Article

Progress in Physical Geography
2020, Vol. 44(5) 591–604

DOI: 10.1177/0309133320946302
journals.sagepub.com/home/ppg
SAGE

The effect of climate on the spread of the COVID-19 pandemic: A review of findings, and statistical and modelling techniques

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Abstract

The new SARS-CoV-2 coronavirus has spread rapidly around the world since it was first reported in humans in Wuhan, China, in December 2019 after being contracted from a zoonotic source. This new virus produces the so-called coronavirus 2019 or COVID-19. Although several studies have supported the epidemiological hypothesis that weather patterns may affect the survival and spread of droplet-mediated viral diseases, the most recent have concluded that summer weather may offer partial or no relief of the COVID-19 pandemic to some regions of the world. Some of these studies have considered only meteorological variables, while others have included non-meteorological factors. The statistical and modelling techniques considered in this research line have included correlation analyses, generalized linear models, generalized additive models, differential equations, or spatio-temporal models, among others. In this paper we provide a systematic review of the recent literature on the effects of climate on COVID-19's global expansion. The review focuses on both the findings and the statistical and modelling techniques used. The disparate findings reported seem to indicate that the estimated impact of hot weather on the transmission risk is not large enough to control the pandemic, although the wide range of statistical and modelling approaches considered may have partly contributed to the inconsistency of the findings. In this regard, we highlight the importance of being aware of the limitations of the different mathematical approaches, the influence of choosing geographical units and the need to analyse COVID-19 data with great caution. The review seems to indicate that governments should remain vigilant and maintain the restrictions in force against the pandemic rather than assume that warm weather and ultraviolet exposure will naturally reduce COVID-19 transmission.

Keywords

COVID-19, SARS-Cov-2, systematic review, meteorological factors, non-meteorological factors, statistical methods, modelling techniques.

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I Introduction

The rapid spread of the COVID-19 pandemic caused by the severe acute respiratory syndrome (SARS)-CoV-2 pathogen, which started in Wuhan, Hubei Province, China in December 2019 (World Health Organization (WHO), 2020b) has had devastating global consequences in terms of health and economics. According to the WHO, the current COVID-19 outbreak has 5,304,772 confirmed cases and 342,029 deaths in 219 countries (WHO, 2020a) (as on 25 May 2020). The present zoonotic coronavirus is similar to the SARS coronavirus (~ 79% similarity) and the Middle East respiratory syndrome (MERS) (~50% similarity) (Jiang et al., 2020; Y Liu et al., 2020; Lu et al., 2020; Ren et al., 2020) and is more closely related (88–89% similarity) to two bat-derived coronaviruses, bat-SL-CoVZC45 and bat-SL-CoVZXC21 (Lai et al., 2020). The SARS-CoV-2 pathogen is stable for up to 3 h in aerosols and up to 4 h, 24 h, and 2–3 days on copper, cardboard, plastic or stainless steel surfaces, respectively (van Doremalen et al., 2020), showing that infections can easily be transmitted through the air (Bourouiba, 2020) via microdroplets or direct contact after touching contaminated surfaces. In fact, it can be spread faster than its two ancestors SARS-CoV and MERS-CoV (Vellingiri et al., 2020) via coughing, sneezing, touching or breathing (American Lung Association, 2020), and more easily via asymptomatic carriers (Bai et al., 2020; Singhal, 2020). Even though the SARS-CoV-2 lockdown produced positive results by flattening the epidemic curve (Tobías, 2020), the new coronavirus continues to spread globally. It has been speculated that climatic conditions can slow down the transmission of COVID-19, as happens with other viruses such as influenza (Shaman and Kohn, 2009), respiratory syncytial virus (Baker et al., 2019; Pitzer et al., 2015) and preliminary evidence from other coronaviruses (Baker et al., 2020) .

The ancestor SARS-CoV-1 rapidly lost viability at higher temperatures and higher relative humidity (e.g. 38°C and relative humidity of >95%) (Chan et al., 2011). The *in vitro* stability of SARS-CoV-2 experiments has shown that the virus is highly stable at 4°C but is sensitive to heat (Chin et al., 2020) and SARS-CoV-2 loses infectivity at normal core body temperature (37°C). However, small reductions at temperatures close to 37°C may substantially increase its viral stability (Kang, 2020). Many recent studies cited here have suggested a correlation between weather conditions and the COVID-19 pandemic in a similar way to other viral infections such as influenza. However, several other studies have reported contradictory results showing that meteorological conditions may not in fact be associated with the COVID-19 expansion. Some of these studies have considered only meteorological factors and others have included other important factors such as population density, which has been shown to be crucial in viral transmissions (Dalziel et al., 2018). The study by Baker et al. (2020) used a negative relationship between humidity and transmission to conclude that even if there was a strong negative relationship between climate and coronavirus transmission, it would not have much impact on COVID-19 cases because the susceptibility population is high. In addition, different statistical and modelling techniques have been used in all these recent studies, which must be analysed very carefully. Therefore, in this systematic review we perform an in-depth analysis of the findings and the statistical and modelling methods used in all the recent studies that have reported different associations between climatic factors (humidity, precipitation, radiation, temperature and wind speed) and COVID-19 transmission.

II Methods

A systematic review was made of the recent COVID-19 literature using three databases (Web of Science, PubMed and Google Scholar) to assess the effect of meteorological factors on the number of confirmed COVID-19 cases. The search was conducted with the Publish or Perish software (Harzing, 2020) considering the fields ‘Title words’ and ‘Keywords’ provided by this software and the R package easyPubMed (Fantini, 2019). The search string used was “(weather OR climate OR climatic OR meteorology OR meteorological OR atmosphere OR atmospheric OR temperature OR humidity OR precipitation OR rain OR pressure OR wind) AND (covid OR covid-19 OR SARS-CoV-2)”. This search was conducted on 16 May and yielded 1357 papers for examination: 196 from Google Scholar considering the ‘Title words’ field of Publish or Perish, 800 from Google Scholar considering the ‘Keywords’ field of Publish or Perish (the search was limited to 800 results), and 361 from PubMed. The Web of Science webpage was explored to confirm that no relevant papers on the topic of interest were missing. Both authors then examined the whole dataset of extracted papers separately by reading the title and abstract. Papers presumably containing a statistical and/or modelling analysis of the effect of one or several climatic factors on COVID-19 expansion were preselected. After resolving the discrepancies between the authors’ preselection, the remaining papers (131) were considered for further inspection. In this stage, both authors read the full content of the papers and selected for the review only those studies that included an original statistical and/or modelling analysis on the effect of climate on the spread of COVID-19. A total of 61 papers were finally available for the review.

III Findings

3.1 Meteorological variables

Figure 1 lists all the 61 studies selected for this systematic review, indicating the type of association (negative, positive, no association, association dependent on the value, unclear association, and not analysed) found between each of the meteorological variables considered (humidity, precipitation, radiation, temperature, and wind speed) and the spread of COVID-19.

Figure 2 summarizes the number of recent studies concluding different types of COVID-19 association with the aforementioned climatic variables.

These results can also be analysed by data reported in each zone of the world (Table 1).

3.1.1 Temperature. Most studies (33 out of 61) suggest a negative correlation between COVID-19 and temperature. A negative correlation was found in worldwide studies (Arumugam et al., 2020; Caspi et al., 2020; Chiyomaru and Takemoto, 2020; Notari, 2020; Pirouz et al., 2020; Sajadi et al., 2020; X Wu et al., 2020; Yu, 2020), in California (Gupta and Gupta, 2020), Japan (Ujiie et al., 2020), Ghana (Abdul et al., 2020), Spain (Abdollahi and Rahbaralam, 2020; Tobías and Molina, 2020), Italy (Livadiotis, 2020) and in China (Oliveiros et al., 2020; Qi et al., 2020; Shi et al., 2020; Sil and Kumar, 2020). However, other studies came to the opposite conclusion (6 out of 61): a positive correlation between COVID-19 and temperature in Jakarta (Tosepu et al., 2020) and New York (Bashir et al., 2020), or no association (9 out of 61) in countries such as Spain (Briz-Redón and Serrano-Aroca, 2020), Iran (Ahmadi et al., 2020; Jahangiri et al., 2020), Nigeria (Taiwo and Fashola, 2020) and in a worldwide study (Jamil et al., 2020). Two worldwide analyses (Kassem,2020) and another one in China (Shahzad et al., 2020) found an unclear association between temperature and COVID-19, or an association depending on the temperature range (11 out of 61) in countries such as Brazil (Auler et al., 2020; Prata et al., 2020), China (Zhu and Xie, 2020) and India (Dangi and George, 2020).

All the studies considered in this systematic review thus obtained controversial results and none found clear evidence that a temperature rise reduces case counts of COVID-19. Nonetheless, most studies suggest a negative correlation

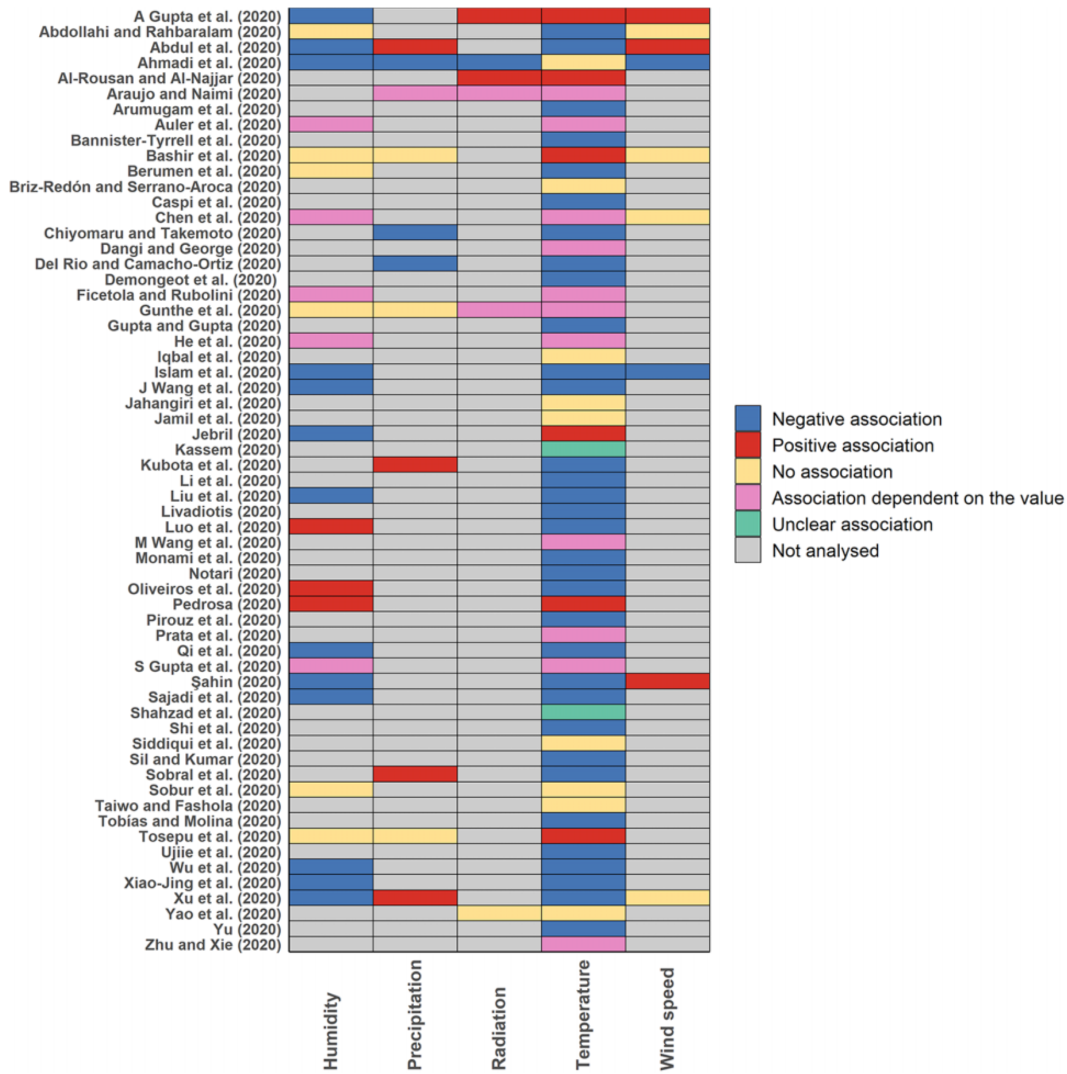

Figure 1. Associations of weather conditions in terms of humidity, precipitation, radiation, temperature, and wind speed with COVID-19 transmission: studies concluding different type of associations with climate variables (negative, positive, no association, association dependent on value, unclear association and not analysed)

between COVID-19 and temperature, which, in combination with *in vitro* experiments on the stabilizing effect of temperature on the virus (Chin et al., 2020), suggest that summer weather could reduce COVID-19 transmission to some extent, but probably not enough to stop the pandemic, in agreement with the rigorous studies by Xu et al. (2020) and Yao et al. (2020), who came to the same conclusion. However, these findings need to be interpreted cautiously given the existing uncertainty of the COVID-19 data and the possible influence of the statistical and modelling framework on the results.

3.1.2 Humidity. Many of the studies presented in Figure 2 show a negative correlation between

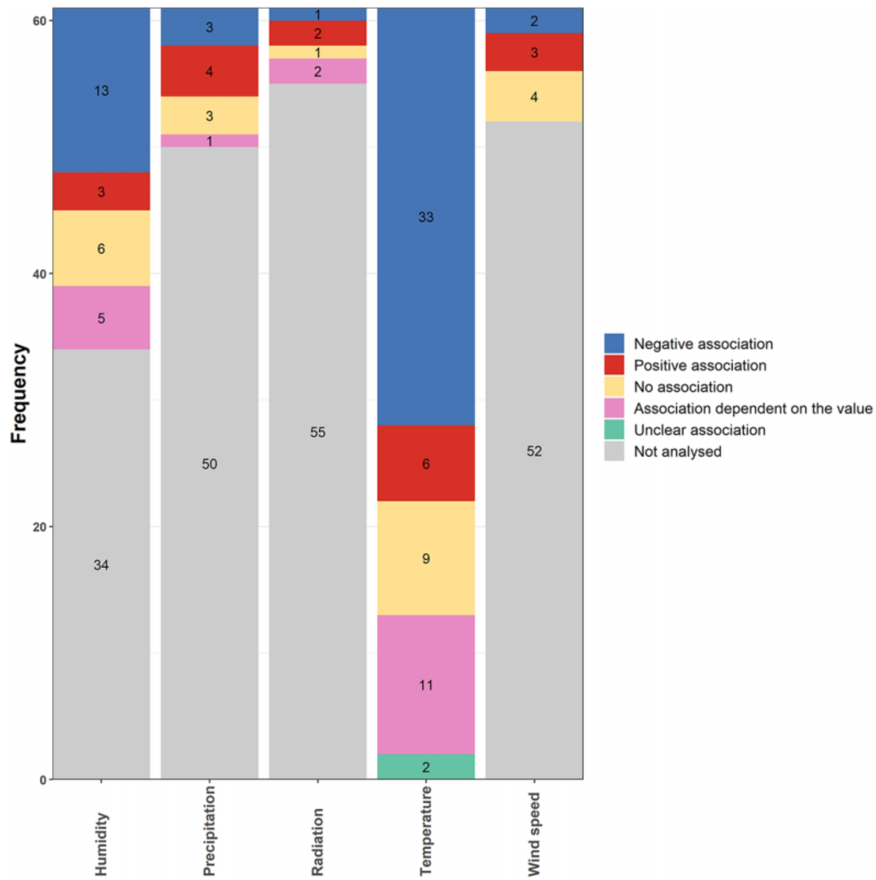

Figure 2. Associations of weather conditions in terms of humidity, precipitation, radiation, temperature, and wind speed with COVID-19 transmission: number of studies concluding different types of association (negative, positive, no association, association dependent on the value, unclear association and not analysed).

COVID-19 and humidity (13 out of 27) in a worldwide context (X Wu et al., 2020), Mainland China (Qi et al., 2020), Ghana (Abdul et al., 2020), India (Ahmadi et al., 2020) and Iraq (Jebril, 2020). However, other studies suggest the opposite association, showing a positive correlation between COVID-19 and humidity (3 out of 27) in China (Luo et al., 2020; Oliveiros et al., 2020) and in a worldwide study (Pedrosa, 2020), or no association (6 out of 27) such as those on New York (Bashir et al., 2020) and Jakarta (Tosepu et al., 2020).

The findings on the effect of temperature and humidity on COVID-19 transmissibility can, therefore, be said to possess wide variability, even though a negative trend can be appreciated (see Figure 2).

3.1.3 Precipitation, radiation and wind speed. The association between COVID-19 and other meteorological factors such as precipitation, radiation and wind speed have hardly been analysed and the findings are unclear (see Figure 2).

In addition to the observation that SARS-CoV-2 has a lower survival rate at higher temperatures, these studies have been interpreted by some as providing enough evidence to assume that rising temperatures in summer are likely to

Table 1. Associations of weather conditions, in terms of humidity, precipitation, radiation, temperature and wind speed, with COVID-19 transmission: number of studies concluding different types of associations that have been conducted with data reported in each zone of the world.

	Humidity						Precipitation						Radiation						Temperature						Wind speed					
	Neg	Pos	No	Dep	Unc	NA	Neg	Pos	No	Dep	Unc	NA	Neg	Pos	No	Dep	Unc	NA	Neg	Pos	No	Dep	Unc	NA	Neg	Pos	No	Dep	Unc	NA
Africa	1	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	2	1	0	1	0	0	0	0	1	0	0	0	1
Asia	8	2	1	1	0	13	2	0	1	0	0	22	1	2	1	0	0	21	11	4	5	4	1	0	1	2	0	0	0	22
Europe	1	0	1	0	0	2	0	0	0	0	0	4	0	0	0	0	0	4	3	0	1	0	0	0	0	0	1	0	0	3
North America	0	0	1	1	0	3	0	0	1	0	0	4	0	0	0	0	0	5	3	1	0	1	0	0	0	0	1	0	0	4
South America	0	0	0	1	0	1	0	0	0	0	0	2	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	2
World	3	1	3	2	0	14	1	3	1	1	0	17	0	0	0	2	0	21	15	1	2	4	1	0	1	0	2	0	0	20
Total	13	3	6	5	0	34	3	4	3	1	0	50	1	2	1	2	0	55	33	6	9	11	2	0	2	3	4	0	0	52

Neg: negative; Pos: positive; No: no association; Dep: association dependent on the value; Unc: unclear association; NA: not analysed.

facilitate COVID-19 control. However, the ability of SARS-CoV-2 to effectively spread globally suggests that weather cannot be considered a key modulating factor in its transmissibility according to this analysis. Further studies on the impact of climate variability, air pollution and other extrinsic factors on its transmission will need to consider population movements in locations with a high incidence, population susceptibility and respiratory infections, among many other factors.

3.2 Non-meteorological variables

With so many contradictory findings, the results of this systematic review are quite surprising. However, these differences could be attributed to the fact that some studies only considered meteorological factors in the statistical and/or modelling analysis. We believe that these meteorological variables alone cannot explain most of the variability in the disease's transmission. The fact that different statistical and modelling techniques were used should also be considered (see Table S1).

Some studies considered several non-meteorological parameters (Ahmadi et al., 2020; Briz-Redón and Serrano-Aroca, 2020) such as population density, population age, number of companies, number of travellers and inter-provincial movement for the analysis. In Iran, the results obtained confirm that population size has high sensitivity (Jahangiri et al., 2020) and suggests that the cities/provinces with a population of over 1.7 million people should impose stricter inspections and controls as their management policy. Other studies considered the role of climate (temperature and precipitation), region-specific susceptibility (Bacillus Calmette–Guérin vaccination, malarial infection and the elderly population) and international travellers (human mobility) in shaping the geographical patterns of COVID-19 cases across 1055 countries/regions (Kubota et al., 2020). In this study, the relative frequency of foreign visitors per population was predominantly positively correlated with the accumulated numbers of COVID-19 cases, while the effects of vaccination and malarial infection were negatively correlated. The population density was slightly positively correlated and the relative frequency of people $\geq$65 years old was also positively correlated with the accumulated numbers of COVID-19 cases.

The results of the study on 50 US states and 110 countries suggest that population density should be used as a control variable (Pedrosa, 2020), for example, US states with a high proportion of Afro-American residents are associated with increased COVID-19 cases (Li et al., 2020). However, the various suggested mechanisms, such as socioeconomic and healthcare predispositions, did not appear to drive the effect of race in the statistical model. Multivariate regression analyses showed that Afro-Americans are at higher risk of worse COVID-19 outcomes, regardless of comorbidities, poverty, access to healthcare and other mitigating factors.

IV Statistical and modelling method

The variety of the findings found in the current scientific literature on the relationship between climatic factors and the COVID-19 transmission is consistent with the wide range of statistical and modelling methods considered by the authors, which we summarize here, highlighting their strengths and weaknesses. A detailed list of the main statistical and modelling techniques that support the findings of each of the papers reviewed is available in Table S1 in Supplementary Material. The many different statistical and modelling methods used and the different zones, geographical units and temporal windows used probably influenced the different findings obtained.

The results of many of the papers reviewed are solely or partly based on the correlation (Pearson's or Spearman's rank correlation) between one or several climatic factors and the number of cumulative or daily COVID-19 cases. This analytic approach can often lead to spurious associations. Indeed, computing correlation coefficients between two time series (e.g. two time series representing, respectively, the number of daily COVID-19 cases and daily average temperatures) do not account for the possible presence of temporal trends in the data, which can strongly affect the correlation value and yield artefactual associations. Hence, correlation coefficients should be used with extreme caution; they are mainly recommended as an exploratory tool before carrying out a more sophisticated analysis.

Several other studies share the use of simple or multiple regression models, sometimes including quadratic or cubic terms for the climatic variables involved in the model. Regression models allow for the consideration of multiple variables that are possibly implicated in the spread of the disease. The fact of accounting for the effect of multiple variables simultaneously entails the need to ensure that multicollinearity issues, namely strong correlations between the variables, are not present in the data being analysed. In particular, it is well known that meteorological variables are highly correlated (Guan et al., 2007). Correlation coefficients or variance inflation factors (Fox, 1991) can be used to discard such issues or to avoid the inclusion of two highly correlated variables in the model. However, this type of preliminary analysis was not included in many of the studies reviewed. Besides these issues, the classical regression model is insufficient to account for certain data characteristics that are very possibly present when one conducts an ecological analysis of the evolution of an infectious disease.

Other authors have there fore made use of more sophisticated mathematical approaches, including Susceptible–Infectious–Recovered–Susceptible (SIRS) models (Bailey, 1975), Susceptible–Exposed–Infectious–Recovered (SEIR) models (Hethcote, 2000), generalized linear models (GLMs) (Nelder and Wedderburn, 1972), generalized additive models (GAMs) (Hastie and Tibshirani, 1990), spatio-temporal models (Meliker and Sloan, 2011), and panel data models (Wooldridge, 2002). Among the papers reviewed, only a few authors chose SIRS and SEIR models to examine the association between climatic factors and COVID-19 transmission (Baker et al., 2020; Lu et al., 2020), GLMs, GAMs, spatio-temporal and panel data models being more popular. Several of these studies are mentioned in the remainder of this section and certain methodological aspects that deserve serious consideration are briefly highlighted.

4.1 Choice of dependent variables

In addition to the choice of model, the studies also differ in their choice of dependent variables. Although the different choices are reasonable (and should be specified in detail, which is sometimes not the case), a study of the different conclusions that can be reached depending on the choice of the dependent variables seems to be lacking.

In most of the papers analysed, the cumulative number of COVID-19 cases or the number of new daily cases is used as the response variable. The choice of the cumulative number of cases allows researchers to model the data through exponential models because the growth of an epidemic is approximately exponential during the initial phase (Ma, 2020), although subexponential growth can also be observed if containment measures are rapidly implemented (Maier and Brockmann, 2020). In these cases, the growth parameter that governs the exponential function is usually modelled as a function of one or several climatic variables. Furthermore, both the number of cumulative or new daily cases can be modelled through more flexible approaches such as GLMs, GAMs, spatio-temporal or panel data models. In contrast, other researchers have estimated the basic reproduction number (the average number of secondary cases generated by every infected person in a fully susceptible population) and have studied how certain climatic factors affect this number (Xu et al., 2020). In this regard, researchers should be aware of the complexity of estimating the reproduction number and use it with great caution (Delamater et al., 2019).

4.2 The choice of the spatial unit of analysis

The choice of a certain geographical unit as the basis of an epidemiological analysis is a capital question that usually affects the study outcomes. This is usually referred to as the modifiable areal unit problem (Openshaw, 1984) in the field of spatial statistics. Multiple and varied criteria can be followed to decide which geographical unit to use for the analysis, including biological relevance, data availability, intra-unit homogeneity and compactness, among others (Arsenault et al., 2013). The choice of the unit of analysis in the currently available research on the association between climate and the evolution of the COVID-19 pandemic mostly depended on data availability; most of the studies were performed at the country or regional level, as data on a smaller spatial scale is rarely available for most countries at this stage of a pandemic. However, several of the studies consisted of city-level analyses (Auler et al., 2020; J Liu et al., 2020; Prata et al., 2020). Studies at the municipal level are useful because they can account for the fast spread of the pandemic in cities with high levels of population density or human mobility, or those with possible super-spreading events and disease clusters. Regarding the latter, spatial clustering of cases can generally be expected, as has already been found for COVID-19 (Pung et al., 2020), or similar respiratory diseases such as SARS (Lai et al., 2004). Choosing a very large geographical unit (as did many of the studies) prevents researchers from accounting for these specific phenomena, which are only observable on a small scale and can dissipate any relationships between climate and the spread of the pandemic.

4.3 Specifying climatic variables

Regarding the choice of the spatial unit of analysis, it is worth noting that using very large geographical areas to study the influence of the physical environment on the spread of a virus can lead to the definition of less representative covariates (to some extent, this resembles the well-known issue of the ecological fallacy that arises when individual-level data is aggregated). Indeed, as the geographical unit of analysis becomes larger, it is more likely that several climatic conditions coexist within it, which prevents the proper characterization of the unit in terms of climatic variables. In the same vein, using a smaller number of (larger) geographical units for modelling COVID-19 data naturally reduces the range and variability of the covariates involved in the analysis (Lee et al., 2018), which can distort or hide the true relationship between the climatic (and non-climatic) factors driving the pandemic and lead to unreliable findings.

The treatment and specification of the climatic variables (regardless of the geographical unit of analysis) are quite diverse. Several authors have considered the daily values of these variables, but others have preferred to consider others, such as monthly or yearly averages. To analyse the relationship between a climatic variable and COVID-19 daily outcomes, the climatic factors should be considered on a daily basis and for the period under study. And to better capture the effect of climate on the propagation of the virus, the variables should be included in the model with a temporal lag, in agreement with the incubation time window observed for COVID-19, as in several of the studies reviewed (Briz-Redón and Serrano-Aroca, 2020; Y Wu et al., 2020; Zhu and Xie, 2020). The use of moving averages to account for the lagged effect of the climatic variables is another strategy that deserves consideration (Qi et al., 2020).

4.4 Spatio-temporal dependence and heterogeneity

Accounting for the spatial relationships between the geographical units considered for the analysis of the disease's incidence is fundamental. The well-known First Law of Geography states that 'everything is related to everything else, but near things are more related than distant things' (Tobler, 1970). In the context of virus propagation, a spatial dependence between the units of analysis is highly probable, as people that become infected are more likely to visit neighbouring units than those further away. This means that overlooking spatial effects when defining a modelling approach can lead to biased analyses and wrong associations. However, only a few of the studies reviewed explicitly include spatial effects in their statistical models (Briz-Redón and Serrano-Aroca, 2020; Chiyomaru and Takemoto, 2020). Similarly, regarding temporal dependence of the data, only a minority of the studies account for the presence of temporal trends through either autoregressive integrated moving average models (Demongeot et al., 2020), random walks (Briz-Redón and Serrano-Aroca, 2020) or spline functions (Qi et al., 2020; Y Wu et al., 2020).

Concerning spatio-temporal heterogeneity, it is also important to explicitly account for location-specific and day-specific effects, which can consider singular COVID-19 outcomes in space and time. Location effects enable the model to identify different trends and relationships for different locations (countries, regions, cities, etc.) included in the analysis. Many of the authors of statistical analyses conducted through GLMs, GAMs, spatio-temporal or panel data models include specific random effects for accounting for this heterogeneity in the data. Simpler approaches (correlation coefficients and basic regression models) do not account for these effects, which can reduce the reliability of the findings and increase the need for caution.

4.5 Underreporting rates

A major issue that researchers should account for when analysing COVID-19 data is the fact that the numbers currently reported by national or regional governments are usually an underestimation of the real incidence of the pandemic, due to the lack of tests and the presence of asymptomatic carriers. If one analyses the evolution of COVID-19 in a set of geographical units suffering from similar underreporting rates, this issue may not be so severe, but it seems clear that the problem of underreporting means that countrywide analyses are highly sensitive. If there is a correlation between underreporting rates and certain climatic conditions, the findings on how the climatic factors drive the pandemic may be unreliable. Some researchers account for this issue by sensitivity analyses of the different statistical models fitted (Xu et al., 2020), or by accounting for the age structure of the population, as detection rates are higher among older people (Briz-Redón and Serrano-Aroca, 2020), but these strategies may be insufficient.

V Conclusions

This review of the relationship between climate and the global expansion of COVID-19 suggests that weather conditions such as humidity, precipitations, radiation, temperature, and wind speed could play a secondary role in the transmission of the disease. There are too many contradictory findings to believe the opposite, although a great number of studies suggest that higher temperatures may help to stop the pandemic. In this regard, the existence of a bias towards negative associations between temperature and COVID-19 transmission because of previous experience with similar respiratory diseases cannot be discarded. From a methodological standpoint, certain questions deserve to be briefly highlighted: small-area studies should be preferred to better characterize each geographical unit involved in the analysis in terms of meteorological conditions, non-meteorological factors and specific effects (including spatio-temporal) that may be missed if larger spatial units are considered. In addition, to avoid or mitigate the consequences of spatially varying underreporting rates, analyses of the data from a single country may be advisable. Alternatively, statistical models explicitly accounting for this issue could be considered. Sensitivity analyses that discard geographical units with extreme values, such as those in which the virus started earlier and spread faster may be desirable, as these singular units can have an excessive influence on the results. Thus, it seems that the summer may offer a modest reduction in COVID-19 transmission but this will not be large enough to control the epidemic.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

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Supplementary material

Table S1 in the supplementary material summarises the characteristics (zone, geographical unit, temporal window, main statistical and modelling method/s) of the studies considered in the present review on the association between climatic factors and COVID-19 transmission.

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