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Weather Conditions (with Focus on UV Radiation) Associated with COVID-19 Outbreak and Worldwide Climate-based Prediction for Future Prevention

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ABSTRACT

Respiratory infectious diseases are highly influenced by climate and feature seasonality, whose peak is December to February in the Northern Hemisphere. SARS-CoV-2 produced consistent debate regarding the relationship between its emergence and weather conditions. Our study explored these conditions, expressed by three main parameters—ultraviolet radiation, air temperature and relative humidity—that characterized Hubei (China), the source region of COVID-19 pandemic, in November 2019–March 2020. During COVID-19 outbreak, the low amounts of UV radiation (down to –273 kJ m^{-2} in January 2020) were associated with the early stage environmental survival of the novel coronavirus. As well, this period was characterized by a high relative humidity during peak hours of the day, and a positive air temperature anomaly (+1.7°C in December 2019), which also favored the outdoor people mobility in winter. Based on Hubei analysis, a presumed optimal weather frame was set in order to identify other world regions with similar weather characteristics. In brief, the „Hubei weather profile" was recorded in those regions of COVID-19 outbreak in February 2020, such as northern Iran, Italy or Spain. Our results, which focused on the role of the UV solar radiation, could be used as a prediction tool for identifying the world regions with a higher risk of future faster increase in COVID-19 cases.

Keywords: COVID-19; UV radiation; Air temperature; Relative humidity; Climate change.

INTRODUCTION

A new SARS-CoV like respiratory virus was detected in late December 2019 in Wuhan, China (WHO, 2020b), with human-to-human transmission (Rodríguez-Morales *et al.*, 2020). It led to a world scale outbreak of COVID-19 disease, being declared a pandemic on March 11th, 2020 by the World Health Organization (WHO, 2020b). Taking into account its incubation period, which is of around two weeks according to Backer *et al.* (2020), as well as the earlier unreported cases and transmission from asymptomatic individuals (Rodríguez-Morales *et al.*, 2020), we presume that the virus has emerged before, in the first half of the month of December or even late autumn.

Studies have already demonstrated that respiratory infectious diseases are influenced by climate (Geller, 2001; du Prel *et al.*, 2009; Fisman, 2012; Mirsaeidi *et al.*, 2016). For example, it is well known that influenza features a yearly peak from mid-December through February in the Northern Hemisphere (Geller, 2001). Seasonality of pneumonia, as well, has been explained by a series of combined factors such as indoor crowding (derived from the colder season and producing closer contacts) and poor indoor air quality in association with other seasonal respiratory pathogens, as well as outdoor conditions such as low relative humidity and low amounts of ultraviolet radiation (Mirsaeidi *et al.*, 2016). Therefore, the relationship between the emergence and development of the COVID-19 outbreak on one side and the weather conditions on the other side should not be neglected.

Gardner *et al.* (2019) have reported an association between climate factors and other types of Coronaviruses, such as MERS-CoV, responsible for the Middle East Respiratory Syndrome, which mostly affected the Arabian Peninsula in 2012 (Rodríguez-Morales *et al.*, 2020). Suhaimi *et al.* (2020) indicated that air temperature significantly affects the SARS-CoV-2 spreading, while Sun *et al.* (2020) identified that high relative humidity during the cold season in South-Eastern China provide conducive environmental conditions for prolonged virus survival in these regions.

Therefore, it is very probable that weather factors play a role at least in the emergence, early stage transmission, and probably in its re-emergence in different areas. Beyond that,

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more attention is given to ultraviolet radiation (Gunthe *et al.*, 2020, Suhaimi *et al.*, 2020), known as one of the most important weather factors for the pathogens control (Sagripanti and Lytle, 2007).

Actually, UV radiation is considered an important environmental limiting factor which contributes to virus inactivation (Sagripanti and Lytle, 2007). This is the reason for developing technical tools based on virus inactivation by UV radiation (Kowalski *et al.*, 2020).

The germicide power of UV light depends on factors such as wavelength and the type of target microorganism. UV radiation is classified in subtypes (Kerr and Fioletov, 2008), depending on their wavelength: UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (100–280 nm). It is widely considered that UV-C types of radiation with shorter wavelength (< 280 nm) is the unique type of UV radiation inducing a germicide effect (Pozo-Antonio and Sanmartin, 2018). Since this type of radiation is totally absorbed by the stratospheric ozone, it was assumed that sunlight lacks efficient germicidal effects and will be inefficient in taming the COVID-19 pandemics (Seyer and Sanlidag, 2020). However, it is known that all the radiation with wavelength < 320 nm (UV-B and UV-C together), have an actinic effect due to their ability to directly damage DNA by forming modified bases (IARC, 1992) and even UV-A can interact with proteins and lipids (Ridley *et al.*, 2009). From a climatic point of view, UV-B radiation represents up to 5% of the total UV radiation (Kerr and Fioletov, 2018), hence it can reach substantial amount for the time of the day when the sun elevation is greater to 60° (Kollias *et al.*, 2011). Moreover, it is also known that the increase in UV dosage, regardless of its subtypes, impose a reduction of microorganism survivors (Diffey *et al.*, 1991). Therefore, despite its resistance to environmental conditions (van Doremalen *et al.*, 2020), it is very likely that UV radiation play a certain role on SARS-CoV-2 evolution worldwide (Gunthe *et al.*, 2020; Poole, 2020).

Overall, taking into account that coronaviruses are known to be influenced by the weather conditions (Sun *et al.*, 2020), and that SARS-CoV-1 outbreak was also influenced by weather factors (Lin *et al.*, 2006), we assumed in our study the same relationship between weather conditions and the ongoing SARS-CoV-2 outbreak. Our hypothesis is that, at least in the early stages, weather conditions (especially UV solar radiation) facilitated the environmental survival of SARS-CoV-2 in the Hubei region in November 2019–January 2020 as well as its propagation at a higher rate in world regions with similar weather conditions. Nevertheless, this propagation is enhanced by numerous other factors like travel patterns, accessibility, social connections and cultural behavior (e.g., mass gatherings) (McCloskey *et al.*, 2020). Thus, our study proposes the understanding of weather pattern in Hubei on the eve of SARS-CoV-2 outbreak and a climate overview, with focus on ultraviolet radiation, on how the COVID-19 could propagate in relation with weather conditions during the year.

DATA AND METHODS

We have acquired weather data at global scale from ERA-5 Dataset of Copernicus Climate Change Service C3S Climate Data Store (CDS) (C3S, 2020), regarding UV radiation (kJ m^{-2}) (UV), mean air temperature (°C) (AT) and mean relative humidity (%) (RH), on a daily and monthly basis. We have chosen only these three parameters since other weather elements (e.g., wind speed, precipitation) do not seem to be linked to the COVID-19 outbreak (Gunthe *et al.*, 2020). The spatial resolution of the ERA-5 atmosphere and land reanalysis is 31 km (0.281°), but the data has been regridded to a regular lat-lon grid of 0.25°. We have based our analysis on monthly average reanalysis data, for the last 19 years (2001–2019), which reflects the recent mean climate conditions. These monthly means are created from the hourly data downloaded through the CDS Application Programming Interface (API) request.

As evidence of an earlier presence of the virus is discussed (Parodi and Aloisi, 2020), we have chosen to investigate the weather conditions not only during, but also before the virus outbreak in China. Thus, for the period November 2019–March 2020 (Table 1), monthly means for UV, AT, and RH were calculated for the lowland of Hubei region in China (within the following coordinates: 29°50′–31°25′N; 111°50′–114°55′E).

Daily data for COVID-19 number of cases were selected for 12 regions highly impacted by the virus outbreak around the world (Hubei province from China, Lombardy for Italy, Sao Paolo and Amazonas states in Brazil, Valparaiso province in Chile, Los Angeles state and New York city in United Stated, Suceava county in Romania, Stockholm county in Sweden, Maharashtra state in India, and London city in United Kingdom). All the regions/cities are known for the high number of COVID-19 recorded until June 2020. The data were acquired from COVID-19 pandemic by

Table 1. Monthly means and standard deviation (stdev) for UV radiation (kJ m^{-2}), air temperature (°C) and relative humidity (%)—in Hubei region, China, during November 2019–March 2020 and their deviation (Δ) from the multi-annual means (2001–2019); statistical significant values of Δ are given in bold numbers.

	Ultraviolet radiation				Air temperature				Relative humidity			
	2019–2020	2001–2019 mean	2001–2019 stdev	Δ	2019–2020	2001–2019 mean	2001–2019 stdev	Δ	2019–2020	2001–2019 mean	2001–2019 stdev	Δ
November	1045.9	1079.8	±130.0	+33.9	13.5	12.0	±1.2	**+1.5**	60.3	67.5	±6.6	**–7.2**
December	930.2	917.8	±138.1	+12.4	7.9	6.2	±1.0	**+1.7**	66.1	63.3	±8.5	+2.9
January	710.9	984.9	±116.3	**–273.9**	5.0	4.5	±1.6	+0.5	80.3	66.7	±6.5	**+13.6**
February	1142.8	1122.4	±229.8	+20.0	9.3	7.0	±2.0	**+2.3**	71.3	70.3	±8.7	+1.0
March	1366.2	1522.7	±112.2	–156.4	13.3	12.3	±1.1	+1.0	72.7	68.4	±4.5	**+4.3**

location data available on Wikipedia (2020) who gathers official information from national sources.

Spearman test were applied for correlation between UV solar radiation data and COVID-19 cases, while significance of weather parameters from long-term means was checked using Student and Mann-Whitney tests.

Since the models based on species distribution are subject to major deficiencies (Chipperfield *et al.*, 2020), our assessment is based strictly on the analysis of the weather conditions in Hubei region during November 2019–March 2020 (Table 1). According to these data, before the COVID-19 outbreak (November 2019–January 2020) the UV downward radiation (defined as radiation with a wavelength from 200–440 nm) at surface barely reached 1.000 kJ m^{-2}, the mean air temperature was 8.8°C and the mean relative humidity was 69%. Based on these concrete values, the presumed optimal weather conditions for SARS-CoV-2 were defined according to the following parameters at monthly level: UV < 1.000 kJ m^{-2}, mean monthly air temperature between 3 and 10°C and mean relative humidity between 60–80%. The thresholds for air temperature and relative humidity correspond to the limits of the diurnal cycle of variation of these elements.

Further, we have searched for the world regions with similar weather conditions. For this, we have established 7 classes of weather similarities (where the above mentioned conditions were simultaneously met). The most complex class is the one combining all indexes together (UV + AT + RH). The following 3 classes indicate a combination of two conditions met (UV + AT, UV + RH, or AT + RH), while the last 3 classes indicate the fulfilment of only one condition (UV, AT, or RH). This was done for each month from November 2019 to January 2020 so as to identify, at global scale, the regions having the similar weather conditions as in the Hubei region before the outbreak and to check if these maps correspond with the further geographic evolution of the COVID-19 outbreak. In order to synthesize the cumulated conditions for more than one month, an additional score model was conceived. In this model, each grid cell on the map received a score, as follows: 3 points if all the 3 conditions regarding UV, AT, and RH were met, 2 points for each combination of 2 conditions met simultaneously, and 1 point for one single condition within threshold. By summing up these monthly scores, we obtained seasonal maps showing a score of optimal weather conditions for SARS-CoV-2 environmental survival.

Based on the findings that the virus survival can be modelled using climate data (Poole, 2020), and that a second peak of COVID-19 could be expected during winter 2020/2021 (Neher *et al.*, 2020), we have applied the analysis presented above for the long term climatic means at monthly level (2001–2019). This way, we have produced monthly maps at global scale showing which regions feature similar monthly climatic conditions with those from the Hubei region in November 2019–January 2020. These maps can serve as prediction tools for understanding the subsequent climate conditions enabling virus propagation.

Also, we mentioned that the data processing described above is based on the code line developed on R language programming and it is available on GitHub repository (https://github.com/vladamihaesei/weather_covid). Hence, the model thresholds we have used can be adapted in the future for the optimal weather conditions which will be better described for COVID-19.

RESULTS AND DISCUSSION

Weather Conditions Associated with the Development of COVID-19 Epidemic

The COVID-19 outbreak occurred in Wuhan (11 mil. inhabitants), the capital and major city of Hubei Sheng province, situated at the very heart of China, equidistant from Beijing and Guangzhou (Canton) on a N–S axis and equidistant from Chongqing and Shanghai on a W–E axis (Pletcher, 2010). Hubei Province has a high population density, with 59 million inhabitants living on 185.900 km^2, comparable with the United Kingdom (66.5 mil. inhabitants and 242.5 km^2). Hubei's relief is dominated by the Jianghan low plain (30–50 m alt.), which occupies the center of the region, and which is bordered by higher mountains to the west (over 3000 m), and lower mountains to the east (up to 400 m), thus behaving like a depression. Hubei Province is situated in a relatively vast continental area, at low latitude (30°N), with climate conditions defined as humid subtropical, specific for south-eastern China (Pletcher, 2010). During winter, the climate is mild, characterized by moist air, mild temperatures (around the mean of 4.5°C in January), and a lasting cloud cover leading to persistent lack of sunshine.

After analyzing the weather conditions before and during the early stage of the SARS-CoV-2 (Table 1), we noticed that the air temperature was considerably above the mean of 2001–2019 from November to March (with statistically significant positive deviations in November, December and February) for the lowest part of Hubei region. In this context, we remark that the most important regions from Asia and Europe (northern Italy, Spain, California, Japan or South Korea) which were subject to the virus outbreaks have recorded a similar warmer winter (see supplementary materials – Fig. S1), with mean monthly air temperature up to 2°C higher than the long term means. Consequently, warmer conditions have played a favorable role in people mobility and gathering, and as well in virus environmental survival. It is well known that modification of geographic landscape, weather anomalies and natural disasters, as features of climate change increases the risk of proliferation of infections and exposure to diseases (Varo *et al.*, 2019). Therefore, a connection between the current pandemic and the global warming should not be neglected, since it is expected that the climate change increases the incidence of infectious diseases in the near future (Rosenthal, 2009; Curseu *et al.*, 2010).

It was assessed that intermediate values of relative humidity favored COVID-19 transmission (Auler *et al.*, 2020). In Hubei region, the relative humidity for the studied period was close to the climatic averages, significantly more humid during January 2020, with values of 80% (Table 1). There is a diurnal variation, with values going up to 100% in the morning, close to condensation level, and more unsaturated conditions in the afternoon. We should mention that morning time generally records the highest relative diurnal humidity and is characterized by a high urban mobility, which seems to be favorable for the virus outbreak.

The analysis of mean UV radiation in the Hubei region over a longer period of time firstly revealed an important negative anomaly for its latitude (supplementary materials – Fig. S2) for the winter period. Actually, the region's depressionary topography enhanced the atmospheric stability, leading to formation of stratiform clouds especially during the cold season which is known to record the lowest level of air quality in central China (Xu *et al.*, 2020). In fact, development of stratiform clouds consistently increased air pollution in the great urban agglomerations, leading to the decrease of the sunshine duration and consequently to a critical drop in the amount of UV radiation. It is worth noticing that the association between atmospheric pollution and COVID-19 incidence observed lately (Zhu *et al.*, 2020) is a possible result of this interplay between atmospheric stability and air pollution, inducing a lack of UV radiation, which characterizes the South–East of the USA, but also South-East China and Northern Italy. On this climatic background, the amount of UV downward radiation reached a consistent negative anomaly in January 2020 in the Hubei region, when the monthly values were below long-term (2001–2019) means by –273 kJ m^{-2} (Table 1; supplementary materials – Fig. S3).

It can be observed that the Hubei outbreak occurred just after the annual minimum amount of UV solar radiation (Figs. 1(a) and 1(b)) amplified in 2019–2020 by a persistent negative anomaly extended from 10 of December until 20 of January. Interestingly, in Lombardy (Italy), the outbreak in February appeared in quite similar conditions regarding the amount of UV solar radiation (Figs. 1(c) and 1(d)). We can observe as well that the minimum in UV radiation during this period was below 1000 kJ m^{-2} in both regions.

The relation between UV radiation amount and the number of COVID-19 cases should be validated taking to account a couple of facts such (a) the lack of homogeneity regarding the reports cases by each state, (b) different mitigation policies adopted worldwide, (c) the lag from the moment of infection and the diagnose which is not very well established or (d) the increase in UV radiation in Northern Hemisphere produced in the same time with COVID-19 outbreak which can induce false positive correlations. Despite these aspects, we found a clear negative correlation between UV radiation amount and COVID-19 cases in spots from both hemispheres. In Northern Hemisphere this relation is shown in Stockholm County (Sweden), a region where the official approach of the epidemics was less restrictive, leaving us the possibility to understand the free relation between UV and COVID-19. Firstly, we can see a stabilization of COVID-19 cases when UV radiation amount crossed the 1000 kJ m^{-2} level (Fig. 2(a)), while the negative correlation after reaching the maximum peak was statistically significant (Spearman coefficient, R = –0.59, $p < 0.001$, Fig. 2(b)). The same relation is found in Valparaiso (Chile), in the South Hemisphere with a strong negative correlation (Spearman coefficient, R = –0.77, $p < 0.001$, Fig. 2(d)) which experienced a rapid increase of COVID-19 cases when UV radiation amount decreased under 1500 kJ m^{-2} (Fig. 2(c)).

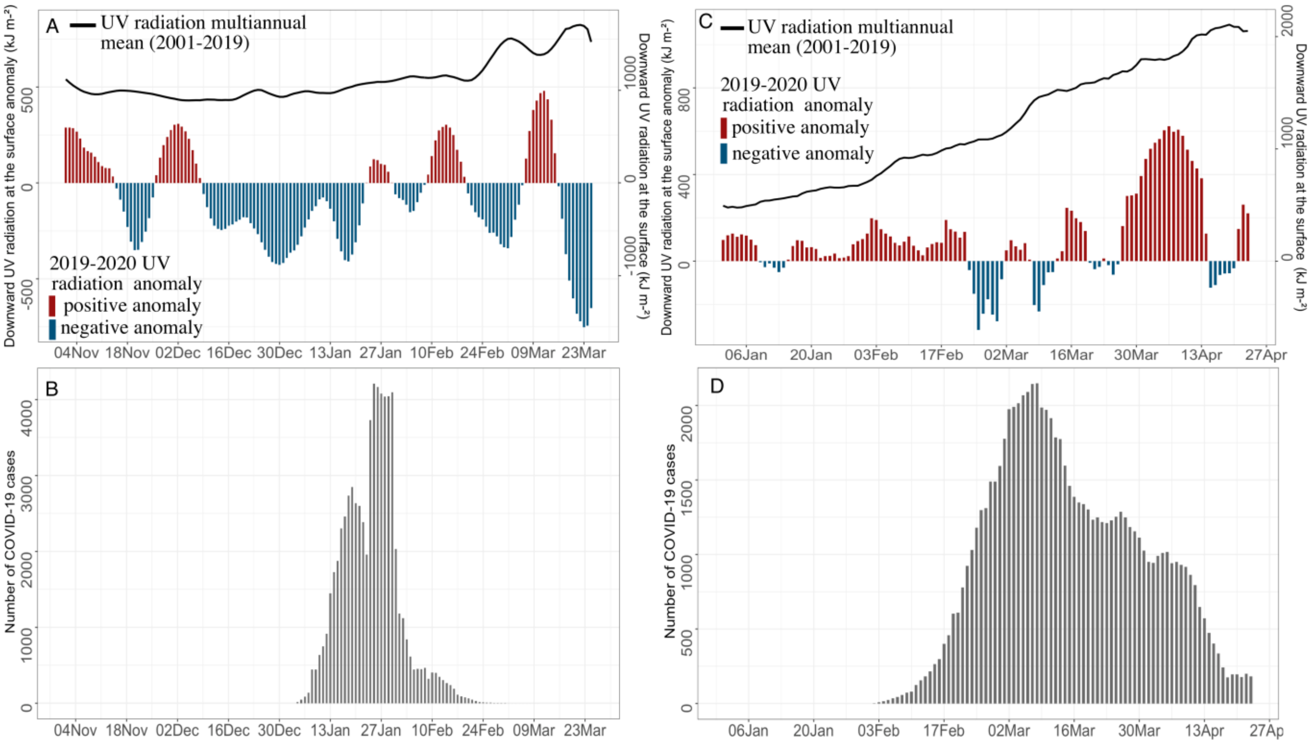

Fig. 1. Daily UV evolution for (a) Hubei (November 2019–March 2020) and (c) Lombardy (January–May 2020) with their deviation from the multiannual mean deviation from the multiannual mean (2001–2019) and the evolution of the number of diagnosed COVID-19 patients (b, d) shifted with 14 days forward taking to account the incubation period; the daily values were smoothed to avoid day-to-day variations applying a 7 days running mean.

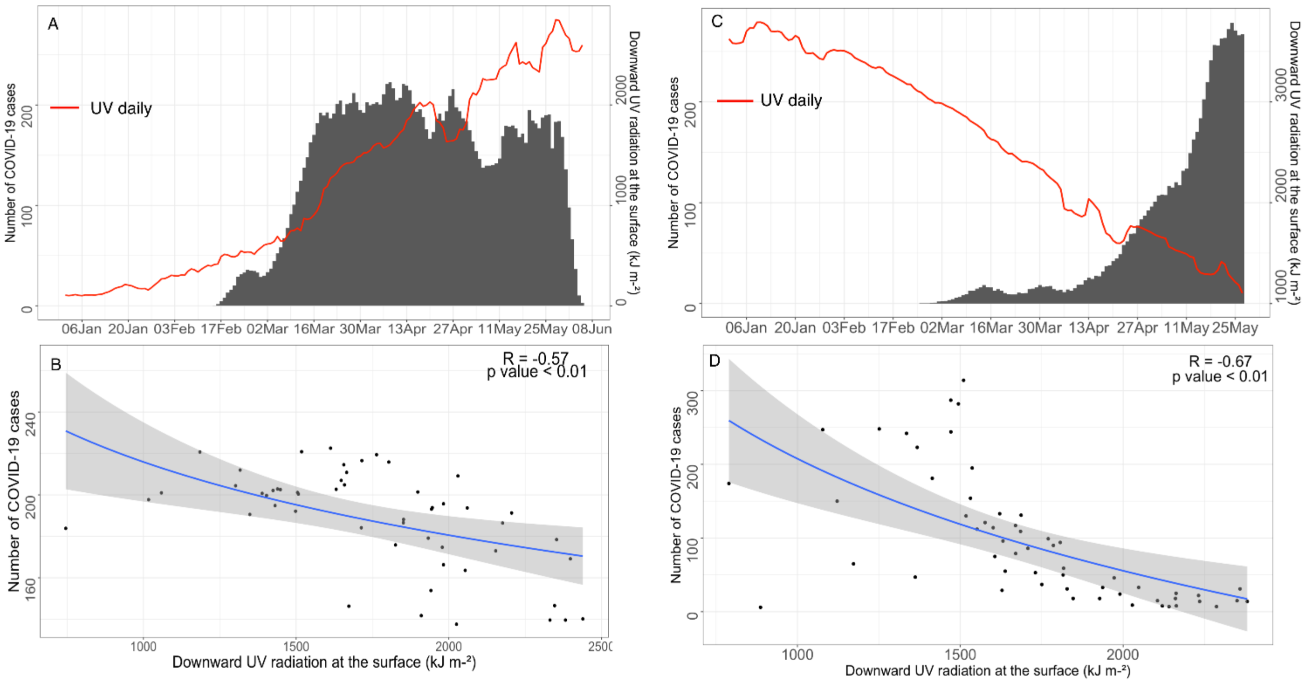

Fig. 2. Evolution of the number of cases of COVID-19, UV radiation amount and correlation between them for (a, b) Stockholm state (Sweden) and (c, d) Valparaiso province (Chile).

Summing up, during the observed period, abnormal lower amounts of UV radiation combined with warmer air and slightly higher relative humidity seem to have been very favorable for virus environmental survival and thus enhanced the spreading of the disease.

Data from November 2019 through January 2020 features the world geographic areas in which the conditions set in the current methodology were met (Fig. 3; supplementary materials – Figs. S4–S5). For example, the red color depicts those regions in which all the three elements recorded monthly values within the mentioned thresholds, while the blue color on the map indicates the accomplishment of only relative humidity conditions. Thus, we can observe that, besides the Hubei region and the surrounding central—south-eastern China, other geographical areas recorded similar conditions in East Asia (South Korean Peninsula and Japan) or in central and western Asia (Turkmenistan and extreme northern Iran). In Europe, the same conditions characterized the Mediterranean basin, with large areas spanning from Spain, southeast France, Italy, Greece, western Turkey and South Caucasus. In the Americas, the same conditions were met in a strip situated in the southeast part of the USA, from Kansas to North Carolina and up to New York State, but also locally on the Pacific coast from Washington to California. Thus, we observe that the major regional outbreaks in February 2020 correspond with the subtropical belt of combined UV-AT-RH suitability for SARS-CoV-2, also observed by Sajadi *et al.* (2020) and Poole (2020).

This can be observed even more clearly on the additional score model results (Fig. 4). Besides the Hubei region, the highest score is recorded in South Korea and Japan in eastern Asia, the first regions experimenting COVID-19 in January 2020 (WHO, 2020a). Iran represents the second major outbreak of COVID-19 outside China (WHO, 2020a) and our results indicate higher scores in the north of the country, the second epicenter next to the city of Qom. Similarly, southern and western Europe recorded a higher suitability score, which is related with the outbreaks from February 2020 in Italy and Spain (WHO, 2020a). Last but not least, the tremendous number of cases recorded in the United States in February and March 2020 could be related to the weather conditions in California and in the south-eastern belt, which replicated very well the optimal conditions in southern-east China.

The slower increase in the number of cases over low latitudes, a phenomenon which was also observed by Poole (2020), is explained by the low climate suitability score over these latitudes. Thus, South-East Asian countries like India, Malaysia, Vietnam, geographically exposed to China, as well as central Africa managed to contain the COVID-19 disease at least in its early stages. In this line, by analyzing 12 regions severely affected worldwide, we have observed the relation between the UV radiation amount for the days passed from the first reported case until reaching an incidence of 1 (one) COVID-19 patient by 100.000 inhabitants. We can observe the tendency toward a slower/faster propagation of the disease induced by higher/lower amount of UV radiation (Fig. 5) which is supported from statistically point of view (Spearman, $r = 0.31$, $p < 0.10$).

Our results reinforce the estimations of Sajadi *et al.* (2020) and Poole (2020) which pointed out that the most cases of COVID-19 occurred in February 2020 between 25°N and 55°N latitude. Moreover, the countries situated in the subtropical region experienced a rapid increase in the number of COVID-19 cases (Fig. 6). In our opinion, this could be induced by the weather optimal conditions for

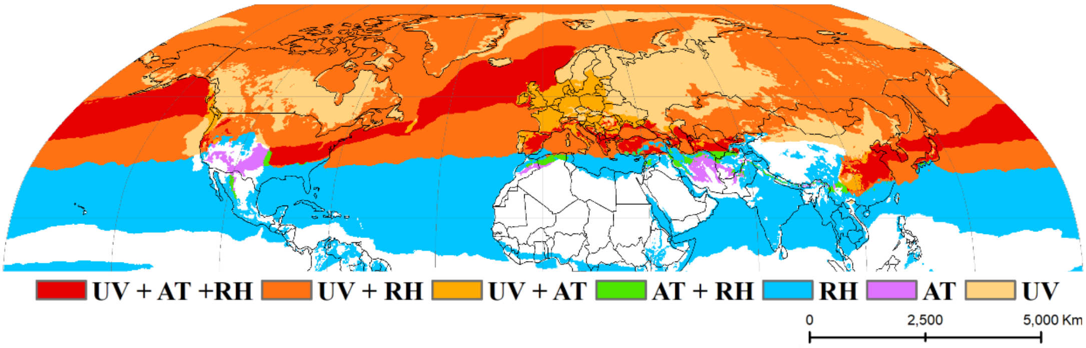

Fig. 3. The distribution of regions with similar weather conditions during November 2019–January 2020 as Hubei, assumed as optimal conditions for SARS-CoV-2.

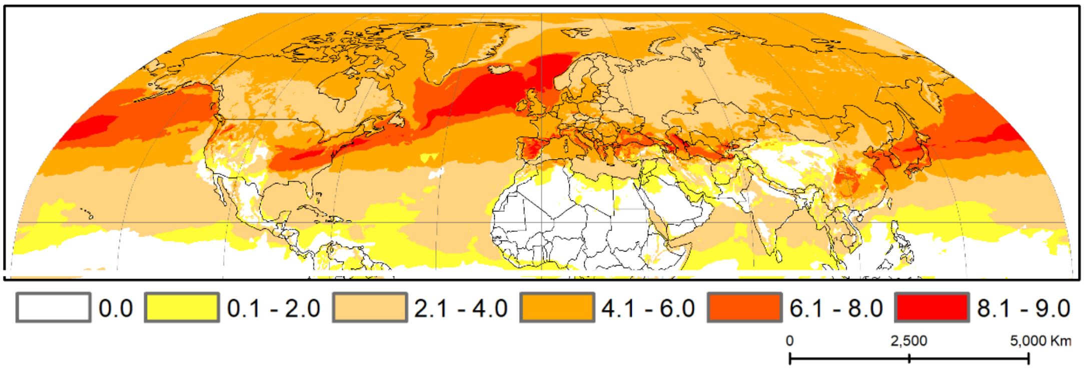

Fig. 4. The distribution of monthly cumulated score of climate suitability for SARS-CoV-2 environmental survival between November 2019 and January 2020.

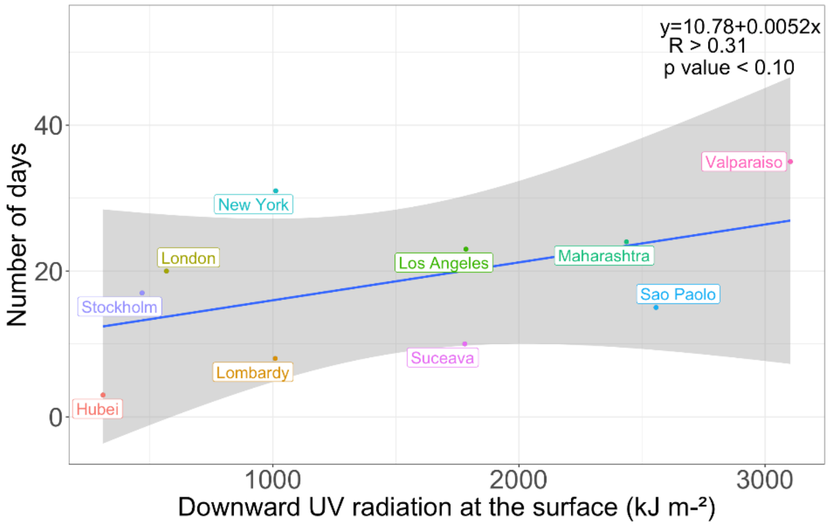

Fig. 5. Regression between UV radiation amount during the early stage propagation of COVID-19 and the number of days until reaching the threshold of 1 (one) COVID-19 patient diagnosed by 100 k inhabitants.

SARS-CoV-2 survival in these regions. There are a few counterexamples in Western Europe, Brazil, Indonesia, countries with the same rapid increase in which other factors such as high mobility of the population or specific social patterns applied. On the other hand, the slowest increase of COVID-19 cases is specific to countries with lower climatic suitability for SARS-CoV-2 during November 2019–January 2020, such as Canada, Australia and Malaysia.

Distribution of Presumed Optimal Climate Conditions at Global Scale

Based on the criteria used to assess the weather conditions favorable for SARS-CoV-2, and on the monthly data for 2001–2019 from the same ERA-5 database, we have obtained

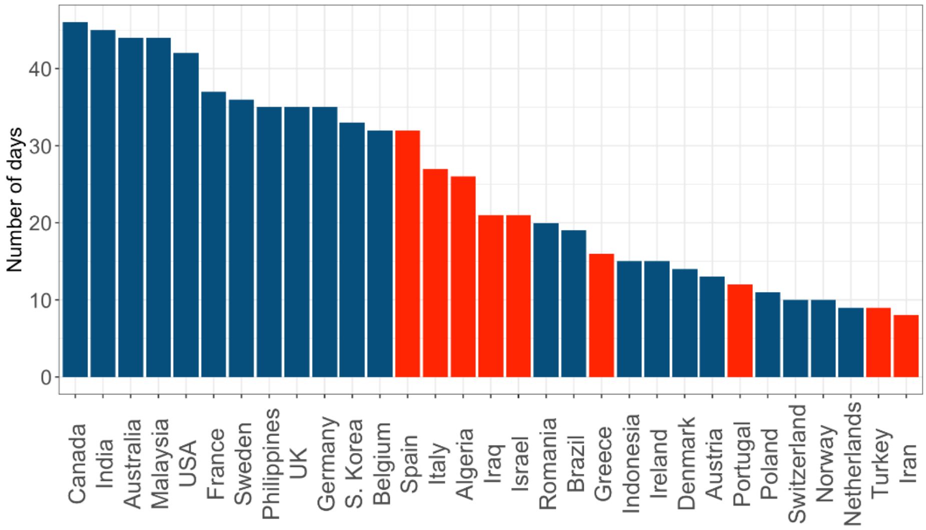

Fig. 6. Number of days between the 1st and the 500th reported case of COVID-19 by country—subtropical countries in red columns (source data: worldometer.info).

monthly maps showing the world regions in which the conditions similar to those in the Hubei region between November 2019 and January 2020 will be met. This analysis is presented separately for the Northern Hemisphere warm season (considered here from April to September) and for the cold season (from October to March), respectively. We have also summarized the results in two seasonal maps of our additional score model for summer (June–August) and winter (December–February), respectively. These monthly maps can work as prediction tools in order to identify the regions where the virus could propagate slower/faster due to lower/higher virus environmental survival. Since it is obvious that the virus can survive in any regions, this prediction tools offer an idea on the speed of propagation of the virus at global scale during the year.

For the cold season, beginning with October (Fig. 7), we may observe that the most suitable conditions for the virus survival cover the Northern Hemisphere north of 45°N, being clearly delimited by the UV radiation flux. Within these areas the maximum is reached over Eastern Europe-north of the Black Sea, central Canada and extreme northern Europe with all the 3 parameters within thresholds. Interestingly, the negative UV anomaly in Sichuan basin already indicates UV values of under 1000 kJ m^{-2} for October due to the same depressionary climatic conditions described above for Hubei. Thus, future epidemiological studies should assess the importance of these unique climate conditions (lack of UV radiation combined with mild winters) for virus environmental survival in South–East China. The maximum suitability during October extends to November over the eastern China, and also covers the largest part of the north-eastern United States. It also reaches the subtropical region, covering the northern part of the Mediterranean basin, large parts of central Asia, as well as Japan and South Korea. In December and January, the weather conditions regarding UV, AT, and RH are quite the same over the Northern Hemisphere. In this period, higher suitability is recorded in East Asia (the source region of the disease in eastern China, Korean Peninsula and Japan), south-eastern and eastern parts of the United States, but also over large parts of continental area north of Mediterranean Sea. February records a decrease in suitability, but this remains higher especially in Europe, while in March the suitability is restrained to the extreme northern parts of Eurasia and North America.

The additional score model results (Fig. 8) indicate the highest score for winter months (December to February) over 3 main regions: (a) subtropical regions from south-eastern parts of China extended over Japan and Korea, and south-eastern part of the United States, the regions having a similar climate; (b) western parts of North America and Europe in the temperate region and (c) the Mediterranean basin extended over Caucasian region north of Iran and southern part of central Asia. Generally, this corresponds to the situation analyzed for 2019–2020. These results are in line with those of Araujo and Naimi (2020), which were based on an ecological niche model taking into account only air temperature and precipitation. Nevertheless, it is no surprise that the results feature similarities since the atmospheric precipitation and UV radiation are both directly related to cloud cover. However, we must emphasize that the decrease of UV radiation level could play a more important role for the virus survival compared to the atmospheric precipitation. Therefore, our model indicates less suitability in the Southern Hemisphere for December–February as shown by Araujo and Naimi (2020), since this region benefits from higher amounts of UV radiation during the austral summer.

During the warm season (April–September), due to high amounts of UV radiation and increased air temperature, the Northern Hemisphere records a decrease in weather suitability for SARS-CoV-2. On the other hand, during the same time, the Southern Hemisphere records the peak in weather suitability for SARS-CoV-2 (Fig. 9), as suggested by other authors (Ficetola and Rubolini, 2020). Due to the limited extension of continents, the maximum suitability will be directly felt during June and July especially for the Chile and Argentina and the extreme South of Australia.

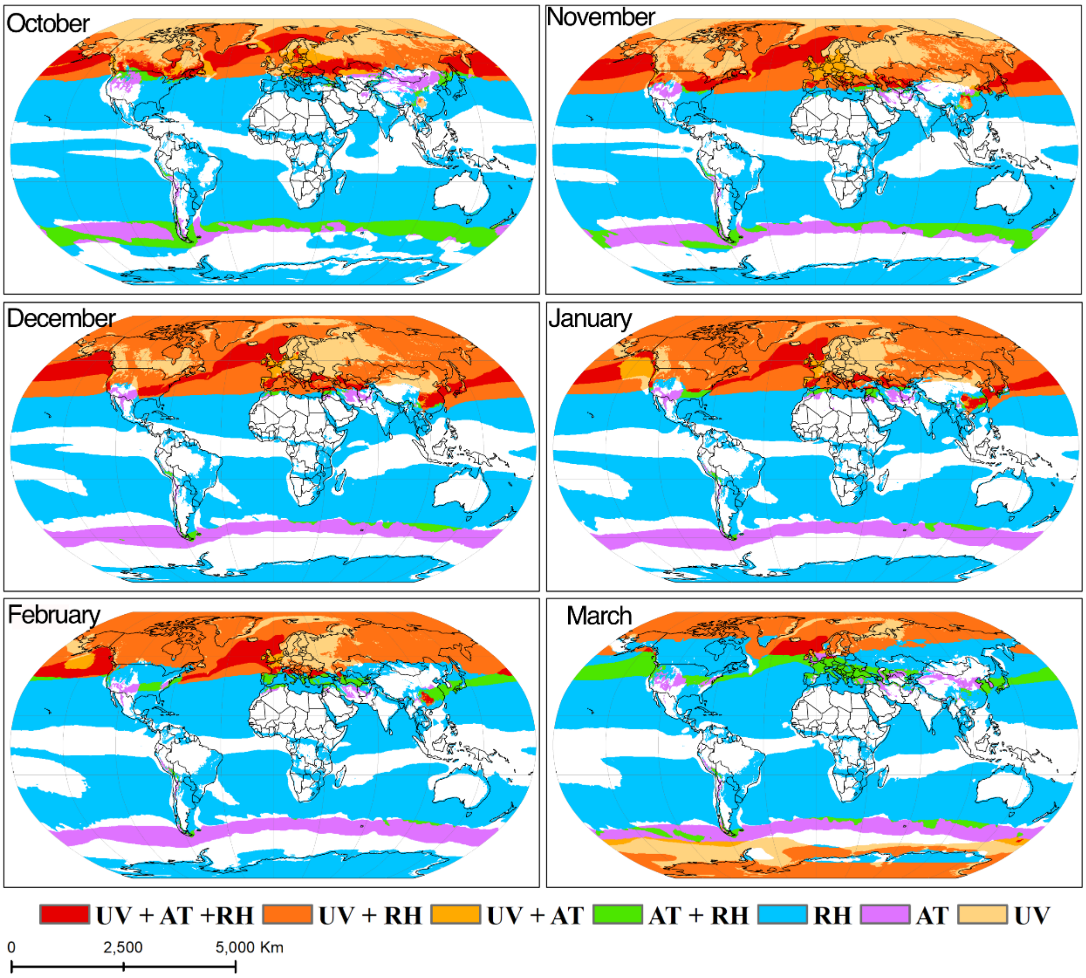

Fig. 7. Presumed optimal climate conditions worldwide for SARS-CoV-2 at monthly level for October–March, based on the monthly means of UV, air temperature and relative humidity 2001–2019.

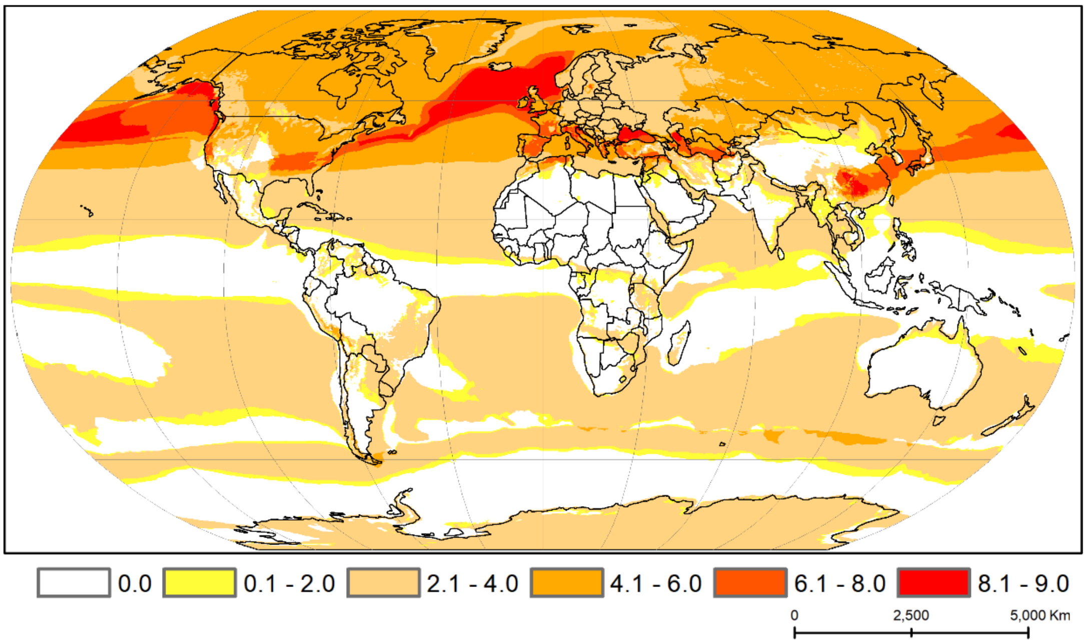

Fig. 8. Score of climate suitability for SARS-CoV-2 for December–February based on the monthly means of UV, air temperature and relative humidity 2001–2019.

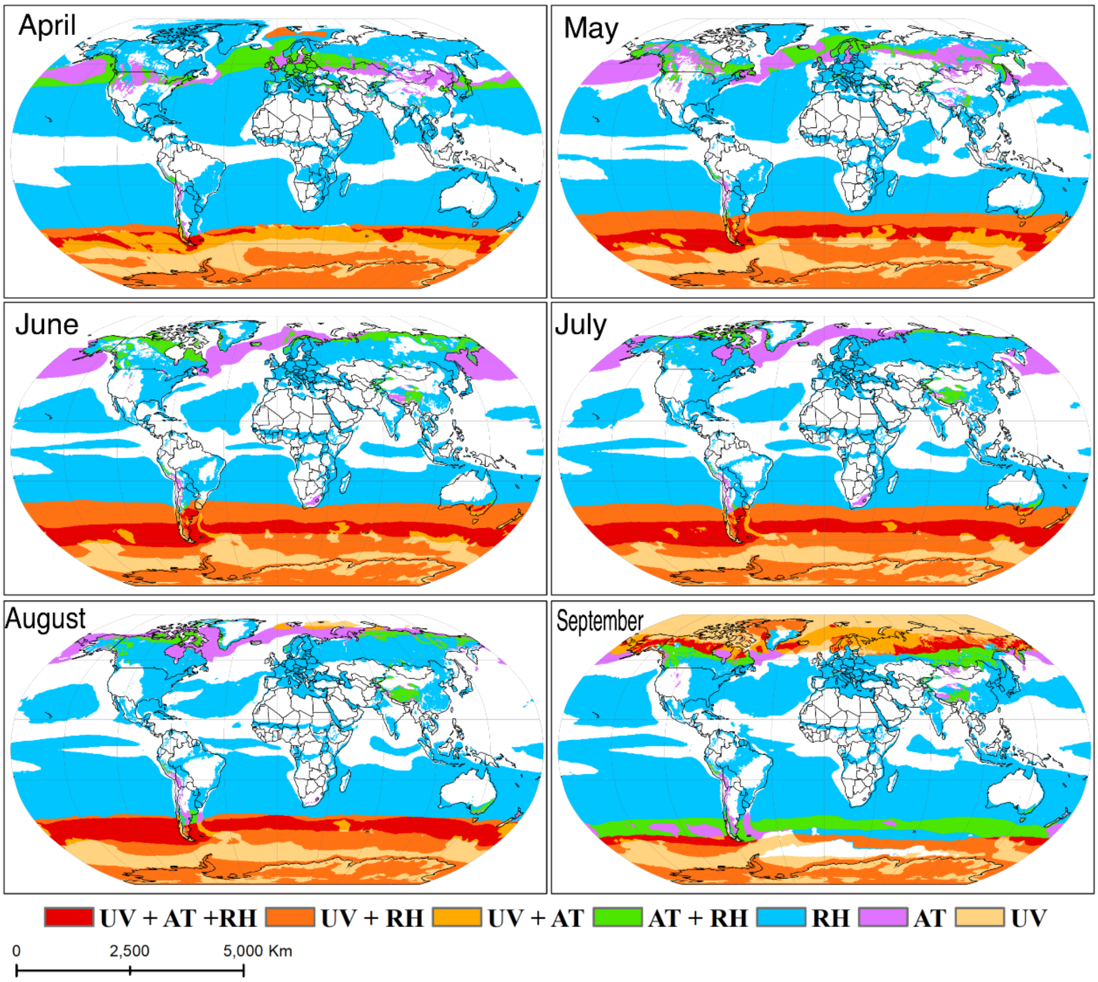

Fig. 9. Presumed optimal climate conditions worldwide for SARS-CoV-2 at monthly level for April–September based on the monthly means of UV, air temperature and relative humidity 2001–2019.

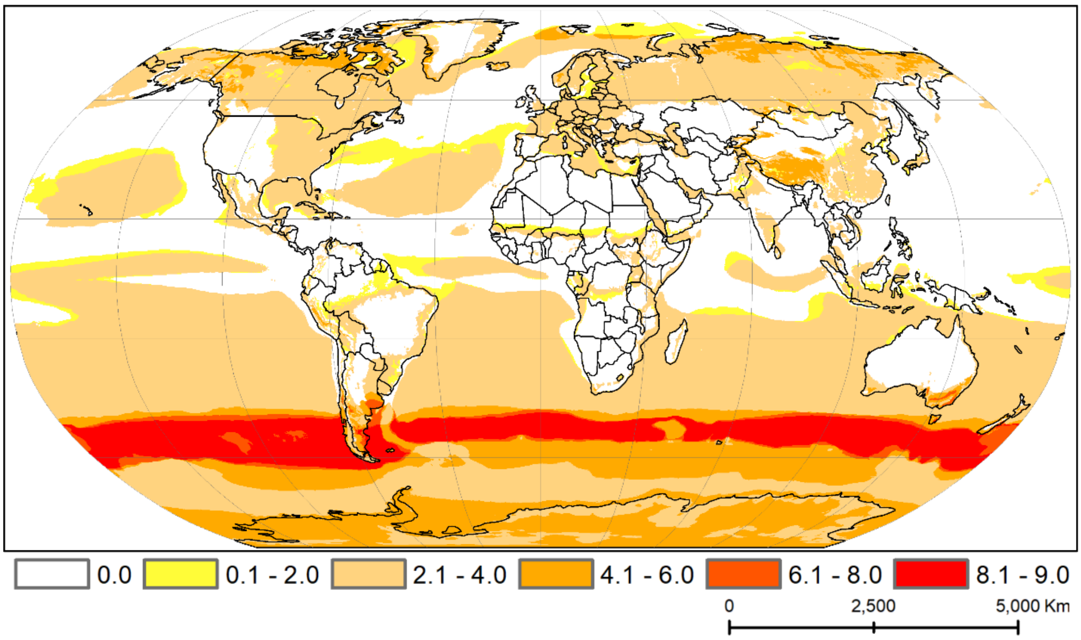

Fig. 10. Score of climate suitability for SARS-CoV-2 for June–August based on the monthly means of UV, air temperature and relative humidity 2001–2019.

New Zealand seems to be the most vulnerable region due to its position at higher latitude, whereas its insular position favors the containment of the disease. Consequently, these are the regions recording the maximum additional scores for June to August (Fig. 10). For this time period our results are not in line with those of Araujo and Naimi (2020) which indicated higher climate suitability for the northern part of Eurasia and North America for July-September, although without taking into account the high amount of UV radiation during this time of the year. In brief, we observe that the gap in climate suitability for SARS-CoV-2 in summer is more consistent in the North Hemisphere given the UV radiation.

It is important to mention that this assessment is reliable for normal climatic conditions, meaning that abnormal weather conditions can shift this risk along the year and other factors may contribute to the phenomena. For instance, an abnormal cloudy June in 2020 in south-east Europe contributed at least partially to SARS-CoV-2 recent increase in in Romania and Bulgaria.

We reiterate that changes in weather alone, including UV radiation, will not necessarily lead to the decline in case count without the implementation and reinforcement of extensive public health interventions (Gherghel and Bulai, 2020). Moreover, it is very likely that the higher the number of COVID-19 cases, the less the virus spread relates to weather conditions.

CONCLUSIONS

Our study depicts relevant associations between the SARS-CoV-2 outbreak in the Hubei region (China) and specific weather conditions. Higher air temperatures and intense negative anomalies in the flux of UV radiation could have played a key role in COVID-19 outbreak in this region. Furthermore, similar weather conditions in terms of air temperature, relative humidity, and UV solar radiation as in the Hubei region were recorded worldwide in other regions most affected by COVID-19 epidemic. According to our analysis, these conditions extended along the Northern Hemisphere subtropical belt: Iran, Italy, Spain, state of California and the northeast area of the United States. This meteorological background for November 2019–January 2020 leads to the idea that the outbreaks were fueled by a match between warmer weather associated with low UV radiation flux, a combination which is favorable for virus environmental survival. Moreover, our study has identified a unique pattern of climate conditions in central and south-eastern China in the current context of climate change. Higher temperature during mild winters, associated with the prominent lack of UV radiation is favorable for pathogen development.

Further laboratory analysis is needed to determine especially the share of UV radiation impact on the virus, within precise air temperature and relative humidity conditions.

Even if the weather factors, especially the increasing UV flux, is playing a role in the reduction of the transmission rate during the summertime in the Northern Hemisphere, they don't impede the further spreading of the disease, since local factors and social practices also have a significant contribution to virus spreading. Moreover, in case of the virus seasonality, based on climate means of 2001–2019, the weather conditions are expected to favor the rapid propagation of the disease in the Northern Hemisphere beginning with the month of October. Thus, the greater understanding of the climate role is needed in order to increase prevention and to set specific guidelines and policies.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at https://aaqr.org/

REFERENCES

Araujo, M.B. and Naimi, B. (2020). Spread of SARS-CoV-2 Coronavirus likely to be constrained by climate. *medRxiv* 2020.03.12.20034728. https://doi.org/10.1101/2020.03.12.20034728

Auler, A.C., Cássaro, F.A.M., da Silva, V.O., and Pires, L.F. (2020). Evidence that high temperatures and intermediate relative humidity might favor the spread of COVID-19 in tropical climate: A case study for the most affected Brazilian cities. *Sci. Total Environ.* 729: 139090. https://doi.org/10.1016/j.scitotenv.2020.139090

Backer, J.A., Klinkenberg, D., and Wallinga, J. (2020). Incubation period of 2019 novel coronavirus (2019-nCoV) infections among travellers from Wuhan, China, 20–28 January 2020. *Eurosurveillance* 25: 2000062. https://doi.org/10.2807/1560-7917.es.2020.25.5.2000062

Chipperfield, J.D., Benito, B.M., O'Hara, R., Telford, R.J. and Carlson, C.J. (2020). On the inadequacy of species distribution models for modelling the spread of SARS-CoV-2: response to Araújo and Naimi. *EcoEvoRxiv* 28. https://doi.org/10.32942/osf.io/mr6pn

Copernicus Climate Change Service (C3S) (2020). Climate Data Store (CDS). https://cds.climate.copernicus.eu/#!/home

Curseu, D., Popa, M., Sirbu, D. and Stoian, I. (2010) Potential impact of climate change on pandemic influenza risk. In *Global warming. Green energy and technology*. Dincer, I., Hepbasli, A., Midilli, A. and Karakoc, T. (Eds.), Springer, Boston, MA. pp. 643–657. https://doi.org/10.1007/978-1-4419-1017-2_45

Diffey, B.L. (1991). Solar ultraviolet radiation effects on biological systems. *Phys. Med. Biol.* 36: 299–328. https://doi.org/10.1088/0031-9155/36/3/001

du Prel, J.B., Puppe, W., Gröndahl, B., Knuf, M., Weigl, J.A.I., Schaaff, F. and Schmitt, H.J. (2009). Are meteorological parameters associated with acute respiratory tract infections? *Clin. Infect. Dis.* 49: 861–868. https://doi.org/10.1086/605435

Ficetola, G.F. and Rubolini, D. (2020). Climate affects global patterns of COVID-19 early outbreak dynamics. *medRxiv* 2020.03.23.20040501. https://doi.org/10.1101/2020.03.23.20040501

Fisman, D. (2012). Seasonality of viral infections: Mechanisms and unknowns. *Clin. Microbiol. Infect.* 18: 946–954. https://doi.org/10.1111/j.1469-0691.2012.03968.x

Gardner, E.G., Kelton, D., Poljak, Z., Van Kerkhove, M., von Dobschuetz, S. and Greer, A.L. (2019). A case-crossover analysis of the impact of weather on primary cases of Middle East respiratory syndrome. *BMC Infect. Dis.* 19: 113. https://doi.org/10.1186/s12879-019-3729-5

Geller, L. (2001). Under the weather: Climate, Ecosystems, and infectious disease. *Emerging Infect. Dis.* 7: 606–608. https://doi.org/10.3201/eid0707.017750

Gherghel, I. and Bulai, M. (2020). Is Romania ready to face the novel coronavirus (COVID-19) outbreak? The role of incoming travelers and that of Romanian diaspora. *Travel Med. Infect. Dis.* 34: 101628. https://doi.org/10.1016/j.tmaid.2020.101628

Gunthe, S.S., Swain, B., Patra, S.S. and Amte, A. (2020). On the global trends and spread of the COVID-19 outbreak: Preliminary assessment of the potential relation between location-specific temperature and UV index. *J. Public Health (Berl.)* https://doi.org/10.1007/s10389-020-01279-y

Kerr, J.B. and Fioletov, V.E. (2008). Surface ultraviolet radiation. *Atmos. Ocean* 46: 159–184. https://doi.org/10.3137/ao.460108

Kollias, N., Ruvolo, E. Jr and Sayre, R.M. (2011). The value of the ratio of UV-A to UV-B in sunlight. *Photochem. Photobiol.* 87: 1474–1475. https://doi.org/10.1111/j.1751-1097.2011.00980.x

Kowalski, W., Walsh, T.J. and Petraitis, W. (2020). 2020 COVID-19 Coronavirus ultraviolet susceptibility. *Purple Sun.* https://doi.org/10.13140/RG.2.2.22803.22566

Lin, K., Fong, D.Y.T., Zhu, B. and Karlberg, J. (2006). Environmental factors on the SARS epidemic: Air temperature, passage of time and multiplicative effect of hospital infection. *Epidemiol. Infect.* 134: 223–230. https://doi.org/10.1017/S0950268805005054

McCloskey, B., Zumla, A., Ippolito, G., Blumberg, L., Arbon, P., Cicero, A., Endericks, T., Lim, P.L. and Borodina, M. (2020). Mass gathering events and reducing further global spread of COVID-19: A political and public health dilemma. *Lancet* 395: 1096–1099. https://doi.org/10.1016/S0140-6736(20)30681-4

Mirsaeidi, M., Motahari, H., Khamesi, M.T., Sharifi, A., Campos, M. and Schraufnagel, D.E. (2016). Climate change and respiratory infections. *Ann. Am. Thorac. Soc.* 13: 1223–1230. https://doi.org/10.1513/AnnalsATS.201511-729PS

Neher, R.A., Dyrdak, R., Druelle, V., Hodcroft, E.B. and Albert, J. (2020). Potential impact of seasonal forcing on a SARS-CoV-2 pandemic. *Swiss Med. Wkly* 150: w20224. https://doi.org/10.4414/smw.2020.20224

Parodi, E. and Aloisi, S. (2020, March 26). *Italian scientists investigate possible earlier emergence of coronavirus.* Reuters. https://www.reuters.com/article/us-health-coronavirus-italy-timing/italian-scientists-investigate-possible-earlier-emergence-of-coronavirus-idUSKBN21D2IG

Pletcher, K. (2010). *The geography of China: Sacred and historic places*. Rosen Educational Services.

Poole, L. (2020). Seasonal influences on the spread of SARS-CoV-2 (COVID19), causality, and forecastabililty (3-15-2020). *SSRN* https://doi.org/10.2139/ssrn.3554746

Pozo-Antonio, J.S. and Sanmartin, P. (2018). Exposure to artificial daylight or UV irradiation (A, B or C) prior to chemical cleaning: an effective combination for removing phototrophs from granite. *Biofouling* 34: 851–869. https://doi.org/10.1080/08927014.2018.1512103

Rodríguez-Morales, A.J., MacGregor, K., Kanagarajah, S., Patel, D. and Schlagenhauf, P. (2020). Going global – Travel and the 2019 novel coronavirus. *Travel Med. Infect. Dis.* 33: 101578. https://doi.org/10.1016/j.tmaid.2020.101578

Rosenthal, J. (2009). Climate change and the geographic distribution of infectious diseases. *Ecohealth* 6: 489–495. https://doi.org/10.1007/s10393-010-0314-1

Sagripanti, J.L. and Lytle, C.D. (2007). Inactivation of influenza virus by solar radiation. *Photochem. Photobiol.* 83: 1278–1282. https://doi.org/10.1111/j.1751-1097.2007.00177.x

Sajadi, M.M., Habibzadeh, P., Vintzileos, A., Shokouhi, S., Miralles-Wilhelm, F. and Amoroso, A. (2020). Temperature and latitude analysis to predict potential spread and seasonality for COVID-19. SSRN https://doi.org/10.2139/ssrn.3550308

Seyer, A. and Sanlidag, T. (2020). Solar ultraviolet radiation sensitivity of SARS-CoV-2. *Lancet Microbe* 1: e8–9. https://doi.org/10.1016/S2666-5247(20)30013-6

Suhaimi, N.F., Jalaludin, J. and Latif, M.T. (2020). Demystifying a possible relationship between COVID-19, air quality and meteorological factors: Evidence from Kuala Lumpur, Malaysia. *Aerosol Air Qual. Res.* 20: 1520–1529. https://doi.org/10.4209/aaqr.2020.05.0218

Sun, Z., Thilakavathy, K., Kumar, S.S., He, G. and Liu, S.V. (2020). Potential factors influencing repeated SARS outbreaks in China. *Int. J. Environ. Res Public Health* 17: 1633. https://doi.org/10.3390/ijerph17051633

van Doremalen, N., Bushmaker, T., Morris, D.H., Holbrook, M.G., Gamble, A., Williamson, B.N., Tamin, A., Harcourt, J.L., Thornburg, N.J., Gerber, S.I., Lloyd-Smith, J.O., de Wit, E. and Munster, V.J. (2020). Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. *N. Engl. J. Med.* 382: 1564–1567. https://doi.org/10.1056/NEJMc2004973

Varo, R., Rodó, X. and Bassat, Q. (2019). Climate change, cyclones and cholera - Implications for travel medicine and infectious diseases. *Travel Med. Infect. Dis.* 29: 6–7. https://doi.org/10.1016/j.tmaid.2019.04.007

Wikipedia (2020). *COVID-19 pandemic by country and territory.* https://en.wikipedia.org/wiki/COVID-19_pandemic_by_country_and_territory

World Health Organization (WHO) (2020a, January 17). Novel Coronavirus – Japan (ex-China). https://www.who.int/csr/don/17-january-2020-novel-coronavirus-japan-ex-china/en/

World Health Organization (WHO) (2020b, July 31). Rolling updates on coronavirus disease (COVID-19) Updated 31 July 2020. https://www.who.int/emergencies/diseases/novel-coronavirus-2019/events-as-they-happen

Xu, K., Cui, K., Young, L.H., Wang, Y.F., Hsieh, Y.K., Wan, S. and Zhang, J. (2020). Air quality index, indicatory air pollutants and impact of COVID-19 event on the air quality near central China. *Aerosol Air Qual. Res.* 20: 1204–1221. https://doi.org/10.4209/aaqr.2020.04.0139

Zhu, Y., Xie, J., Huang, F. and Cao, L. (2020). Association between short-term exposure to air pollution and COVID-19 infection: Evidence from China. *Sci. Total Environ.* 727: 138704. https://doi.org/10.1016/j.scitotenv.2020.138704

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