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Author's contribution

A.S.L., J.V.M., J-M.V. and M.A. designed the research. A.S.L., J.V.M and J-A.L.B conducted the analyses. A.S.L., J.C., M.W., A.S. and M.A. refined the interpretations. A.S.L. wrote the manuscript. J.V.M, J.C., M.W., A.S., J-A.L.B, J-M.V. and M.A. provided comments and contributed to the text.

Did anomalous atmospheric circulation favor the spread of COVID-19 in Europe?

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Abstract

The current pandemic of coronavirus disease 2019 (COVID-19) caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is having negative health, social and economic consequences worldwide. In Europe, the pandemic started to develop strongly at the end of February and beginning of March 2020. Subsequently, it spread over the continent, with special virulence in northern Italy and inland Spain. In this study we show that an unusual persistent anticyclonic situation prevailing in southwestern Europe during February 2020 (i.e. anomalously strong positive phase of the North Atlantic and Arctic Oscillations) could have resulted in favorable conditions, e.g., in terms of air temperature and humidity among other factors, in Italy and Spain for a quicker spread of the virus compared with the rest of the European countries. It seems plausible that the strong atmospheric stability and associated dry conditions that dominated in these regions may have favored the virus propagation, both outdoors and especially indoors, by short-range droplet and aerosol (airborne) transmission, or/and by changing social contact patterns. Later recent atmospheric circulation conditions in Europe (July 2020) and the U.S. (October 2020) seem to support our hypothesis, although further research is needed in order to evaluate other confounding variables. Interestingly, the atmospheric conditions during the Spanish flu pandemic in 1918 seem to resemble at some stage with the current COVID-19 pandemic.

Keywords: COVID-19 disease, atmospheric circulation, North Atlantic Oscillation, air humidity, 1918 Spanish flu

1. Introduction

The world is currently undergoing a pandemic associated with the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which is a new coronavirus first noticed in late 2019 in the Hubei province, China (Huang et al., 2020; WHO, 2020). The virus has a probable bat origin (Liao et al., 2020; Zhou et al., 2020), and causes the ongoing coronavirus disease 2019 (COVID-19). Although it is crucial to find a proper vaccine and medical treatment for this pandemic, it is also relevant to know the main factors controlling the transmission of the virus and disease, including the role of meteorological conditions in the spread of the virus.

Respiratory virus infections can be transmitted by means of particles (droplets or aerosols) emitted after a cough or sneeze or during a conversation with an infected person. The large particles (>5 μm in diameter) are referred to as respiratory droplets and tend to settle down quickly on the ground, usually within one meter of distance. The small particles (<5 μm in diameter) are referred to as droplet nuclei and are related to an airborne transmission. These particles can remain suspended in the air for longer periods of time and can reach a longer distance from the origin (Gralton et al., 2011).

Recent studies have pointed out a role of temperature and humidity in the spread of COVID-19. Warm conditions and wet atmospheres tend to reduce the transmission of the disease (Alkhowailed et al., 2020; Araujo and Naimi, 2020; Barcelo, 2020; Ma et al., 2020; Sajadi et al., 2020; Smit et al., 2020). For example, it has been pointed out that the main first outbreaks worldwide occurred during periods with temperatures around 5-11ºC, never falling below 0ºC, and specific humidity of 3-6 g kg^{-1} approximately (Sajadi et al., 2020). Nevertheless, there are still some uncertainties about the role of climate variability in modulating COVID-19 outbreaks (Jamil et al., 2020; Martinez-Alvarez et al., 2020).

The first major outbreak in Europe was reported in northern Italy in late February 2020. Following that, several major cases were reported in Spain, Switzerland and France in early March, with a subsequent spread over many parts of Europe. On late March 2020, Italy and Spain were the two main contributors of infections and deaths in the continent.

The main hypothesis of this work is that the atmospheric circulation pattern in February 2020 helped to shape the spatial pattern of the outbreak of the disease during the first stages of the pandemic in Europe, i.e., when public health strategies were still not in force in the major part of the European countries and, consequently, meteorological factors could have taken a more relevant role than later on. The main goal of this study is to add some relevant information regarding the possible role of climate variability to the outbreaks of the COVID-19 disease, which can be helpful in order to implement early alert protocols.

2. Materials

- Covid-19 data

Accumulated COVID-19 data on country basis were obtained on March 26th, 2020 from the website https://www.worldometers.info/coronavirus/, which it is mainly based on the data provided by the Coronavirus COVID-19 Global Cases by the Center for Systems Science and Engineering (CSSE) at the Johns Hopkins University. Accumulated data from Spain on regional scale were obtained on March 28th, 2020 from the Spanish Government through the Institute of Health Carlos III (ISCIII): https://covid19.isciii.es/

- Reanalysis data

NCEP/NCAR (Kalnay et al., 1996), ERA5 (Copernicus Climate Change Service (C3S), 2017) and ERA20C (Poli et al., 2015) atmospheric data are used in this manuscript. More details about the spatial and temporal resolution, vertical levels, assimilation schemes, etc. can be consulted in their references. In brief, an atmospheric reanalysis like those used here is a climate data assimilation project which aims to assimilate historical atmospheric observational data spanning an extended period. It uses a single consistent assimilation scheme throughout, with the aim of providing continuous gridded data for the whole globe.

For the link between the COVID-19 spread on European scale and atmospheric circulation we have extracted the monthly anomalies of sea level pressure (SLP) and 500 hPa geopotential height for February 2020 over each grid point of the 15 capitals of the European countries. We have selected the SLP and 500 hPa fields in order to summarize the meteorological conditions over each location, as it is known that several meteorological variables can be involved in the transmission of respiratory viruses (Fuhrmann, 2010; Lowen et al., 2007). With this approach we also avoid the lack of properly updated data for all potential meteorological variables involved in the COVID-19 spread, which needs further research as soon as the pandemic ends and a more reliable and complete database of both COVID-19 impact and meteorological data can be compiled (Araujo and Naimi, 2020).

- Surface weather observations

For Spain, several meteorological variables with high-quality records were obtained from the Spanish State Meteorological Agency (AEMET) based on surface observations for each of the capital cities of the provinces inside each autonomous region; specifically, monthly averages for February 2020 of 2-m temperature, 2-m maximum temperature, 2-m minimum temperature (°C), air pressure (hPa), wind speed (km h^{-1}), specific humidity (g kg^{-1}), relative humidity (%), total precipitation (mm), and days of more than 1 mm of precipitation. The arithmetic average was computed for the autonomous regions with more than one province.

3. Results

The main atmospheric circulation pattern during February 2020 is characterized by an anomalous anticyclonic system over the western Mediterranean basin, centered between Spain and Italy, and lower pressures over northern Europe centered over the Northern Sea and Iceland (Fig. 1, Fig. S1). This spatial configuration represents the well-known North Atlantic Oscillation (NAO) (Hurrell, 1995; Jones et al., 1997) in its positive phase, which is the teleconnection pattern linked to dry conditions in southern Europe whereas the opposite occurs in northern Europe (Calbó and Sanchez-Lorenzo, 2009).

Fig. 2 and Fig. S2 show maps for February 2020 for several meteorological fields that provide clear evidence of the stable atmospheric situation in southern Europe, with a tendency towards very dry (i.e., lack of precipitation) and calm conditions, in line with recent results from Japan where sunny conditions were associated with an increase in the spread of the COVID-19 infection (Azuma et al., 2020). As suggested in an earlier analysis (Sajadi et al., 2020), the SARS-CoV-2 virus seems to be transmitted most effectively in dry conditions with daily mean air temperatures between around 5ºC and 11ºC, which are the conditions shown in Fig. 2 for the major part of Italy and Spain. By contrast, northern Europe experienced in February 2020 mainly wet and windy conditions due to an anomalous strong westerly circulation that is linked to rainy conditions.

These spatial patterns fit with the well-known climate features associated over Europe during positive phases of the NAO (Hurrell et al., 2003). The Arctic Oscillation (AO), which is a teleconnection pattern linked to NAO, showed in February 2020 the strongest positive value during 1950-2020 (Fig. S3). The AO reflects the northern polar vortex variability at surface level (Baldwin et al., 2003), and it consists of a low-pressure center located over the Norwegian sea and the Arctic ocean and a high-pressure belt between 40 and 50ºN, forming an annular-like structure. Positive values of the AO index mean a strong polar vortex, and the anomalous positive phase experienced during early 2020 has been linked with the outstanding ozone loss registered over the Arctic region during March 2020 (Witze, 2020). In a separate study, we have hypothesized that this strong AO positive phase could have played a non-negligible role in the first steps of the disease worldwide. Specifically, it is worth remembering that the COVID-19 pandemic started to develop strongly by the end of January, first in China with subsequent rapid spread to other countries concentrated mainly within the 30-50ºN latitudinal regions. This feature seems to be in line with unusual persistent anticyclonic situation prevailing at latitudes around 40ºN, which was observed on global scale due to the strong positive phase of the AO described above. This atypical situation could have helped to provide favourable meteorological conditions for a quicker spread of the virus (for more details, see Sanchez-Lorenzo et al., 2020, Fig. S4).

Back to Europe, we argue that this spatial configuration of the atmospheric circulation (Fig. 1) might have played a non-negligible role in the modulation of the early spread of the COVID-19 outbreaks over Europe. It is known that some cases were reported already in mid-January in France, with subsequent cases in Germany and other countries (Spiteri et al., 2020). Thus, the SARS-CoV-2 virus was already in Europe in early 2020, but maybe it started to extend rapidly only when suitable atmospheric conditions for its spread were reached. It is possible that these proper conditions were met in February, mainly in Italy and Spain, due to the meteorological conditions previously mentioned.

The link between the COVID-19 spread and atmospheric circulation has been tested as follows. We have extracted monthly anomalies of sea level pressure (SLP) and 500 hPa geopotential height for February 2020 over each grid point of the 15 capitals of the European countries (Fig. S5) with the highest number of COVID-19 cases reported on late March (see Section 2). Fig. 3 shows that there is a clear relationship between the anomalies of the 500 hPa and the total cases per population, which is given by a statistically significant (R^2=0.481, p<0.05) second order polynomial fit. Italy, Spain, and Switzerland, which are the only countries with more than 1,000 cases/million inhabitants in our dataset, clustered together in regions with very large positive anomalies of 500 hPa geopotential heights. Similar results are obtained using SLP fields (not shown).

These results evidence that it seems plausible that the positive phase of the NAO, and the atmospheric conditions associated with it, provided optimal conditions for the spread of the COVID-19 in southern European countries like Spain and Italy, where the start of the outbreak in Europe was located. To test this hypothesis further we have also analyzed the relationship between the disease and meteorological data within Spain (see Section 2 and Fig. S6). The results show that mean temperature and specific humidity variables have the strongest relation with infections and deaths of COVID-19 and fit with an exponential function (Fig. 4). They indicate that those meteorological conditions given by lower mean temperatures (i.e., average of around 8-11ºC) and lower specific humidity (e.g., <6 g kg^{-1}) are related to a higher number of cases and deaths in Spain. Nevertheless, it is worth mentioning that both meteorological variables are highly correlated (R^2=0.838, p<0.05) and are not independent of each other. The temperatures as low as 8-10ºC are only reached in a few regions such as Madrid, Navarra, La Rioja, Aragon, Castilla and Leon and Castilla-La Mancha. These areas are mainly located in inland Spain where drier conditions were reported the weeks before the outbreak. The rest of Spain experienced higher temperatures and consequently were out of the areas of higher potential for the spread of the virus, as reported so far in the literature. In addition, higher levels of humidity also seemed to limit the impact of the disease (Barcelo, 2020), and therefore the coastal areas seem to benefit from lower rates of infection. Thus, the southern regions of Spain (all of them with more than 13ºC and higher levels of specific humidity) reported lower rates of infection and deceases. This is in line with the spatial pattern in Italy, with the most (least) affected regions by COVID-19 mainly located in the North (South). In contrast, when the whole of Europe is considered on a country by country basis (see above and Fig. 3), the opposite is found, a clear gradient with more severity from North to South as commented previously.

The spatial pattern of COVID-19 described above has some intriguing resemblances with the 1918 influenza pandemic, which is the latest deadly pandemic in modern history of Europe. The excess-mortality rates across Europe in the 1918 flu also showed a clear north-south gradient, with a higher mortality in southern European countries (i.e., Portugal, Spain and Italy) as compared to northern regions, an aspect that could not be explained by socio-economic or health factors (Ansart et al., 2009). In Spain, a south-north gradient was also reported in the 1918 flu after controlling for demographic factors (Chowell et al., 2014). The central and northern regions of Spain experienced higher rates of mortality, and this has been suggested to be linked to more favorable climate conditions for influenza transmission as compared to the southern regions (Chowell et al., 2014). Interestingly, the SLP anomalies of the months previous to the major wave of this pandemic (which occurred in October-November 1918) showed a clear south-north dipole with positive anomalies in southern Europe centered over the Mediterranean, and negative ones in northern Europe (Fig. 5). In other words, the NAO was also in its positive phase just before the major outbreak of the 1918 influenza pandemic. This resembles the spatial patterns described above for the current COVID-19 outbreak, both in terms of the spatial distribution of the mortality of the pandemic over Europe as well as in prevailing atmospheric circulation conditions before the outbreak. These intriguing coincidences should motivate further research in order to better understand the spatial and temporal distribution of large respiratory-origin pandemics over Europe.

4. Discussion

Taking into account these results, we claim that the major initial outbreaks of COVID-19 in Europe (i.e., Italy and Spain) may have been favored by an anomalous atmospheric circulation pattern in February, characterized by a positive phase of the NAO. Considering current evidences in the literature, it seems that suitable conditions of air temperature and humidity were reached in northern Italy and inland Spain. Indeed, meteorological conditions can affect the susceptibility of an infected host by altering the mucosal antiviral defense (Kudo et al., 2019) and the stability and transmission of the virus (Lin and Marr, 2020; Moriyama et al., 2020), as well as social contact patterns (Azuma et al., 2020; Willem et al., 2012). It is worth mentioning that meteorological conditions can also affect indoors environment (Shaman and Galanti, 2020; Shaman and Kohn, 2009). Indeed, the air humidity is lowered in indoor conditions with respect to outdoors due to the heating (except if a humidity controlled approach is installed).

We also hypothesize that the anomalous meteorological conditions experienced in Italy and Spain promoted the airborne contagion (Lowen and Palese, 2009), especially in indoors situations, in addition to the direct and indirect contact and short-range droplets, which all together may have helped to speed up the rates of effective reproductive number (R) of the virus (Fig. 6). Regarding airborne transmission, it has been suggested that it can play a key role in some diseases like tuberculosis or measles, and even in coronaviruses (Kutter et al., 2018; Tellier et al., 2019; Yu et al., 2004) including COVID-19 disease (Dancer et al., 2020; Jayaweera et al., 2020; Morawska et al., 2020; Morawska and Cao, 2020; Prather et al., 2020). Another study describes that the SARS-CoV-2 virus can remain viable at least up to 3 hours in airborne conditions (van Doremalen et al., 2020). Respiratory droplets and aerosols loaded with pathogens can reach distances up to 7-8 meters under some specific conditions such as a turbulence gas cloud emitted after a cough of an infected person (Bourouiba, 2020). A study performed in Wuhan, the capital of the Hubei province, shows that the SARS-CoV-2 virus was present in several health care institutions, as well as in some crowded public areas of the city. It also highlights a potential resuspension of the infectious aerosols from the floors or other hard surfaces with the walking and movement of people (Liu et al., 2020). Another study also shows evidence of potential airborne transmission in a health care institution (Santarpia et al., 2020). Additionally, another recent study suggests that strong stability associated with anticyclonic conditions may have promoted airborne transmission (Bhaganagar and Bhimireddy, 2020).

Equally, it has also been suggested that high atmospheric pollutant concentrations can be positively related to increase fatalities related to respiratory virus infections (Chen et al., 2017; Cui et al., 2003) and even COVID-19 (Azuma et al., 2020; Coccia, 2020a, 2020b; Ogen, 2020). This is a relevant issue as the main hotspot of COVID-19 in Italy was located in the Po valley (EEA, 2019). Further research is needed in order to study the COVID-19 incidence and concentration of the main air pollutants in Europe to test this latter hypothesis.

In order to give some information regarding the possible role of atmospheric circulation in early COVID-19 outbreaks during the second wave of virus, Fig. 7 shows the anomaly geopotential 500 hPa field over Europe for July 2020, which was characterized by anticyclonic conditions over the Atlantic Ocean and affected southwestern Europe. This state of the atmospheric circulation should imply stable and dry conditions over most of the region affected by the positive anomaly values. Interestingly, at the end of the next month, Spain and France were the countries with the highest detected 14-days COVID-19 incidence in Europe (Fig. S7), which seems to be in line with the results reported above for the first wave of virus infection in winter-spring.

In addition to Europe, Fig. 8 shows the anomaly 500 hPa field over North America for October 2020, which was characterized by anticyclonic conditions over the Atlantic and Pacific coastal regions of the U.S., whereas a very low pressure center in central-eastern Canada enhanced a northwesterly flow circulation over the northern and central inland U.S. This atmospheric circulation is associated with lower temperature and very low specific humidity in these regions. The 7-days COVID-19 cases incidence map in early November over the U.S. (Fig. S8) shows that most of the central and northern states reported the highest number of cases, which seems to be aligned with the areas that experienced the northwestern wind flows during October. It is interesting to note that several atmospheric conditions might drive large outbreaks (i.e., not only anomalous anticyclonic conditions could trigger COVID-19 outbreaks), which should be taken into account in further studies as we can expect that these atmospheric patterns can be different along the year and also highly geographical dependent, i.e., mid-latitudes vs tropical regions (Lowen and Palese, 2009).

Overall, in the context of anthropogenic climate change, it has been shown that in future emissions scenarios a poleward expansion of the Hadley cell is expected (Collins et al., 2013; Gillett and Stott, 2009), which in turn is in line with a tendency to increase the frequency of positive phases of the NAO (Deser et al., 2017) (Figure S9). This should be taken into account for planning against future epidemics and pandemics that arise from respiratory viruses, especially in terms of environmental and health policies implemented by policymakers to minimize future pandemics.

5. Conclusions

Although the outbreak of a pandemic is controlled by a high number of biological, health, political, social, economic and environmental factors, with complex and non-linear interrelationships between them (Coccia, 2020c), with government strategies likely playing the major role in the control of the spread of the pandemic, the results of this study indicate for the first time that an anomalous atmospheric circulation may play a role in (partly) explaining why the first COVID-19 outbreak in Europe developed more easily (or faster) in the south-west (mainly north of Italy and inland of Spain). It should be noted that the current research is performed on COVID-19 incidence data until the end of March 2020, that is when governmental strategies could not have resulted yet in an impact on the evolution of the spread.

Specifically, the extreme positive phase of the NAO during February 2020 could have modulated the beginning of the major outbreaks of COVID-19 in Europe. This detected anomalous atmospheric pattern, which produces dry conditions over southwestern Europe, may have provided optimal meteorological conditions for the virus propagation at mid-latitudes (Lowen and Palese, 2009); this feature should be taken into account for future outbreaks of the disease. Nevertheless, this issue needs further research in order to prove the cause-effect relationship suggested in our study which is based in simple correlation analysis and does not include any other socio-economical confounding factors.

The results presented in this study could involve some health policy implications, as the lag between large atmospheric circulation anomalies and the COVID-19 outbreaks could be used for implementing early alert protocols using weather and seasonal forecasting models that can predict atmospheric circulation patterns several days/weeks in advance. Future research is needed in order to study other mid-latitude regions, as well as other possible atmospheric patterns with the potential to trigger COVID-19 outbreaks, as they can be spatially and temporally variable throughout the year.

Interestingly, the conditions during the latest major pandemic experienced in Europe (the Spanish flu in 1918) seem to resemble the current spatial pattern of affectation with more cases in the South of Europe as compared to the North. Equally, the dominant atmospheric situation was strongly affected by anticyclonic (cyclonic) conditions in the South (North) of Europe. More research is needed in order to better understand the spatio-temporal patterns of large epidemic and pandemic situations on historical times, and their connection with the prevailing atmospheric conditions patterns, which can be also used for implementing future environmental, health and social policies.

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CRediT authorship contribution statement

A.S.L., J.V.M., J-M.V. and M.A. designed the research. A.S.L., J.V.M and J-A.L.B conducted the analyses. A.S.L., J.C., M.W., A.S. and M.A. refined the interpretations. A.S.L. wrote the manuscript. J.V.M, J.C., M.W., A.S., J-A.L.B, J-M.V. and M.A. provided comments and contributed to the text.

Declaration of competing interest

The authors declare that they have no known competing financial interests that could have appeared to influence the work reported in this study.

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Figures

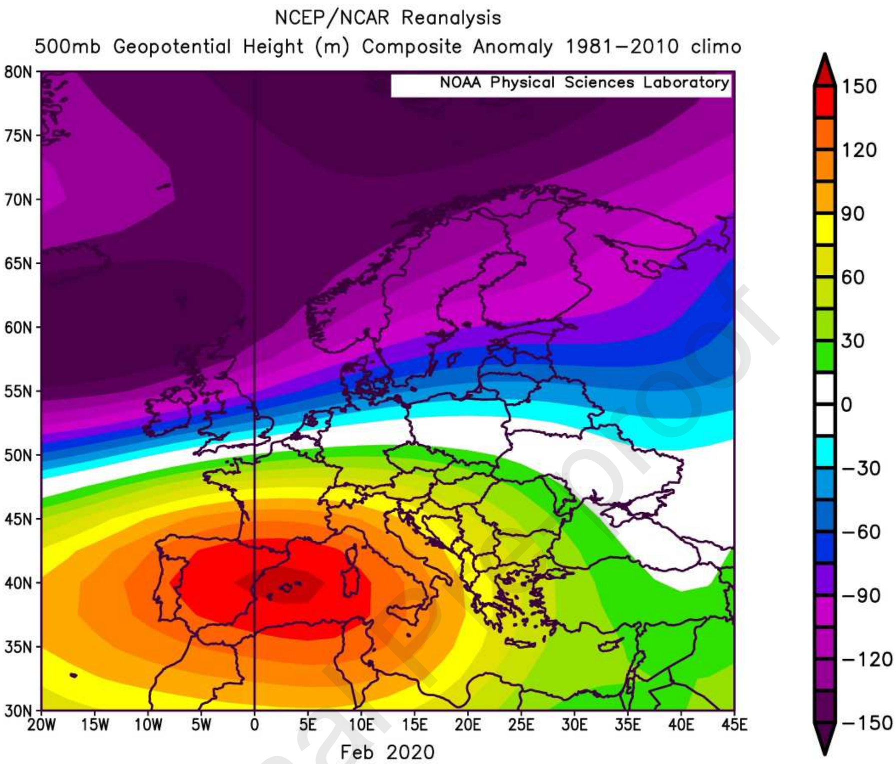

Figure 1. Anomaly pattern of 500 hPa geopotential height (m) for February 2020 over Europe as compared to the climatology mean (1981-2010 period). Image generated with the Web-based Reanalysis Intercomparison Tool provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado from their Web site at http://psl.noaa.gov/

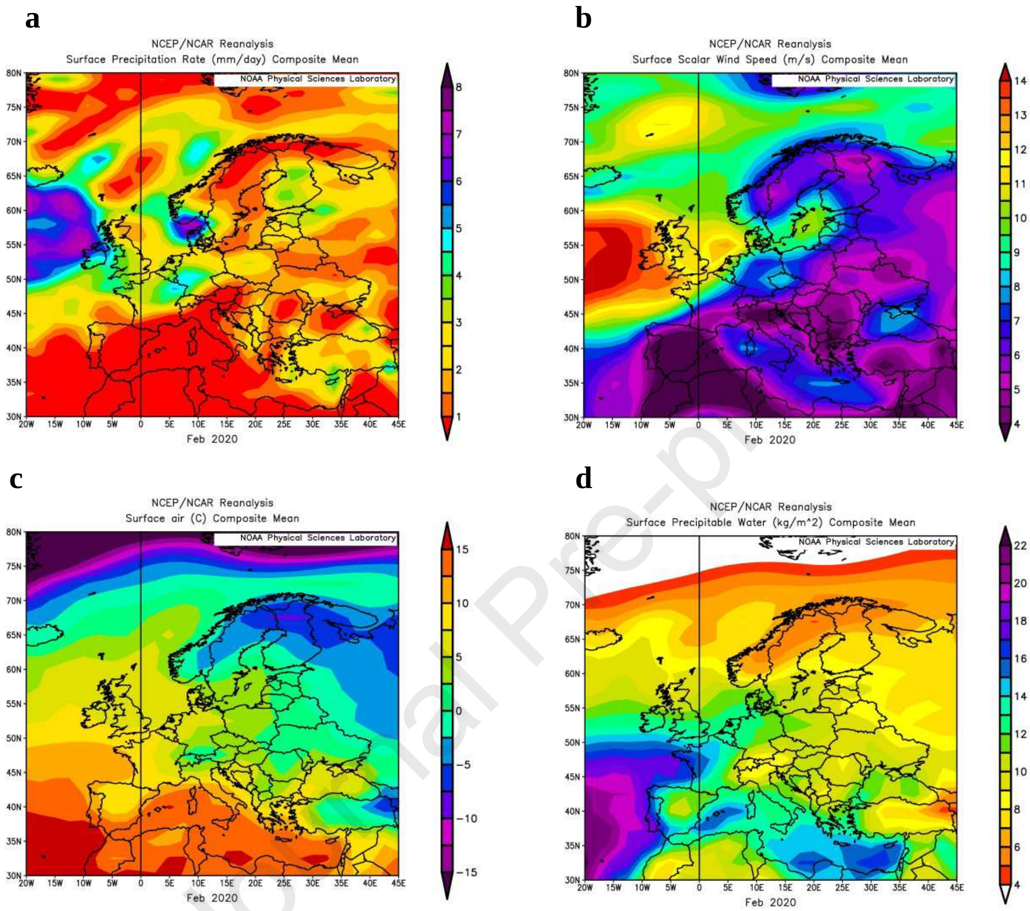

Figure 2. Mean values of several meteorological variables for February 2020 over Europe. a) Precipitation rate (mm/day), b) Surface wind speed (m/s), c) Surface air temperature (ºC), and d) Precipitable water (kg/m^2). Image generated with the Web-based Reanalysis Intercomparison Tool provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado from their Web site at http://psl.noaa.gov/

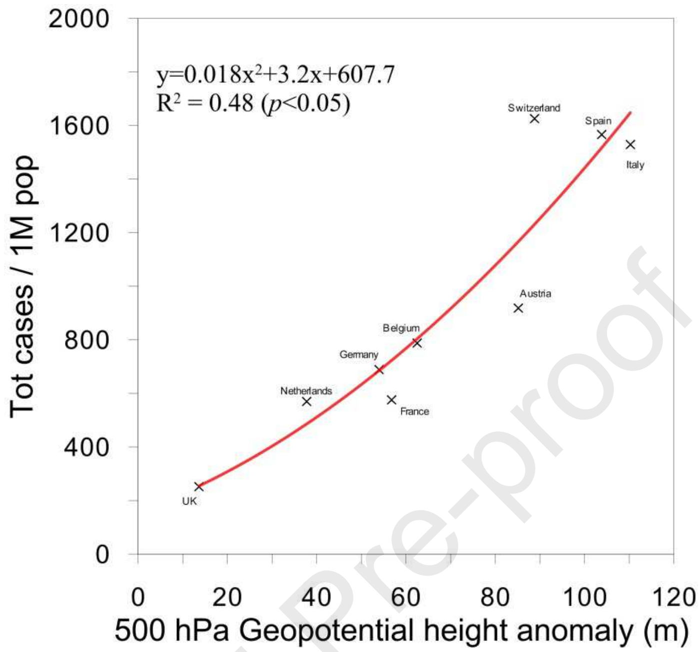

Figure 3. Relationship between accumulated COVID-19 cases in Europe reported up to March 26th, 2020 and 500 hPa geopotential height anomalies (m) over the capital of each country. Each point represents one of the 15 countries with more cases reported up to March 26th, 2020. The 500 hPa geopotential height anomalies are calculated for February 2020 with respect to the 1981-2010 climatological mean.

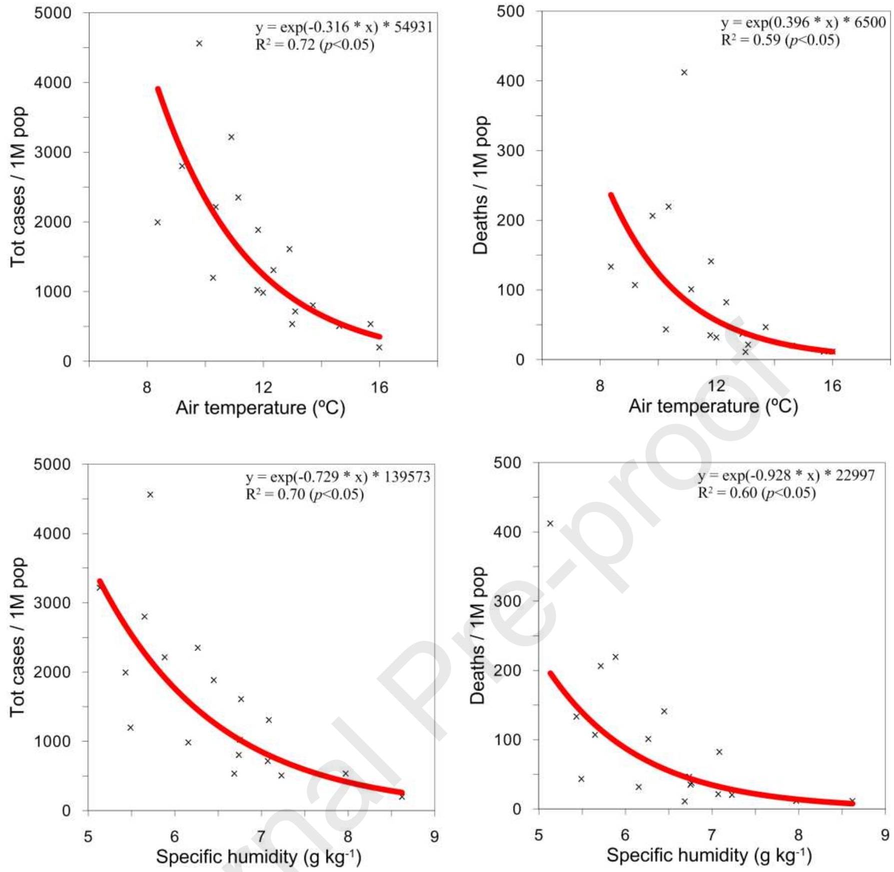

Figure 4. Relationship between mean (top) air temperature (ºC) and (bottom) specific humidity (g kg^{-1}) against accumulated COVID-19 cases (left) and deaths (right) in Spain as reported up to March 28th, 2020. Each cross indicates a region of Spain. The meteorological data refer to the average of February 2020.

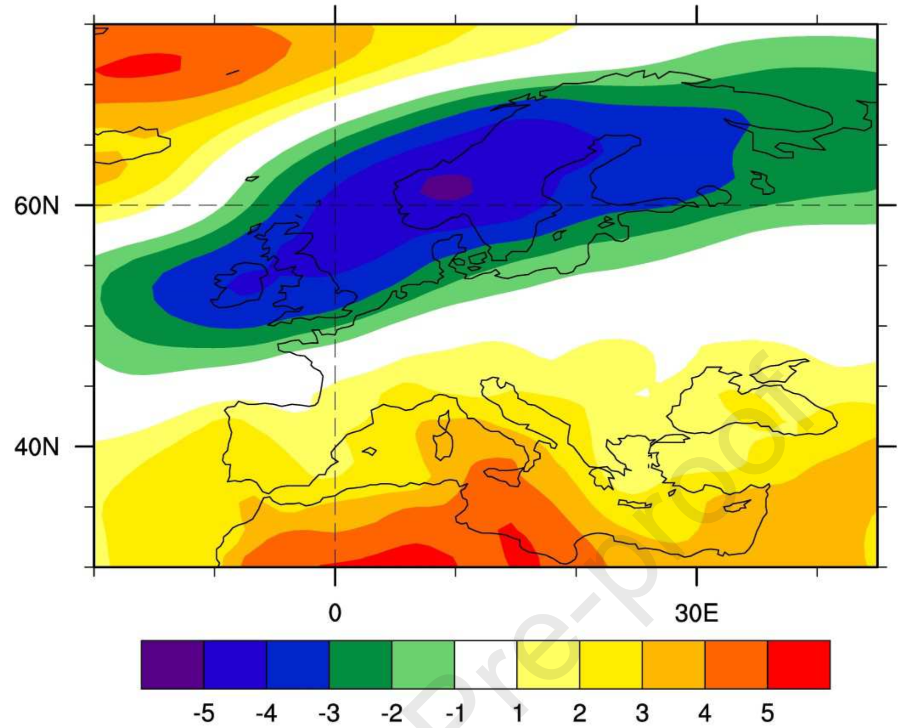

Figure 5. Anomaly map of the sea level pressure (SLP) field extracted from ERA20C reanalysis of August and September 1918 as compared to the climatological mean (1981-2010 period). Image generated with the Web-based Reanalysis Intercomparison Tool provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado from their Web site at http://psl.noaa.gov/

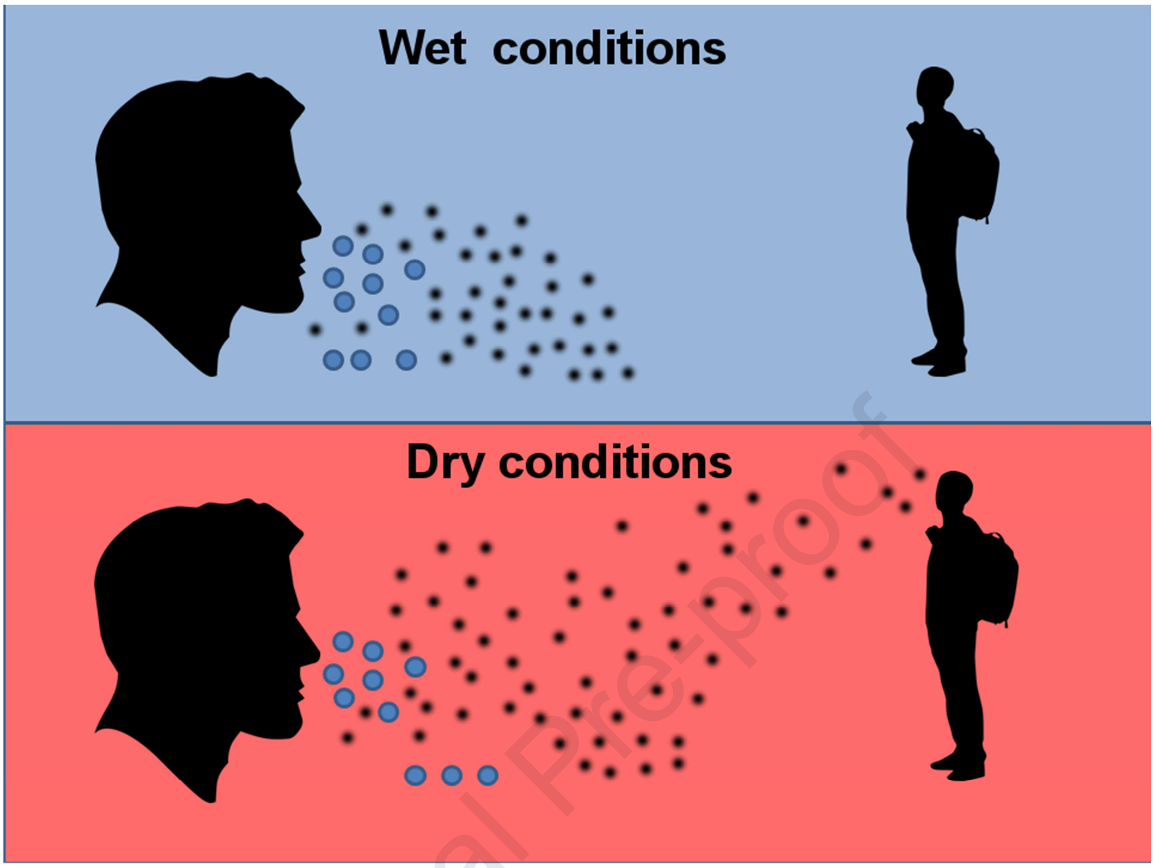

Figure 6. Schematic representation of particles emitted by a cough, with the large droplets settled down nearby (e.g., 1 m distance) and the smaller airborne particles spreading in suspension for longer time, and reaching longer distances, especially in dry and stable indoor conditions as compared to wet environments. It is also possible that a resuspension of aerosol particles can eventually happen due to human activities (e.g., walking, cleaning, etc.) or air flows, which is enhanced under dry conditions.

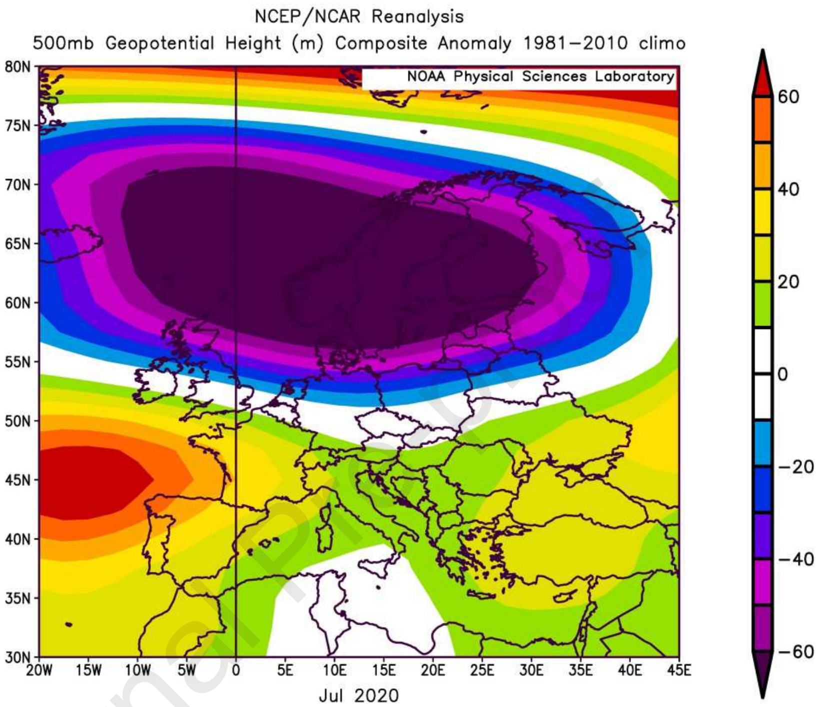

Figure 7. Anomaly pattern of 500 hPa geopotential height (m) for July 2020 over Europe as compared to the climatology mean (1981-2010 period). Image generated with the Web-based Reanalysis Intercomparison Tool provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado from their Web site at http://psl.noaa.gov/

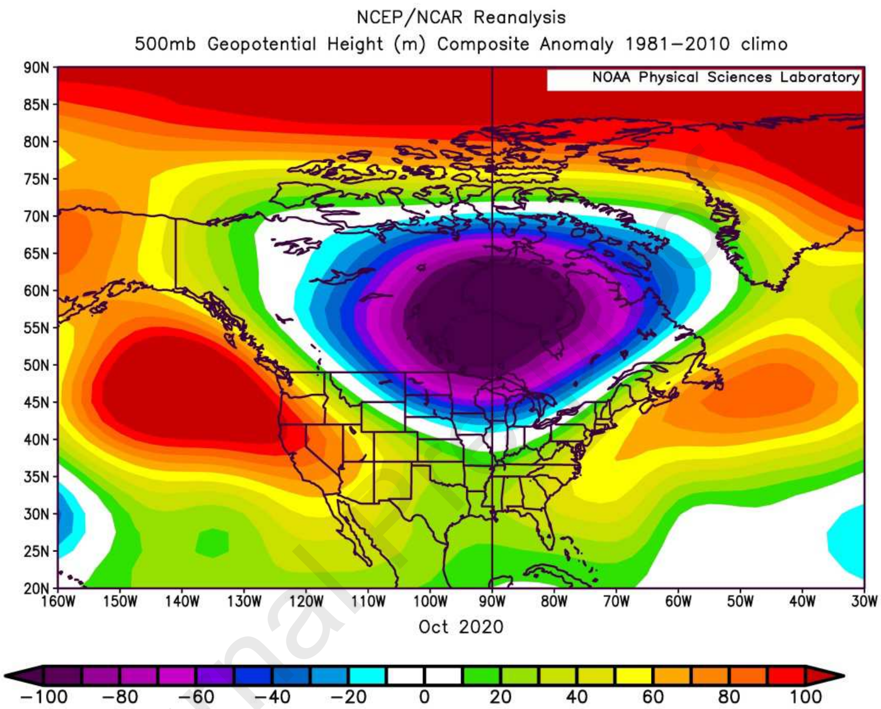

Figure 8. Anomaly pattern of 500 hPa geopotential height (m) for July 2020 over North America as compared to the climatology mean (1981-2010 period). Image generated with the Web-based Reanalysis Intercomparison Tool provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado from their Web site at http://psl.noaa.gov/

Highlights

- First study to explore the effects of large-scale atmospheric patterns on COVID-19.
- Anticyclonic conditions could have favored the COVID-19 disease over Europe.
- Transmission by droplets and/or aerosols, and social contact could be enhanced.
- Resemblances with spatial and atmospheric conditions during the 1918 Spanish flu.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: