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A review of the impact of weather and climate variables to COVID-19: In the absence of public health measures high temperatures cannot probably mitigate outbreaks



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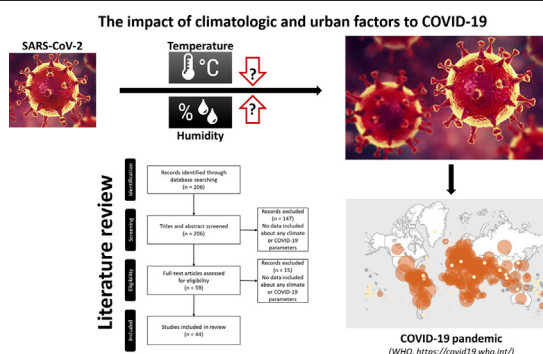
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HIGHLIGHTS

- The effect of climate on COVID-19 is contradictory.
- The urban environment and air pollution can affect the transmission dynamics of COVID-19.
- The effect of climate on COVID-19 is confounded by the public health measures implemented previously.
- The effect of climate factors, in the absence of public health interventions cannot mitigate COVID-19.

GRAPHICAL ABSTRACT



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ABSTRACT

The new severe acute respiratory syndrome-coronavirus 2 (SARS-CoV-2) pandemic was first recognized at the end of 2019 and has caused one of the most serious global public health crises in the last years. In this paper, we review current literature on the effect of weather (temperature, humidity, precipitation, wind, etc.) and climate (temperature as an essential climate variable, solar radiation in the ultraviolet, sunshine duration) variables on SARS-CoV-2 and discuss their impact to the COVID-19 pandemic; the review also refers to respective effect of urban parameters and air pollution. Most studies suggest that a negative correlation exists between ambient temperature and humidity on the one hand and the number of COVID-19 cases on the other, while there have been studies which support the absence of any correlation or even a positive one. The urban environment and specifically the air ventilation rate, as well as air pollution, can probably affect, also, the transmission dynamics and the case fatality rate of COVID-19. Due to the inherent limitations in previously published studies, it remains unclear if the magnitude of the effect of temperature or humidity on COVID-19 is confounded by the public health measures implemented widely during the first pandemic wave. The effect of weather and climate variables, as suggested previously for other viruses, cannot be excluded, however, under the conditions of the first pandemic wave, it might be difficult to be uncovered. The increase in the number of cases observed during summertime in the Northern hemisphere, and especially in countries with high average ambient temperatures, demonstrates

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that weather and climate variables, in the absence of public health interventions, cannot mitigate the resurgence of COVID-19 outbreaks.

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1. Introduction

The severe acute respiratory syndrome-coronavirus 2 (SARS-CoV-2) has caused a devastating pandemic that first diagnosed in December 2019 in Wuhan province in China. SARS-CoV-2 belongs to the genera of betacoronaviruses similarly to SARS-CoV-1 and Middle East respiratory syndrome coronavirus (MERS-CoV), which first identified in China in 2002 (Peiris et al., 2003) and in Middle East in 2012 (van Boheemen et al., 2012), respectively. The case fatality rate of SARS-CoV-1 and MERS-CoV was 9 and 36%, respectively, but their spread remained limited (Su et al., 2016).

In the absence of a prophylactic vaccine and effective treatment, public health measures such as social distancing, hand hygiene, contact tracing and quarantine provide the only way to prevent SARS-CoV-2 transmission in the community. The implementation of these measures depends on the intensity and the characteristics of the pandemic waves within each country. During the first pandemic wave, many countries adopted strict measures including lock down, stay-at-home recommendations, mass gathering cancellations, schools and non-essential shops closure. The successful control of the first wave resulted to a gradual lift of restrictions with recurrent increase in the number of SARS-CoV-2 during the summer period in several areas in the Northern hemisphere.

The new pandemic has raised global concern and became one of the worst public health crises. The pandemic and post-pandemic transmission dynamic will depend on the levels and the duration of immunity, on the effect of climate to transmissibility, the degree of cross-immunity between SARS-CoV-2 and common cold coronaviruses (HCoV-OC43 and HCoV-HKU1), as well as the effectiveness of public health measures (Kissler et al., 2020). The other human coronaviruses (OC43 and KU1) are associated with asymptomatic infection or mild symptoms and follow a seasonal pattern causing winter outbreaks (Killerby et al., 2018). Immunity to HCoV-OC43 and HCoV-HKU1 declines within one year, while SARS-CoV-1 can induce longer immunity (Kissler et al., 2020).

One of the critical questions is the extent of the seasonal variation in transmissibility and how weather and climate variables can affect the

transmission dynamics of SARS-CoV-2. To date, several studies have shown that ambient temperature and humidity have a reverse association with COVID-19 cases, while in some other no association was found; similar is the case with ultraviolet solar radiation or the average ambient temperature. Our primary aim was to review the current literature about the effect of weather and climate variables to SARS-CoV-2, as well as the effect of these variables to influenza and other human coronaviruses, and to discuss the effect of these variables to the current pandemic. For the purposes of the study, some of the examined variables are termed as climate (e.g. solar radiation in the ultraviolet, sunshine duration or when they refer temperature as an essential climate variable which characterizes the climate of the region concerned), whereas others are termed as weather (for instance when the *day-to-day state of the atmosphere, and its short-term variation in days or weeks* is considered). Thus, temperature can be either a climate or a weather variable, depending the time scale. Even if vaccines become available, development of herd immunity in the populations will be achieved after a long-time, suggesting that the global threat of SARS-CoV-2 will remain high. Under these circumstances, knowledge about the effect of weather and climate variables in periods when public health measures of different strictness are applied, is essential for the better understanding of the variables that may affect COVID-19 transmission or mortality.

2. Materials and methods

2.1. Bibliographic search

In order to investigate the impact of weather and climate variables on COVID-19, a literature search was performed in PubMed on June 20th 2020, using the following combinations of keywords: (Temperature & COVID: Number of results: 206), (Temperature & SARS-CoV-2: Number of results: 146), (Climate & COVID: Number of results: 126), (Humidity & COVID: Number of results: 59) and (Latitude & COVID: Number of results: 15). The results of the bibliographic search using the combination of keywords with the maximum hits (Temperature & COVID: Number of results: 206) are

provided as Supplementary Information. The initial number of studies assessed for the aim of the review was 206. After the initial assessment, the number of papers reduced at 59 and the final number of studies included in the review was 44. The initial and the final assessment was conducted by two independent reviewers (EGK and DP) (Table 1). Studies were considered as eligible if any of the variables as explicitly described in Tables 2 and 3, have been used in their analyses. The initial assessment was based on the review of the abstract and the final assessment was based on the review of the full text of the papers. A flow chart detailing the number of abstracts and full texts reviewed is provided (Fig. 1).

Similarly for the effect of weather and climate variables as well as of air quality variables (Table 4) to the COVID-19 pandemic, a literature search was performed in PubMed using the following combination of keywords: climate and weather variables & COVID; cities-urban settings & COVID; geographic location & COVID; seasons & COVID; air pollution & COVID. The final number of selected papers were 25 and among them 3 were duplicates with the 44 publications selected from our previous search. The assessment of studies was performed by two independent reviewers (DP and CC). For the review of the effect of weather and climate variables as well as of air pollution to COVID-19, only peer-reviewed studies were selected. Given that the focus of our study was

Table 1
Description of studies selected after the initial assessment.

PMID	Full name of the first author	Study location	Study period
32339844	Shi Peng	China	Jan. 20 - Feb. 29, 2020
32330766	Tobías Aurelio	Spain (Barcelona)	Mar. 2 - Apr. 5, 2020
32361443	Prata David N.	Brazil	Feb. 27 - Apr. 1, 2020
32360939	Ujii Mugen	Japan	Jan. 15 - Mar. 16, 2020
32269084	Yao Ye	China	Mar. 9 - Feb. 10, 2020
32265220	Wynants Laure	excluded as not relevant	
32408450	Xie Jingui	China	Jan. 23 - Feb. 29, 2020
32408453	Ma Yueling	China (Wuhan)	Jan. 20 - Feb. 29, 2020
32361460	Wu Yu	166 countries	up to Mar. 27, 2020
32415548	Eslami Hadi	excluded as not relevant	
32375234	Demongeot Jacques	21 countries, French administrative regions	Feb. to Mar. 14, 2020
32380010	Del Rio Carlos	China, Italy, South Korea, Iran, Philippines, Belgium, Finland, Egypt, Australia	Dec. 31, 2019 - Feb. 29, 2020
32540732	Goswami Kuldeep	India	Apr. 1 - May 10, 2020
32298883	Tosepu Ramadhan	Indonesia (Jakarta)	Jan. - Mar. 29, 2020
32470687	Shahzad Farrukh	China	Jan. 22 - Mar. 31, 2020
32334162	Bashir Muhammad Farhan	the USA (New York)	Mar. 1 - Apr. 12, 2020
32335405	Qi Hongchao	China	Dec. 1, 2019 - Feb. 11, 2020
32337151	Gunthe Sachin S	85 geographic locations	Feb. 2 - Mar. 7, 2020
32502664	Li He	China (Wuhan, XiaoGan)	Jan. 26 - Feb. 29, 2020
32304942	Liu Jiangtao	China	Jan. 20 - Mar. 2, 2020
32138266	Sun Zhong	excluded as not relevant	
32388129	Iqbal Najaf	China (Wuhan)	Jan. 21 - Mar. 31, 2020
32479958	Huang Zhongwei	185 countries/geographic regions	Jan. 21 - May 6, 2020
32361118	Briz-Redón Álvaro	Spain	Feb. 25 - Mar. 28, 2020
32540744	Runkle Jennifer D	the USA	Feb. 29 - Apr. 23, 2020
32334207	Wang Lishi	excluded as not relevant	
32334158	Şahin Mehmet	Turkey	Mar. 21 - Apr. 3, 2020
32389157	Jiang Ying	China (Wuhan, Xiaogan, Huanggang)	Jan. 25 - Feb. 29, 2020
32492607	Menebo Mesay Moges	Norway (Oslo)	Feb. 27 - May 2, 2020
32525550	Sajadi Mohammad M	China, Japan, South Korea, Iran, Italy, France, the USA, Spain	Jan. 11 - Mar. 10, 2020
32547889	Pequeno Pedro	Brazil	Feb. 26 - Mar. 26, 2020
32402910	Xu Hao	excluded as not relevant	
32503659	Tharakan Serena	excluded as not relevant	
32464409	Méndez-Arriaga Fabiola	Mexico	Feb. 29 - Mar. 31, 2020
32335407	Jahangiri Mehdi	Iran	Feb. 15 - Mar. 22, 2020
32334160	Gupta Sonal	the USA	Jan. 1 - Apr. 9, 2020
32361432	Ahmadi Mohsen	Iran	Feb. 19 - Mar. 22, 2020
32353724	Sobral Marcos Felipe Falcão	249 countries	Dec. 1, 2019 - Mar. 30, 2020
32504748	Kratzel Annika	excluded as not relevant	
32388162	Yao Maosheng	excluded as not relevant	
32470237	Pan Yingxiao	excluded as not relevant	
32544431	Hsu Yu-Lung	excluded as not relevant	
32554505	Roy Manas Pratim	excluded as not relevant	
32385067	Jüni Peter	144 geopolitical areas	Mar. 21 - Mar. 27, 2020
32469989	Livadiotis George	the USA, Italy	up to Apr. 1, 2020
32544735	Pani Shantanu Kumar	Singapore	Jan. 23 - May 31, 2020
32373996	Al-Rousan Nadia	China	Jan. 22 - Mar. 1, 2020
32388137	Auler André C	Brazil	Mar. 13 - Apr. 13, 2020
32275090	de Ángel Solá David E	excluded as not relevant	
32531684	Iqbal Muhammad Mazhar	210 countries/territories	Dec. 31, 2019 - June 5, 2020
32325763	Pirouz Behrouz	Italy	Feb. 14 - Mar. 14, 2020
32438520	Ward Michael P	Australia (New South Wales)	Jan. - Mar. 31, 2020
32534259	Wang Yaqi	excluded as not relevant	
32516636	Sarmadi Mohammad	207 countries	up to Apr. 2, 2020
32429517	Scafetta Nicola	151 countries	up to Apr. 15, 2020
32466199	Shaffiee Haghshenas Sina	Italy	Feb. 14 - Mar. 24, 2020
32540837	Mani Vishnu R	excluded as not relevant	
32517160	Passerini Giorgio	Italy	Feb. 29 - Mar. 29, 2020
32506109	Khalil Ibrahim	excluded as not relevant	

Table 2
Variables related to COVID-19.

n	Variables
1	Daily number of newly confirmed cases; daily incidence rate of diagnosed cases (percentage of PCR positive cases); daily number of accumulated confirmed cases; proportion of cases per 10 ⁵ population
2	Accumulated number of patients per 10 ⁵ population
3	Substantial community spread (as at least 10 reported deaths in a country); community death (defined as community spread of COVID-19 resulting in death); documented local transmission (based on the WHO's situation report)
4	Daily death numbers or daily new deaths; COVID-19 mortality rates; proportion of deaths per 10 ⁵ population
5	Local COVID-19 confirmed positive cases, or imported COVID-19 confirmed positive cases
6	Infection dates
7	Epidemic growth (expressed as a rate ratio of the cumulative number of reported cases versus the cumulative number of cases reported 1 week before); exponential growth rates of the infected cases
8	Contamination rate (calculated per 100 thousand habitants)

on COVID-19, the text related to the effect of the weather and climate variables on influenza and other corona viruses was not based on all the available papers on this topic.

2.2. Description of studies

The effect of weather and climate variables as well as of air pollution on COVID-19 was investigated using different approaches across diverse locations and time periods. It was found that ambient temperature, humidity and the number of newly confirmed cases were the most frequently used variables. However, diverse variables were also used, as shown in Tables 2 and 3. Besides the number of newly confirmed cases, some studies analysed the number of deaths, the number of local confirmed cases or the epidemic growth. Different single variables or a combination of variables were used in the studies and the analysed data were retrieved from national or global observatories, such as WHO, John Hopkins University, etc.

A small number of studies investigated the impact of geography by considering the geographic latitude or by dividing the geopolitical areas into temperate and tropical or into four parts: northeastern, northwestern, southeastern, and southwestern (Table 3). In addition, a number of studies also used additional covariates in their analyses, such as: 1) the number of travellers, or the number of arriving flights from areas with community spread, or the number of flight passengers per capita, 2) old-age dependency ratio, 3) city population density, 4) citizen mean income, 5) intra-provincial movement, 6) measures of social distancing, 7) altitude, 8) gross domestic product (GDP) per capita, 9) health expenditure as percent of GDP, 10) life expectancy, 11) the Infectious Disease Vulnerability Index, 12) urban population

Table 3
Variables related to weather and climate.

n	Variable
1	Minimum, maximum, average temperature
2	Absolute humidity, relative humidity (RH), maximum relative humidity (RHmax), average relative humidity (RHavg), minimum relative humidity (RHmin),
3	Long term average of ambient temperature, UV index, average solar radiation, sunshine duration
4	Rainfall, maximum dew point (DPmax), average dew point (DPavg), minimum dew point (DPmin)
5	Precipitation, cloud cover
6	Air quality
7	Maximum surface pressure (Pmax), average surface pressure (Pavg), minimum surface pressure (Pmin), maximum wind speed (WSmax), average wind speed (WSavg), and minimum wind speed (WSmin)
8	Geographic latitude, temperate and tropical regions, northeastern, northwestern, southeastern, and southwestern parts

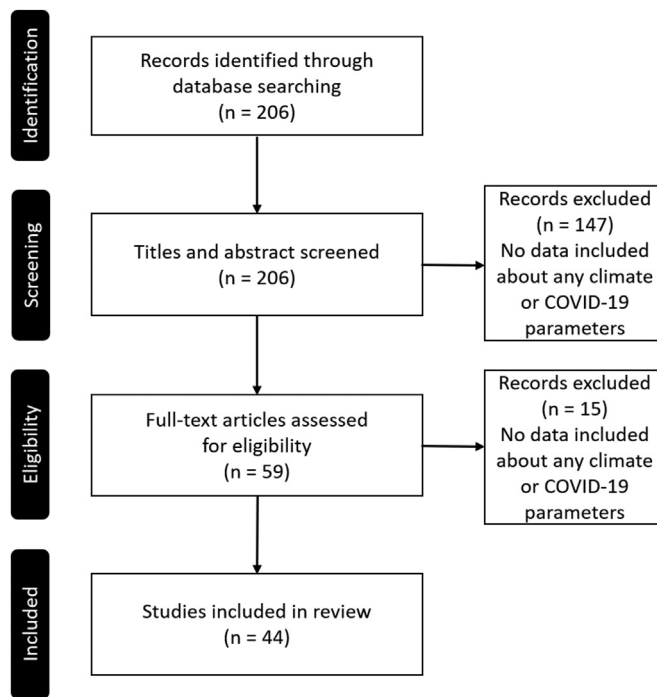


Fig. 1. Flowchart for the literature search on the impact of weather and climate variables on COVID-19.

density, and 13) closest distance to a country with already established epidemic.

3. Results

3.1. Studies using data from multiple geographic locations

Twelve studies used data from different territories around the world (Table 1). Specifically, in 7 out of 12 studies a significant negative correlation was reported between COVID-19 cases or deaths and climate variables.

The first study by Wu et al. (2020) which was performed over 166 countries as of 27th of March, showed that 1 °C increase in temperature was associated with a 3.08% (95% CI: 1.53% - 4.63%) decrease in the daily new cases and a reduction of 1.19% (95% CI: 0.44% - 1.95%) in the daily new deaths (Wu et al., 2020). A similar relationship was found for relative humidity where a 1% increase was associated with a 0.85% (95% CI: 0.51% - 1.19%) and a 0.51% (95% CI: 0.34% - 0.67%) reduction in the daily new cases and in the daily new deaths, respectively. Interestingly, after controlling for potential confounders (i.e. wind speed, median age of the population, Global Health Security Index, Human Development Index and population density), the association between the daily new cases or the daily new deaths and temperature and relative humidity remained robust (Wu et al., 2020).

Table 4
Variables related to air quality.

n	Variable
1	Nitrogen oxides
2	Sulphur dioxide
3	Tropospheric ozone
4	Particulate matter
5	Secondary inorganic aerosols
6	Ventilation rate
7	Wind speed

A similar trend was documented by Demongeot et al. (2020) between the rate of infection and the mean temperatures in different regions in France during the first half of March (Demongeot et al., 2020). From the same study, the cumulative number of cases was negatively correlated with the mean annual temperature in countries with more than 100 documented cases as of 14th of March (Demongeot et al., 2020). Sobral et al. (2020) showed that temperature was negatively correlated with the number of infections, and the significance of this relationship remained even after the inclusion of additional variables, such as maximum and minimum temperatures (averages) and time of exposure to the disease. The data implemented in this study were collected from 249 countries between 1st of December 2019 and 30th of March 2020 (Sobral et al., 2020).

In the analysis of data collected from Italy and the USA as of April 1st, the exponential growth rate of cases was negatively correlated with the average temperature (Livadiotis, 2020). This was robust and characterized by a high statistical confidence. The investigators estimated that the critical temperature that eliminates the exponential growth rate (basic reproduction number - $R_0 \sim 1$) was $\sim 86^\circ\text{F}$ or $\sim 30^\circ\text{C}$, while the corresponding value at 0°C was $R_0 \approx 2.5$ (Livadiotis, 2020).

A negative correlation was reported by Iqbal et al. (2020a) between the average high and the average low temperature or daylight hours and the total cases or deaths per 10^6 population (Iqbal et al., 2020a). The measures were collected as of 5th of June 2020 from 210 countries across the globe. The coefficient of determination as related to the number of cases was the highest for the average high temperature ($R^2 = 0.59$) followed by the average low temperature ($R^2 = 0.43$) and the daylight hours ($R^2 = 0.42$). The coefficient of determination regarding the total deaths was the highest for the average high temperature ($R^2 = 0.42$). The weakest coefficient, on the other hand, was observed between the daylight hours and the total deaths ($R^2 = 0.24$) (Iqbal et al., 2020a).

Besides the negative correlation of temperature with the proportion of cases or deaths per 10^5 population, Sarmadi et al. (2020) reported an interesting finding: the proportion of confirmed cases or deaths were positively correlated with the GDP across the different countries (Sarmadi et al., 2020). Data were collected as of April 2nd 2020 from 207 countries over three months period (Sarmadi et al., 2020).

Lastly, in the study by Jüni et al. (2020) the effect of weather variables was assessed in 144 geopolitical areas using a prospective cohort design (Jüni et al., 2020). The study period was between the 21st and 27th of March for countries with at least 10 cases as of Mar. 20th and documented local transmission (total cases included $n = 375,609$) according to the WHO (World Health Organization, 2020a). The potential association to COVID-19 was ascertained during an exposure time period of 14 days (March 7th to March 13th) before the follow-up (Jüni et al., 2020). The time interval between exposure and follow-up was set at 14 days, to reflect the lag between transmission and reporting of the confirmed cases. Besides the primary (latitude) and secondary exposure variables (mean temperature, absolute humidity, measures of social distancing), the analysis included additional covariates such as GDP per capita, health expenditure as percent of GDP, percentage of people aged older than 64 years, life expectancy, the Infectious Disease Vulnerability Index, urban population density, number of flight passengers per capita and closest distance to a country with already established epidemic (i.e. city of Wuhan, South Korea, Iran, Italy) (Jüni et al., 2020). In univariate analysis no significant association was found between the epidemic growth and the latitude or mean temperature, but a negative association was detected with relative humidity or with absolute humidity. In multivariable analysis, however, the relationship with temperature and humidity was non-significant. Following to the inclusion of social distancing measures, the multivariate analysis showed a weak non-significant correlation with relative humidity (ratios of rate ratios: RRR: 0.92, 95% CI: 0.84 – 1.00, $p = 0.06$), but the correlation with the number of public health interventions to remain significant (p for trend = 0.004) (Jüni et al., 2020).

Regarding the existence of an optimum range of weather and climate variables, three different studies suggested that most COVID-19 cases were detected in geographic locations with a specific range of temperature, humidity or ultraviolet (UV) index. These studies were reviewed separately due to the emphasis given to the role of secondary variables.

In the study of Gunthe et al. (2020) where data under study were collected from 85 locations in Asia, Europe and the USA during February 2nd and March 7th 2020, the majority (90%) of the total cases were found within a narrow temperature window of $5\text{--}15^\circ\text{C}$. Moreover, total cases were the highest for a UV index of 2.5 and declined for values higher than 3.5, suggesting a decreased number of cases in areas with high UV index (Gunthe et al., 2020). Huang et al., (2020) after the analysis of data from 185 countries/regions between 21st of January and 6th of May, illustrated that 60% of the COVID-19 cases were detected within a temperature range from 5°C to 15°C , with a peak at 11°C . However, a few cases were confirmed outside this temperature window at cold (lower than 0°C) or hot (higher than 30°C) environments. In the same study, the global COVID-19 cases was found to increase by 27,536 cases per 1°C lower than 10°C . COVID-19 cases peaked at 65% relative humidity, but the distribution of cases according to this parameter was much broader (30% to 100%) than the distribution according to temperature. It should be noted that most cases ($\sim 74\%$) were aggregated in areas with absolute humidity in the range between 3 g/m^3 to 10 g/m^3 , with a peak at 5 g/m^3 .

Lastly, Del Rio and Camacho-Ortiz (2020) found significant differences in temperature between the areas with ongoing COVID-19 transmission versus the areas without ongoing transmission, based on data collected as of February 29th (Del Rio and Camacho-Ortiz, 2020). The areas with ongoing transmission had lower temperature than the rest (Del Rio and Camacho-Ortiz, 2020).

The results of all studies which used data collected globally showed a significant correlation between temperature or/and humidity with the number of documented cases or deaths or that the majority of analyses was found within a specific range of geographic latitude and temperature. In one study, however, the association between the weather variables and COVID-19 was not significant when additional covariates related to social distance measuring were included in the analysis (Jüni et al., 2020). These findings suggest that the observed trend in the number of cases might not be due to the effect of weather variables but rather due to the implementation of public health interventions. The above may imply that the effect of weather variables to COVID-19 may not be negligible, yet, it is detected with difficulty due to the stronger effect of social distance measures.

3.2. Studies using data from single countries

Results were reviewed from a total number of 32 studies using measurements from single countries over different time periods with a range of 1st of December 2019 to 10th of May (Table 1).

In 20 studies, a negative correlation was described between weather variables (temperature, relative humidity, precipitation) and air quality with COVID-19. The majority analyses ($n = 13$) showed that temperature was associated with a lower number of COVID-19 cases. In some studies, additional variables, such as absolute humidity (Liu et al., 2020; Ma et al., 2020), relative humidity (Goswami et al., 2020; Qi et al., 2020), sunshine duration (Li et al., 2020), wind level (Jiang et al., 2020), dew point and humidity (Sahin, 2020) and diurnal temperature range (Liu et al., 2020), were correlated with the number of COVID-19 cases. In two of the previous studies, heterogeneous results were found about the type of association across different areas in India (Goswami et al., 2020) and China (Shahzad et al., 2020); in some areas a positive relationship between temperature and COVID-19 was reported, while in some others this association was negative. In six studies, air quality (Bashir et al., 2020), wind speed (Ahmadi et al., 2020; Pirouz et al., 2020), precipitation level (Menebo, 2020) and relative

humidity (Passerini et al., 2020; Ward et al., 2020) were reversely associated with COVID-19, while a positive correlation was found for relative humidity (Pirouz et al., 2020), maximum or minimum and average temperature (Bashir et al., 2020; Menebo, 2020; Passerini et al., 2020). According to the study by Ward et al. (2020), under high temperature conditions in Southern hemisphere summertime (January to March 2020), relative humidity could affect transmission (Ward et al., 2020).

In the study by Shi et al. (2020) the strongest relationship between the measured weather variables and COVID-19 was found for a lag period of 2 days; similarly a lag period of 3 or 3 – 5 days was reported elsewhere (Liu et al., 2020; Ma et al., 2020; Shi et al., 2020). Prata et al., (2020) showed that the association was linear within a specified temperature range (16.8 °C – 25.8 °C) and then became flat. In another study, and following to the adjustment of the used model for the population's age ratio and for arrivals from China in January 2020, the effect of lower temperature was enhanced (Ujii et al., 2020). The inclusion of additional covariates provides a significant advance in Ujii's approach (Ujii et al., 2020). Pequeno et al. (2020) included in addition to temperature, the number of inbound flights, time and population density (Pequeno et al., 2020). The model of Pequeno et al. (2020) suggested that time, population density and inbound flights had the strongest effect (positive relationship) followed by temperature (Pequeno et al., 2020). Notably, the number of cases increased earlier in areas with higher number of inbound flights. In the same study, it was found that an increase of about 1 °C in average temperature reduces the number of cases by about 8%, independently of other variables (Pequeno et al., 2020).

Méndez-Arriaga (2020) also analysed the effect of weather variables to the total number of imported and local cases in Mexico, where only the local cases were found to be negatively correlated with temperature or mean evaporation (Méndez-Arriaga, 2020). In this study, the impact of weather variables to COVID-19 was assessed during the epidemic stage, although before the effect of containment measures (epidemic stage 1), as implemented in March 23rd, 2020. The study suggested that the containment measures did not have an impact on the number of daily cases and, thus facilitated the assessment of the effect of weather variables to the COVID-19 cases in an unbiased way, as far as the effect of public health interventions is concerned (Méndez-Arriaga, 2020). Finally and from a climatic point of view, COVID-19 cases were less frequent in high temperature tropical areas than in temperate regions under low temperature and low evaporation conditions (Méndez-Arriaga, 2020).

In contrast to the previous ones, in four studies no correlation was observed between weather variables and COVID-19, and in 8 studies a positive relationship was reported. No association was found across 224 cities in China during 10th of February and 9th of March (Yao et al., 2020), across the provinces of Spain in the period between 25th of February and 28th of March (Briz-Redon and Serrano-Aroca, 2020), in Iran during 15th of February and 22th of March (Jahangiri et al., 2011), and across 50 US states during 1st of January and 9th of April (Gupta et al., 2020).

In the group of 8 studies, Xie and Zhu (2020) reported a positive association between temperature and COVID-19 when the average temperature was below 3 °C (Xie and Zhu, 2020). On the contrary, no significant association was detected when the mean temperature was above 3 °C (Xie and Zhu, 2020). Similarly findings were reported in Wuhan (Iqbal et al., 2020b), in 8 US cities (Runkle et al., 2020), in Singapore (Pani et al., 2020), in 30 Chinese provinces (Al-Rousan and Al-Najjar, 2020), and in 5 Brazilian cities (Auler et al., 2020). In the study by Shaffiee Haghshenas et al. (2020), relative humidity was positively correlated to the number of cases in Northern Italy (Shaffiee Haghshenas et al., 2020). Lastly, Tosepu et al. (2020) reported a significant correlation for the average temperature, while no significant effect was detected for minimum and maximum temperature, humidity and rainfall (Tosepu et al., 2020).

3.3. Studies on the link of weather and climate variables to COVID-19

Emerging evidence suggests that weather and climatic variables are also controlling variables in the COVID-19 epidemiology as cold climatic conditions are favourable for the virus survival (Sun et al., 2020). In a systematic review study of 23 studies, Chatziprodromidou et al. (2020) conclude that in principle high temperature and humidity, reduce the COVID-19 transmission (Chatziprodromidou et al., 2020). Although the exact mechanisms are largely unknown, a possible process is that higher ambient temperatures, through faster evaporation, might prevent the spread of droplets that transmit the virus (Demongeot et al., 2020). On the contrary, O'Reilly et al. (2020) denote that the seasonal temperature effects still remain questionable and cannot be considered a key modulating factor of SARS-CoV-2 transmissibility.

Li et al. (2020) examined the transmission risk and spread of infections as a function of seasonal climate conditions (wintertime in temperate and subtropical climates). They found that the peak infection is delayed and lowered in locations with a shorter and warmer winter whereas a longer and colder winter increases the time indoors, leading to a persistent inflation of transmission and a larger and earlier peak of infection.

Xu et al. (2020) examined the relative risk of COVID-19 due to weather and climate variables and air pollution levels at global scale. They found a negative relationship for temperature: each degree Celsius above 25 °C is associated with 3.8% lower reproduction number of COVID-19. From a climatic point of view, this suggests that many temperate zones with high population density may face larger risks in winter, while some warmer areas of the world may experience slower transmission rates in general. They also found that the negative effect of mean temperature above 25 °C is attenuated with higher SO₂ levels and there may be a positive effect of PM_{2.5} which is attenuated with increased air pressure. Finally, a U-shaped relationship between UV index and transmission was deduced which may help more temperate regions during summer, but impose higher risks in equatorial regions with very high UV exposure. In another worldwide study, Sajadi et al. (2020) examined weather data (for the period January 11 to March 10, 2020) from cities with significant community spread of COVID-19 (at least 10 deaths in a country as of March 10th) using ERA-5 reanalysis, and compared the data to areas that are either not affected, or did not have significant community spread. They found a negative correlation between the total number of cases and the mean temperature or the specific humidity but not with the relative humidity. They also recognized a weather related pattern with average ambient temperature between 5 °C and 11 °C combined with low specific (3 – 6 g/kg) and absolute humidity (4 – 7 g/m³) values; interestingly enough, the pattern was associated with established community outbreaks that had similar weather in the latitude zone between 30 °N and 50 °N. In the event that such a weather related pattern is validated, it may be possible to use weather modelling and climate prediction in the short and long term respectively, so as to predict the regions of higher risk as far as the spread of COVID-19 is concerned. The pattern above needs to be further examined, by also considering the COVID-19 cases in the respective zones in the southern hemisphere.

Scafetta (2020) also suggests that COVID-19 has a main geographical climatic preference (dry and moderate cold weather) that favours its spread (Scafetta, 2020). By examining in particular the link between the Severe Acute Respiratory Syndrome CoronaVirus 2 (SARS-CoV-2) pandemic and the prevailing weather conditions, it was found that the 2020 winter weather in the region of Wuhan (China) was strikingly similar to that of the Northern Italian provinces of Milan, Brescia and Bergamo, where the pandemic broke out and spread rapidly from February to March 2020. According to these findings, 4 – 12 °C isotherm zones were defined extending, for the period February to March 2020, mostly from Central China toward Iran, Turkey, West-Mediterranean Europe (Italy, Spain and France) and to the United States of America. In the same research study, it was predicted that as temperature increases in the spring time, the pandemic would likely worsen in

northern regions (the United Kingdom, Germany, East Europe, Russia and North America) taken while the situation would likely improve in the southern regions (Italy and Spain); as a matter of fact, the rise in springtime temperatures in the northern regions would place them in the range of 4 – 12 °C, whereas the respective rise in southern regions, would place them away from the above range.

In a study that involved 27 countries (including China), Wang and Di (2020) collected the cumulative number of confirmed cases of all cities and regions affected by COVID-19 in the world from January 20 to February 4, 2020, and calculated the daily means of the average, minimum and maximum temperatures (Wang and Di, 2020). They suggested that temperature could significantly change COVID-19 transmission, and that there might be a best temperature for the viral transmission; they also claim that an increase in the minimum temperature was associated with a decrease in COVID-19 cases. Despite the fact that the nonlinear dose-response relationship was concluded, no causal relationship was proven as the study was a time-space cross-sectional one.

3.4. Studies on the effect of weather and climate variables on influenza and other corona viruses

Numerous studies have investigated the effect of weather and climate variables on the stability and spread of viruses in populations (Leclercq et al., 2014; Ma et al., 2020; Tamerius et al., 2013; Yuan et al., 2006). Environmental variables (e.g. fluctuation of temperature and humidity of the inhaled air) can affect the host susceptibility by modulating airway mucosal surface defence mechanisms (Moriyama et al., 2020). The mechanisms which affect the viral transmission rates are not obvious since each virus exhibits different characteristics. For example, influenza clearly shows peak incidences in the winter months (winter viruses) (Sooryanarain and Elankumaran, 2015; Tamerius et al., 2013), while enteroviruses cases peak in summer (summer viruses). On the other hand, human metapneumovirus (hMPV) and rhinovirus prevail throughout the year (all-year viruses) (Moriyama et al., 2020).

Diverse findings exist on how temperature can affect transmission of the MERS-CoV (Altamimi and Ahmed, 2020; Gardner et al., 2019). Several studies revealed that high UV index, low wind speed, and low relative humidity are associated with increased MERS-CoV cases (Altamimi and Ahmed, 2020; Gardner et al., 2019; Leclercq et al., 2014). Similarly to MERS-CoV, SARS-CoV can turn inactive in conditions of high relative humidity (Chan et al., 2011; Kim et al., 2007), as found also for other coronaviruses such as the transmissible gastroenteritis virus (TGEV) (Kim et al., 2007). Relative humidity is the most important factor in controlling virus infectivity in droplets (Prussin et al., 2018), which remain viable longer in an airborne state (Kim et al., 2007). Previous findings have shown that SARS-CoV can be inactivated by high temperature (Chan et al., 2011; Lin et al., 2006; Tan et al., 2005) and UV radiation (Duan et al., 2003). This may explain why areas such as Malaysia, Indonesia, Thailand and Hong Kong did not experience major outbreaks of SARS-CoV (Chan et al., 2011). Most coronaviruses, with the exception of MERS-CoV, seem to be inactivated by the exposure to the solar UV radiation (Charland et al., 2009; Sagripanti and Lytle, 2007; Yusuf et al., 2007) and more specifically due to the diffuse (scattered) component of solar UV (Ben-David and Sagripanti, 2010).

In terms of the transmission dynamics of some viruses, weather variables are the only ones to influence their dispersion. Additional variables, as for example population density and movement, age distribution, number of imported cases and indoor conditions, are also associated with transmission of viral respiratory infections (Ahmadi et al., 2020; Briz-Redon and Serrano-Aroca, 2020; Moriyama et al., 2020; Pirouz et al., 2020).

3.5. Studies on the effects of air pollution to the COVID-19 pandemic

Several studies have referred to the linkage between air pollution and infectious diseases. Cienciewicki and Jaspers (2007) have provided

a review of the epidemiologic and experimental literature linking air pollution to infectious diseases (Cienciewicki and Jaspers, 2007), whereas Cui et al. (2003) reported that locations in China with a moderate or high long term air pollution index (API) (Cui et al., 2003), had SARS-CoV case fatality rates 126% and 71% higher, respectively, than locations with low API.

In terms of the recent COVID-19 crisis, one of the first direct findings about the SARS-CoV-2 spread is the correlation of the COVID-19 health outcomes with urban density and air quality levels. Travaglio et al. (2020) recognized the links between air pollution and COVID-19 in England, by analysing the associations between cumulative numbers of COVID-19 cases and deaths with the concentrations of three major air pollutants recorded between 2018 and 2019, when no COVID-19 cases were reported (Travaglio et al., 2020). The spatial pattern of COVID-19 deaths matched the geographical distribution of COVID-19-related cases, with the largest numbers of COVID-19 deaths occurring in London and in the Midlands, i.e. areas presenting the highest annual average concentration of nitrogen oxides (Travaglio et al., 2020). By means of a negative binomial regression model, they identified nitrogen oxides and sulphur dioxide as important contributors to COVID-19 mortality. An interesting result is the negative association between ozone levels and COVID-19 infection and mortality. This may be attributed to reduced nitrogen oxide conversion to ozone in urban areas (Travaglio et al., 2020).

Wu et al. (2020) examined the hypothesis that the long-term exposure to PM_{2.5} adversely affects the respiratory and cardiovascular systems and increases mortality risk (Wu et al., 2020), it also enhances the severity of COVID-19 infection. By using negative binomial mixed models with county-level COVID-19 deaths as the outcome and county-level long-term average of PM_{2.5} as the exposure, they found that a 1 µg/m³ increase in PM_{2.5} is associated with an 8% increase in COVID-19 death rate in the USA (Wu et al., 2020). An important aspect of the analysis is the use of twenty potential confounding variables: days since first COVID-19 case reported (a proxy for epidemic stage), population density, percent of population ≥65 years of age, percent of the population 45 – 64 years of age, percent of the population 15 – 44 years of age, percent of the population living in poverty, median household income, percent of black, percent of Hispanic, percent of the adult population with less than a high school education, median house value, percent of owner-occupied housing, percent of obese, percent of current smokers, number of hospital beds per unit population, average daily temperature and relative humidity for summer (June – September) and winter (December – February) for each county, and days since issuance of stay-at-home order for each state (Wu et al., 2020).

In Northern Italy, air pollution was also identified as a potential additional co-factor of the high level of COVID-19 mortality. In particular, Conticini et al. (2020) investigated the reasons of the high mortality rate (12%) in Lombardy and Emilia Romagna, and concluded that the high level of pollution in these two regions could partly explain a higher prevalence and lethality of SARS-CoV-2, also considering the relatively high average age of the population (Conticini et al., 2020).

Long-term exposure to air pollution and COVID-19 case fatality rate was also investigated in regions of Italy, Spain, France and Germany using Sentinel-5P tropospheric NO₂ data along with the prevailing atmospheric dispersion conditions (Ogen, 2020). The results highlighted two hotspot regions (Northern Italy and Madrid metropolitan area) as well as that 83% of all fatalities occurred in regions with NO₂ concentrations higher than 100 µmol/m².

Apart from the impact of air pollution to public health, Setti et al. (2020) highlighted the role of airborne particles in spreading the virus based on the presence of SARS-CoV-2 RNA on particulate matter (Setti et al., 2020). On the other hand, the lockdown control measures imposed by governments had a positive short-term impact on the levels of air quality in multiple urban locations (Bauwens et al., 2020), highlighting the potential of social and behavioural change (Shi and Brasseur, 2020).

Despite the inherent limitations of all studies above, their results reflect the importance of air pollution regulations to protect human health both during and after the COVID-19 crisis. Future studies need also to consider air pollution variables when estimating the SARS-CoV-2 infection rate (R_0), whereas they need also to address additional variables such as the prevailing meteorological conditions, the state of the thermal environment, in particular in urban areas, and local and regional transport. In terms of the latter, Chang et al. (2020) performed an investigation of China's haze puzzle in Shanghai in early 2020, a period when over two-times higher mass concentrations of fine particles were observed despite the record economic slowdown and associated decline in pollutant emissions from business, transportation, and industry due to the COVID-19 lockdown (Chang et al., 2020). Fast formation of secondary inorganic (mostly nitrate) aerosols was identified as the main factor contributing to the relatively high atmospheric particle concentrations (>80%). In particular, particulate nitrate formation can be largely enhanced during lasting regional transport, suggesting that differential transport patterns, rather than local emissions, may be responsible for fluctuations in aerosol concentrations (Chang et al., 2020).

Finally, Sagripanti and Lytle (2020) used a model to estimate the inactivation of the SARS-CoV-2 virus, by artificial Ultraviolet C (UVC) and by solar UV radiation in several cities of the world during different times of the year (Sagripanti and Lytle, 2020). The results indicated that sunlight has a role in such characteristics of the pandemic as the occurrence, spread rate and duration. In particular, SARS-CoV-2 could remain infectious outdoors for considerable time during the winter in many cities in temperate zones, whereas could be inactivated relatively fast during summer. Results need to be validated accordingly during the ongoing summer season, in conjunction with the number of cases.

3.6. Studies on COVID-19 in the urban world

The global COVID-19 crisis has emerged urban concerns. Hakovirta and Denuwara (2020) proposed to rethink and redefine urban sustainability as the intersection of economy, environment, society and human health (Hakovirta and Denuwara, 2020). The consideration of these interlinkages can play an important role in the management of future epidemics though policy making. Efficient urban climate-sensitive planning also needs to address this challenge and can promote well-being by reducing air pollution and decreasing the COVID-19 spread. In the course of the COVID-19 crisis, several cities worldwide have modified their resilience programs in order to accommodate new challenges associated with the pandemic (United Nations, 2020). As a matter of fact the traditional *single risk* approach – regardless if it refers to forest fires, extreme weather events, floods, or droughts – is inadequate, taken the interactions between multiple risks as well as, and more importantly, feedback mechanisms which may enhance or ameliorate a risk.

Preparedness in cities and communities is critical for effective national, regional and global responses to a health crisis, such as the COVID-19 pandemic. Urban settings face dynamics resulting in their expansion and/or in the formation of dense urban districts which may be also characterized by inappropriate sanitation and hygiene provisions; they also exhibit high case numbers, a fact which reflects the ease of introduction and spread of the virus in densely populated areas which are also travel hubs (World Health Organization, 2020b). In parallel, the likely increasing urbanization rate in the forthcoming decades is an additional concern, as more than 66% of the world's population will be living in cities by 2050 and the total global urban land area is expected to increase by more than 1.5 million square kilometres by 2030 (Seto et al., 2012).

The intensity of anthropogenic activities, high building density, extensive impervious cover, the increased use of vehicles and the depletion of greenery have led to the deterioration of urban climate (Agathangelidis et al., 2019). In this context, urban climate is largely determined by the limitation of air exchange, caused by the presence of

high roughness variables as well as the obstruction of natural ventilation routes due to constructions (Ng et al., 2011). Specifically, the insufficient dispersion of air pollutants emitted by near-surface sources increases the environmental impact on the population and the likelihood of COVID-19 transmission rates. The effects of this inadequate ventilation are critical during periods of extremely low prevailing winds, usually associated with stagnant high-pressure systems (Kassomenos et al., 2014). In fact, this problem has received limited consideration by urban scientists and planners as well as of public health experts. The increase of urban wind speed could be achieved by activating ventilation corridors which are linear areas, characterized by relatively low surface drag. Urban regeneration could offer considerable potential for the improvement of public health through interventions with the potential to support the unhindered flow of air masses close to the ground (Serrano et al., 2016).

4. Discussion

Regarding the effect of weather and climate variables on COVID-19, the results of previously published studies that used measurements from single countries were conflicting. Specifically, most analyses revealed a negative correlation between temperature or other weather variables and the number of COVID-19 cases, while several analyses demonstrated a positive correlation instead. Taking into consideration the findings from localized and global analyses, the reverse correlation between weather (i.e. temperature or humidity) and climate (i.e. site incident ultraviolet radiation, sunshine duration) and COVID-19 is the most likely scenario. However, it remains obscure if it is the rise in temperature or humidity that had some effect in the decline of transmission and thus COVID-19 cases or if this decline is due to the public health interventions that took place. When the latter covariates were included in the model, no significant correlation was detected between the prevailing climatic conditions and COVID-19 (Jüni et al., 2020). The effect of weather and climate variables, as suggested in the past for other coronaviruses or influenza virus, cannot be excluded, however, under the conditions of the first pandemic wave where multiple measures were implemented, it might be difficult to be uncovered. It has been shown that containment measures have a much stronger impact than the weather and climate variables, which can explain only the 18% of the variation in COVID-19 doubling time (Oliveiros et al., 2020). The impact of weather variables was also shown in a single study conducted in Mexico, where data on COVID-19 cases was collected before the effect of containment measures; in this case temperature was found to be negatively associated with local cases (Méndez-Arriaga, 2020). Other important variables for COVID-19 transmission are human mobility and the impact of imported cases, as considered in several studies assessing the impact of climate to SARS-CoV-2 transmission.

On the contrary, during summertime 2020 several countries in the Northern hemisphere experienced a significant increase in the number of daily COVID-19 cases, named a second pandemic wave (<http://www/who.int>). Specifically, following to the discontinuation of public health measures, Albania, Bulgaria, North Macedonia and Serbia were among the first countries in Europe that experienced an increase in the number of cases in June 2020, followed by many others such by Austria, Croatia, Denmark, France, Greece, Romania, Spain, the Netherlands and Ukraine in which the second pandemic wave appeared between July and August 2020 and continues. The significant increase in the number of cases suggests that SARS-CoV-2 is capable of producing outbreaks at high ambient temperatures such as during summertime period in Southern Europe (e.g. Spain, Greece, Bulgaria). These findings highlight that in the absence of public health measures climate conditions cannot mitigate SARS-CoV-2 outbreaks, and that the seasonality of SARS-CoV-2 differs greatly compared to common cold coronaviruses or influenza. The seasonal pattern of the latter pathogens is due to a combination of weather and immunological variables (e.g. cross-immunity, duration of immunity).

Air pollution can also affect the COVID-19 transmission. Specifically, an important parameter associated with virus transmissibility is ventilation and air changes rate in an area. Ventilation rate in high population and building density areas is limited and certain measures are needed for the improvement of public health. Air pollution can probably affect the COVID-19 case fatality rate, however, due to several limitations in previously published studies, further investigation is needed to draw conclusions about the effect of these variables on COVID-19.

5. Conclusions

Although the impact of weather and climate variables to the COVID-19 transmission rate seems likely, a solid conclusion on the degree of impact needs further investigation. On the contrary, it can be stated with confidence that the increase in the number of COVID-19 cases during summertime period in countries with high ambient temperatures, implies that in the absence of public health measures, weather and climate variables cannot mitigate the resurgence of outbreaks. To this end, further study is needed to precisely assess the impact of weather and climate variables to the COVID-19 transmission rate and to the resulting number of cases, especially in the absence of public health measures.

CRedit authorship contribution statement

Conceptualization, D.P., N.S.T., C.C., S.T. and M.A.D.; Investigation-sample collection and analysis, D.P., E.G.K., N.A., N.S.T. and C.C.; Data Curation, D.P., E.G.K. N.A., N.S.T. and C.C.; Writing – Original Draft Preparation, D.P., E.G.K., N.A. and C.C.; Writing – Review & Editing, D.P., E.G.K., N.A., N.S.T., C.C., S.T. and M.A.D.; Supervision, D.P., N.S.T., C.C., S.T. and M.A.D.; All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

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