction between AT and ARH was tested and included in the model if significant. The short-term temporal trend was indicated using natural splines of time with two degrees of freedom. The model is given by:

$$E(y_t) = \mu_t$$

$$\log \mu_t = \beta_0 + \beta_1 \times \text{matemp}_t + \beta_2 \times \text{mahmd}_t + \beta_3 \times \text{matemp}_t \times \text{mahmd}_t$$

$$+ \beta_4 \times \text{mabindex}_t + \beta_5 \times \text{ns}_1 + \beta_6 \times \text{ns}_2,$$

where y_t is the daily counts of COVID-19 at day t , μ_t is the expected value of daily counts at day t , β_0 is the intercept, β_1 denotes the effect of moving average of AT, β_2 is the effect of moving average of ARH, β_3 is the interaction between AT and ARH, β_4 denotes the effect of moving average of Baidu index, and β_5 and β_6 are the regression coefficients of natural splines of time with two degrees of freedom.

Considering the effect of the interaction between AT and ARH, effect plots were shown with the change in log-transformed daily counts over AT (or ARH) given the ARH (or AT) at its 25th, 50th, and 75th percentiles. Additionally, the effects of meteorological factors were parameterized with the incidence rate ratio (IRR) assuming the number of persons at risk stayed stable during the study period. IRRs of AT (or ARH) given the ARH (or AT) of the 25th, 50th, and 75th percentiles in models were estimated and depicted using forest plots and geographic maps.

2.3. Sensitivity analysis

To verify model results, a sensitivity analysis was performed in which the time-series in Wuhan and in Hubei province were restricted

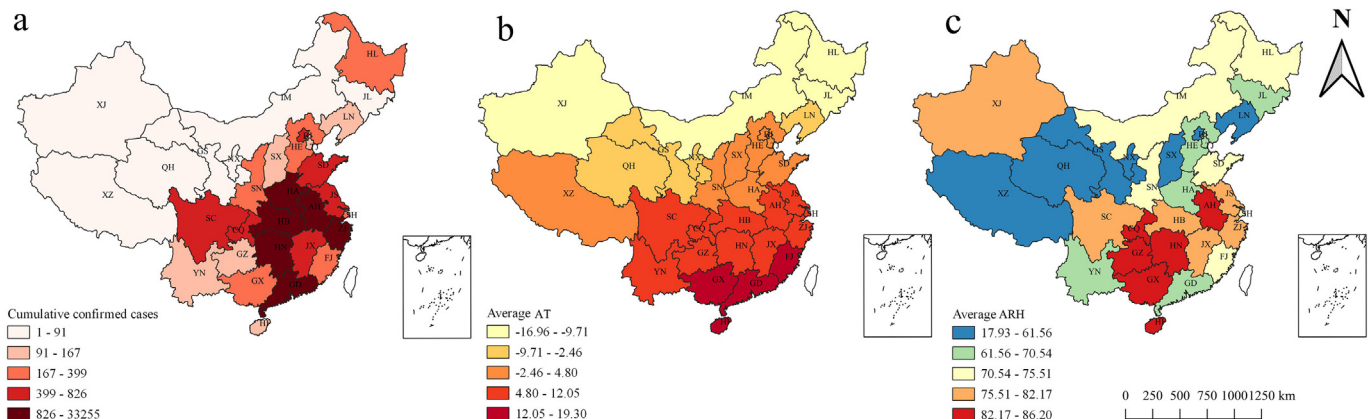


Fig. 1. The distribution of (a) cumulative confirmed cases, (b) average AT, and (c) average ARH in all provinces surveyed in China.

to the period the same as that in other provinces - i.e. January 20 to February 11 - with the same GAM fit to the data (the results of sensitivity analysis in Figs. A8–A10).

The R software (version 3.5.3, <http://cran.r-project.org>; R Foundation for Statistical Computing, Vienna, Austria) was used to perform statistical analyses. QGIS Desktop (version 3.4.14, <https://www.qgis.org/>; Open source geospatial foundation project) from the open-source geospatial foundation project was used to plot the geographic patterns.

3. Results

The daily counts of confirmed cases, AT, and ARH for 31 provinces were summarized in Table A1. The cumulative confirmed cases varied from one (Tibet) to 33,453 (Hubei), and 74.7% of all confirmed cases occurred in Hubei for the periods (Fig. 1a). The average AT ranged from -16.96°C to 19.3°C (Fig. 1b), and the average ARH ranged from 17.93% to 86.20% (Fig. 1c).

Fig. 2 shows that the daily counts in Hubei increased sharply after January 20, 2020. The daily AT varied from 1.5°C to 11.42°C , fluctuating mostly around 6°C . The daily ARH varied from 42.17% to 96.92%, remaining above 70% on most days (68.49%). For other provinces, >88% confirmed cases occurred between January 23, 2020 and February 8, 2020, and the time series of the confirmed cases appeared in an "M"

shape, especially in Guangdong and Zhejiang (Fig. A1). ARH and AT varied across provinces (Figs. A2 and A3).

The estimates of regression coefficients of the GAM for Hubei province are listed in Table 1. There was a significant interaction between AT and ARH (0.04, 95% confidence interval (CI): 0.004–0.07), and the effect of the Baidu index was also statistically significant. Significant interactions between AT and ARH were also found in Zhejiang, Shandong, Hebei, Jilin, and Gansu (Table A2).

The associations of meteorological factors and the daily counts of COVID-19 for Hubei province are visualized in Fig. 3. With ARH fixed at its 25th, 50th, and 75th percentiles, AT showed a negative association with COVID-19, with the IRRs being 0.43 (95% CI: 0.25–0.73), 0.5 (95% CI: 0.32–0.78), and 0.64 (95% CI: 0.43–0.94), respectively. Similarly, there was a negative relationship between ARH and COVID-19 with the AT fixed at its 25th, 50th, and 75th percentiles. The IRRs here were 0.78 (95% CI: 0.69–0.89), 0.84 (95% CI: 0.75–0.93), and 0.89 (95% CI: 0.8–1). Every 1°C increase in AT led to a decrease in the daily confirmed cases by 36% to 57% when ARH was in 67% to 85.5% and every 1% increase in ARH led to a decrease in the daily confirmed cases by 11% to 22% when AT was 5.04°C to 8.2°C .

Fig. 4 shows the IRRs for AT in association with COVID-19 when ARH was fixed at its median for each province. There was also a statistically significant effect of AT in Hunan, Anhui, Jiangsu, Chongqing, Liaoning,

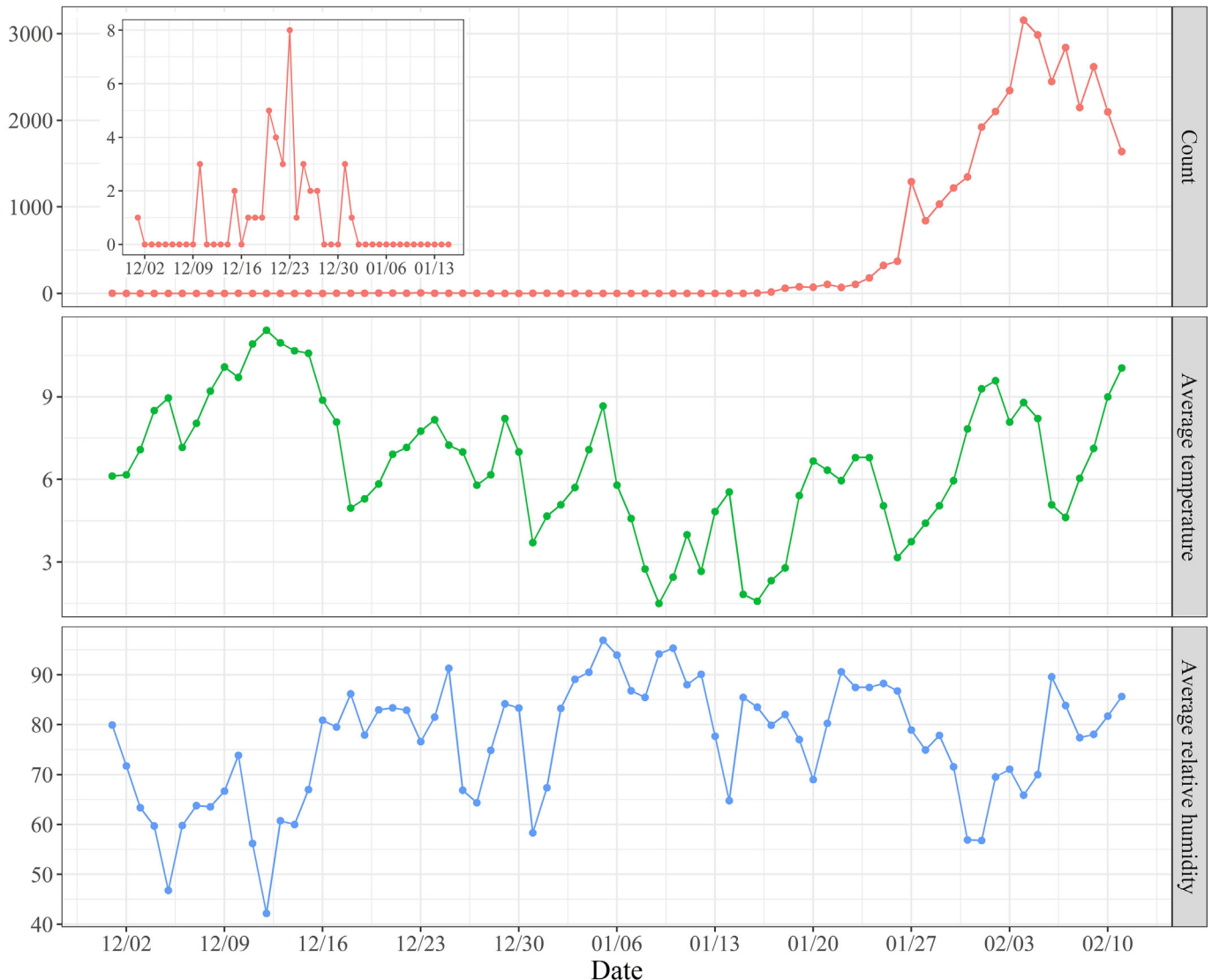


Fig. 2. The time series of the daily counts, daily AT, and daily ARH in Hubei province from December 1, 2019 to February 11, 2020.

Table 1
Estimates of regression coefficients of the GAM for Hubei province.

Parameter	Estimate (95% CI)	Z-value	p-Value
Intercept, β_0	38.14 (14.54–61.74)	3.17	0.002
AT, β_1	−3.61 (−6.46 to −0.75)	−2.47	0.013
ARH, β_2	−0.43 (−0.7 to −0.16)	−3.16	0.002
AT × ARH, β_3	0.04 (0.004–0.07)	2.18	0.029
Baidu index, β_4	3.51×10^{-5} (1.96×10^{-5} , 5.06×10^{-5})	4.43	<0.001
Time			
β_5	3.42 (−0.9, 7.74)	1.55	0.120
β_6	4.96 (2.87–7.04)	4.66	<0.001

and Jilin in addition to Hubei. However, AT showed an opposite effect in the nearby provinces of Hubei and two provinces in northeast China. We conducted a sensitivity analysis by fixing ARH at its 25th and 75th percentiles (Figs. A4 and A5), and the variation in the association of AT with COVID-19 with ARH alteration was not substantial.

Fig. 5 shows the IRRs for ARH in association with COVID-19 when AT was fixed at its median for each province. Unlike Hubei province, other provinces including Henan, Anhui, and Chongqing had a positive relationship between ARH and COVID-19. The estimates of IRRs and the forest plots of the ARH with AT fixed at its 25th and 75th percentiles as a sensitivity analysis are presented in Figs. A6 and A7, and there were notable variations in the relationship between ARH and COVID-19 at the different levels of AT.

4. Discussion

Our study suggests that both daily temperature and relative humidity influenced the occurrence of COVID-19 in Hubei province and in some other provinces. However, the association between COVID-19 and AT and ARH across the provinces was not consistent. We found spatial heterogeneity of COVID-19 incidence, as well as its relationship with daily AT and ARH, among provinces in Mainland China.

The study period - and hence time series length - was longer for Hubei province than other provinces. The longer the study period, the more stable the model results are expected to be. Considering the incubation period of COVID-19, we used the 14-day EMA of daily AT and ARH to investigate the effects of ARH and AT on COVID-19. Most of the confirmed cases (and therefore meteorological data) were derived from the period before travel restrictions were enacted for Wuhan city (January 23, 2020); therefore, the Hubei model most likely reflected the real (unconfounded) effect of meteorological factors on COVID-19, where negative correlations between AT and ARH and the incidence of COVID-19 were found. Evidence from previous epidemiological studies and laboratory investigations have documented negative associations between ARH and AT and other coronavirus-related diseases (Chan et al., 2011; Gardner et al., 2019; Zhang Qiang et al., 2004). One study reported that the risk of an increased daily incidence of SARS was 18.18 (95% CI: 5.6–58.8) times greater at lower temperature during the

outbreak than on warmer days (Lin et al., 2006). SARS-CoV (Cai et al., 2003) and MERS-CoV (Gardner et al., 2019; van Doremalen et al., 2013) are more stable in cold and dry conditions; low temperature and low humidity lead to an increase of suspended matter in the atmosphere, facilitating ideal conditions for virus attachment, replication and transmission, while low temperature can also dry out the mucous membrane, reduce the function of cilia, and support the survival and transmission of the virus and the spread of diseases (Casanova et al., 2010; Chan et al., 2011; Guionie et al., 2013; Lowen and Palese, 2009; Tan et al., 2005).

A novel finding of this study is the significant interaction between ARH and AT, and COVID-19 incidence. In Hubei province, the interaction between ARH and AT was found to have a positive effect on transmission (0.04, 95% CI: 0.004–0.07). Increased AT (ARH) led to a decreased effect of ARH (AT) on the incidence of COVID-19 in Hubei province. The exact mechanism of the interaction is unclear. One probable reason might be that a combination of low AT and humidity make the nasal mucosa prone to small ruptures, creating opportunities for virus invasion (Zhou and Jiang, 2004). A previous study observed an interaction between minimum temperature and humidity on influenza (Firestone et al., 2012; Liu et al., 2019). However, previous studies have seldom analyzed the effects of the interaction of meteorological factors, focusing on the single effect of humidity or temperature on the development of COVID-19 (Luo et al., 2020; Wang et al., 2020). Hence, when estimating the impact of climate on the risk of COVID-19 transmission, the interaction between meteorological factors should be considered. Research findings on meteorological factors and their interactions should be incorporated into the prevention and control of COVID-19. With the arrival of spring in China, the increased AT in the southern region might lead to a decrease in the incidence of the disease. Conversely, in northern regions with continuing low ATs and low ARH levels there should be more attention given to monitoring and prevention of COVID-19 due to continuing suitable climatic conditions in these regions.

The effects of AT and ARH showed spatial heterogeneity and there are several possible reasons. The between-region variability of meteorological factors is likely the main reason for the heterogeneity of effects. Small sample size in some provinces leads to model instability and invalid estimates. Most of the daily counts of confirmed cases in provinces other than Hubei included in our models (68.6%) (Novel Coronavirus Pneumonia Emergency Response Epidemiology Team, 2020) were identified as imported cases from Hubei province or cases having a close contact with imported cases for the study period. Meteorological factors mainly affect COVID-19 transmission by affecting the survival of the coronavirus in the environment, and we assume that the coronavirus was unlikely to exist in the environment in other provinces, where most cases were imported during the study period. The city of Wuhan was forced to shut down both outbound and inbound traffic on January 23, 2020, and other provinces then also gradually placed restrictions on the movement of their populations. These intervention measures are expected to also have an important impact on the associations between

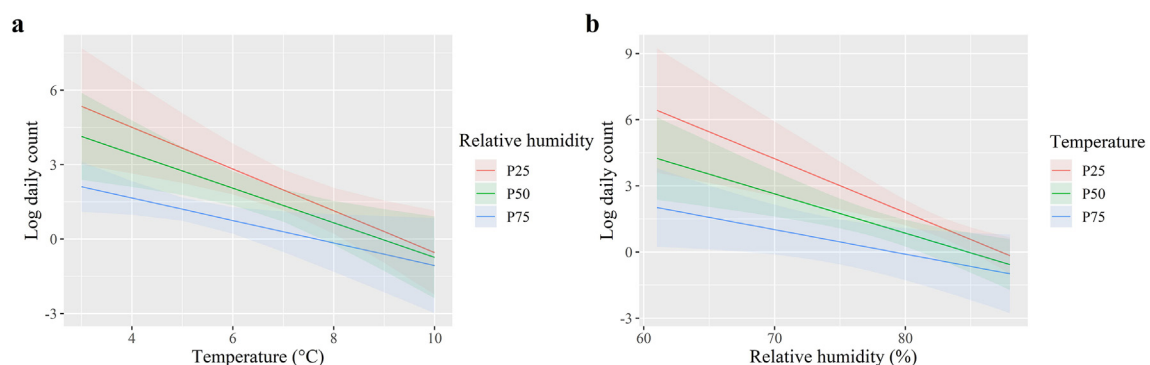


Fig. 3. Effect plots for the impact of (a) AT and (b) ARH on the daily counts of COVID-19.

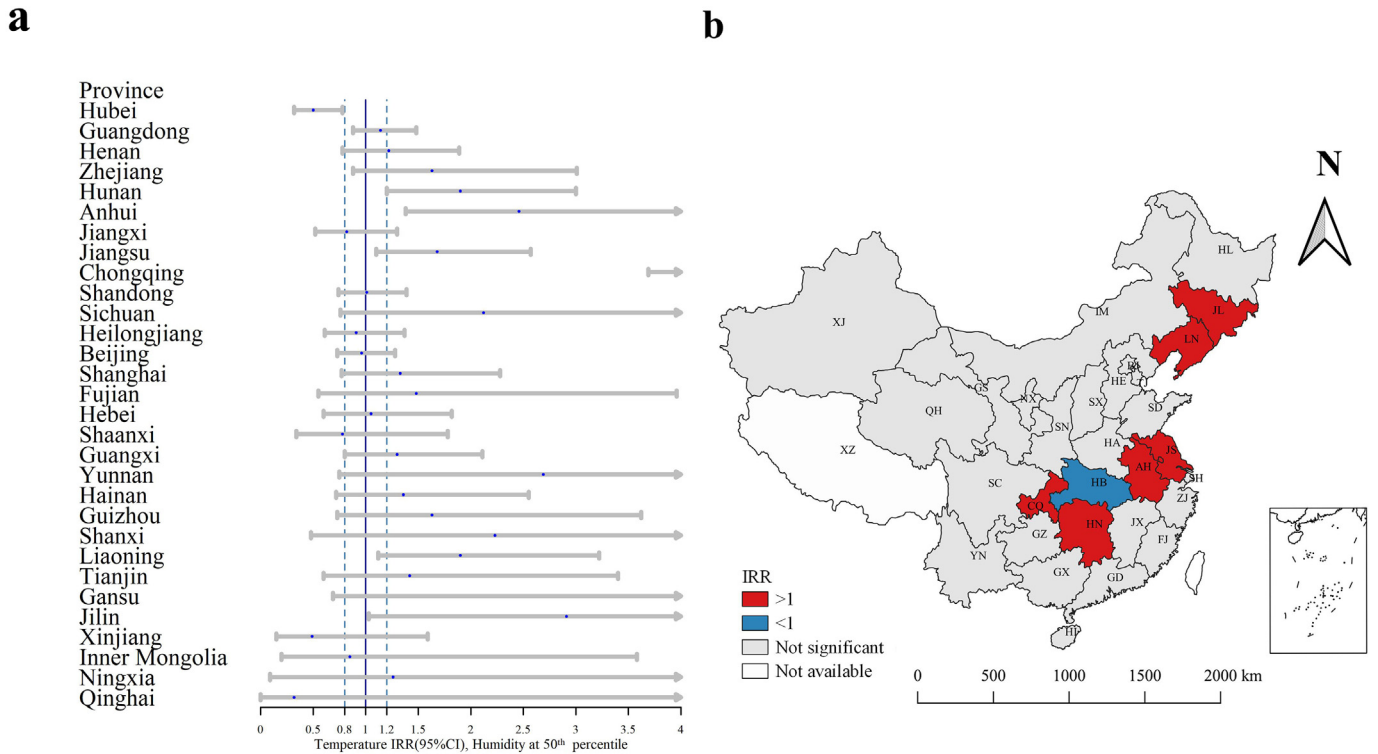


Fig. 4. The forest plot (a) and spatial distribution (b) of IRRs of AT with ARH fixed at its median in all the provinces in China.

meteorological factors and the transmission of the virus. However, because of the interventions that were progressively imposed during January and February 2020, the least biased (confounded) time series of COVID-19 cases is that derived from Wuhan and Hubei province, which showed a negative relationship between AT and ARH and cases, with a positive interaction between AT and ARH.

There are some limitations in our study. First, some potential risk factors that could impact the incidence of COVID-19, for example, province-specific social-economic status, were not included in the model. The study period is short, so that it can be assumed that many covariates did not vary substantially during such a short time period. Second, the incidence of COVID-19 in provinces other than Hubei was

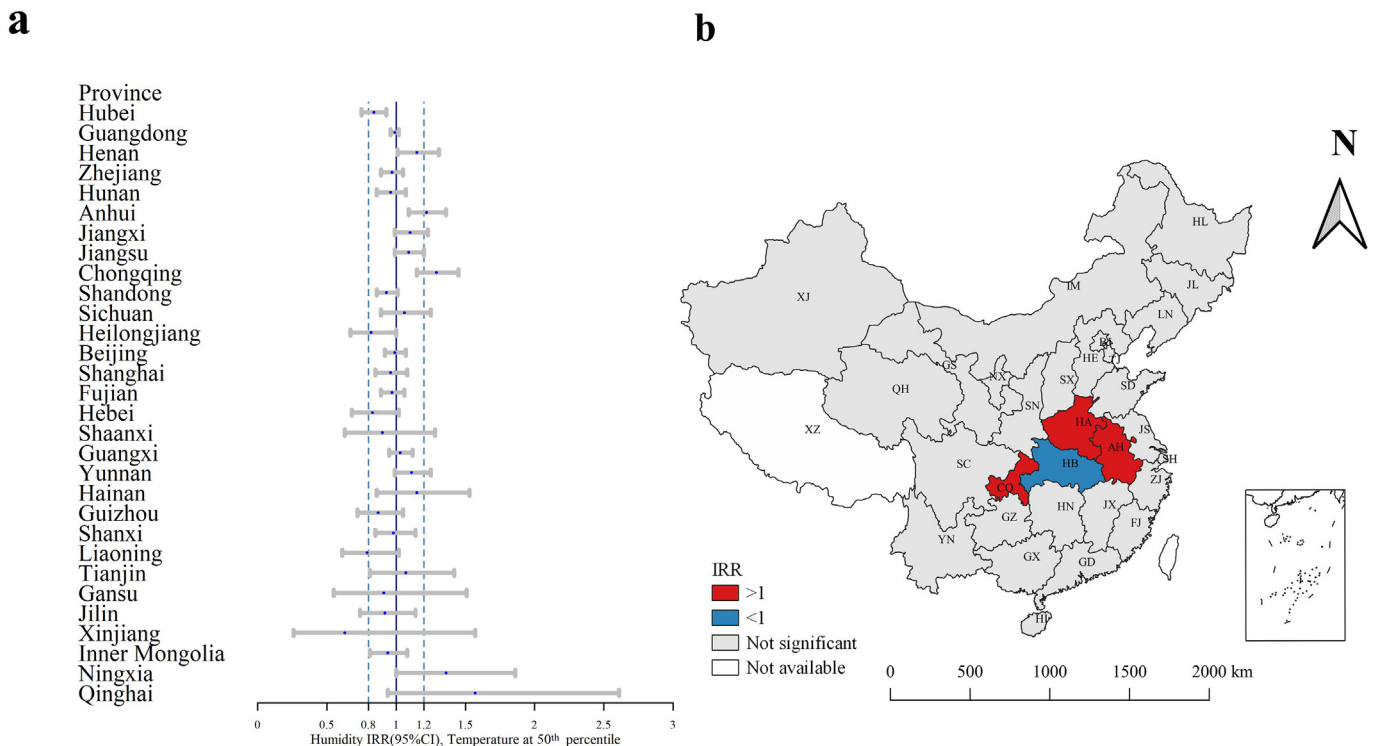


Fig. 5. The forest plot (a) and spatial distribution (b) of IRRs of ARH with AT fixed at its median in all provinces in China.

more likely to be influenced by interventions after the outbreak in Hubei province. In addition, the meteorological data were collected from the Weather Underground for the capital city for each province only, and data accuracy and representativeness can be improved in future studies. Provinces (except for Hubei) had a short study period and included many imported cases.

In conclusion, meteorological factors influence COVID-19 transmission and spread, potentially with an interactive effect between daily temperature and relative humidity on COVID-19 incidence. There were spatial and temporal heterogeneities in COVID-19 occurrence, which could be attributed to meteorological factors as well as interventions measures across provinces. The reasons for the inconsistency in the impact of meteorological factors on COVID-19 among provinces needs further study.

CRediT authorship contribution statement

Hongchao Qi: Conceptualization, Methodology, Software, Writing - original draft, Formal analysis. **Shuang Xiao:** Software, Visualization, Writing - original draft. **Runye Shi:** Visualization, Investigation. **Michael P. Ward:** Writing - review & editing, Methodology, Validation. **Yue Chen:** Writing - review & editing, Methodology, Validation. **Wei Tu:** Writing - review & editing, Methodology, Validation. **Qing Su:** Software, Validation. **Wenge Wang:** Software, Validation, Investigation. **Xinyi Wang:** Software, Validation. **Zhijie Zhang:** Supervision, Funding acquisition.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2020.138778>.

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