Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Is coronavirus disease (COVID-19) seasonal? A critical analysis of empirical and epidemiological studies at global and local scales

Woo Seok Byun 1, Sin Woo Heo 1, Gunhee Jo 1, Jae Won Kim 1, Sarang Kim 1, Sujie Lee 1, Hye Eun Park 1, Jea-Hyun Baek *

School of Life Science, Handong Global University, Pohang, Gyeongbuk, 37554, Republic of Korea

ARTICLE INFO

Keywords: COVID-19 Epidemiology SARS-CoV-2 Meteorologic factors Seasonality

ABSTRACT

Coronavirus disease (COVID-19) has infected more than 50 million people and killed more than one million, worldwide, during less than a year course. COVID-19, which has already become the worst pandemic in the last 100 years, is still spreading worldwide. Since the beginning of the outbreak, it has been of particular interest to understand whether COVID-19 is seasonal; the finding might help for better planning and preparation for the fight against the disease. Over the past 12 months, numerous empirical and epidemiological studies have been performed to define the distinct diffusion patterns of COVID-19. Thereby, a wealth of data has accumulated on the relationship between various seasonal meteorological factors and COVID-19 transmissibility at global and local scales. In this review, we aimed to discuss whether COVID-19 exhibits any seasonal features in a global and local perspective by collecting and providing summaries of the findings from empirical and epidemiological studies on the COVID-19 pandemic during its first seasonal cycle.

1. Introduction

Seasonality is a common feature of viral infections in humans and various animals (Dowell and Ho, 2004; Moriyama et al., 2020). For example, while human influenza virus, coronaviruses (HCoVs), and orthopneumoviruses exhibit an annual increase in incidence during winter (Shaman and Kohn, 2009), some non-polio enteroviruses have seasonal peaks in summer (Pons-Salort et al., 2018). As common HCoVs show seasonality, it is plausible to believe that severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), a member of the same family, could also exhibit seasonal features (Killerby et al., 2018; Ye et al., 2020).

SARS-CoV-2, the virus that causes coronavirus disease (COVID-19), was first identified in Wuhan, China, in December 2019. Since then, the virus has rapidly spread worldwide. As of November 9, 2020, more than 50,000,000 confirmed cases with more than 1,250,000 deaths have been reported (case fatality rate [CFR] of approximately 2.5%). During the first months of the outbreak, COVID-19 has shown an interesting diffusion pattern, as the transmission was restricted to a certain range of latitude, temperature, and humidity (Sajadi et al., 2020; Sarmadi et al., 2020). As COVID-19 is a novel disease, it has been challenging so far to corroborate its seasonality because of its short existence. However, statistical data on SARS-CoV-2 transmission have accumulated over the past 12 months, and this new information could provide clues that may explain the distinct diffusion patterns of COVID-19 in the pandemic.

The restricted pattern of spread of COVID-19 has been of great interest. This is because identifying the cause of the disparate diffusion pattern could prove useful in predicting how the COVID-19 situation might unfold. Although vaccine administrations have already begun, there have been reports of new variants of SARS-CoV-2, against which the already developed vaccines may be ineffective (Callaway, 2021). Furthermore, how long the antibody response will be sustained following a natural infection with SARS-CoV-2 is questionable as recent studies suggest that the humoral immunity against SARS-CoV-2 may be short-lived (Anna et al., 2020; Ibarrondo et al., 2020). In line with this, it was recently found that naturally infected individuals, especially those with mild symptoms, are prone to a reinfection (Ibarrondo et al., 2020; Seow et al., 2020). In fact, mounting evidence suggests that COVID-19 has the potential to become a seasonal illness like seasonal influenza (Lavine et al., 2021). This emphasizes the importance of understanding the transmission patterns of SARS-CoV-2, that is, whether it is a seasonal virus. While human-to-human interactions play a great role in viral diffusion, temperature and humidity can still alter human behavioral
patterns, immune system functioning/response, and viral survivability in the external environment; these all ultimately contribute to high SARS-CoV-2 transmission (Al Huraimel et al., 2020; Bontempi et al., 2020; Bontempi, 2020, 2021; Courtemanche et al., 2020; Tammes, 2020). If the development of new vaccines will be constantly required, as with the yearly flu vaccine, establishing whether COVID-19 has seasonality will play a crucial role in future planning of vaccine development.

Here, we aimed to provide a synthesized summary of the findings of empirical and epidemiological studies on the impact of season on the meteorological factors (e.g., temperature; absolute [AH], relative [RH], and specific humidity [SH]; precipitation; solar radiation/ultraviolet [UV]; wind speed; latitude; and air pollution) on COVID-19 transmissibility during the first seasonal cycle of the pandemic. Of note, we explicitly evaluated the findings of global and local studies separately; this is because sample size and regional disparities may have impacted the findings. By “global study”, we refer to cross-country analysis with a dataset comprising data from 50 or more countries. Conversely, by definition, “local study” refers to cross-category analysis in a single country or cross-country analysis with a dataset of fewer than 50 countries.

2. Temperature forms an inverse relationship with the global transmission of SARS-CoV-2

Since the first COVID-19 case was reported in December 2019, the disease has now completed a full seasonal cycle. Between the time when COVID-19 transitioned from being an epidemic to being declared a real pandemic of global significance, regions with higher temperatures (≥20°C) still reported lower numbers of COVID-19 cases than those with lower temperatures. Notably, 90% of SARS-CoV-2 transmission occurred within temperatures ranging between 3°C and 17°C in February and March 2020 (Bukhari and Jameel, 2020). Interestingly, the first few countries and cities with a rapid spread of COVID-19 (Italy, Iran, South Korea, and the US cities such as New York and Washington) exhibited a climate similar to the original hotspots of SARS-CoV-2 (Hubei and Hunan) with average temperatures between 3°C and 10°C (Bukhari and Jameel, 2020). In line with these observations, cities with substantial community spread (>10 deaths as of March 10, 2020) showed average temperatures between 5°C and 11°C, which is indicative of a direct relationship between temperature and the transmission of SARS-CoV-2 (Sajadi et al., 2020). Comprehensively, the preferential distribution of SARS-CoV-2 globally is along the inverse latitudinal gradients (Bajaj and Arya, 2020); SARS-CoV-2 initially spread less prominently around the equator, but more prominently in regions with moderate and cold climates. Overall, these descriptive analyses from the early studies on COVID-19 raised the possibility that SARS-CoV-2 could be temperature-sensitive.

In congruence with these observations, empirical and epidemiological studies have corroborated an inverse relationship between temperature and global distribution of COVID-19 (Table 1). Correlation studies reported that the average temperature is negatively associated with both the proportion of deaths (r = −0.5, p < 0.01) and cases (r = −0.5, p < 0.01) per 105 population (Sarmadi et al., 2020). Pearson correlation analysis in another study revealed that average temperature negatively correlates with the attack rate, a similar concept as the CFR in terms of infectivity (r = −0.36, p = 0.02) (Hassan et al., 2020). This result is consistent with that of a study that used Spearman correlation analysis (Bezabih et al., 2020).

A simple linear regression (LR) model found that the air temperature at 2 m above the surface was a strong inverse relationship with the log of the total number of cases in 50 different countries (R2 = 0.26, p < 0.001) (Sajadi et al., 2020). In another simple LR analysis, average high temperature was reciprocally related to both total deaths (β = −0.0377, R2 = 0.4192) and total cases per million population (β = −0.0037, R2 = 0.5875) (Sajadi et al., 2020). A stepwise LR model fitted with R0 displayed a negative relationship between temperature and SARS-CoV-2 infectivity (Metelmann et al., 2020). Fitting a simple LR on the exponential spread rate with the average temperature again exhibited a decreasing slope (β = −0.0035, R2 = 0.18) (Notari, 2021). Equivalently, in studies using multiple meteorological variables, temperature showed a negative relationship with the total number of cases of SARS-CoV-2 infection (β = −6.40, p < 0.01) (Sobral et al., 2020). Accordingly, the Gutenberg-Richter law equation showed that a 1°C increase in temperature results in decreased number of COVID-19 infections by 13–16 cases per day (Sil and Kumar, 2020). In addition, a generalized additive model (GAM), with a penalized spline function on the time variable, resulted in a negative trend between average temperature and the number of daily new cases in 166 countries (β = −2.85%, p < 0.01) (Wu et al., 2020b). In accordance with all these studies, a micro-analysis of 9 locations across the globe (Italy, the United Kingdom, France, Sweden, Iran, the USA, South Korea, and Australia) showed a similar pattern, where regions with higher atmospheric temperature exhibited higher growth rates in the daily number of new cases with a median lag of 10 days (Rouen et al., 2020).

Whereas there was also a small number of studies showing no correlation between temperature and COVID-19 transmissibility (Islam et al., 2020; Jamil et al., 2020; Jüni et al., 2020) (Table 1), most studies showed an inverse relationship between temperature and the transmission of SARS-CoV-2 (Fig. 1).

3. Consistent with the global data, temperature forms an inverse relationship with local transmission of SARS-CoV-2

As COVID-19 was first reported in Wuhan, China, initial research regarding the effects of meteorological factors on SARS-Cov-2 transmission was heavily based toward China. Analysis of data collected from multiple Chinese provinces between December 2019 and February 2020 revealed that temperature and COVID-19 infection rates formed a negative relationship (Jiang et al., 2020; Wang et al., 2020). A parameterization analysis revealed that Chinese provinces with temperatures ranging from −9.41 to −13.87°C experienced higher SARS-CoV-2 transmission rates (Lin et al., 2020a). Pearson correlation analyses on data collected from 31 Chinese provinces identified 14 provinces with a significant correlation (p < 0.05). Out of those 14 provinces, 12 showed a negative correlation between daily temperature and the number of infected cases (Rahman et al., 2020). A group of studies reported that with regression and correlation analysis, increment in temperature resulted in a decrease in the daily number of confirmed cases (Li et al., 2020a, 2020b; Liu et al., 2020b; Luo et al., 2020; Rouen et al., 2020; Oliveira et al., 2020; Qi et al., 2020; Xie and Zhu, 2020). Several other studies analyzed variables from the Susceptible-Exposed-Infectious-Recovered (SEIR)
Table 1
The impact of temperature on the transmissibility of COVID-19.

| Relation    | Country           | Statistical method used                          | Ref.                 |
|-------------|-------------------|--------------------------------------------------|----------------------|
| Negative    | Global (≥50 countries) | Mapping to Köppen’s climate | Bajaj and Aryas (2020) |
|             |                   | Spearman correlation                         | Bezabih et al. (2020) |
|             |                   | Simple LR model; Pearson correlation         | Hassan et al. (2020)  |
|             |                   | Simple LR model                              | Iqbal et al. (2020)   |
|             |                   | Multivariate LR model                        | Luo et al. (2020)     |
|             |                   | Stepwise LR model                            | Metelmann et al. (2020) |
|             |                   | Simple LR model                              | Notari (2021)         |
|             | Brazil            | Mann-Whitney test; LR model                  | Sajadi et al. (2020)  |
|             |                   | Pearson correlation                          | Sarmadi et al. (2020) |
|             |                   | Gutenberg-Richter law model                  | Sil and Kumar (2020)  |
|             |                   | Uni/Multivariate LR model (by panel data strategy) | Sobral et al. (2020) |
|             | Brazil            | GAM; Polynomial regression model             | Wu et al. (2020b)     |
|             |                   | Shapiro-Wilk test; Spearman correlation      | Prata et al. (2020)   |
|             | China             | SEIR model with simple LR model; Pearson correlation | Guo et al. (2020)     |
|             |                   | Multivariate Poisson regression model        | Jiang et al. (2020)   |
|             |                   | Simple LR model                              | Li et al. (2020a)     |
|             |                   | Spearman correlation                         | Li et al. (2020b)     |
|             |                   | Mechanism-based parameterization model with spatial correlation and exponential regression model | Lin et al. (2020a)    |
|             |                   | Multivariate regression model                | Lin et al. (2020b)    |
|             |                   | Meta-analysis with generalized linear models | Liu et al. (2020b)    |
|             |                   | Stepwise LR model                            | Metelmann et al. (2020) |
|             | Europe; USA       | Combination of linear and exponential models  | Oliveira et al. (2020) |
|             |                   | GAM                                            | Qi et al. (2020)      |
|             |                   | Spearman correlation                         | Rahman et al. (2020)  |
|             |                   | Uni/Multivariate LR model (by panel data strategy) | Ozyigit (2020)       |
|             | Europe; USA       | Polynomial regression model                   | Benedetti et al. (2020) |
|             | Brazil            | Spearman correlation                         | Bolaño-Ortíz et al. (2020) |
|             | Mexico            | Spearman correlation; clustering              | Méndez-Arriaga (2020) |
|             | Spain             | Polynomial regression model                   | Sanchez-Lorenzo et al. (2021) |
|             | Turkey            | Spearman correlation                         | Sahin (2020)         |
|             | USA               | Gaussian function model; Pearson correlation  | Scatetta (2020)      |
|             |                   | Negative binomial regression model (with generalized estimating equations) | Sehra et al. (2020)  |
|             | Worldwide (5 countries) | Multivariate LR model                           | Lao et al. (2020)    |
|             | Worldwide (9 countries) | Micro-correlation with Spearman correlation | Rouen et al. (2020)  |
| Positive    | Brazil            | Canonical correlation                         | Auler et al. (2020)   |
|             | China             | Simple LR model; Spearman correlation         | Yao et al. (2020a)    |
|             | India             | GAM                                            | Xie and Zhu (2020)    |
|             |                   | Spearman correlation                         | Das and Chatterjee (2020) |
|             | Norway            | GAM                                            | Gupta et al. (2020)   |
|             | Singapore         | Spearman correlation                         | Mangla et al. (2020)  |
|             |                   | Spearman/Kendall correlation                  | Menebo et al. (2020)  |

Table 1 (continued)

| Relation    | Country           | Statistical method used                          | Ref.                 |
|-------------|-------------------|--------------------------------------------------|----------------------|
| No          | Global (≥50 countries) | Multilevel mixed-effects regression model       | Islam et al. (2020)  |
|             |                   | Gaussian function model                         | Jamil et al. (2020)  |
|             |                   | Weighted random-effects regression model        | Jini et al. (2020)   |
| China       | South Africa      | Multivariate LR model                           | Yao et al. (2020b)   |
|             | Spain             | Pearson correlation                             | Chetty et al. (2020) |
|             |                   | Spatiotemporal latent Gaussian model            | Britz-Reidn and Serrano-Aroca (2020) |
| USA         | Maxent model       | Negative binomial mixed model                   | Harbert et al. (2020) |

model with regression analysis and showed that the transmission rate was negatively related to temperature (Guo et al., 2020; Lin et al., 2020b). Similarly, a stepwise LR model, used to analyze data collected up to May 2020, when the COVID-19 spread was largely under control in China, displayed a negative relationship between the temperature and COVID-19 infectivity (Metelmann et al., 2020).

Studies showed that the acceleration of transmission dynamics of COVID-19 throughout Europe had a strong association with temperature (Benedetti et al., 2020; Ozyigit, 2020; Sanchez-Lorenzo et al., 2021). A simple LR analysis of the relationship between average temperature and COVID-19 case growth in EU-15 area countries (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the United Kingdom) following each country’s 100th reported case, confirmed the coefficient for temperature effect on the COVID-19 case growth rate as −0.009 (p < 0.01). Therefore, a 0.9% decrease in SARS-CoV-2 transmission was expected following a 1 °C increase in the average temperature (Ozyigit, 2020). A model analysis of 25 locations from Europe and the USA suggested that the average monthly high temperature is inversely associated with COVID-19 deaths per million population (Benedetti et al., 2020). For Spain, an exponential regression model indicated that the temperature of a region (between 5°C and 11°C) determined the total number of cases and deaths due to COVID-19 (Sanchez-Lorenzo et al., 2021).

For Brazil, the dose-response relationship shown by a GAM suggested that temperature and the total number of daily cumulative confirmed cases of COVID-19 forms a negative relationship (Prata et al., 2020). Each 1°C rise in temperature led to a decrease in the cumulative daily number of COVID-19 confirmed cases by 5.18%. Likewise, Spearman correlation test results demonstrated that the average and maximum temperatures correlated negatively (p < 0.01) with the number of COVID-19 cases (Rosario et al., 2020). Not only in Brazil, but also in Latin America and the Caribbean (LAC), a negative relationship was shown between temperature and COVID-19 cases (Bolaño-Ortíz et al., 2020).

In the USA, from January 20, 2020, COVID-19 spread across its states at exponential rates (Holshue et al., 2020). In the US, states with maximum daily temperature above 52 °F (11 °C) showed an inverse relationship with the rate of new cases (incidence rate ratio = 0.85, 95% confidence interval (CI) = [0.76, 0.96], p = 0.009) (Sehra et al., 2020). A Gaussian function model demonstrated that deaths per million population in the largest cities of each state in the US peaked between 4 °C and 12 °C (Scatetta, 2020). Similar results were obtained in Mexico, where high temperatures established harsh conditions for SARS-CoV-2 survival and led to lower local transmission ratio and confirmed cases for a month (Méndez-Arriaga, 2020).

Although most data indicated an inverse association of viral spread with temperature, few findings were inconsistent with these. From March to April 2020, New York City experienced increasing new COVID-
19 confirmed cases and mortality rates along with increasing city temperatures that ranged between 0°C and 18°C (Bashir et al., 2020). Similarly, Brazil and China also reported a positive relationship between temperature and the number of COVID-19 cases. Five state capitals in Brazil showed a higher case rate at elevated temperatures (Auler et al., 2020). As for China, 112 cities located on the northeast side of mainland China as well as 31 major cities across China followed the positively associated tendency (Xie and Zhu, 2020; Yao et al., 2020a). Besides, positive correlation between temperature and COVID-19 was observed in India, Norway and Singapore studies (Das and Chatterjee, 2020; Gupta et al., 2020; Mangla et al., 2020; Menebo, 2020; Pani et al., 2020). Notably, although SARS-CoV-2 first spread in the temperate zone (Chennakesavulu and Reddy, 2020; Huang et al., 2020; Sajadi et al., 2020; Sarmadi et al., 2020), India and Singapore are located outside the temperate zone, while Norway is at the most northern edge of the temperate zone. Interestingly, some studies also reported no correlation between temperature and the local transmission of SARS-CoV-2 (Briz-Rédon and Serrano-Aroca, 2020; Chetty et al., 2020; Harbert et al., 2020; Wu et al., 2020a; Yao et al., 2020b) (Table 1).

Nevertheless, in the analysis of the association of temperature with
the local transmission of SARS-CoV-2, most studies reported, overall, an inverse relationship (Table 1 and Fig. 2). This is consistent with the general pattern observed for the global transmission of SARS-CoV-2 (Table 1).

4. Humidity tends to negatively correlate with the global transmission of SARS-CoV-2

Humidity, which is the concentration of water vapor present in the air is a decisive factor that determines the formation and size of aerosol droplets, which the virus can use as a medium to infect new hosts. Thus, humidity is an important meteorological variable that could affect the transmission of SARS-CoV-2 (Harper, 1961; Yang and Marr, 2011).

Pearson correlation analysis showed that RH is negatively correlated with the log of cases per million population \( (r_H = -0.23 \text{ with } P_{151}(-1 \leq r \leq 0.1) = 0.2\% ) \) and the log of deaths per million population \( (r_H = -0.31, P_{151}(-1 \leq r \leq 0.1) \leq 0.01\% ) \) (Scafetta, 2020). When the effect of RH on daily new cases and daily new deaths was log-linearly analyzed using a GAM, a 1% increase in RH was associated with a 0.85% (95% CI = [0.51%, 1.19%]) reduction in the daily new cases and a 0.51% (95% CI = [0.34%, 0.67%]) reduction in daily new deaths (Wu et al., 2020b).

A weighted random-effects regression analysis was concluded and showed that the epidemic growth of COVID-19 was reciprocally associated with both RH (ratios of rate ratios [RRR] per 10% increase in RH = [0.85, 0.96]) and AH (RRR per 5 g/m\(^3\) = [0.92, 95% CI = [0.85, 0.96]) (Jüni et al., 2020). Congruently, studies using a LR model revealed a negative correlation between humidity and SARS-CoV-2 transmission (Metelmann et al., 2020; Sajadi et al., 2020). Only one study showed no correlation of humidity with global transmission of SARS-CoV-2 at all (Islam et al., 2020) (Table 2).

Overall, a fairly unequivocal effect of humidity on the global transmission of SARS-CoV-2 is observed (Table 2). Mounting evidence suggests that humidity negatively affects the global transmission of SARS-CoV-2 (Fig. 1).

5. Humidity may be a lesser determinant factor for local transmission of SARS-CoV-2

Till date, some studies have shown that humidity is negatively associated with SARS-CoV-2 transmission in China. In four major cities of China, RH correlated negatively with the reproductive rate \( (R_0) \) of SARS-CoV-2 \( (r = -0.391, p = 0.000) \) (Guo et al., 2020). Similar patterns were reported for AH, because a 1 g/m\(^3\) increase in AH resulted in a decrease of 0.92 in the overall relative risk in 17 capital cities of China (Liu and Zhang, 2020).

Besides China, in some countries such as Spain, Italy, Turkey, LAC, and India, RH and SH were found to be inversely associated with local COVID-19 cases (Table 2). A polynomial regression analysis of cumulative data showed that SH is negatively associated with SARS-CoV-2 transmission in Spain (Sanchez-Lorenzo et al., 2021). A Pearson correlation analysis of regions in Italy revealed that RH is negatively correlated with the log of deaths per million population \( (r_H = -0.37, P_20(-1 \leq r \leq \text{SH}) = 5.4\%) \) (Scafetta, 2020). The same study showed, using a Gaussian function model, that states in the US with RH levels between 60 and 75% were the most affected by COVID-19, accounting for 80% of deaths in the USA. Studies that analyzed the association of humidity with COVID-19 cases using Spearman correlation analysis also drew consistent results. In New Delhi, RH was negatively associated with the number of daily COVID-19 infections between March 4 and June 24, 2020 \( (r_H = -0.63, p < 0.05) \) (Mangla et al., 2020). In addition, the number of COVID-19 infections was found to be negatively associated with SH in India (Gupta et al., 2020). In agreement, analysis of the data collected from 9 cities in Turkey between March 10 and April 5, 2020, revealed a negative relationship between RH and SARS-CoV-2 transmission \( (r_H = -0.317) \) (Sašin, 2020).

Contrarily, other studies indicated that humidity has no or a positive effect on the transmission of SARS-CoV-2 in China. In 31 Chinese provinces, a negative relationship between RH and doubling time of cumulative COVID-19 cases was shown; meaning that RH was positively associated with the rate of local COVID-19 progression (Oliveiros et al., 2020). Another analysis of data from 16 Chinese provinces concluded that RH and SARS-CoV-2 transmission rates have no significant spatial correlation \( (R = -0.17, p = 0.48) \) (Lin et al., 2020a). Similarly, multiple other studies did not find a significant association between RH and SARS-CoV-2 transmission in China (Li et al., 2020b; Metelmann et al., 2020; Rahman et al., 2020; Yao et al., 2020b).

Humidity was also observed to have a positive relationship with local SARS-CoV-2 transmission rates in the USA, Singapore, and the Netherlands (Table 2). When the relationship between RH and SARS-CoV-2 transmission in the USA was investigated using a distributed lag non-linear model with data collected from California, high RH was a

| Table 2 The impact of humidity on the transmissibility of COVID-19. |
|-----------------------|---------------------|-----------------|----------|
| Relation               | Country             | Statistical method used          | Ref.     |
| Absolute humidity (AH) | Negative            | Weighted random-effects regression | Jüni et al. (2020)                              |
| Global (>50 countries) | China               | Meta-analysis with generalized linear models | Liu et al. (2020b)                              |
| Positive              | Netherlands         | Pearson correlation; spatiotemporal model | Raveli and Gonzalez-Martinez (2020) |
| Singapore             | Spearman-Kendall correlation test | Pani et al. (2020) |
| Worldwide (5 countries)| Multivariate LR model | Luo et al. (2020) |
| Relative humidity (RH) | Negative            | Weighted random-effects regression | Jüni et al. (2020)                              |
| Global (>50 countries) | Multivariate LR model | Metelmann et al. (2020) |
| China                 | SEIR model with simple LR model; Pearson correlation | Wu et al. (2020b) |
| India                 | Spearman correlation | Guo et al. (2020) |
| Turkey                | Spearman correlation | Qii et al. (2020) |
| Positive              | Multivariate Poisson regression models | Oliveira et al. (2020) |
| No                    | Multilevel mixed-effects regression model | Islam et al. (2020) |
| Global (>50 countries)| Brazil              | Spearman correlation | Rosario et al. (2020) |
| China                 | Spearman rank correlation | Li et al. (2020b) |
| USA                   | Combination of linear and exponential regression models | Fang et al. (2020) |
| Specific humidity (SH) Negative | Global (>50 countries) | Simple LR | Sajadi et al. (2020) |
| India                 | GAM | Polynomial regression analysis | Gupta et al. (2020) |
| Spain                 |                | Sanchez-Lorenzo et al. (2021) | |
risk factor; RH of around 98% was related to an increased risk of SARS-CoV-2 transmission (RR = 1.703, 95% CI = [1.049, 2.765]) (Fang et al., 2020). In Singapore, both RH and AH were positively correlated to new COVID-19 cases, when analyzed using Spearman (RH: \( r_s = 0.21, p < 0.05 \); AH: \( r_s = 0.59, p < 0.01 \)) and Kendall rank correlation analyses (RH: \( \tau = 0.15, p < 0.05 \); AH: \( \tau = 0.45, p < 0.001 \)) (Pani et al., 2020). The average RH was 91% and the average AH was 22 g/m\(^3\) over the period of the data collection. In the Netherlands, from March to July 2020, a spatiotemporal disease model affirmed that SH was strongly correlated with the number of daily COVID-19 cases (\( r = 0.701, p = 0.000 \); \( r_s = 0.838, p = 0.000 \)) (Ravelli and Gonzales Martinez, 2020).

Overall, humidity may be a lesser determinant factor for local SARS-CoV-2 transmission (Fig. 3). Nevertheless, we cannot exclude the possibility that these inconsistent findings in the relationship between humidity and local transmission of SARS-CoV-2 may be attributed to sample size differences. Further studies are needed to clearly address the relationship between (absolute, relative, and specific) humidity and COVID-19 transmissibility.

6. Other meteorological factors related to SARS-CoV-2 transmission: Air pollution, wind speed, latitude, precipitation and solar radiation

Air pollution, wind speed, latitude, precipitation, and solar radiation are influential factors in determining seasonality in other respiratory viral infections (Domingo et al., 2020; du Prel et al., 2009; Price et al., 2019). However, whether there is a link between COVID-19 transmissibility and the aforementioned meteorological factors remains unclear (Table 3). As compared to temperature or humidity, fewer results are published regarding their possible contribution to SARS-CoV-2 transmission (Table 3). Additionally, the studies included in this review did not report cohesive results to indicate a distinct relationship between each of the factors and the transmission of SARS-CoV-2 (Figs. 2 and 3).

7. Discussion

Meteorological factors play a vital role in the transmissibility of HCoVs. In general, human and animal CoVs show a much higher persistence under low temperature and low RH (Aboubakr et al., 2020). Similarly, the spread of SARS-CoV-2 could be seasonally associated with the colder months. This phenomenon may be closely related to the increased persistence of airborne aerosols under a low temperature and low humidity environment, which increase the chance of infection of a new host (Harper, 1961). The amount of water vapor that a unit of air can hold diminishes at lower temperatures, and a reduction in the size of aerosol droplets occurs at lower humidity due to evaporation (Yang and Marr, 2011).

Higher persistence of SARS-CoV-2 resulting from low temperature could also be explained by the effects of temperatures on the structure of viruses. In high-temperature environments, the order of phospholipids in the viral envelope is disrupted, thus hindering the stability of the viral envelope (Polozov et al., 2008). Higher infectivity in low-temperature conditions could also be attributed to the changes in the receptor-binding motif (RBM) conformation. At temperatures between 10 and 30°C, the RBM is in an open conformation, which is more favorable for host cell receptor recognition and binding (Rath and Kumar, 2020).

It is also evident that meteorological factors have a strong impact on host susceptibility (Dowell, 2001; Fisman, 2007). A typical example would be the effects of temperature and humidity on the mucosal layer lining of the host respiratory tract (Moriyama et al., 2020). Prior studies found that both lower temperature and humidity trigger mucus hypersecretion, which impede the appropriate removal of viruses or foreign substances by the host mucociliary mechanisms, leading to increased virion stability in the host upper respiratory mucosa (Lowen et al., 2007; ...
perception leads to fluctuations in certain gene expression levels (Dop et al., 2019). Furthermore, decreased body temperature is linked with epithelial cell integrity and impairs the re-epithelialization process, -Tian and Wen, 2015; Wise et al., 2018). Reduced humidity also damages transmissibility of COVID-19.

The impact of other meteorological factors (w/o temperature, humidity) on the transmission of COVID-19.

| Relation | Country | Statistical method used | Ref. |
|----------|---------|-------------------------|------|
| Air pollution | Negative China | Simple LR model; Spearman correlation | Yao et al. (2020a) |
| | Negative India | GAM | Das and Chatterjee (2020) |
| | Positive USA | Spearman correlation; Kendall correlation | Bashir et al. (2020) |
| | Positive China | Simple LR model | Li et al. (2020a) |
| | Positive USA | Negative binomial mixed models | Wu et al. (2020a) |
| Latitude | Negative Global (≥50 countries) | Stepwise LR model | Metelmann et al. (2020) |
| | Positive Global (≥50 countries) | Spearman correlation | Bezabih et al. (2020) |
| | No Global (≥50 countries) | Pearson correlation | Sarmadi et al. (2020) |
| | No Brazil | Spearman correlation | Rosario et al. (2020) |
| | No India | Spearman correlation | Mangle et al. (2020) |
| Solar radiation/UV | Negative Global (≥50 countries) | Simple LR model | Iqbal et al. (2020) |
| | Negative Brazil | Stepwise LR model | Metelmann et al. (2020) |
| | Negative China | Spearman correlation | Rosario et al. (2020) |
| | Positive India | LR model | Li et al. (2020a) |
| | Positive Global (≥50 countries) | Multivariate LR model (by panel data strategy) | Sobral et al. (2020) |
| | No Global (≥50 countries) | Spearman correlation | Bezabih et al. (2020) |
| | No Brazil | Spearman correlation | Rosario et al. (2020) |
| | No India | Spearman correlation | Metelmann et al. (2020) |
| | No USA | Multivariate LR model | Yao et al. (2020b) |
| Wind speed | Negative Brazil | Spearman correlation | Rosario et al. (2020) |
| | Negative Singapore | Spearman/Kendall correlation test | Pani et al. (2020) |
| | No India | Spearman correlation | Mangle et al. (2020) |
| | No Norway | Spearman correlation | Metelmann et al. (2020) |

Reduced humidity also damages epithelial cell integrity and impairs the re-epithelialization process, allowing easier opportunities for the transmission of infection (Kudo et al., 2019). Furthermore, decreased body temperature is linked with lower expression of interferon-stimulated genes that are actively involved in the primary antiviral defense mechanisms (Foxman et al., 2015; Ivashkov and Donlin, 2014).

Factors such as solar radiation may alter the seasonal perceptions of the human body by inducing changes in the melatonin mediated circadian rhythm (Nelson and Drazen, 1999). Such shifts in the seasonal perception leads to fluctuations in certain gene expression levels (Dopico et al., 2015; Goldinger et al., 2015). About 147 genes in our immune system are affected by meteorological changes; they are also associated with the processes involving B-cell receptor signaling, Fc receptor-gamma-associated processes, lysosomes, chemokine signaling, and phagosomes (Dopico et al., 2015). The same study proposed that the immune system-related genes are observed in a higher inflammatory status during winter months. This raises the likelihood of cardiovascular, autoimmune, and neurological diseases, further leading to human immune system susceptibility to viral infection.

Population density is another possible contributing factor to a high SARS-CoV-2 transmission rate (Diao et al., 2021; Li et al., 2018; Randolph and Barreiro, 2020; Sil and Kumar, 2020; Tarwater and Martin, 2001). A positive correlation between the population density of an area and the transmission rate has also been observed for viruses other than SARS-CoV-2, emphasizing the importance of taking population density into account when studying the seasonality of SARS-CoV-2 (Vanden Broecke et al., 2019). Mounting evidence suggests that population density has a high impact on the spread of COVID-19 by affecting contact rates (de Lusignan et al., 2020; Han et al., 2021; Kodera et al., 2020; Rocklov and Sjödin, 2020; Tamnes, 2020). The differences in the targeted region’s population density could be a possible reason for the contradictory reports on the effect of various meteorological factors. Studies that collected data from cities with higher population densities reported a positive relationship between meteorological factors and SARS-CoV-2 transmission and vice versa (Bashir et al., 2020; Das and Chatterjee, 2020; Menebo, 2020; Pedrosa, 2020). Besides population density, variability in population behavior, air pollution, sewage, natural water has been proposed as other factors that may contribute to the different transmission rates of SARS-CoV-2 (Al Huraimel et al., 2020; Bontempi et al., 2020; Bontempi, 2020, 2021; Courtemanche et al., 2020; Liu et al., 2020a; Tamnes, 2020). Behavioral measures such as wearing of masks have been proven to effectively prevent the spread of other known viruses like the influenza virus (Greenhalgh et al., 2020; Liu and Zhang, 2020). Such results indicate that other social factors should be considered when looking into the possible seasonality of COVID-19.

It is important to mention that this review could not have avoided some methodological limitations. Firstly, most studies included in this review only considered the effects of meteorological factors on SARS-CoV-2 transmission, while neglecting the effects of factors that are dependent on human-to-human interaction. Such factors include social and economic factors such as population density, population behavior, lockdown policies and telecommuting. Certainly, there is a consensus on the fact that virus transmission is mainly caused by human-to-human interaction. Thus, any analysis claiming to find strong correlations without considering human-to-human interaction cannot establish a definite causal explanation (Bontempi, 2020). Secondly, each study included different types of data and utilized different methods in their analysis; these could possibly bring about contradictory findings amongst studies. For example, while some researchers used the absolute number of confirmed/death cases in their analysis, others employed a wide range of metrics such as the number of cumulative confirmed/death cases and incidence rate. Coupled with the disparity in the use of a consistent metric of viral transmission, the variability in data collection, data screening approaches and statistical procedures renders the comparison amongst studies as an arduous task. This is especially true when comparing studies from a wide range of locations, where elements other than meteorological factors such as socioeconomic, geographic factors and spatiotemporal patterns are involved in the COVID-19 contagion. Indeed, considering the aforementioned limitations, we are not making a hasty claim that meteorological conditions are the only causative factors or the dominant factor of SARS-CoV-2 transmission. However, we conclude that a clear pattern can be observed, which is an inverse forcing of temperature and humidity on the spread of COVID-19 on a global scale.
8. Conclusion

Several empirical and epidemiological studies have indicated that temperature and humidity are the most significant factors affecting SARS-CoV-2 transmission. Studies collectively agree with the inverse forcing of temperature and humidity (AH, RH, and SH) on the global transmission of SARS-CoV-2. These general tendencies observed for SARS-CoV-2 transmission is consistent with the survivability of other HCoVs in various environmental conditions. Based on the studies presented here, COVID-19 appears to be temperature-sensitive and, therefore, seasonal. Along with the other meteorological factors, such as air pollution, wind speed, etc., analyses on local regions drew ambiguous conclusions on the effect of humidity on SARS-CoV-2 transmission. These discrepancies could be the product of other social and biological factors, such as population density, population behavior, social distancing, and host susceptibility. Nevertheless, as the coronavirus pandemic has just completed a full seasonal cycle, further studies are desirable to corroborate the negative correlation of AH, RH, and SH with the SARS-CoV transmissibility at local scales, if possible, with increased sizes of datasets.

Credit roles

Woo Seok Byun, Investigation, Validation, Writing – original draft, Writing – review & editing. Sin Woo Heo, Investigation, Writing – original draft, Writing – review & editing. Sunhee Jo, Investigation, Writing – original draft. Jae Won Kim, Conceptualization, Investigation, Writing – original draft. Sarang Kim, Investigation, Writing – original draft. Hyeyun Park, Investigation, Writing – original draft, Writing – review & editing. Jeahyun Baek, Conceptualization, Writing – original draft, Writing – review & editing. Supervision.

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.

References

Aboubakr, H.A., et al., 2020. Stability of SARS-CoV-2 and other coronaviruses in the environment and on common touch surfaces and the influence of climatic conditions: a review. Transboundary and Emerging Diseases 1–17. https://doi.org/10.1111/tbed.13707, 2020.
Al Huraimel, K., Alhosani, M., Kunhabdulla, S., Stietiya, M.H., 2020. SARS-CoV-2 in the environment: modes of transmission, early detection and potential role of pollution. Sci. Total Environ. 744, 140946. https://doi.org/10.1016/j.scitotenv.2020.140946.
Anna, F., et al., 2020. High sero prevalence but short-lived immune response to SARS-CoV-2 transmission. Studies collectively agree with the inverse forcing of temperature and humidity (AH, RH, and SH) on the global transmission of SARS-CoV-2. These general tendencies observed for SARS-CoV-2 transmission is consistent with the survivability of other HCoVs in various environmental conditions. Based on the studies presented here, COVID-19 appears to be temperature-sensitive and, therefore, seasonal. Along with the other meteorological factors, such as air pollution, wind speed, etc., analyses on local regions drew ambiguous conclusions on the effect of humidity on SARS-CoV-2 transmission. These discrepancies could be the product of other social and biological factors, such as population density, population behavior, social distancing, and host susceptibility. Nevertheless, as the coronavirus pandemic has just completed a full seasonal cycle, further studies are desirable to corroborate the negative correlation of AH, RH, and SH with the SARS-CoV transmissibility at local scales, if possible, with increased sizes of datasets.

Credit roles

Woo Seok Byun, Investigation, Validation, Writing – original draft, Writing – review & editing. Sin Woo Heo, Investigation, Writing – original draft, Writing – review & editing. Sunhee Jo, Investigation, Writing – original draft. Jae Won Kim, Conceptualization, Investigation, Writing – original draft. Sarang Kim, Investigation, Writing – original draft. Hyeyun Park, Investigation, Writing – original draft, Writing – review & editing. Jeahyun Baek, Conceptualization, Writing – original draft, Writing – review & editing. Supervision.

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.

References

Aboubakr, H.A., et al., 2020. Stability of SARS-CoV-2 and other coronaviruses in the environment and on common touch surfaces and the influence of climatic conditions: a review. Transboundary and Emerging Diseases 1–17. https://doi.org/10.1111/tbed.13707, 2020.
Al Huraimel, K., Alhosani, M., Kunhabdulla, S., Stietiya, M.H., 2020. SARS-CoV-2 in the environment: modes of transmission, early detection and potential role of pollution. Sci. Total Environ. 744, 140946. https://doi.org/10.1016/j.scitotenv.2020.140946.
Anna, F., et al., 2020. High sero prevalence but short-lived immune response to SARS-CoV-2 transmission. Studies collectively agree with the inverse forcing of temperature and humidity (AH, RH, and SH) on the global transmission of SARS-CoV-2. These general tendencies observed for SARS-CoV-2 transmission is consistent with the survivability of other HCoVs in various environmental conditions. Based on the studies presented here, COVID-19 appears to be temperature-sensitive and, therefore, seasonal. Along with the other meteorological factors, such as air pollution, wind speed, etc., analyses on local regions drew ambiguous conclusions on the effect of humidity on SARS-CoV-2 transmission. These discrepancies could be the product of other social and biological factors, such as population density, population behavior, social distancing, and host susceptibility. Nevertheless, as the coronavirus pandemic has just completed a full seasonal cycle, further studies are desirable to corroborate the negative correlation of AH, RH, and SH with the SARS-CoV transmissibility at local scales, if possible, with increased sizes of datasets.

Credit roles

Woo Seok Byun, Investigation, Validation, Writing – original draft, Writing – review & editing. Sin Woo Heo, Investigation, Writing – original draft, Writing – review & editing. Sunhee Jo, Investigation, Writing – original draft. Jae Won Kim, Conceptualization, Investigation, Writing – original draft. Sarang Kim, Investigation, Writing – original draft. Hyeyun Park, Investigation, Writing – original draft, Writing – review & editing. Jeahyun Baek, Conceptualization, Writing – original draft, Writing – review & editing. Supervision.

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.

References

Aboubakr, H.A., et al., 2020. Stability of SARS-CoV-2 and other coronaviruses in the environment and on common touch surfaces and the influence of climatic conditions: a review. Transboundary and Emerging Diseases 1–17. https://doi.org/10.1111/tbed.13707, 2020.
Al Huraimel, K., Alhosani, M., Kunhabdulla, S., Stietiya, M.H., 2020. SARS-CoV-2 in the environment: modes of transmission, early detection and potential role of pollution. Sci. Total Environ. 744, 140946. https://doi.org/10.1016/j.scitotenv.2020.140946.
Anna, F., et al., 2020. High sero prevalence but short-lived immune response to SARS-CoV-2 transmission. Studies collectively agree with the inverse forcing of temperature and humidity (AH, RH, and SH) on the global transmission of SARS-CoV-2. These general tendencies observed for SARS-CoV-2 transmission is consistent with the survivability of other HCoVs in various environmental conditions. Based on the studies presented here, COVID-19 appears to be temperature-sensitive and, therefore, seasonal. Along with the other meteorological factors, such as air pollution, wind speed, etc., analyses on local regions drew ambiguous conclusions on the effect of humidity on SARS-CoV-2 transmission. These discrepancies could be the product of other social and biological factors, such as population density, population behavior, social distancing, and host susceptibility. Nevertheless, as the coronavirus pandemic has just completed a full seasonal cycle, further studies are desirable to corroborate the negative correlation of AH, RH, and SH with the SARS-CoV transmissibility at local scales, if possible, with increased sizes of datasets.

Credit roles

Woo Seok Byun, Investigation, Validation, Writing – original draft, Writing – review & editing. Sin Woo Heo, Investigation, Writing – original draft, Writing – review & editing. Sunhee Jo, Investigation, Writing – original draft. Jae Won Kim, Conceptualization, Investigation, Writing – original draft. Sarang Kim, Investigation, Writing – original draft. Hyeyun Park, Investigation, Writing – original draft, Writing – review & editing. Jeahyun Baek, Conceptualization, Writing – original draft, Writing – review & editing. Supervision.

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.

References

Aboubakr, H.A., et al., 2020. Stability of SARS-CoV-2 and other coronaviruses in the environment and on common touch surfaces and the influence of climatic conditions: a review. Transboundary and Emerging Diseases 1–17. https://doi.org/10.1111/tbed.13707, 2020.
Al Huraimel, K., Alhosani, M., Kunhabdulla, S., Stietiya, M.H., 2020. SARS-CoV-2 in the environment: modes of transmission, early detection and potential role of pollution. Sci. Total Environ. 744, 140946. https://doi.org/10.1016/j.scitotenv.2020.140946.
Anna, F., et al., 2020. High sero prevalence but short-lived immune response to SARS-CoV-2 transmission. Studies collectively agree with the inverse forcing of temperature and humidity (AH, RH, and SH) on the global transmission of SARS-CoV-2. These general tendencies observed for SARS-CoV-2 transmission is consistent with the survivability of other HCoVs in various environmental conditions. Based on the studies presented here, COVID-19 appears to be temperature-sensitive and, therefore, seasonal. Along with the other meteorological factors, such as air pollution, wind speed, etc., analyses on local regions drew ambiguous conclusions on the effect of humidity on SARS-CoV-2 transmission. These discrepancies could be the product of other social and biological factors, such as population density, population behavior, social distancing, and host susceptibility. Nevertheless, as the coronavirus pandemic has just completed a full seasonal cycle, further studies are desirable to corroborate the negative correlation of AH, RH, and SH with the SARS-CoV transmissibility at local scales, if possible, with increased sizes of datasets.

Credit roles

Woo Seok Byun, Investigation, Validation, Writing – original draft, Writing – review & editing. Sin Woo Heo, Investigation, Writing – original draft, Writing – review & editing. Sunhee Jo, Investigation, Writing – original draft. Jae Won Kim, Conceptualization, Investigation, Writing – original draft. Sarang Kim, Investigation, Writing – original draft. Hyeyun Park, Investigation, Writing – original draft, Writing – review & editing. Jeahyun Baek, Conceptualization, Writing – original draft, Writing – review & editing. Supervision.

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.

References
Wu, X., et al., 2020a. Air pollution and COVID-19 mortality in the United States: strengths and limitations of an ecological regression analysis. Science Advances 6 (45), eabd4049. https://doi.org/10.1126/sciadv.abd4049.

Wu, Y., et al., 2020b. Effects of temperature and humidity on the daily new cases and new deaths of COVID-19 in 166 countries. Sci. Total Environ. 729, 139051. https://doi.org/10.1016/j.scitotenv.2020.139051.

Xie, J., Zhu, Y., 2020. Association between ambient temperature and COVID-19 infection in 122 cities from China. Sci. Total Environ. 724, 138201. https://doi.org/10.1016/j.scitotenv.2020.138201.

Yang, W., Marr, L.C., 2011. Dynamics of airborne influenza A viruses indoors and dependence on humidity. PloS One 6, e21481. https://doi.org/10.1371/journal.pone.0021481.

Yao, M., et al., 2020a. On airborne transmission and control of SARS-Cov-2. Sci. Total Environ. 731 https://doi.org/10.1016/j.scitotenv.2020.139178, 139178.

Yao, Y., et al., 2020b. No association of COVID-19 transmission with temperature or UV radiation in Chinese cities. Eur. Respir. J. 55, 2000517. https://doi.org/10.1183/13993003.00517-2020.

Ye, Z.-W., et al., 2020. Zoonotic origins of human coronaviruses. Int. J. Biol. Sci. 16 (10), 1686–1697. https://doi.org/10.7150/ijbs.45472.