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Original Article

Association of temperature and relative humidity with the growth rate of the coronavirus disease 2019 epidemic

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Abstract: The effects of temperature and relative humidity on the growth of coronavirus disease 2019 (COVID-19) remain unclear. Data on the COVID-19 epidemic that were analyzed in this study were obtained from the official websites of the National Health Commission of China and the Health Commissions of 31 provinces in China. From January 26 to February 25, 2020, the cumulative number of confirmed COVID-19 cases in each region was counted daily using data from our database. Curve fitting of daily scatter plots of the relationship between epidemic growth rate (GR) with average temperature (AT) and average relative humidity (ARH) was conducted using the loess method. The heterogeneity across days and provinces was calculated to assess the necessity of using a longitudinal model. Fixed-effect models with polynomial terms were developed to quantify the relationship between variations in the GR and AT or ARH. An increased AT markedly reduced the GR when the AT was lower than -5°C, the GR was moderately reduced when the AT ranged from -5°C to 15°C, and the GR increased when the AT exceeded 15°C. ARH increased the GR when it was less than 72% and reduced the GR when it exceeded 72%. The temperature and relative humidity curves were not linearly associated with the GR of COVID-19. The GR was moderately reduced when the AT ranged from -5°C to 15°C. When the AT was lower or higher than -5°C to 15°C, the GR of COVID-19 increased. An increased ARH increased the GR when the ARH was lower than 72% and reduced the GR when the ARH exceeded 72%.

Keywords: COVID-19, temperature, relative humidity

Introduction

Globally, tens of millions of confirmed cases of coronavirus disease 2019 (COVID-19) have been reported [1, 2]. Since the first case was reported at the end of 2019 in Wuhan, a city in China's Hubei Province, more than 80,000 COVID-19 cases have been reported in China, with the majority reported in Hubei and surrounding provinces [1, 2]. A joint World Health Organization (WHO)-China fact-finding mission estimated that the epidemic in China peaked between late January and early February in 2020, and the rate of new cases substantially decreased in early March 2020 [1, 2].

However, cases have been reported in all continents except Antarctica and have been steadily increasing globally. In the United States, COVID-19 cases have been reported in all 50 states, Washington DC, and at least 4 territories [3]. The cumulative incidence varies by state and likely depends on various factors, including population density and demographics, the extent of testing and reporting, and the timing of mitigation strategies [3]. Understanding of transmission risks remains incomplete. Epidemiologic investigations in Wuhan at the beginning of the outbreak identified an initial association of the outbreak with a seafood market that sold live animals, where most patients worked or visited. This market was subsequently closed for disinfection [1]. However, as the outbreak progressed, person-to-person spread became the main mode of transmission of COVID-19 [4].

No clear evidence has explained the findings of COVID-19 or other viruses such as influenza or severe acute respiratory syndrome (SARS). The incidence of a viral infection and the infectivity of a virus transmitted by airborne or contact routes indoors are influenced by several factors [5]. These include relative humidity, temperature, population density, number of people susceptible to infection, length of exposure, number of infected people producing contaminated aerosols, ventilation rate, infectious particle settling rate, whether the virus has a lipid or nonlipid envelope, the presence of surrounding organic material, exposure to ultraviolet light or antiviral chemicals, microorganism resistance to antibiotic or antiviral therapy, type and degree of invasive procedures, spatial considerations such as seating or sleeping arrangements and contact with carriers, persistence of pathogens within hosts, immuno-epidemiology, evolution and spread of resistance, and host genetic factors [6]. The characteristics of COVID-19 infection have too many unclear factors and unknown data. The airborne spread of COVID-19 is postulated to occur when weather conditions are favorable, that is, weak winds, high relative humidity, and cool temperatures [7]. Another hypothesis is that low relative humidity hinders the immune response of animals in 3 ways [8, 9].

Upper respiratory tract infections reach epidemic proportions during winter [10-13]. Key outbreaks of viruses that cause SARS and the infection due to SARS coronavirus 2 (SARS-CoV-2), named COVID-19, also occurred in winter [11]. Extensive research has been conducted on the link between viral outbreaks and seasons [12, 14]. In particular, differences in temperature and relative humidity affect the stability and transmissibility of viruses [13, 15-17]. For example, some studies have reported that cold, dry, and unventilated environments may contribute to the transmission of influenza in winter [13, 18, 19]. Whether the COVID-19 outbreak will reduce gradually as summer arrives and temperatures increase, such as during the SARS era, remains uncertain [20, 21]. Therefore, this study estimated the correlation of different weather factors such as temperature and relative humidity with the growth rate (GR) of COVID-19.

Methods

Data source and sample

Cumulative number of confirmed COVID-19 cases: Data on the COVID-19 epidemic that were analyzed in this study were obtained from the official websites of the National Health Commission of China and the Health Commissions of 31 provinces (autonomous regions and municipalities) in China. From January 26 to February 25, 2020, the cumulative number of confirmed COVID-19 cases in each region was counted daily using data from our database.

Average temperature and relative humidity: The meteorological data analyzed in this study were provided by the China Meteorological Administration. The daily average temperature (AT) and relative humidity of each province from January 26 to February 25, 2020, were calculated using hourly data from several weather stations in each province.

Statistical analysis

This was a longitudinal observational study of the GR of COVID-19, AT, and average relative humidity (ARH). Curve fitting of the daily scatter plots of the relationship between the GR of cumulative confirmed COVID-19 cases and the AT and ARH from January 26 to February 19, 2020, was conducted using the loess method. Heterogeneities across days and provinces were used to assess the necessity of using a longitudinal model.

To quantify the relationship between variations in the GR of COVID-19 and the AT or ARH, we fitted 2 fixed-effect models: the AT-GR and ARH-GR models. Let $W_{i,t}$ be the cumulative number of confirmed COVID-19 cases in province i (i = 1,...,31) over time t (i = 1,...,T). Subsequently, the GR of the COVID-19 epidemic was calculated as $Y_{i,t} = (W_{i,t} - W_{i,t-1})/W_{i,t-1}$. We used models 1 and 2 to analyze the 2 climatic conditions independently. The method and models used in this study were based on those used in a previous study [22].

Model 1: $Y_{i,t} = f(AT_{i,t}) + \mu_i + \upsilon_t + \varepsilon_{i,t}$,

Model 2: $Y_{i,t} = g(ARH_{i,t}) + \mu_i + \upsilon_t + \varepsilon_{i,t}$.

Where μ_i represents the region-fixed effects and υ_t represents the time-fixed effects. We used the polynomial function (maximal order of 4) to describe the nonlinear relationship between variations in the GR of COVID-19 and the AT or ARH.

$$f(AT_{i,t}) = \alpha_1 AT_{i,t} + \alpha_2 AT_{i,t}^2 + \alpha_3 AT_{i,t}^3 + \alpha_4 AT_{i,t}^4,$$

$$g(ARH_{i,t}) = \beta_1 ARH_{i,t} + \beta_2 ARH_{i,t}^2 + \beta_3 ARH_{i,t}^3 + \beta_4 ARH_{i,t}^4.$$

To explore the combined influence pattern of the AT and ARH on the GR of cumulative confirmed COVID-19 cases, we constructed a more complex model as follows:

Model 3: $Y_{i,t} = f(AT_{i,t}) + g(ARH_{i,t}) + \mu_i + \upsilon_t + \varepsilon_{i,t}$.

The combined function $f(AT_{i,t}) + g(ARH_{i,t})$ was visualized using a 2-dimensional (2D) heat map to present the optimal regimen for promoting or inhibiting the GR of the COVID-19 epidemic.

Model 4: $Y_{i,t} = f(AT_{i,t}) + g(ARH_{i,t}) + \theta SI_{i,t} + \vartheta BI_{i,t} + \mu_i + \upsilon_t + \varepsilon_{i,t}$.

Considering the incubation period of COVID-19, we adjusted the model by using the response variable $Y_{i,t}$ with 10-day exponential moving averaging to account for potential lag effects.

Model 5: $Y_{i,t}^* = f(AT_{i,t}) + g(ARH_{i,t}) + \theta SI_{i,t} + \vartheta BI_{i,t} + \mu_i + \upsilon_t + \varepsilon_{i,t}$.

The combined function $f(AT_{i,t}) + g(ARH_{i,t})$ was visualized using a 2D heat map to present the optimal regimen for promoting or inhibiting the GR of the COVID-19 epidemic.

Results

Figures 1 and **2** present the daily scatter plots of the relationship between the GR of the COVID-19 epidemic and the AT and ARH. From the curve fitting of the plots for February 4, 7, 10, and 19, the effect of the AT on the GR of the COVID-19 epidemic resembled a W shape (**Figure 1**), whereas from the plots for January 29 and February 4, 7, 13, and 16, the effect of the ARH on the GR of the COVID-19 epidemic presented an inverted U shape (**Figure 2**).

The heterogeneity across days and provinces before modeling is presented in Figures S1 and S2, respectively. In general, the GR of cumulative confirmed cases was influenced by the overall trend (heterogeneity across days; Figure S1), region-specific effects (heterogeneity across provinces; Figure S2), and effects of the AT and ARH. The overall trend reflected the effectiveness of government policies in controlling COVID-19 at the country level, and the GR of confirmed COVID-19 cases gradually decreased from January 26 to February 25. The region-specific effect reflected the severity of the COVID-19 outbreak at the province level; for example, the mean GR in Hubei Province was markedly high, whereas that in Tibet was nearly zero (Figure S2). The clear heterogeneity across days and provinces illustrated the need for longitudinal models in our statistical analysis.

Figure 3 displays the crude influence of the AT and ARH on the GR of the COVID-19 epidemic estimated using models 1 and 2. **Figure 4** shows the adjusted influence estimated using model 3. During estimation, we deleted nonsignificant polynomial functions to reduce variance from redundant variables. The crude and adjusted influences were similar, which indicated that the effects of temperature and relative humidity were independent. The slope of the influence indicated that temperature markedly reduced the GR of the COVID-19 epidemic when it was less than -5°C, moderately reduced the GR of the epidemic when it ranged from -5°C to 15°C, and increased the GR of the epidemic when it exceeded 15°C. In **Figure 5**, a positive slope between the excess GR (EGR, which was calculated by subtracting the provincial GR from the national GR) and the AT was observed in warm regions such as Guangxi Province and Hainan Province, whereas a negative slope was observed in cold regions such as Heilongjiang Province and Jilin Province. Increased relative humidity increased the GR of the COVID-19 epidemic when it was lower than 72% and decreased the GR of the epidemic when it exceeded 72% (**Figure 6**). In **Figure 6**, a positive slope between the EGR and the ARH was observed in dry regions such as Qinghai Province and Yunnan Province, whereas a negative slope was observed in humid

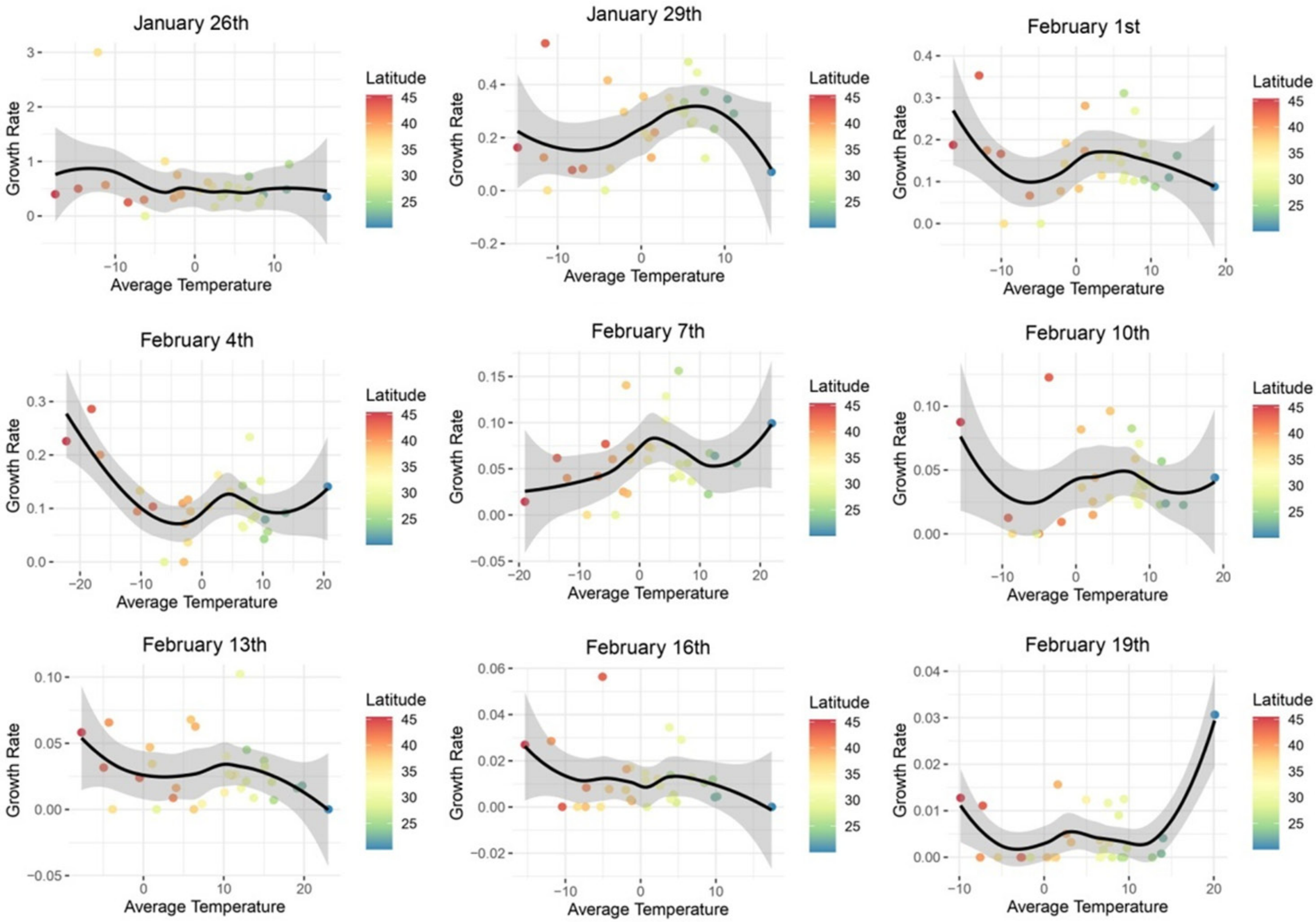

Figure 1. Daily scatter plots of the relationship between the growth rate and average temperature.

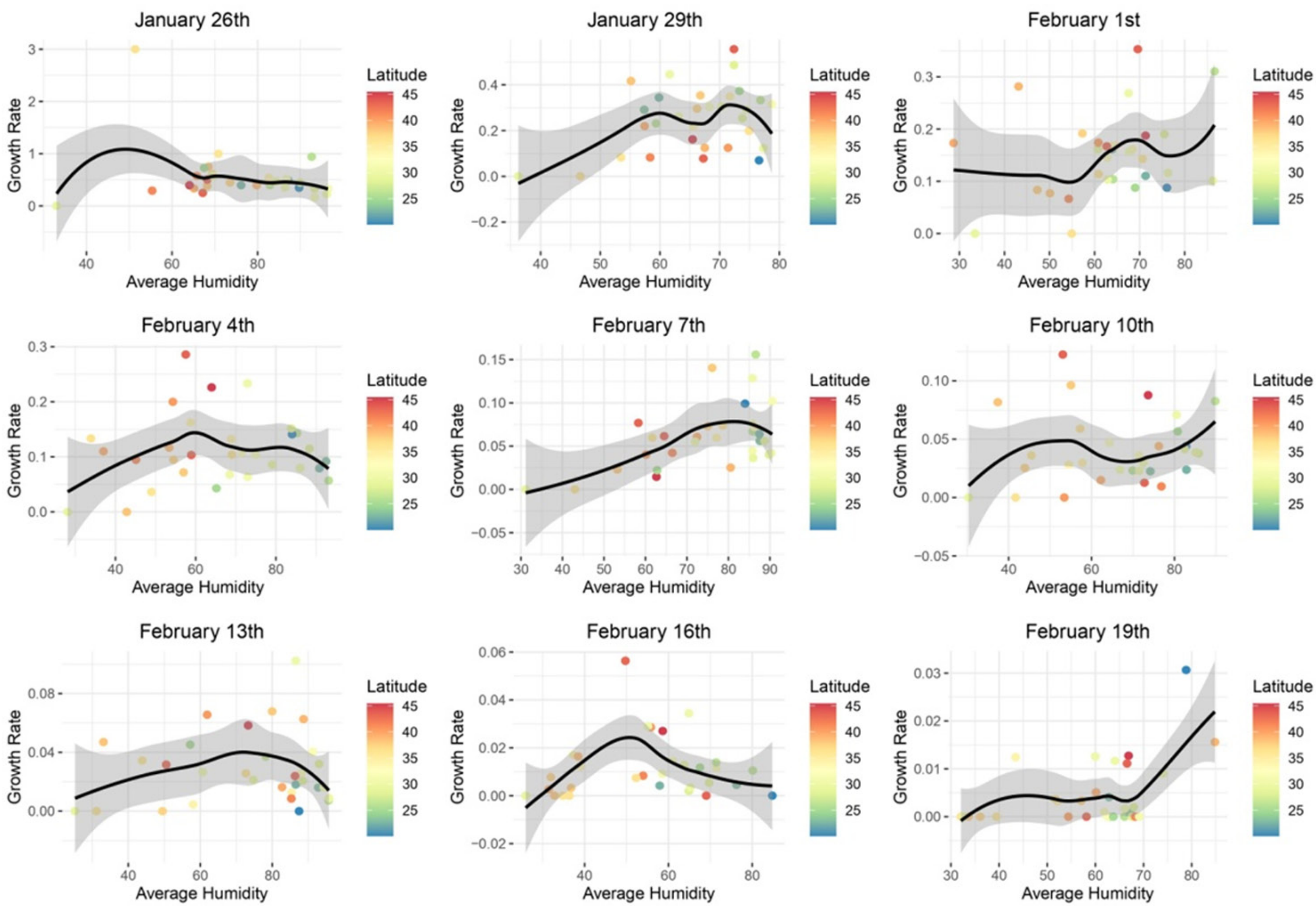

Figure 2. Daily scatter plots of the relationship between the growth rate and average relative humidity.

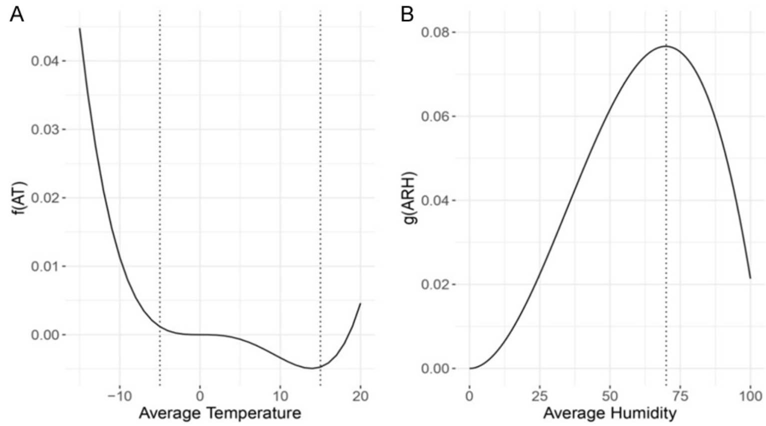

Figure 3. Influence of the average temperature and average relative humidity on the growth rate estimated separately by models 1 and 2.

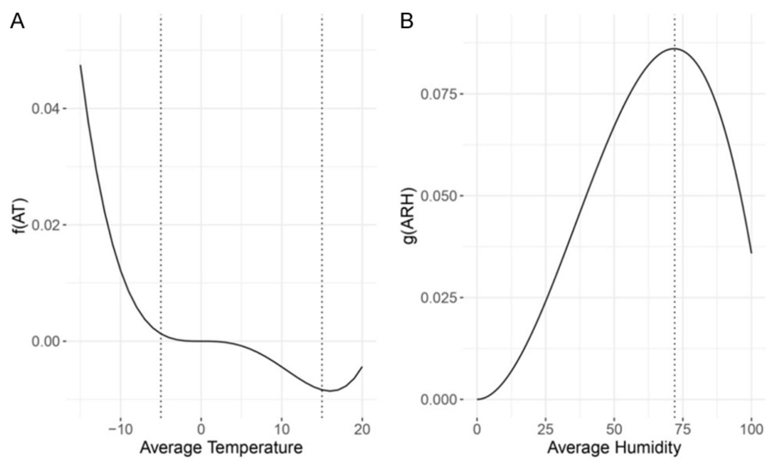

Figure 4. Influence of the average temperature and average relative humidity on the growth rate estimated by model 3.

regions such as Hunan Province and Hainan Province.

The combined influence estimated using model 3 was visualized using a 2D heat map, as presented in **Figure 7**. Low temperatures and high relative humidity increased the GR of the epidemic (left part of the heat map), whereas high temperatures (-5°C to 15°C) and low relative humidity (<72%) reduced the GR of the epidemic (bottom part of the heat map). The combined influence of the AT and ARH on the GR of the COVID-19 epidemic estimated using model 4 (after controlling for confounding variables) are displayed in Figure S3, and the results after adjustment for the response variable are presented in Figure S4. The results were consistent with previous analysis results. However, in Figure S4A, a slight increase in the GR was observed when the AT was more than 15°C. Thus, this finding suggests that increasing temperatures (>15°C) may not completely eliminate viruses. The combined influence estimated using model 5 was visualized using a 2D heat map, as presented in Figure S5. Regardless of whether model 3, 4, or 5 was applied, the trends of temperature or relative humidity with the GR of COVID-19 were extremely similar.

Discussion

The WHO-China fact-finding mission estimated that the epidemic in China peaked between late January and early February 2020, and the rate of new cases decreased substantially in early March [1, 2]. Thus, we estimated the epidemic duration to be from January 26 to February 25, 2020. Our study examined whether the spread of the COVID-19 outbreak is affected by changing seasons, particularly by temperature and relative humidity, because the number of seasonal flu cases in the Northern Hemisphere subsides as winter ends [23]. Whether the same is applicable to the COVID-19 outbreak remains unclear.

Seasonal viral outbreaks are frequently observed during winter [24-26]. A study reported the mechanism of easy influenza transmissions in cold temperatures [27]. To explain the striking regularity of wintertime epidemics, various theories have been developed [25, 28, 29]. These include fluctuations in host immune competence mediated by seasonal factors such as melatonin and vitamin D levels, seasonal changes in host behavior such as school attendance and indoor crowding during inclement weather, and environmental factors including temperature, relative humidity, ultraviolet irradiation, and the direction of air movement

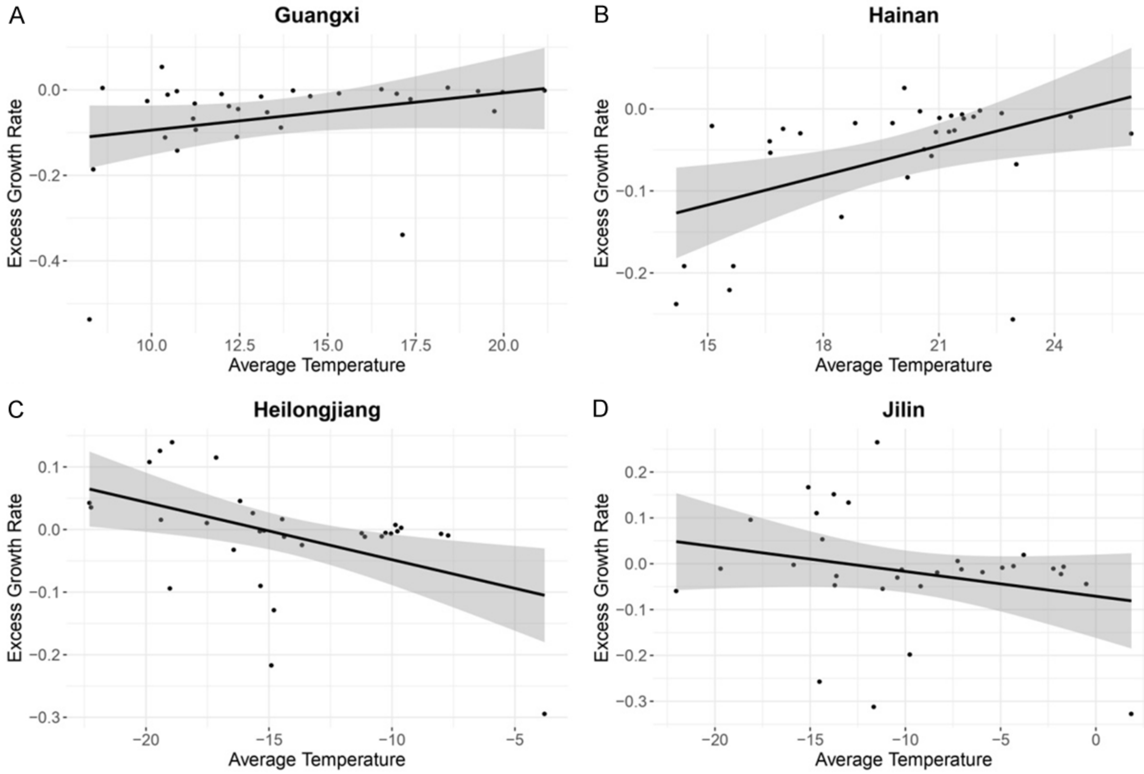

Figure 5. Influence pattern of the average temperature and excess growth rate in cold and warm regions.

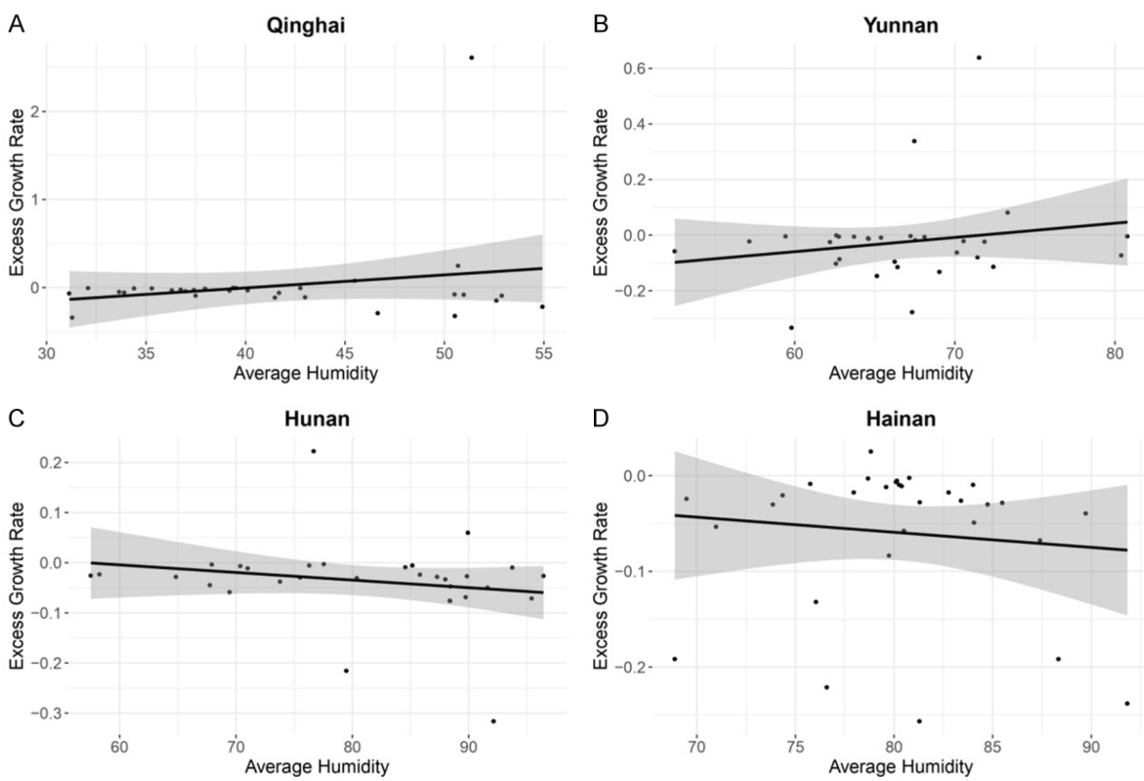

Figure 6. Influence pattern of the average relative humidity and excess growth rate in dry and humid regions.

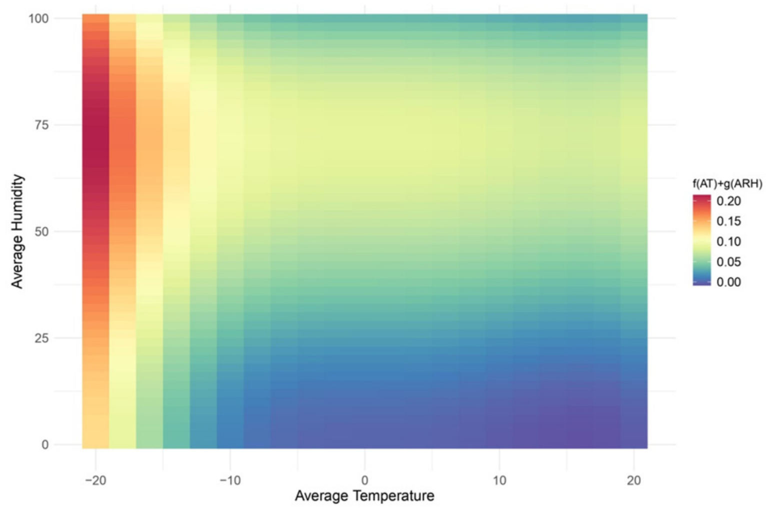

Figure 7. Combined influence of average temperature and average relative humidity on the growth rate estimated by model 3.

in the upper atmosphere [25, 28, 29]. An animal study revealed that in a guinea pig model, the transmission of human influenza viruses through respiratory droplets or the aerosol route proceeded most readily under cold and dry conditions [27]. These findings suggest two methods through which environmental factors drive the wintertime seasonality of influenza in the Northern Hemisphere [24]. Exposure to cold air outdoors or dry air indoors during winter may increase influenza virus transmission and trigger a flu season [24]. Moreover, the climate is drier in winter. According to Scafetta (2020) [30], in most COVID-19-affected regions, the air temperature is low but not freezing, and relative humidity is neither too low nor too high, as it is in winter. The aforementioned findings indicate associations of temperature and relative humidity with viral outbreaks; thus, we estimated the association of temperature and relative humidity with the GR of COVID-19.

The association of a high AT with a low GR of COVID-19 was reported in a previous study, but this might not be entirely correct [31]. Although several recently published articles have demonstrated this association, the effects of confounding variables must be accounted for in the study model, such as isolation, social distance, immigration policies, population density, public health systems, and mass testing. The aforementioned study [31] found that a 1°C increase in temperature and 1% increase in relative humidity lower R by 0.0383 and 0.0224, respectively. This result is consistent with the fact that the high temperature and high relative humidity significantly reduce the transmission of influenza. It indicates that the arrival of summer and rainy season in the Northern Hemisphere can effectively reduce the transmission of the COVID-19. Another study showed no association of COVID-19 transmission with temperature in Chinese cities [32]. These conclusions are controversial [31, 32]. In our study, we discovered an association of the AT and ARH with the GR of newly confirmed COVID-19 cases (**Figures 3** and **4**). The association between the AT and newly confirmed COVID-19 cases was W-shaped and nonlinear (**Figure 1**). By contrast, the association between the ARH and the GR of the COVID-19 epidemic presented an inverted U shape and was nonlinear (**Figures 2** and **4**). Because the association of the AT and ARH is nonlinear, the conclusion of our study cannot be generalized, and establishing a range of temperature and relative humidity values that supposedly reduce the GR of COVID-19 worldwide is crucial. Countries with a high annual AT are not associated with low GRs of outbreaks [1, 2]. Thus, the Philippines, a country with a high annual AT, had the most COVID-19 cases in Southeast Asia as of April 15, 2020 [33]. In terms of the number of COVID-19 cases, the Philippines is followed by Malaysia and Indonesia according to data compiled by the United States-based Johns Hopkins University [33]. Singapore has the fourth most COVID-19 cases in Southeast Asia, followed by Thailand and Vietnam (thus far) [33]. Thus, high temperatures are not the only factor driving COVID-19 transmission because outbreaks are large in many countries with a high annual AT [33]. However, it is not easy to disassociate the confounding variables and public health policies from the influence of climatic factors on the GR of the new coronavirus. The aforementioned countries are among the so-called New Asian Tigers, which comprise underdeveloped countries that have recently reached high levels of industrialization due to foreign investment, such as Thailand and Vietnam, which is also mentioned in the statistics of the paragraph. In these countries, appropriate public health policies might have been implemented to curb the spread of COVID-19, thus influencing the GR. In our study, the effects of temperature and relative humidity were independent because the crude and adjusted influences were similar in models 1, 2, and 3 (**Figures 3** and **4**). This is the first study to report that AT and ARH are independent and significant factors for the GR of COVID-19. **Figures 3** and **4** show that the two temperature turning points were -5°C and 15°C. Temperatures lower than -5°C were associated with a high number of confirmed COVID-19 cases, and temperatures of at least -5°C were associated with a low number of confirmed COVID-19 cases. The temperature of 15°C, another turning point, was associated with the lowest GR of the COVID-19 outbreak. Temperatures lower than -5°C or higher than 15°C were associated with high numbers of confirmed COVID-19 cases. A relative humidity of 72% was the peak point for the GR of confirmed COVID-19 cases. Relative humidity lower or higher than 72% was associated with a high GR of COVID-19 cases. An increase in relative humidity increased the GR of the COVID-19 epidemic when relative humidity was lower than 72% and reduced the GR of the epidemic when relative humidity exceeded 72%. We present nonlinear curves for the GR of the COVID-19 epidemic (**Figures 3** and **4**). Our study results differ slightly from those of Scafetta [30]. Scafetta (2020) [30] showed that temperatures between 4°C and 12°C together with low relative humidity values between 60% and 80% and low-speed winds (approximately 10 km/h) may favor the spread of COVID-19 and/or aggravate the susceptibility of the population to its secondary pneumonia. In **Figures 3** and **4**, when the relative humidity value exceeds 72%, the GR starts to decrease. Our findings can be explained and corroborated by the findings that high relative humidity (>72%) curbs the spread of the new coronavirus.

The individuals most at risk of infection are those who are in close contact with a patient with COVID-19, those who came in contact with airborne transmission, or those caring for patients with COVID-19 [34]. The increased AT (from -5°C to 15°C) reduced the GR potentially because at temperatures lower than -5°C, spending more time indoors is postulated to increase close contact with patients with infection, which increases COVID-19 transmissibility [35]. The characteristics of COVID-19 have too many unclear factors and unknown data. The airborne spread of COVID-19 is postulated to occur if weather conditions are favorable, that is, weak winds, high relative humidity (ARH exceeded 72% in our study of COVID-19), and cool temperatures (lower than -5°C in our study of COVID-19) [7]. Another hypothesis is that low relative humidity (from 80% to 72%) hinders the immune response of animals in 3 ways [8, 9]. First, regarding COVID-19, low relative humidity prevents cilia, which are hair-like structures in airway cells, from removing viral particles and mucus. Second, it also reduces the ability of airway cells to repair damage caused by COVID-19 in the lungs. The third mechanism involves interferons, which are signaling proteins released by virus-infected cells to alert neighboring cells of the viral threat. In low-humidity environments, this innate immune defense system fails [8, 9].

Our study revealed differences in the GR of COVID-19 across regions and days (Figures S1 and S2). The considerable heterogeneity across days and regions illustrated the need for longitudinal models in our statistical analysis. Thus, we included regions and days in our longitudinal models. Our models may be limited in terms of extrapolation to other countries to predict the association of the AT and ARH with the GR of confirmed COVID-19 cases. Our model predicted that high temperatures (-5°C to 15°C) and low relative humidity (<72%) reduced the GR of COVID-19 outbreaks in China (**Figure 7**). Our findings might be partially compatible with current data compiled by Johns Hopkins University [33].

In this study, we estimated the AT and AHR of regions according to the different average annual temperatures of different provinces (**Figures 5** and **6**). In provinces with an extremely high average annual temperature (>15°C) such as Guangxi and Hainan, the GR of confirmed COVID-19 cases was associated with an extremely high AT (>15°C) (**Figure 5**). However, in provinces with a low average annual temperature such as Heilongjiang and Jilin, the GR of newly confirmed COVID-19 cases decreased with a ATs between -5°C and 15°C. The findings in **Figure 5** were compatible with those in **Figures 2** and **3**. The GR curve of COVID-19 was not linear or associated with AT, and the GR curve for AT was W-shaped (**Figures 3**, **4** and **7**). Another independent factor of the GR of confirmed COVID-19 cases was ARH, and the curve between ARH and the GR of COVID-19 cases was nonlinear and presented an inverted U shape (**Figures 3**, **4** and **7**). The findings of **Figure 6** were compatible with those of **Figures 3** and **4**. A positive slope between the EGR and ARH was observed in dry provinces such as Qinghai and Yunnan, whereas a negative slope was observed in humid provinces such as Hunan and Hainan. In our study, temperature and relative humidity were both independent factors of the GR of COVID-19. However, we noted no simple linear curves for temperature and relative humidity with the GR of COVID-19 (**Figures 3**, **4** and **7**). Thus, we used a 2D heat map between the ARH and EGR in dry and humid regions. **Figure 7** indicates that a low temperatures (<-5°C) and increasing relative humidity (from 0% to 72%) increased the GR of the COVID-19 epidemic, whereas high temperatures (-5°C to 15°C) and low relative humidity (<72%) reduced the GR of the epidemic (bottom part of the heat map). **Figures 3**, **4** and **6** show that when relative humidity is high (>72%), the GR decreases. No absolute relationship was found between high relative humidity (>72%) and low GR of COVID-19 cases in the present study, and our findings differ from those of previous studies on the transmission of SARS [20]. The higher stability of the SARS coronavirus at low temperatures and relative humidity may have facilitated its transmission in subtropical regions (such as Hong Kong) during spring and in air-conditioned environments [20]. Our study results may aid future policy formulations for reducing the GR of COVID-19. Maintaining high temperatures (-5°C to 15°C) and low relative humidity (<72%) may reduce the GR of COVID-19.

SARS was highly transmissible during winter [21]. Temperature and relative humidity were associated with SARS, and high temperatures or high relative humidity reduced its transmissibility [20]. Therefore, according to some inferential hypotheses, COVID-19 transmission will decrease in summer. However, the effects of relative humidity in our study differ from those in SARS studies, in which high relative humidity was associated with decreased transmission [20]. In our study, the association between the ARH and the GR of the COVID-19 epidemic presented an inverted U shape, and when relative humidity increased from 0% to 72%, the GR of COVID-19 cases increased (**Figures 3**, **4** and **7**). In our study, low relative humidity (<72%) may have reduced the transmissibility of COVID-19 (**Figure 7**).

Our study is the first to estimate the influence of temperature and relative humidity on the GR of COVID-19. The largest data outcomes of newly confirmed COVID-19 cases were combined with meteorological data in our study for the first time. Our findings may predict the future GR of COVID-19 from local meteorological data. When summer arrives, the GR of COVID-19 may decrease in areas with low relative humidity (<72%). Based on our findings, the following hypothesis is proposed: the COVID-19 outbreak may be partially reduced in future summers, although the outbreaks in Indonesia and Philippines occurred despite the high relative humidity in these countries [2, 33]. Low relative humidity (<72%) was an independent factor of decreased GRs of COVID-19 (such as in Burundi, São Tomé and Príncipe, South Sudan, and Yemen). In addition, this model can estimate the GR of COVID-19 under different weather conditions. The predictions from our model can be used to determine effective actions for preventing COVID-19 outbreaks. Our findings are compatible with those of similar studies with similar outcomes without specific ranges of temperature and relative humidity [36-38]. The main goal of our study was to determine the association of the AT and ARH with the GR of new confirmed cases of COVID-19 instead of death or transmission. Moreover, we found a specific range of AT and ARH for the GR of COVID-19. High temperatures (-5°C to 15°C) and low relative humidity (<72%) may reduce the GR of COVID-19 outbreaks. However, the GR curve of COVID-19 is not linear or associated with temperature and relative humidity.

Our study has some limitations. First, other crucial factors may have affected the GR of COVID-19, such as governmental interventions, public health policies, and medical resources. However, similar interventions and public health policies in China were controlled for in the data compiled by the Chinese Center for Disease Control and Prevention. The degree of bias in these interventions may be low. Moreover, the main goal of analyses of the effects of the AT and ARH on the GR of COVID-19 could be that even considering those obvious bias we would not be able to quantify them as low; there is an unanimity of conclusions, if the arguments mentioned above regarding the association of the ARH in the GR of COVID-19 are considered. However, public health policies must be included to benefit the population in the course of the pandemic. Second, our model can only be extrapolated if data and research results from other countries with different climates as well as AT and ARH data are included in the research design. However, data on the daily AT, ARH, and GR of COVID-19 from other countries are unavailable. Third, these data were compiled over a short period (between January 26 and February 25, 2020). Nevertheless, the pandemic period of China ended in February based on data from the official websites of the National Health Commission of China and the Health Commissions of 31 provinces in China. There were not much new confirmed COVID-19 cases in the longer period. Fourth, COVID-19 transmission in China mainly occurred in Wuhan, Hubei province and was dramatically affected by the strict isolation policy. The infection data in China may be less influenced by temperature and relative humidity and the model, which is not good for the establishment of the model. Therefore, we collected data during the pandemic period from January 26 to February 25, 2020. The pandemic period from January 26 to February 25, 2020 might be good for the establishment of the model. Fifth, the data we used to establish the model is only derived from January 26 to February 25, 2020. The temperature in northern hemisphere during this period time is cold, and the span of temperature is limited. Nevertheless, our data on the COVID-19 epidemic that were analyzed in this study were reported by the official websites of the National Health Commission of China and the Health Commissions of 31 provinces (autonomous regions and municipalities) in China. Although the temperature in most northern hemisphere during this period time (from January 26 to February 25, 2020) is cold, the temperature in the southern provinces like Guangxi Province and Hainan Province is getting warm and even hot (**Figure 5**). We believe that the epidemic data in China including 31 provinces from the areas with a really large span of temperature (from -20°C to 24°C) have been helpful to establish the temperature-transmission (COVID-19) model. Sixth, the outbreak of COVID-19 in China have been controlled. The relationship between temperature and relative humidity with transmission of COVID-19 could be verified by other countries like India or United States with high prevalence of COVID-19.

Conclusions

High temperatures (-5°C to 15°C) and low relative humidity (<72%) may reduce the GR of COVID-19 outbreaks. However, the GR curve of COVID-19 was not linear or associated with temperature and relative humidity. Temperature and relative humidity alone are not associated with the GR curve of COVID-19. Public health policies, which serve as confounding variables and influence this scenario, should be considered in future studies to improve our study results; this would provide a positive direction for pandemic mitigation, including the creation of global climate maps as a possible prevention approach.

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Disclosure of conflict of interest

None.

Abbreviations

COVID-19, novel coronavirus disease 2019; GR, growth rate; AT, average temperature; ARH, average relative humidity; WHO, World Health Organization; SARS, severe acute respiratory syndrome; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2; EGR, excess growth rate.

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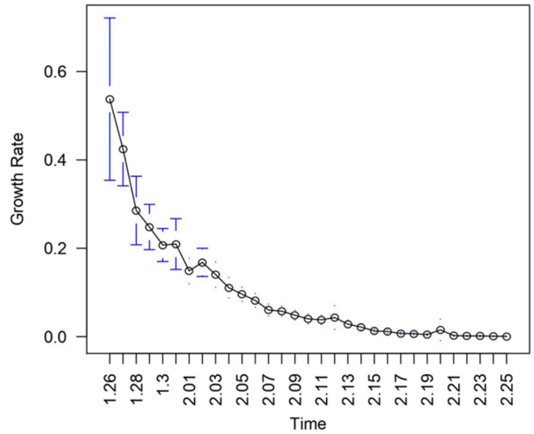

Figure S1. Heterogeneity across days.

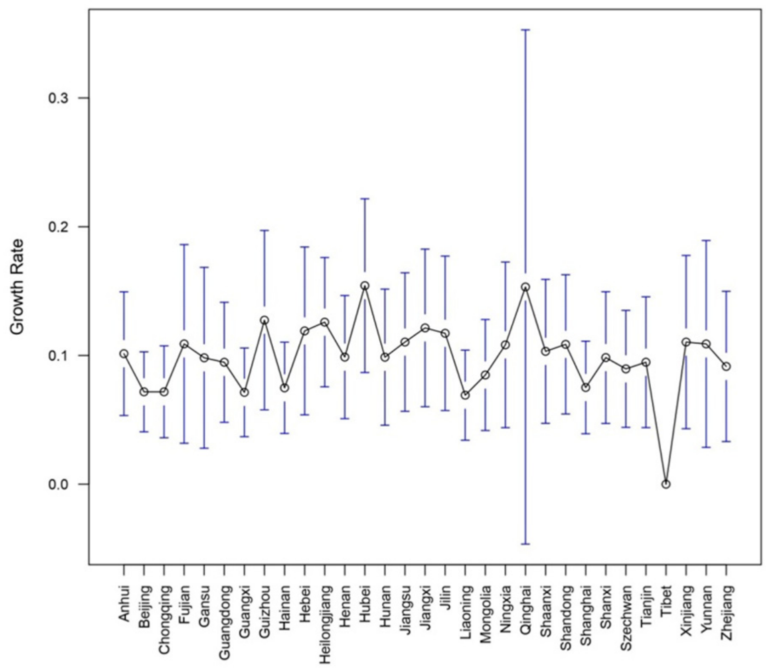

Figure S2. Heterogeneity across provinces.

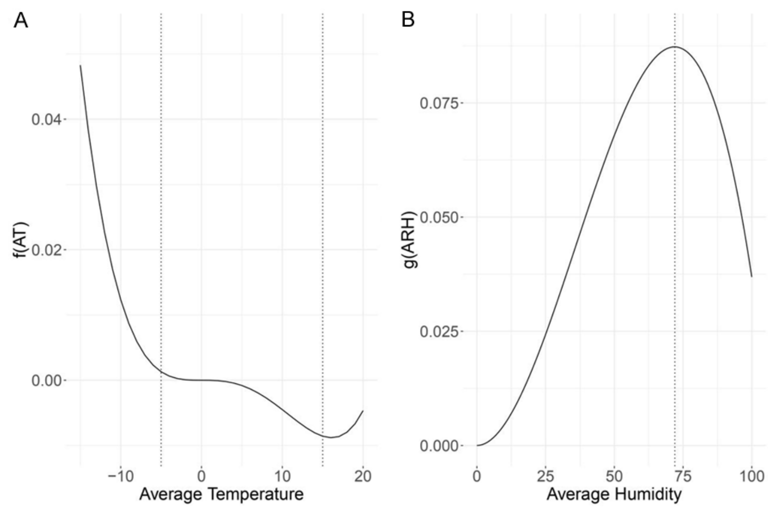

Figure S3. Influence of average temperature and average relative humidity on the growth rate estimated by model 4.

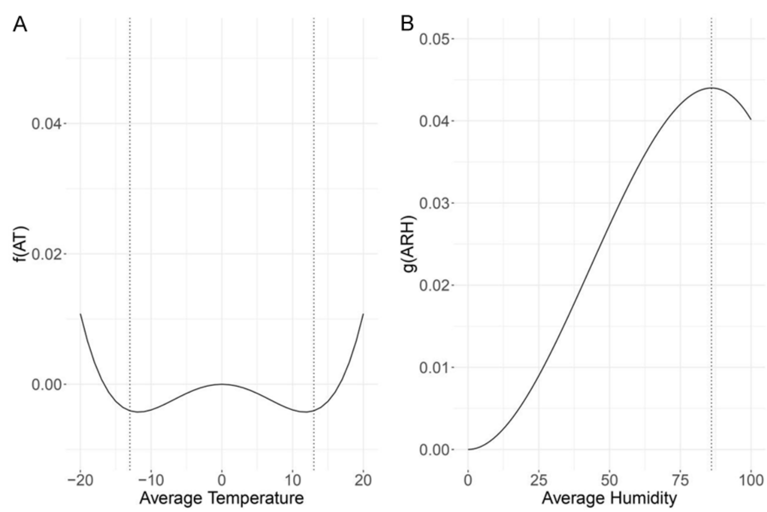

Figure S4. Influence of average temperature and average relative humidity on the growth rate estimated by model 5.

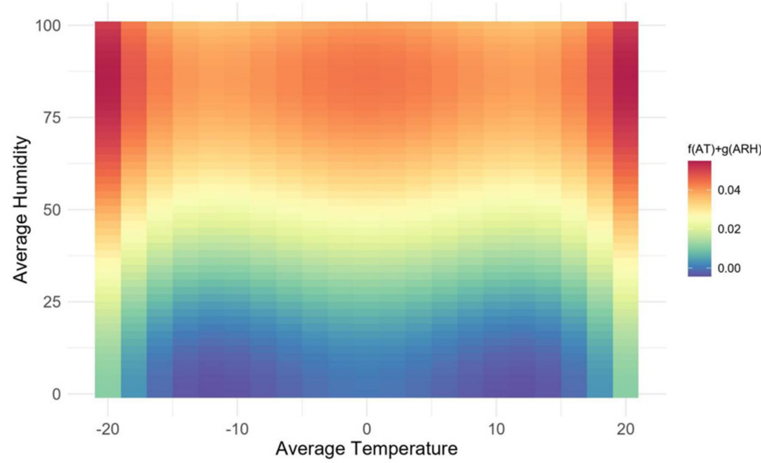

Figure S5. Combined influence of average temperature and average relative humidity on the growth rate estimated by model 5.