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Do environmental factors such as weather conditions and air pollution influence COVID-19 outbreaks?

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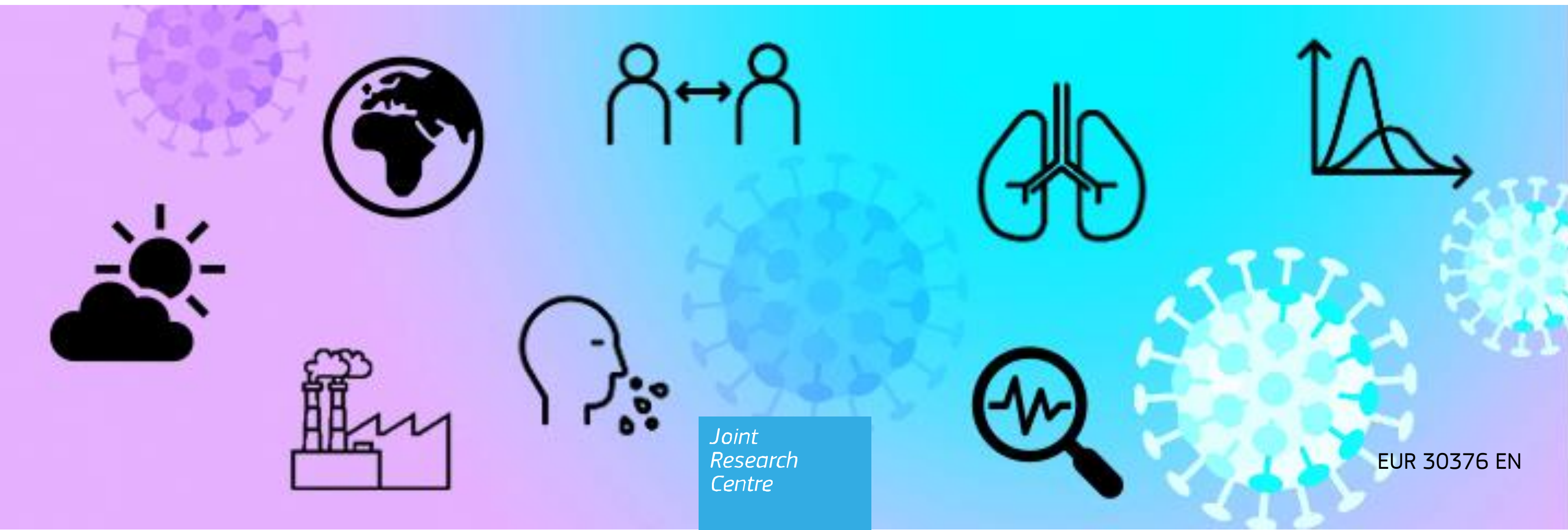

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Contents

Abstract

The first major outbreaks of Coronavirus disease (COVID-19) were seen in a narrow latitude band in areas sharing similar meteorological conditions and having high levels of air pollution. A large number of scientific studies have addressed the possible relationship between meteorological conditions, air pollution and COVID-19 pandemics. In this report we provide a critical overview of selected studies. We further evaluate the importance of air pollution for the transmission of COVID-19 by aerosols in the ambient outdoor conditions, provide an estimate of the upper bound for the impact of air pollution on the COVID-19 mortality and maps showing the probability of the occurrence of potentially favourable environmental conditions which could favour the SARS-CoV-2 transmission over Europe during the year.

Foreword

Foreword by Stephen Quest, Director-General, Joint Research Centre, European Commission

Knowledge management in times of pandemics

The worldwide scientific response to the COVID-19 pandemic and the many potential factors influencing its development has produced numerous studies that have sought to make sense, in a short period of time, of a deluge of information.

I am therefore particularly pleased that the JRC has been able to act as a knowledge manager, applying the highest standards of scientific rigour. In this report, our experts have critically evaluated the available evidence describing the relationship between meteorological conditions, air pollution and COVID-19. They have concluded that a robust relationship between transmission of COVID 19 and air pollution has yet to be found. This conclusion reminds us that correlation does not necessarily mean causality, and that scientific rigour is key. I am confident that this painstaking work will result in valuable guidance for policy makers, both in the Commission and the Member States, in dealing with the response to the pandemic.

Foreword by Roberto Viola, Director-General, Communications Networks, Content and Technology, European Commission

No stone left unturned in our understanding of Covid-19 pandemic

Much has been written about the alleged relationship between the spread of Covid-19 virus and environmental factors. Most of these contributions, which sometimes had quite some resonance in the media, are missing a sufficiently robust evidence base. This report makes an important contribution to our understanding of the relationship between COVID-19 infection spread and the environmental factors. It explores without preconceived ideas the possible direct and indirect relationships between meteorological factors such as temperature, humidity and solar radiation on COVID-19 spread. It also explores the potential role of air pollution as a factor responsible for increased susceptibility to infections and as a potential vehicle for virus transmission. Better understanding of these factors is key to support the work of epidemiologists and to tailor preparedness and response strategies in the context of the COVID-19 crisis.

The report also provides novel insights on the possible directions to fill knowledge gaps in our understanding of outbreak dynamics, and improve the quality of modelling and forecasting for the pandemic. Comprehensive, reliable models are crucial to inform public health interventions, help contain the spread of the virus and support the effective delivery of critical services. This report encourages us to consider a wide range of COVID-19 determinants and have a broad overview of outbreak dynamics. In doing so, it adds to the bigger picture of the coronavirus spread that is being developed by the Member States, with the support of the Commission, through coordinated actions on disease modelling and the use of mobility data. This approach can enable cross links between population movements, as part of predictive models, and environmental data, so that all angles are explored, and no stone left unturned in our understanding of this complex, new health threat.

Ultimately, this report is a call for further multidisciplinary research on environmental factors and the COVID-19 pandemic. Gaining a deeper understanding regarding the relative impact of indoor and outdoor conditions of the pandemic dynamics seems, for instance, to be particularly promising. For example, the report highlights that indoor aerosol levels are generally not well correlated with outdoor levels, and are strongly dependent on ventilation and filtering. There is a need to disentangle the variability of conditions, including air pollution in the indoor vs outdoor environment. We should seek to gain a more granular understanding of indoor conditions in order to fully account for the complexity of this interplay and its effects on COVID-19 transmission. As this picture becomes clearer, Member States and EU authorities will be in a stronger position to predict the spread of the coronavirus, and assess the impact of social distancing measures on mobility.

I see this excellent report as the first stepping stone in a long journey. It is important that we continue to work together to advance research and knowledge, bringing together our multi-disciplinary expertise. A bold approach and a collective, cross-sectoral effort is vital in delivering effective solutions to overcome this crisis.

A big thank you to the colleagues of JRC for this comprehensive work and I encourage them to go further together with the scientific community in the understanding of the multiple facets of this complex challenge.

Acknowledgements

The work has been executed as part of the Letter signed by JRC and DG CNECT on Collaboration against Coronavirus, to analyse the dynamics of the COVID-19 epidemic and quantify the impact of measures, including those on social distancing and mobility.

For their reviews and suggestions, we would like to thank Marco Marsella (DG CNECT), Giulio Gallo (DG SANTE), Vicente Franco and Thomas Henrichs (DG ENV) and Fabrizia Cavalli, Jean-Philippe Putaud, Diana Rembges and Mauro Petrillo (JRC).

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Executive summary

The first major outbreaks of Coronavirus disease (COVID-19, caused by the virus SARS-CoV-2) were seen in December 2019 in Wuhan (Hubei province, China), and later in January and February 2020 in Daegu (South Korea), Tokyo (Japan), Qom (Iran) and Lombardy region (Italy). These cities and regions are located in a latitude band (30 – 50°N) that experience similar stable temperature and humidity conditions in Northern Hemisphere wintertime. These areas are also characterised by high levels of air pollution and poor air quality is a persistent condition particularly during wintertime.

In the report we address the following questions:

Is COVID-19 spread dependent on ambient meteorological conditions?

Does exposure to air pollution play a role in the outcomes of COVID-19 for those infected?

Can particulate air pollution be an efficient carrier for the SARS-CoV-2 virus?

Like for other viruses, meteorological variables, particularly temperature and humidity, can determine favourable or adverse conditions for the SARS-CoV-2 to survive in ambient conditions, while laboratory studies found that increasing solar radiation, temperature and humidity may reduce the survival of SARS-CoV-2 virus in the air and on surfaces. Studies of COVID-19 infection cases have identified ranges of temperature and humidity that seemed to favour the spread of the disease.

Air pollution has a strong impact on human health. Decades of epidemiological science support a causal relationship between long-term exposure to air pollution and respiratory and cardiovascular disease. Studies linking ambient conditions to fatalities during the SARS outbreak in China in 2002, indicate that the fatalities across China might be explained by air pollution levels.

Numerous biological, socio-behavioural and environmental factors govern pathogen transmission. Evidence indicates that COVID-19 is transmitted from human to human by infectious droplets. Based on experience with previous outbreaks of SARS and on experimental evidence, longer-range airborne transmission via aerosols has also been proposed by a large number of scientists and the WHO.

Policy context

This work has been undertaken as a contribution to the common European response to the Coronavirus outbreak that is being coordinated by the European Commission, including the provision of objective information about the spread of the virus, efforts to contain it and the preparation of the proposed EU Recovery Plan for Europe. This plan will "help repair the economic and social damage brought by the coronavirus pandemic, kick-start a European recovery and protect and create jobs".

The purpose is the investigation of a possible relationship between environmental factors and COVID-19 spread and health outcomes and the eventual inclusion of the quantified link into epidemiological models. Furthermore, a link to environmental factors could anticipate a possible seasonal trend of the disease.

Key conclusions

Taking the three questions in turn:

We conclude that laboratory studies have shown that increasing solar radiation, temperature and humidity may directly reduce the survival rate of COVID-19 virus in the air and on the surfaces. Statistical studies find the relationship between the initial development of the pandemics and meteorological variables consistent with findings from laboratory experiments, although it is not clear whether the link is direct or indirect (in that increased solar radiation and temperatures also influence behaviour). Most of the studies show that increasing sun radiation, temperature and relative humidity should reduce the spreading of the pandemic in the middle latitudes, but several studies find that the epidemic intensity may only be attenuated and does not diminish in summer in the middle latitudes or in sub-tropical and tropical climates.

The role of air pollution in the transmission of the SARS-CoV-2 virus by aerosols is still under debate. Observations and laboratory experiments indicate that COVID-19 virus could be transmitted by aerosols in specific indoor conditions, but the relative importance of aerosols compared to droplets and fomites is not yet established. Our conclusion from a simple aerosol dynamic modelling exercise is that in outdoor conditions, high ambient pollution levels produce similar atmospheric lifetime and respiratory track deposition efficiency of virus-laden particles, compared to clean continental conditions.

Indoor aerosol concentrations are strongly dependent on ventilation and filtering. However, in the absence of details of actual ventilation and/or filtering effects, it is reasonable to assume that, different indoor ambient PM conditions produce similar airborne virus particle properties, either in terms of lifetime or inhalation efficiency.

So far studies statistically relating air pollution to the number of positive cases, deaths or mortality rate do not capture the complexity of the seeding and spreading dynamics sufficiently to allow the identification of any actual air pollution contribution. For this to be possible, more comprehensive studies will be needed.

By combining the comorbidity statistics of COVID-19 deaths and previous epidemiological estimates of the attributable fraction of air pollution in the total mortality, we estimate the share of COVID-19 deaths with comorbidities attributable to long-term air pollution impacts. Assuming the same share of comorbidities of Europe for China, leads to an estimate of 6.6% (EU) and 11% (China) as an upper limit for the contribution of air pollution to COVID-19 mortalities.

The available literature overview indicates that there is still lack of the full understanding of the relationship between environmental factors and the COVID-19 pandemics. It is, therefore, necessary to further investigate their relationship by developing uniform and internationally agreed protocols on the pandemic data collection and involving as much as possible multidisciplinary research teams combining statistical studies with laboratory and field experiments. The longer time series of data should further improve the robustness of the analysis and provide information on different stages in the evolution of the pandemic. If a reliable mathematical relationship can be shown to exist, it can be introduced in epidemiological models for improved monitoring and predicting the pandemics.

Main findings

The detailed literature review of selected studies, representing a wide range of environmental impacts on the pandemic and different methodological approaches, showed that many of the articles analysing epidemiological data or using laboratory experiments presented a possible effect of temperature, humidity or solar radiation on COVID-19 spread, while a few have also looked at outcomes such as mortality. The role of air pollution in transmission of the SARS-CoV-2 virus has drawn a lot of attention from policy makers and media and is still debated and a large number of publications have been produced on this matter in a very short period of time. A robust relationship with air pollution is, however, yet to be found, as some of the methodologies used for the investigation seem to have been chosen rather arbitrarily.

By using a simple aerosol physics modelling we find that high ambient pollution levels should not create significant differences in lifetime and respiratory track deposition efficiency of virus-laden particles, relative to clean outdoor air. We further estimate the maximum share of COVID-19 deaths with comorbidities attributable to long-term air pollution impacts, providing an upper bound on the possible impact of air pollution on the mortality rate from the COVID-19 pandemics (7% for the EU and 11% for China).

We map the environmental conditions that the current studies suggest potentially favour COVID-19 showing their probability over Europe. Monthly European maps show that potentially favourable air pollution and climate conditions for COVID-19 may be found over large areas of Europe in Autumn and Winter.

Related and future JRC work

JRC has a long experience in evaluating the health impact of air quality and in climate modelling. JRC has also evaluated the impact of the lockdown in northern Italy on the air pollution in the region ([1]).

In this report we critically reviewed a selection of scientific publications that have appeared in the past months (March-July 2020) linking meteorological conditions and air pollution to COVID-19 outbreaks. We have complemented this critical review with our own preliminary analyses, to provide a critical assessment identifying characteristic features and shortcomings common to several studies.

Our own analyses have:

— Comment to the paper by Ogen, 2020, as an example of possible shortcomings in the recent literature on the links between air pollution and spread of the COVID-19 (Pisoni and van Dingenen, 2020);

([1]) Putaud JP et al., Impacts of the COVID-19 lockdown on air pollution at regional and urban background sites in northern Italy, 2020, in preparation.

- Preliminary analysis of air quality data and number of COVID-19 cases in some provinces of northern Italy;
- Simulations with a basic aerosol physics model to simulate the coagulation of virus micro-droplets with ambient aerosol particles;
- We provide an analysis with maps showing the temporal evolution, spatial variability and monthly probability of environmental conditions in Europe that, several of the publications discussed above hypothesise as favouring the development of COVID-19 outbreaks;
- By combining the comorbidity statistics of COVID-19 deaths and past epidemiological estimates of the attributable fraction of air pollution in the total mortality, we estimated the share of COVID-19 deaths with comorbidities attributable to long-term air pollution impacts.

In the short to medium term, the JRC will continue following the work done by other institutions on deriving a possible relationship between meteorological variables and air quality and COVID-19 with the purpose of including its mathematical description in epidemiological models.

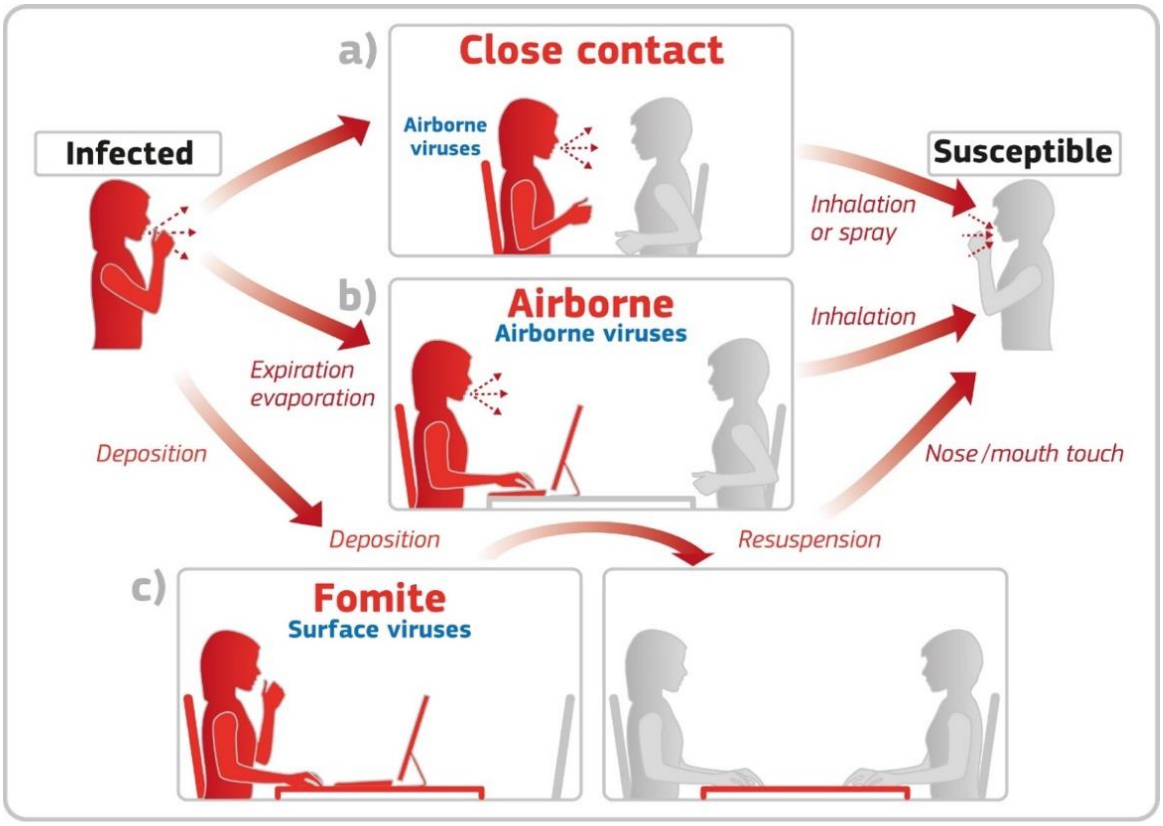
1 Introduction

Coronaviruses cause respiratory and intestinal infections in animals and humans. They were not considered to be highly pathogenic to human until the outbreak of the severe acute respiratory syndrome (SARS) in 2002 (Zhong et al., 2003). Ten years later, another highly pathogenic coronavirus, Middle East respiratory syndrome coronavirus (MERS-CoV) emerged in the Middle Eastern countries (Zaki et al., 2012).

By early 2020, soon after its first reported appearance in the Hubei province in China, a new severe acute respiratory and multi-organ disease named COVID-19 was spreading to neighbouring and remote areas over the globe. On 11 March, the World Health Organisation (WHO) classified the outbreak as a pandemic. In the following months, the pandemic became a major health crisis worldwide and strongly impacted European societies and economies. A major difficulty with the global spread of COVID-19 is that the pathogen (SARS-CoV-2) is new and consequently a full understanding of the dynamics governing the spread of the disease and factors determining the severity and excess mortality it is causing are still lacking.

In order to address the pandemic outbreak in Member States, the European Commission is coordinating a common European response, reinforcing public health sectors and mitigating socio-economic impacts ([2]). This response should be based on the most reliable information regarding the ongoing and future development of the pandemic. In particular, there is a need to understand how the SARS-CoV-2 pathogen that causes COVID-19 infects, is transmitted and how the resulting disease affects individuals. Information on these processes may then be used in epidemiological models to predict the evolution of the epidemic, in order to recommend appropriate actions to contain the spread of the disease.

Figure 1. Schematic representation of possible transmission routes of the respiratory infection between an infected (the red person) and a susceptible individual, in grey. The upper images (a) and (b) are the main exposure route and depending on air droplet size through the viral transmission occurs. The infected person can release air droplet of different size by coughing, sneezing and breathing as the case for airborne viruses. For this latter, as shown in the image (b), the air droplets can be suspended over long distance and time, depending also on environmental factors. The third route of exposure is shown in the image (c), the airborne droplets can settle on surfaces (fomites) from where they can be touched and carried on hands leading to further self-inoculation routes. (image adapted from Tellier, et al. 2019).



([2]) https://ec.europa.eu/info/live-work-travel-eu/health/coronavirus-response_en

In general, it is understood that viral respiratory infections such as COVID-19 are spread by being in close proximity to an infected person and by inhalation of larger respiratory droplets that have a short lifetime, or being in contact with fomites (surfaces and inanimate objects contaminated with respiratory secretions or droplets expelled by infected individuals) (Morawska, 2006) which may remain infective for days (van Doremalen et al., 2020). Although the virus seems to be stable on the surfaces, the contribution to the viral spread seems to be low compared to person-person close contact (within 1 meter) which remains the main driver for SARS-CoV-2 virus spreading ([3]). Recently WHO updated its scientific brief on a potential airborne transmission route for SARS-CoV-2, following the published letter of Morawska and Milton (2020), signed by 239 scientists. The authors asked the national and international medical communities to recognise the potential for airborne spread of COVID-19, based on several retrospective studies conducted after the SARS-CoV-1 epidemic and reported COVID-19 cases where the mechanism of exposure excluded close contacts with infected people, and rather supported airborne transmission by smaller air droplets capable of travelling long distances (Box 1). WHO, together with the scientific community, is evaluating whether SARS-CoV-2 can be spread through airborne transmission (at distances above 1 meter), particularly in indoor environments with poor ventilation. Box 1 provides more details of the transmission pathways, schematically represented in Figure 1.

Box 1. Possible modes of transmission for SARS-CoV-2

Viruses can be classified in two categories, airborne or non-airborne, based on their capability of transmission in the air. They are airborne if their transmission occurs through small droplets i.e. below 10 μm in diameter (1 μm = 1 micro meter = 10^{-6} meter) because it is generally accepted that these droplets are respirable and capable of penetrating below the glottis and in the lower respiratory tract when smaller than 5 μm. This kind of transmission route is also named "aerosol transmission" to describe viruses and generally pathogens that cause disease through droplet nuclei (aerosols) that remain infectious when suspended in air over long distances and time. For droplets larger than 20 μm, the viruses are not airborne since the droplets rapidly fall out of the air, predominantly due to the influence of gravity. In this case, only close contact can lead to infection and this kind of particles are defined as inspirable but are deposited in the upper airways. Droplets whose size is between 10-20 μm of diameter could share some properties of both small and larger droplets (Tellier, et al. 2019). However, it is possible that the patients produce infective droplets of varying sizes by breathing, sneezing and coughing, which could transmit the virus either as airborne or as close contact. In both cases, an additional transition route is the fomite, where the respiratory droplets could be deposited e.g. through coughs of an infected person and then transferred by the hands to the eyes or mouth of the new host (Figure 1).

Among the coronaviruses, those responsible for severe acute respiratory disease such as SARS-CoV-1, MERS-CoV and SARS-CoV-2, were more consistent with the hypothesis of airborne transmission for their capability to infect the lower respiratory tract, although the proportion of infections by this airborne route may vary in different situations depending on e.g. host or environmental factors (ventilation) (Tellier, et al. 2019, Morawska and Milton, 2020).

In addition to the transmission routes, environmental factors may play a role in modulating (enhancing or dampening) the intensity of spreading, the lifetime of the airborne or deposited virus particles, the risk of infection and the impact or outcome for infected individuals. Initial research and the resulting publications have focused on human infection, testing, therapies and vaccine development, understanding the stability of the virus in the air and correlations with atmospheric conditions indicated potential impacts on outbreak dynamics i.e. on spread and intensity (Box 2).

At the beginning of the COVID-19 pandemic, major outbreaks were located in the Northern Hemisphere in the latitude band between 30 ^{0}N and 50 ^{0}N (Wuhan, China; Daegu, South Korea; Tokyo, Japan; Qom, Iran; and northern Italy). Several studies suggested that the specific temperature range and humidity levels could favour the outbreak dynamics (eg. Sajadi et al. 2020). Other papers (e.g. Wu et al., 2020) identified air pollution as another factor correlated with the outbreaks. This was picked up by the media, with reporting that highly polluted areas had higher numbers of COVID-19 cases than "cleaner" regions, without considering that generally polluted areas have at the same time high population density. Although several studies indicate links between climate, air pollution and COVID-19 outbreaks, many of them were published rapidly without necessarily completing the usual scientific peer-review process.

([3]) https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions

This report addresses the following questions:

- Is COVID-19 spread dependent on ambient meteorological conditions?
- Does exposure to air pollution play a role in either the risk of COVID-19 infection or the outcomes of COVID-19 for those infected?
- Can particulate air pollution be an efficient carrier for the SARS-CoV-2 virus?

It provides an overview of scientific publications that have appeared in the past months (March-July 2020) linking meteorological conditions and air pollution to COVID-19 outbreaks. This overview cannot be exhaustive, given the large number of publications on COVID-19, but it is intended to provide a critical assessment identifying characteristic features and shortcomings common to several studies. We have complemented this critical review with our own analyses. In Section 2 we discuss the impact of meteorological variables, such as temperature and humidity, on the spread of COVID-19. We looked at laboratory studies on the environmental conditions affecting the SARS-CoV-2 survival time in the environment (Section 2.1) and at statistical analysis and modelling studies (Section 2.2). Section 3 addresses the two questions of the role of air pollution being a possible carrier of the virus (Section 3.1) and of air pollution in increasing both the spread and the severity of the health impacts of COVID-19 (Sections 3.2 and 3.3). The report additionally provides an analysis with maps showing the temporal evolution, spatial variability and monthly probability of environmental conditions in Europe that, several of the publications discussed above hypothesise as favouring the development of COVID-19 outbreaks (Section 4).

Box 2. Metrics indicating the COVID-19 impact

The impact of COVID-19 may be quantified through a number of metrics:

Mortality rate: number of deaths per population, during a given period, in a given location. The number is easily calculated from reported deaths, provided that COVID-19 is correctly listed as the cause of death

Fatality rate: number of deaths among incident cases per total number of incident cases, during a given period in a given location. The number can only be correctly evaluated if the total number of incidences (positive cases) is known, which is not the case. A good proxy of the fatality rate is the number of reported deaths divided by the number of reported hospital admissions. This number is more robust than reported deaths/reported cases because the number of reported positives is strongly affected by the testing capacity and protocols which may change during the development of the epidemic.

Basic reproduction number, R_0: the average number of secondary infections produced by a typical case of an infection in a population where everyone is susceptible. It is used to measure the transmission potential of a disease in the absence of control measures or acquired immunity among the population. In general, for an epidemic to occur in a susceptible population R_0 must be >1, so the number of cases is increasing.

Reproduction number, Rt: the actual average number of secondary cases per primary case at calendar time t (for t>0). Rt shows time-dependent variation due to the decline in susceptible individuals (intrinsic factors) and the implementation of control measures (extrinsic factors). If Rt<1, it suggests that the epidemic is in decline and may be regarded as being under control at time t (vice versa, if Rt>1)

The mortality rate is directly related to the (actual and unknown) number of persons infected (hence to the reproduction number Rt) and to the severity of the disease for those infected (hence to the fatality rate).

The reproduction number Rt is affected by factors driving person-to-person contacts, such as **population density**, **mobility**, social, cultural and leisure activities, **presence of specific economic activities**, housing infrastructure, number of nursing homes, containment measures, as well as susceptibility of the population and (potentially) environmental factors such as weather conditions.

The fatality rate (as a metric for severity or outcome) is related to demographic structure, **pre-existing conditions**, performance and capacity of the health care system, lag time after first observed local case, lag time after the first observed casein the affected cluster, and (potentially) environmental factors such as exposure to air pollution.

The determinants in bold are normally positively correlated with air pollution and are thus likely confounding factors when evaluating the contribution of the latter on COVID-19 health impacts.

2 Meteorological conditions and COVID-19

Soon after the notification of the first epidemic outbreaks in January and February 2020, it was observed that COVID-19 outbreaks appeared predominantly in areas with a temperate winter climate (Sajadi et al. 2020) located between 30 and 50 0N (Figure 2). While in early 2020 the virus was spread from its origin in China by travellers to other areas of the globe, other major outbreaks in areas to the south or north of Wuhan province in China were not reported. Chinese provinces surrounding Wuhan or having strong economic interconnections with Wuhan are characterised by some of the highest population densities in the world. Areas of similarly high levels of urbanisation and population density are also found in other South Asian countries. Nevertheless, new epidemic outbreaks appeared elsewhere predominantly concentrated in this narrow latitudinal band, first in South Korea and Japan, later in Iran, Italy, Spain and France (Figure 2). Winter temperatures in this latitudinal band are not uniform, temperatures decrease from south to north and at the same latitude, they were also higher in the western parts of continents, and lower in central and eastern parts due to oceanic influence and prevailing westerly winds in winter. Empirically, it is estimated that the strongest outbreaks at the beginning of the pandemic initially appeared in areas within a narrow temperature range in winter between 5 and 11 ºC and a specific humidity range between 3 and 6 g/kg (or absolute humidity between 4 and 7 g/m^3, Box 3) (Sajadi et al. 2020) shown in Figure 2. The main conclusion of the paper is that if COVID-19 were to have the behaviour of a seasonal respiratory virus, then atmospheric temperature and humidity could be possible predictors of regions with higher risks of diffusion. Another study (Bukhari et al. 2020) estimated that most of the outbreaks happened with wider ranges with temperature between 3 and 17 ºC and with absolute humidity between 3 and 9 g/m^3, but these areas cover a much larger portion of the Northern Hemisphere in winter. Bukhari et al. (2020) predicted that increased temperatures and humidity in the summer would reduce the risk for COVID-19 outbreaks.

Figure 2. Atmospheric specific humidity (g/kg) between isotherms of 5 and 11ºC: a) mean over January 2020, b) mean over February 2020.

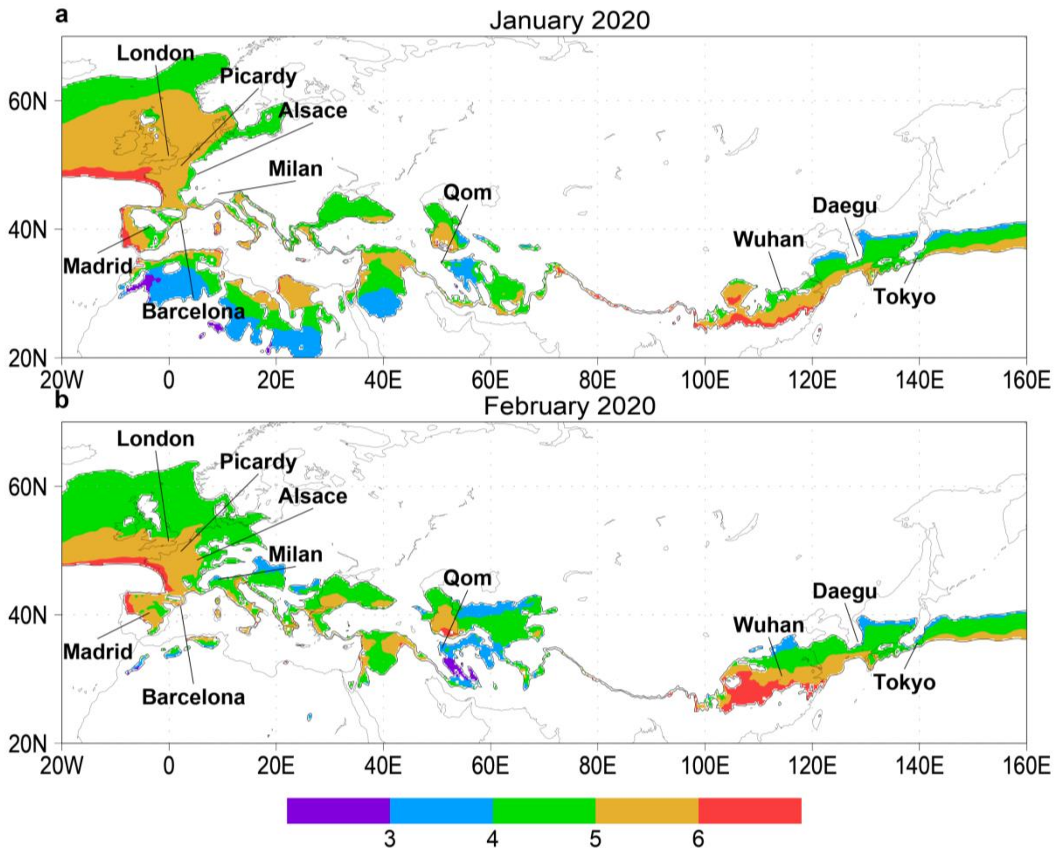
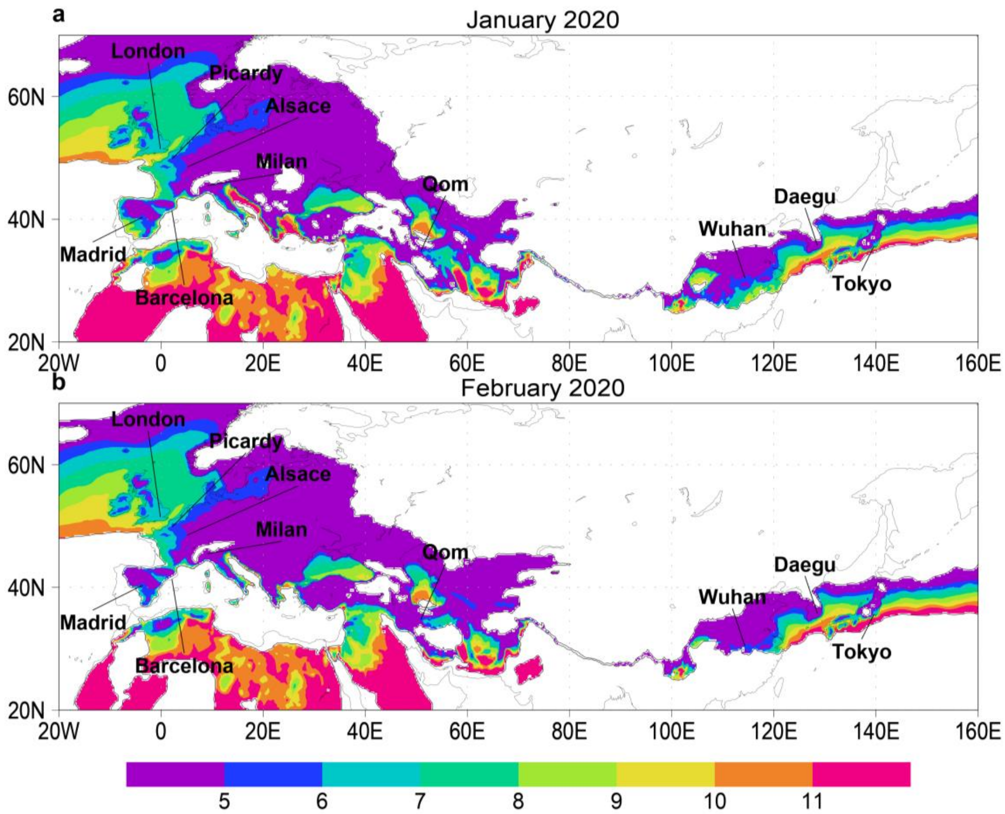


Figure 2 shows the area bounded by the temperature range estimated by Sajadi et al. (2020). If, on the other hand, the area is bounded by the specific humidity range estimated by Sajadi et al. (2020), it becomes much larger (Figure 3), indicating that the humidity range estimated by Sajadi et al. (2020) may be a less stringent factor for estimating favourable conditions for new outbreaks.

Box 3. Three definitions of atmospheric humidity

There are three definitions of atmospheric humidity: Specific humidity is the water vapour content of a specified mass of the air, absolute humidity is the water vapour content of a specified volume of the air, whereas relative humidity is the water vapour content relative to the maximum possible water vapour content at a given temperature. At a constant temperature, the water vapour content of the air can increase until it reaches the condensation point and the air is said to be saturated. The maximum possible water vapour content in the air increases with increasing temperature. Some studies use dew point temperature instead of humidity. Dew point temperature is the temperature at which the actual water vapour present in the air becomes saturated.

Figure 3. Atmospheric temperature (^{0}C) between specific humidity isolines of 3 and 6 g/kg: a) mean over January 2020, b) mean over February 2020.



2.1 Evidence from laboratory studies

The impact of meteorological conditions on the spread of viruses affecting the human respiratory system has been observed in the past (e.g. Moriyama et al. 2020). Cohort studies have shown that influenza and coronaviruses exhibit strong seasonal variability with pronounced reductions in summer (Aldridge et al., 2020; Fragaszy et al., 2017; Gaunt et al., 2010). Meteorological conditions might directly impact the epidemy by either modifying personal response or by influencing the lifecycle of the virus in the environment (e.g. Moriyama et al. 2020). The attenuation of the annual influenza and likewise coronavirus epidemic in summer may also be explained by other determinants such as school closures or changes in social behaviour patterns with longer periods of time spent outdoors and increased ventilation of indoor spaces in the warmer months and during longer days (e.g. Morales et al., 2017, Moriyama et al. 2020).

Past laboratory studies and in-situ observations have provided some evidence that changing atmospheric conditions might impact the lifecycle and transmission of different viruses impacting the respiratory system in indoor and outdoor environments, and this can partly explain correlations between COVID-19 and weather conditions. A laboratory study by Lowen et al. (2007) found that variations in temperature and relative humidity had a strong effect on the spread of influenza among guinea pigs, while Kudo et al. (2019) found that low humidity was associated with weaker resistance of mice respiratory systems and a higher mortality from influenza.

The evaluation of in-situ conditions indicated the important role in certain conditions, of contact with contaminated surfaces for the transmission of influenza and coronaviruses and estimated that they could survive for long time on surfaces (Otter et al. 2016; Kampf et al., 2020; van Doremalen et al., 2020). The lifetime of coronaviruses on surfaces may vary significantly depending on environmental conditions (Casanova et al., 2010; Chan et al., 2011). Laboratory experiments by Ratnesar-Shumate et al. (2020) demonstrate that simulated solar radiation rapidly diminishes active COVID-19 virus concentrations on surfaces and the process is especially fast with strong solar radiation typical for tropical and subtropical regions and the middle latitudes in summer. Laboratory experiments by the U.S. Department for Homeland Security ([4]), indicate that the COVID-19 virus survives longer on indoor surfaces at lower temperatures and lower humidity, having at the same temperature two times longer half-life time at relative humidity of 20% than of 60%, and at the same relative humidity two times longer half-life time at 24 °C than at 32 °C (Biryukov et al., 2020).

The pathway of respiratory virus transport by droplets and aerosols originating from infected persons in close proximity to uninfected persons may be the most important transmission mechanism. Laboratory experiments show that solar radiation can significantly reduce the COVID-19 virus stability in droplets and aerosols by doubling the decay rate with the doubling of the simulated sunlight (Schuit et al., 2020). Preliminary results of laboratory experiments made by the U.S. Department for Homeland Security also demonstrate that COVID-19 virus survives longer in the atmosphere at lower temperatures and humidity, having at the same solar radiation and relative humidity the half-life time about 30 % shorter at temperature of 20 °C than at 10 °C, and at the same solar radiation and temperature the half-life time about 30 % shorter at relative humidity of 70% than at of 20%.

2.2 Statistical relationship and modelling

Several studies have attempted to establish statistical relationships between meteorological variables and COVID-19 cases. By evaluating observations at about 100 cities in China during the first three days of the outbreak, the first version of the Wang et al. (2020) study found a significant linear correlation between the effective reproductive number (Rt, Box 2), temperature and relative humidity. Wang et al. (2020) applied the linear correlation to forecast outbreak risks in many large cities in the world between March and July. In March, even the relatively short-term forecast showed the highest risks in Russia, Scandinavia, Canada, Japan and Middle East (Wang et al. 2020), but none of these countries and regions experienced major outbreaks at that time. In the updated online version Wang et al. (2020) extended the study to 1000 counties in the United States and made local linear correlations by calculating linear regressions in temporally moving windows. The second version of the study also found a significant influence of temperature and relative humidity on the virus diffusion, but it reduced the estimate of their importance and also found that summer conditions may only partly reduce the Rt. Ficetola and Rubolini (2020) related mean monthly temperatures and absolute humidity with growth rates (defined as the ratio between new cases between two different times) of COVID-19 cases in different countries and produced global forecasts of outbreak risks at spatial resolution of 10 km for July and September. This study found a non-linear correlation between growth rates, mean monthly temperatures and absolute humidity in the early stages of the pandemic. By using observations from 25 countries, the study by Notari (2020) found linear and non-linear correlations between the growth rate of coronavirus cases and mean temperature in March—with the strongest growth rates observed when the mean temperature was 9.5 °C —and concluded that the temperature increase in summer might reduce the pandemic in the Northern Hemisphere. Livadiotis (2020) correlated pandemic growth rate and temperature at the early stage of the pandemic in the United States and Italy to predict that the pandemic would stop growing once air temperatures reached 30 °C.

Benedetti et al. (2020) found a significant correlation between monthly mean temperature and the number of deaths in April 2020, which did not exist in March 2020. The authors attribute this difference to the fact that in March 2020, the difference between countries that had experienced an earlier outbreak of the epidemic and those where it broke out later were greater. Ma et al (2020) found significant correlations between daily deaths and relative humidity and the daily temperature variation. The study used the meteorological variables to predict the variation of daily deaths with meteorological variables but did not provide a statistical validation of those estimates. During a short period until the beginning of March 2020 Gunthe et al. (2020)

([4]) https://www.dhs.gov/sites/default/files/publications/sars-cov-2_environment_predictive_model_factsheet_4.pdf found a correlation between cumulative number of deaths and temperature and solar radiation. In a study estimating the impacts of meteorology, population density and the fraction of elderly people in the population, Merow and Urban (2020) found that about one half of explained variability of the pandemic can be explained by demography and meteorology (mainly solar radiation). They concluded that increasing solar radiation would help to reduce the pandemic during the Northern Hemisphere summer, but that it could re-emerge in autumn and winter. Similarly, Nicastro et al. (2020) suggest that the evolution and strength of the recent SARS-CoV-2 pandemics, might be modulated by the intensity of solar radiation between January and May 2020. The impact of temperature was also evaluated during the early phase of the epidemic in Brazil, where higher temperatures and humidity reduced the outbreak intensity even in tropical and sub-tropical regions of Brazil (Prata et al., 2020). Qi et al. (2020) found a linear relationship between the number of COVID-19 cases in mainland China at the early stage of the epidemic and temperature and humidity. The study by Kifer et al. (2020) finds a correlation between the number of cases with the severe disease in about one half of the arbitrary selected hospitals in Europe and China explaining this result by the hypothesis that the low ambient temperature in winter could increase time spent indoors in the environment with low humidity.

Box 4. COVID-19 and influenza

The COVID-19 virus has some similarities with other coronaviruses and the influenza virus. All viruses may produce similar symptoms often attacking the respiratory system. They are primarily transmitted from person to person by saliva in the air or on the surfaces. The similarities in the transmission of viruses allow some level of comparison and studies on meteorological conditions influencing influenza virus or some other coronaviruses might be also used as a proxy for estimating the influence meteorological conditions on COVID-19 epidemics. On the other hand, the COVID-19 virus differs from the influenza virus and other coronaviruses and the impact of meteorological conditions might differ significantly. COVID-19 also is associated with a higher mortality rate than influenza and probably a higher transmission rate ([5]).

The study by Baker et al. (2020) applied a dynamic model accounting for the seasonal variability of pandemics. In the model, the global growth of infected cases by influenza and two coronaviruses is simulated according to the observed seasonal variation of infected cases in the United States in relationship to the observed variation of specific humidity. Assuming that COVID-19 epidemic evolves with a similar dynamic to other coronaviruses, the study provides an estimate of the possible impact of environmental conditions on the evolution of the pandemic. The study found that, although weaker and more slowly growing than in the middle latitudes, the strong outbreaks are also likely to appear in moist conditions and warmer weather in summer and therefore that these summertime conditions may not completely attenuate the pandemic growth.

All studies finding statistically significant linear correlations estimate decreasing number of COVID-19 cases with increasing temperatures, humidity and solar radiation (e.g. Benedetti et al. 2020, Merow and Urban 2020). The studies finding non-linear relationships evaluate the most favourable conditions at a certain temperature and humidity range (e.g. Sajadi et al. 2020, Ficetola and Rubolini 2020).

Several studies, however, could not find important impacts of meteorology on the COVID-19 pandemic. Triplett (2020) found that during the early stage of the pandemic there were fewer outbreaks south of 30 °N and concluded that seasonal temperature variability could modify the epidemics, but the locally more detailed variability of outbreaks could not be explained by geography and temperature variability. Studies of the variability in mortality due to COVID-19 in Italy concluded that it was not correlated with meteorology (Coccia et al., 2020; Coker et al., 2020). In India, the geographical variability of the COVID-19 cases was found to be correlated with temperature, but it was estimated that the correlation was not sufficient to significantly modify the seasonal variability of the epidemic (Kumar et al., 2020). Temperature was also found to be of less significant impact in the influenza pandemics of 2009 (Box 4) and instead demographic factors were identified as potentially more important than geographical variations in temperature in the Northern Hemisphere (e.g. Morales et al. 2017).

Most of the studies presented in this subsection are based on correlations between COVID-19 outbreaks and climatic conditions, as measured by a number of meteorological variables. The time series covering the COVID-19 dynamics is, however, only few months long and does not cover the full annual variation of meteorological variables. Any relationship between meteorological variables and the COVID-19 pandemic might not therefore be valid for the different meteorological conditions found at other times during the year.

([5]) https://www.ecdc.europa.eu/en/covid-19/questions-answers

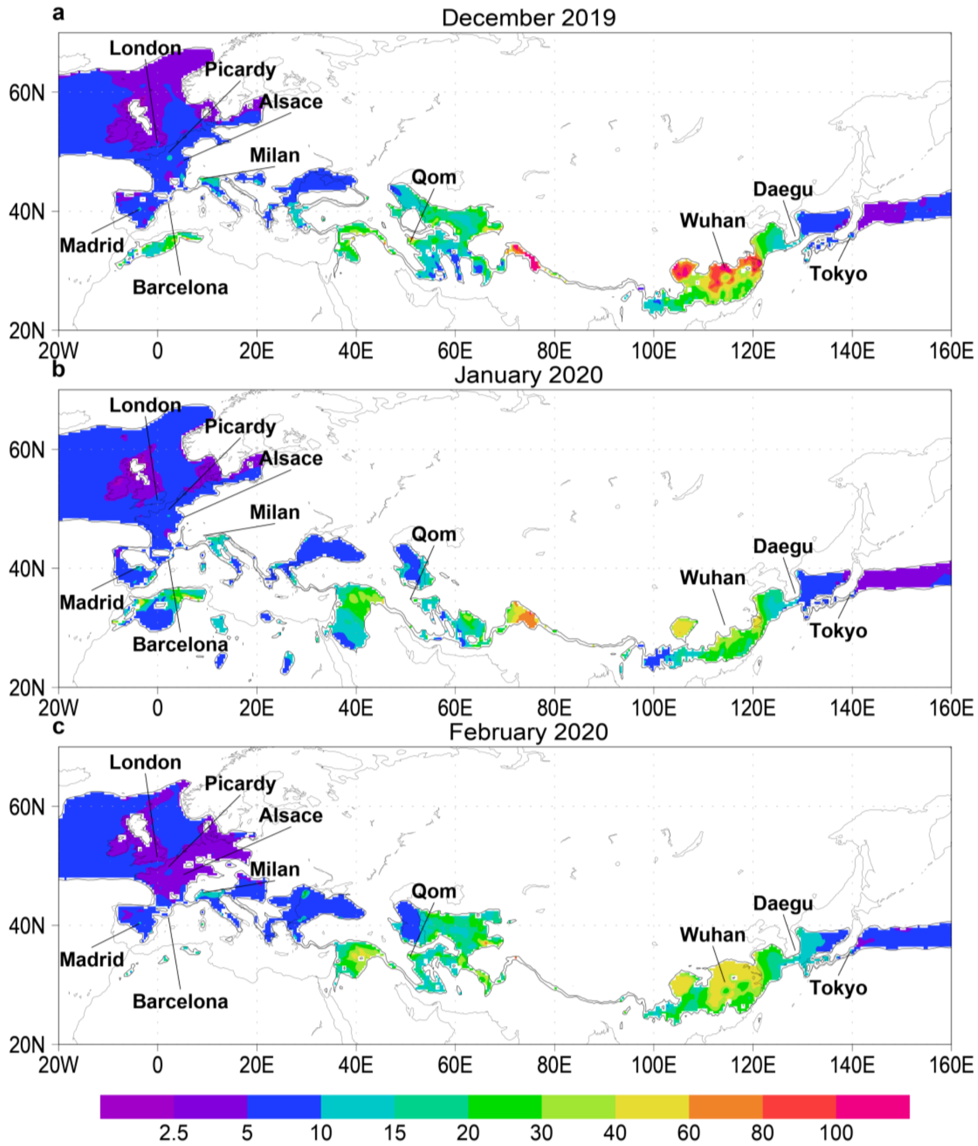
In fact, the study by Baker et al. (2020), that combined a dynamical model of the pandemic with observations of humidity impacts on the past coronavirus epidemics, found that strong outbreaks could also occur with a warm and humid climate. This result can provide an explanation for strong outbreaks happening later during the year in Brazil, California, Texas and Florida characterised by warm and often humid climate and the intensification of the pandemic in south-eastern Europe in early summer, while the later outbreaks in Sweden and Russia could be consistent with the seasonal warming and meteorological conditions becoming similar to those found in Southern and Western Europe in February. The studies can be grouped into those that consider the impact of a single meteorological variable like temperature (Notari et al., 2020; Livadiotis et al., 2020; Benedetti et al., 2020, Kifer et al. 2020) or humidity (Baker et al., 2020), while the others evaluate several meteorological variables at once. All studies arbitrarily apply temporal and spatial averaging of the meteorological variables investigated.

A fundamental point to consider regarding nearly all of the above studies is that the analyses may find statistical correlations between meteorological conditions and intensity of outbreaks but establishing causality will require independent experiments and more detailed analyses of the results.

3 Air quality impacts on the spread and severity of COVID-19

Since the onset of the COVID-19 epidemic, several reports have appeared in scientific and general media, hypothesising that air pollution (in particular fine particulate matter, PM2.5 ([6])) could be a major factor influencing the number of COVID-19 spread and deaths. The potential causal relationship between air pollution and COVID-19 deaths was triggered by the observation that at the beginning of the pandemic Wuhan (China, December 2019), and later (January 2020) Daegu (South Korea), Tokyo (Japan), Qom (Iran) and Milan (Italy, February 2020) were strongly affected by COVID-19 mortality. All these places have in common with Wuhan similar meteorological conditions (Section 2) but also high levels of air pollution (Figure 4). Possible associations between air pollution and the spread and impact of COVID-19 have been considered also in other countries (e.g. USA).

Figure 4. Mean near-surface concentration of PM2.5 (micrograms/m^3) between isotherms of 5 and 11 ºC: a) December 2019, b) January 2020 and c) February 2020 obtained from the CAMS reanalysis (Benedetti et al., 2009).



The potential role of air pollution in increasing the diffusion of COVID-19 (e.g. measured with the reproduction rate Rt, Box 2) and the fatality rate (number of deaths per total infected, Box 2) could be threefold:

([6]) Particulate matter refers to airborne microscopic particles with a diameter of some micrometres or less. PM2.5 is a frequently used metric in the field of ambient health impacts, defined as the subset of airborne particles having a diameter below 2.5 micrometres. Another term for airborne particles 'atmospheric aerosol' or simply 'aerosol'.

1. by providing an atmospheric carrier (via clustering between originally exhaled virus particles and ambient particles), eventually enhancing the atmospheric lifetime and therefore the transmission efficiency of the SARS-CoV-2 virus
2. by modifying the size of the originally exhaled particles (again via clustering) and eventually enhancing the deposition efficiency in the respiratory tract
3. by increasing the severity of the health impact of those infected, via the contribution of air pollution to COVID-19 aggravating comorbidities.

The first two pathways should increase a metric like reproduction number, Rt, which is used to measure the 'speed' of the pandemic. The third pathway should be observed in an enhanced fatality rate. The three pathways will be introduced here and addressed in the next sections.

3.1 Could air pollution efficiently carry and transmit SARS-CoV2?

Numerous biological, socio-behavioural and environmental factors govern pathogen transmission. Evidence indicates that COVID-19 is transmitted from human to human by infectious droplets which are expelled when a person with COVID-19 coughs, sneezes, or speaks. These droplets are relatively heavy, do not travel far and quickly sink to the ground. People can catch COVID-19 if they breathe in these droplets from a person infected with the virus (Figure 1 and Box 1). Based on experiences with previous outbreaks of SARS and on experimental evidence, one possible additional route is the so-called long-range airborne route via aerosols, and this concern has been expressed by a large number of scientists (e.g. Morawska and Milton, 2020) and by the WHO (8). Setti et al. (2020) indeed demonstrated the presence of SARS-Cov-19 virus RNA (however not the presence of vital virus) in ambient aerosol samples in Bergamo (Italy) during the initial phase of the epidemic, providing support for the hypothesis that the long-range airborne route cannot be excluded as transmission pathway. On the other hand, to date, only van Doremalen et al. (2020) and Santarpia et al. (2020) provide evidence of the short-term survival of coronavirus within aerosols, even if not on outdoor air samples. Consequently, the hypothesis for the SARS-CoV-2 spreading by outdoor aerosols and being able to infect needs further research (IAS, 2020; ACTRIS, 2020).

For SARS-CoV-1, both evidence from modelling studies (Xiao et al., 2017; Yu et al., 2014) and positive air samples from a patient's room (Booth et al., 2005) indicated a potential for airborne transmission. Recent (but limited) data from Wuhan hospital areas indicate that airborne particles containing the SARS-CoV-2 virus are most numerous in the range 250-500 nm (1 nm = 1 nanometer = 10^{-9} meter) aerodynamic diameter at ambient relative humidity (roughly corresponding to 170 – 350 nm geometric diameter) however also sizes in the size classes 10-250 nm and 2.5-10 µm have been observed (Liu et al., 2020). The particles are in the correct size range to be readily inhaled deep into the respiratory tract of an individual. Furthermore, the suspended virus particles in this size range reside long enough in the air to interact with ambient aerosols and to undergo clustering (coagulation) with the latter, which modifies their initial size and consequently their atmospheric lifetime and deposition efficiency in the respiratory tract. Their final fate depends on the initial size of the exhaled virus-laden particles, and on the concentration and size of the surrounding ambient aerosol particles. It has to be noted that even in clean (continental) conditions, one cm^3 of air contains several hundreds of microscopic 'pollution' aerosol particles, while the concentration of virus-laden aerosol particles is several orders of magnitude lower.

Although the long-range transmission pathway could be potentially relevant, the presence of the SARS-CoV-2 virus in ambient particulate matter does not necessarily imply a boosting effect from air pollution on the reproduction number – relative to clean ambient conditions. This would only be the case if the clustering of ambient particles with virus-laden particles would (1) significantly increase the airborne lifetime of the virus-laden particles compared to cleaner continental areas and/or (2) increase the lung deposition fraction of inhaled particles, compared to low-pollution conditions. Further, the virus would need to remain viable at a sufficient infectious dose during its airborne lifetime (1 – 2 hours, according to Van Doremalen et al., 2020)

To evaluate the fate of virus-laden particles during their air-borne lifetime amidst ambient aerosols, we apply a basic aerosol physics model for coagulation, showing that particles with any initial diameter below 100 nm, within a time span of 30 minutes agglomerate with surrounding ambient particles to reach a size of about 100 nm, and once they reach that size they do not grow significantly anymore. This is true both for highly polluted urban conditions, and for clean continental air. In fact, airborne particles would grow within 5 minutes to at least 70% of their final size, both under clean and polluted conditions (Figure 5). Virus-laden particles, originally sized 100 nm or larger, do not grow significantly through clustering with ambient particles, regardless of the pollution load. Because the lung-deposition efficiency of airborne particles displays a minimum for particle sizes around 250 nm (see Figure 6, modified from Rissler et al., 2017), this implies that the clustering between ambient air pollution and airborne virus particles leads to a decrease in lung deposition fraction if the originally exhaled virus particles were smaller than 250 nm, and that the lung deposition fraction does not change in case they were larger than 250 nm (because they do not change size). Our conclusion from this simple modelling exercise is that high ambient pollution levels cannot explain eventual differences in lifetime and respiratory track deposition efficiency of virus-laden particles, relative to clean continental conditions. This analysis applied to outdoor conditions.

Figure 5. Growth of virus-laden particles with initial sizes of 20, 50, 100, 200 and 500 nm under urban background (left panel) and clean continental conditions (right panel).

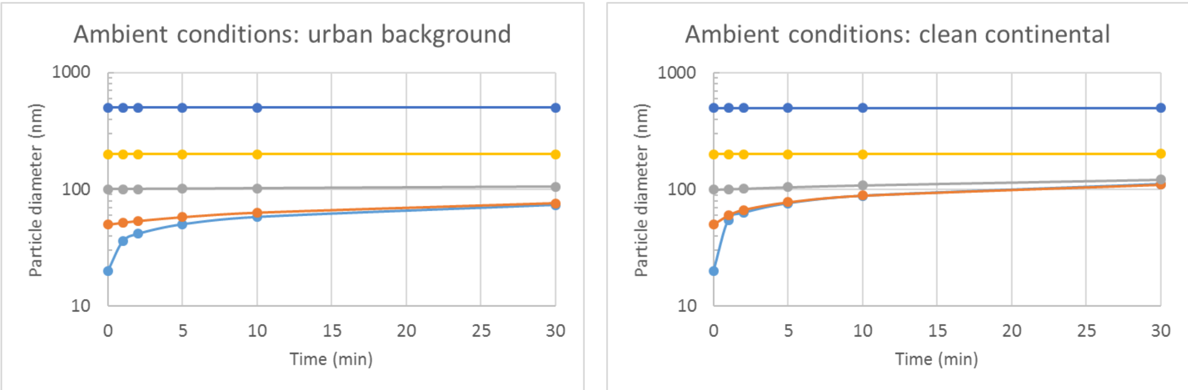
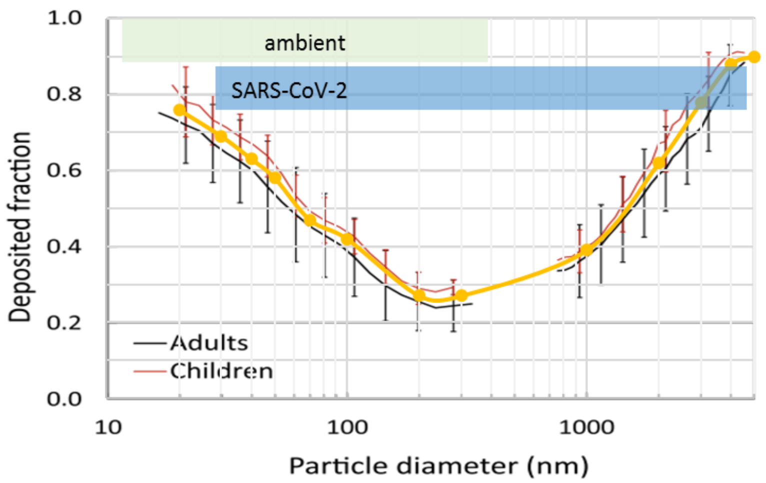


Figure 6. Lung deposition fraction of inhaled particles as a function of particle (geometric) size. Yellow line: eyeball interpolation of measured 'Adults' and 'Children' data, used for this analysis. The blue area indicates the observed range where largest numbers of SARS-CoV-2 respiratory aerosols have been observed in Wuhan, China (Liu et al., 2020). The green area indicates the size range of most ambient particles (in terms of number concentration).



Indoor aerosol concentrations are generally not well correlated with outdoor levels (Meier et al., 2015) and are strongly dependent on the availability and operation of ventilation and filtering installations. However, in the absence of details of actual ventilation and/or filtering effects, it is reasonable to assume that, similar to outdoor conditions, different indoor ambient PM conditions will not produce significant differences in airborne virus particle properties, either in terms of lifetime or inhalation efficiency.

3.2 Do recent studies provide insights on the possible role of ambient pollution on COVID-19 transmission?

A number of recent studies have claimed to find more or less strong associations between air pollution and number of incidences (infected cases), number of deaths, or mortality rates (deaths normalized by population number).

In this section we report a few examples of recent studies linking air pollution to increasing spread of COVID-19 among the population in regions with long- and short-term exposure to high levels of atmospheric pollution.

Zhu et al. (2020) suggested a significantly positive association between short-term exposure to atmospheric pollutants and COVID-19 confirmed cases in China. They found that, considering the average concentrations of air pollution over a period of 2 weeks, an increase of 10 μg/m3 in PM2.5 and PM10 is associated with a 2.24% and 1.76% increase in daily counts of confirmed cases. Larger impacts were found for ozone (6.94%) and NO2 (4.76%), while a decrease of 7.79% was found for increasing SO_2 concentrations.

A number of studies have focused on the situation in northern Italy, as it is the region with the first COVID-19 outbreak in Europe, with a large number of infected people and at the same time is a region with high atmospheric pollution levels. For example, Coccia et al. (2020), based on simple linear regression analysis, concluded that an acceleration of the spread of COVID-19 is associated with high levels of atmospheric pollution, for example in cities where the PM10 and ozone limits are exceeded for more than 100 days per year. Fattorini et al. (2020) analysed the correlation between COVID-19 cases and pollution concentrations in Italian provinces and interpreted this as an “additional evidence on the possible influence of air quality on COVID-19, particularly in terms of chronicity of exposure on the spread viral infection in Italian regions”.

Other studies have evaluated the association between air pollution and the number of deaths or the death rate. Note that these metrics do not properly describe the severity of the COVID-19 impact (i.e. the case fatality rate). As it is the case for the number of infected, differences in mortality (rates) between locations may be driven by differences in timing of the local onset, differences in social-cultural events, transport modes, urban fabric, industrial activities etc… and for several of these factors, air pollution is correlated in a trivial way.

Wu et al. (2020) used COVID-19 deaths in USA and county-level long-term averages of PM2.5 concentrations as the exposure. They suggested that an increase of only 1 $\mu g/m^3$ in PM2.5 could be associated with an 8% (15% in an earlier version of the study) increase in the COVID-19 death rate. The authors mention that association does not imply causality. In their statistical analysis, the authors of the study included 20 potential confounding factors such as the population size and density, hospital beds, number of individuals tested, weather and several socioeconomic and behavioural aspects. Our preliminary comparisons with equivalent data from the two least effected provinces among Lombardy, Piedmont and the Veneto (selected to exclude possible “mismanagement” effects and thus maximise any impact of PM on mortality), where mean annual PM2.5 concentrations are approximately 3 times the mean of the USA samples, do not appear to demonstrate “as strong as”/”the same” relationship between PM2.5 and mortality, but further investigation is required. We must also note that this study, as well as all the others, is based on an ongoing epidemic (until April 22 in the case of Wang et al., 2020), with different starting dates in different counties and two thirds of them without any deaths at this date. It follows that the epidemics could start in more populated counties with higher pollution and produce a higher mortality rate more quickly.

Cole et al. (2020) found a correlation between air pollution and the number of COVID-19 related deaths in the Netherlands. They do take into account some measure for proximity (e.g. Carnival events) which could affect the transmission, but this is clearly not the only pathway, as is demonstrated by recent new outbreaks.

The relationship between long-term exposure to NO_2 and COVID-19 fatalities in some European countries was also investigated by Ogen (2020), concluding that this pollutant may be one of the most important contributors to fatality caused by the COVID-19 virus. However, the author reached this conclusion by simply comparing column NO_2 concentrations from satellite data with the absolute number of deaths due to COVID-19 over Europe. The limitations of this study in terms of data quality and methodology have been highlighted by both Pisoni and van Dingenen (2020) and Chudnovsky (2020).

Another study (Conticini et al., 2020) concluded that “the high level of pollution in Northern Italy should be considered an additional co-factor of the high level of lethality recorded in that area”. However, these studies did not consider possible overlapping variables of various nature other than only environmental ones and the methodologies used in many of the papers discussed present many limitations. As a consequence, it is difficult to draw robust conclusions.

The mentioned studies have in common that they apply a relatively simple statistical regression model (in some cases including some proxy to account for the frequency of person-to-person contacts, in other cases not). It is important to realize that the number of interpersonal contacts is the overwhelming factor determining the number of cases (infections, hospital admissions, deaths), as illustrated by the impact of confinement measures (or their recent relaxation) on the trends of infections, hospital admissions and mortalities. Therefore, studies relating air pollution to the number of positive cases, deaths or mortality rate (deaths normalized by population) actually evaluate the relation between air pollution and the frequency of person-to-person contacts, which is a rather trivial relation (pollution is expected to be higher in areas with more population and socio-cultural activities), and does not prove (or disprove) any causal relationship. A further confounding element is the onset of the epidemic in different cities at different times. Most of the studies have been analysing data from the early phase of the epidemic when the dynamics were still fully developing. The number of positives may thus be higher in cities with the highest population (and population density), or where the epidemic started first and accumulated numbers are highest by the date the study sample stopped. A further complication is the efficiency of treatment strategies (e.g. performance of the health care system, the administering of blood thinners, etc.) which evolved quickly during the first phase of the epidemic, with the consequence that beneficial treatments and practices that had to be developed from scratch in the early affected regions could be implemented in the later affected regions right from the start.

In conclusion, the statistical approaches applied in those studies, based on linear regression techniques, even when they are accounting for population (density) as a possible confounding factor, or including another proxy for person-to-person contacts, cannot fully encompass the complexity of the seeding and spreading dynamics to allow extraction of the sole air pollution contribution.

The Italian Istituto Superiore di Sanitá confirms our considerations regarding the alleged role of air pollution in the spread of SARS-CoV-2 (citation translated from Italian ([7])): “the complexity of the phenomenon, together with the partial knowledge of some factors that may play or have played a role in the transmission and spread of SARS-CoV-2 infection, currently makes a direct association assessment between high levels of air pollution and the spread of the COVID-19 epidemic, or its role in amplifying the infection, very uncertain. It therefore seems necessary to plan and carry out studies characterized by adequate survey designs and protocols, and accompanied by analysis models that allow to understand the role played by the multiple variables involved in the phenomenon, also carrying out a comparative analysis on a larger scale, both European and international.”

3.3 Is exposure to air pollution increasing the fatality rate of COVID-19?

Air pollution causes an estimated 7 million premature deaths worldwide each year ([8]). It is known that long-term exposure to PM poses a significant health risk in the form of cardio-vascular and respiratory diseases (Chronic obstructive pulmonary disease (COPD), ischaemic heart disease, stroke, lower respiratory infections, lung cancer) and type 2 diabetes (Burnett et al., 2018). At the same time, hypertension, diabetes, COPD, cardiovascular disease, and cerebrovascular disease have been identified as significant risk factors for COVID-19 patients (Wang et al., 2020). It is therefore reasonable to assume a higher prevalence of those comorbidities in areas with high levels of air pollution, potentially creating conditions for a higher fatality rate amongst COVID-19 patients than regions with cleaner air. The main hypothesis discussed here is that exposure to air pollution may increase the severity of the consequences of the SARS-CoV-2 infection. This hypothesis may be based on observations of long-term pollution effects on chronical and acute diseases of respiratory systems (Anenberg et al., 2018; Cui et al., 2003). Currently, clinical and experimental studies have found relationships between pollution with SARS deaths (Cui et al., 2003), between tobacco smoking and MERS deaths (Halim et al., 2016) and between tobacco smokers and COVID-19 deaths (Cai et al., 2020). However, the link between long- and short-term exposure to air pollution and the severity of SARS-CoV-2 infections has still to be verified.

It is however likely that air pollution plays a role in the severity of the COVID-19 health impact. Indeed, a substantial fraction of comorbidities observed in deceased COVID-19 patients are diseases for which air pollution has been identified as a risk factor (Ischemic heart disease (IHD), Stroke, Lung cancer, Chronic Obstructive Pulmonary Disease (COPD), Type 2 Diabetes mellitus) (Burnett and Cohen, 2020). Italian statistics from the Istituto Superiore di Sanità ([9]) show that 96% of deceased patients had 1 or more comorbidity, and 61% 3 or more comorbidities. 33% of all observed comorbidities belong to the category affected by air pollution.

Table 1 gives for some countries, for the year 2017, the attributable fraction of air pollution in the total mortality for the relevant diseases (Global Burden of disease 2017). The highest occurring attributable

([7]) https://www.epicentro.iss.it/coronavirus/sars-cov-2-inquinamento-atmosferico

([8]) https://www.who.int/mediacentre/news/releases/2014/air-pollution/en/

([9]) https://www.epicentro.iss.it/en/coronavirus/bollettino/Report-COVID-2019_9_july_2020.pdf fraction is observed for COPD in China (round 30%), which means that 30% of the COPD mortalities in China can be attributed to air pollution. In Western countries, air pollution contributes for less than 11% to lung cancer and ischemic heart disease, and for less than 20% to diabetes mellitus and COPD. Based on these numbers, we can provide a rough upper limit estimate of the air pollution contribution. Assuming that air pollution attributes to 20% of its combined affected diseases, and 33% of the patients have one or more air pollution-related comorbidity, we obtain a conservative estimate of 6.6% air pollution contribution to COVID-19 mortality in Europe. Assuming the same share of comorbidities for China, the higher attributable fraction for air pollution leads to an estimate of 11% as an upper limit for the contribution of air pollution to COVID-19 mortalities.

Table 1. Air pollution (ambient PM2.5, indoor PM2.5, ozone) mortality attributable fraction (95% confidence interval) for diseases qualified as aggravating comorbidities in COVID-19 and for which air pollution has been established to be a risk factor.

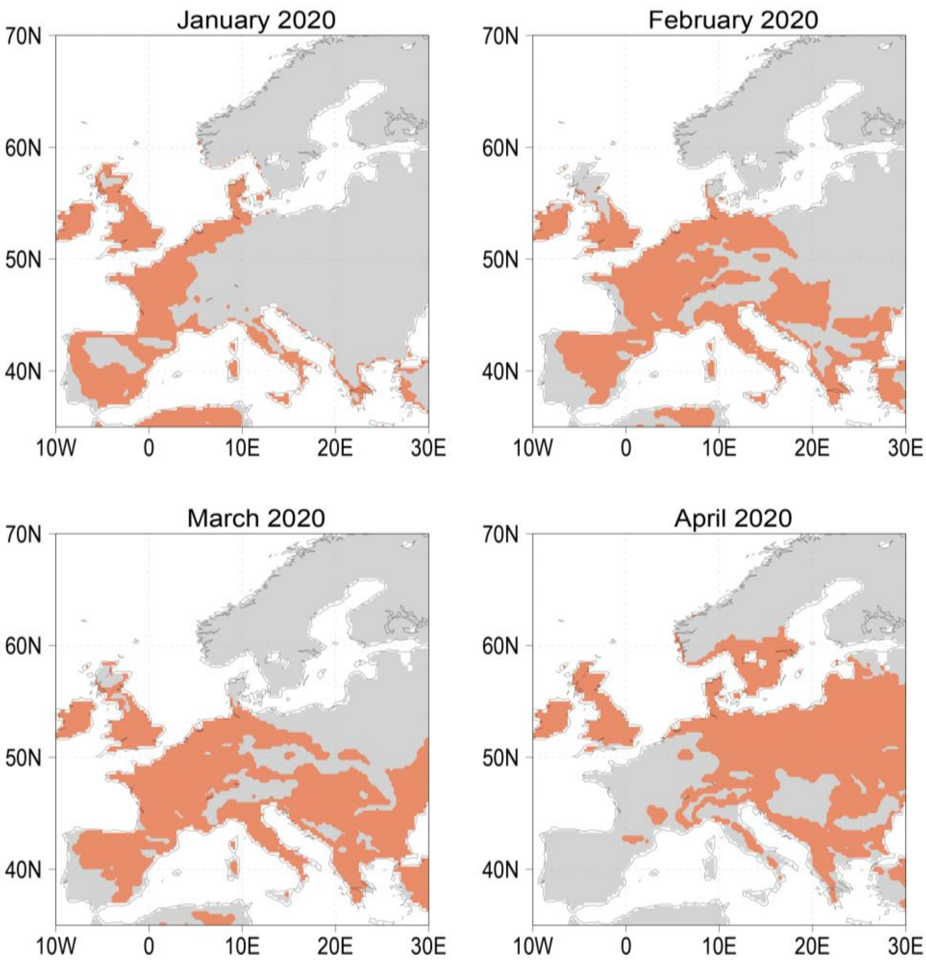
Country	Lung cancer (%)	T2 diabetes mellitus (%)	COPD (%)	IHD (%)	Stroke (%)
Italy	11.0 (4.8–18.2)	20.4 (9.5–27.2)	18.7 (7.9–30.0)	8.8 (6.4–11.3)	5.7 (3.8–7.8)
Belgium	9.0 (4.6–14.2)	19.9 (10.5–27.2)	16.6 (7.8–25.8)	8.6 (6.7–10.5)	5.6 (3.9–7.5)
Spain	6.9 (2.6 - 12.1)	18.3 (5.6–28.3)	13.9 (5.1–23.3)	7.4 (5.2–9.6)	4.7 (3.0–6.7)
USA	4.7 (1.9–8.5)	13.1 (3.9–23.7)	10.6 (4.04–19.1)	6.8 (5.1–8.5)	4.5 (3.1–6.0)
China	25.9 (19.2–32.6)	21.3 (14.3–24.6)	32.0 (20.9–41.0)	16.7 (14.7–18.6)	11.7 (9.4–14.0)
World	18.6 (13.2–24.0)	20.2 (13.7–24.1)	31.1 (21.3–39.8)	15.5 (13.8 -17.3)	11.0 (9.0–13.1)

Source: Global Burden of Disease Collaborative Network. Global Burden of Disease Study 2017 (GBD 2017) Results. Seattle, United States: Institute for Health Metrics and Evaluation (IHME), 2018. Available from https://vizhub.healthdata.org/gbd-compare/

4 Estimating environmental conditions for COVID-19 spread in Europe

The links between climate conditions and air pollution with the spread of COVID-19 are still highly uncertain (sections 2 and 3). Nevertheless, despite the main driver for the virus diffusion being close contact with infected persons or fomites, in this section we examine be the geographical and temporal distribution in Europe of the hypothetical favourable environmental conditions for the spread of the virus. Evaluation of the global distribution of temperature and humidity experienced in the major COVID-19 outbreaks in winter 2020 indicated that the outbreaks happened in relatively narrow ranges of temperatures and humidity (Sajadi et al. 2020, Bukhari and Jameel 2020). Figure 7 shows the distribution of the areas of Europe with temperatures between 3 and 15 °C and specific humidity between 3 and 6 g/kg in the first four months of 2020 that favour the development of outbreaks, according to Sajadi et al. (2020). Starting from February 2020, they cover all areas which experienced major outbreaks, although we must note that several regions with favourable conditions avoided or were less affected by the pandemic (e.g. Eastern Europe, the Balkans and Greece) in these months.

Figure 7. Areas with possibly favourable temperatures and humidity for spread of SARS-CoV2 estimated between January and April 2020.



If the favourable climatic condition hypothesis is true, then it would be useful to evaluate when these climatic conditions appear in Europe during the year, in order to anticipate possible future outbreaks. At the same geographical location, monthly mean temperatures and humidity typically vary between different years. Several processes contribute to this variation. Global warming slowly increases monthly mean temperatures, while the interannual differences in different European regions depend on the internal variability of the climate system. Therefore, in order to estimate possibly favourable environmental conditions for outbreaks over Europe, it is also necessary to account for both the slow change of temperatures by global warming and the interannually variable change of temperatures and humidity.

Figure 8. Percentage of years between 2000 and 2019 with possibly favourable temperatures and humidity [monthly averaged].

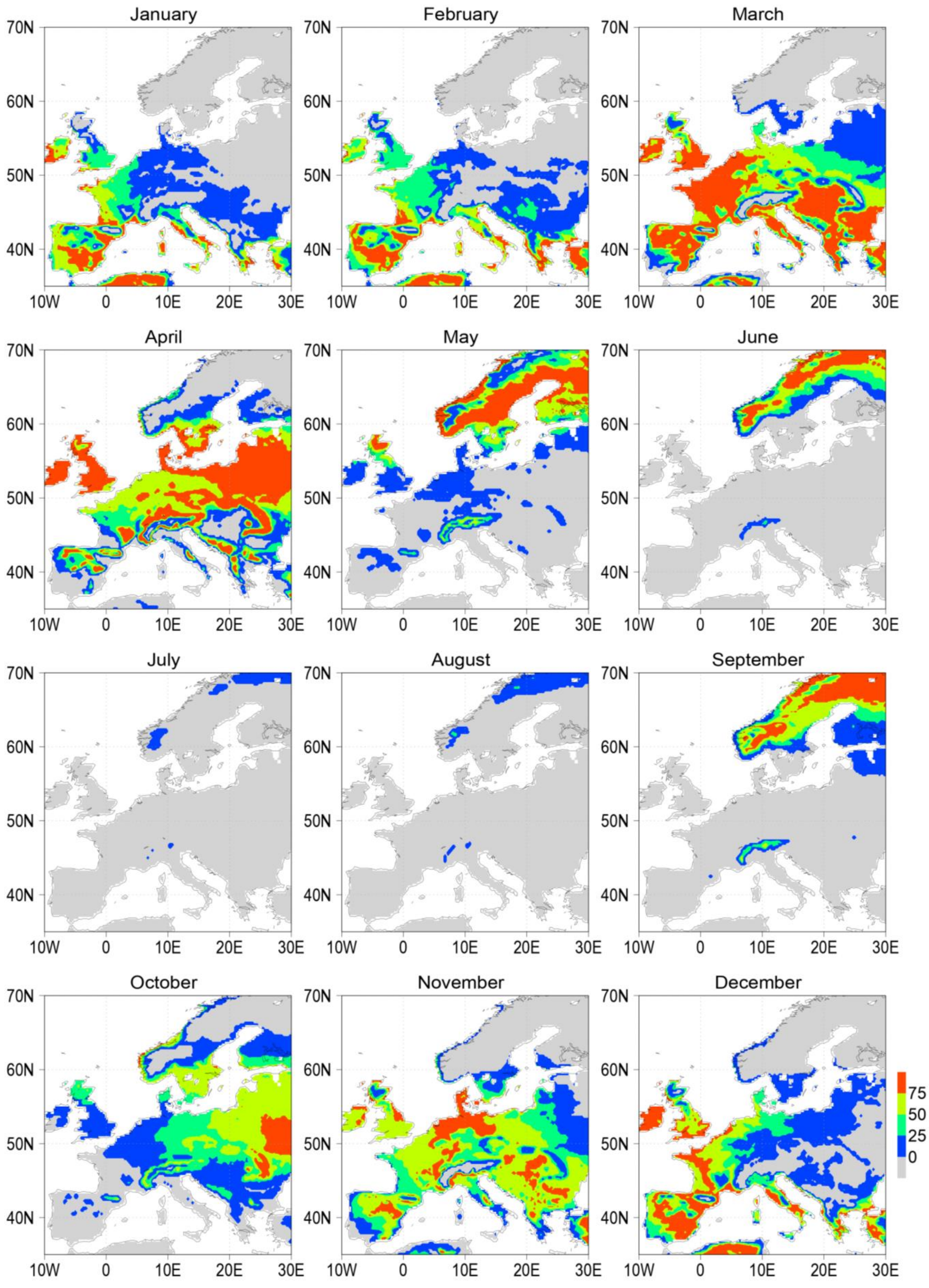


Figure 9. Average monthly PM2.5 concentrations (µg/m³) between 2015 and 2019 overlaid over areas where possibly favourable temperatures and humidity occurred at least once between 2000 and 2019. Data described in Annex 1.

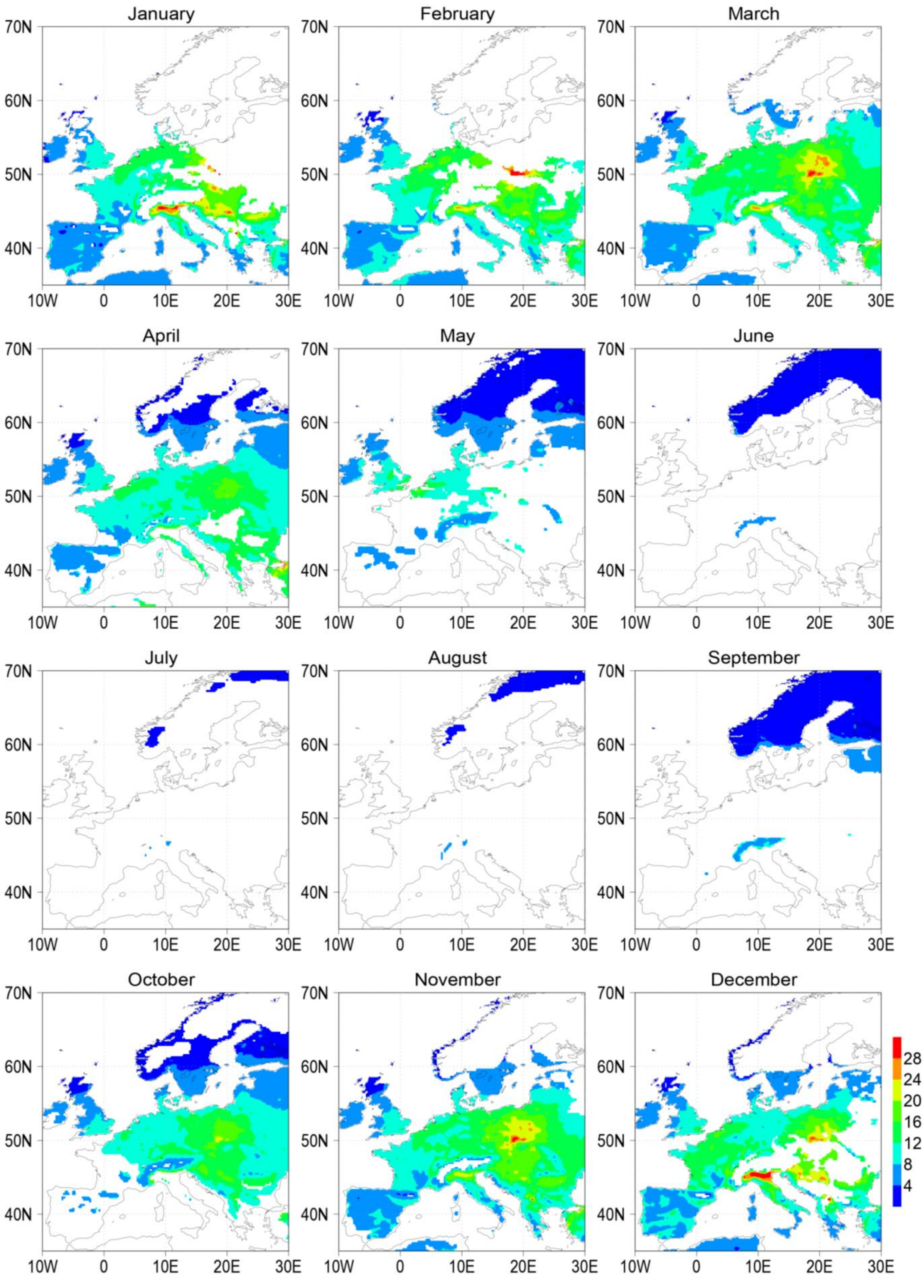
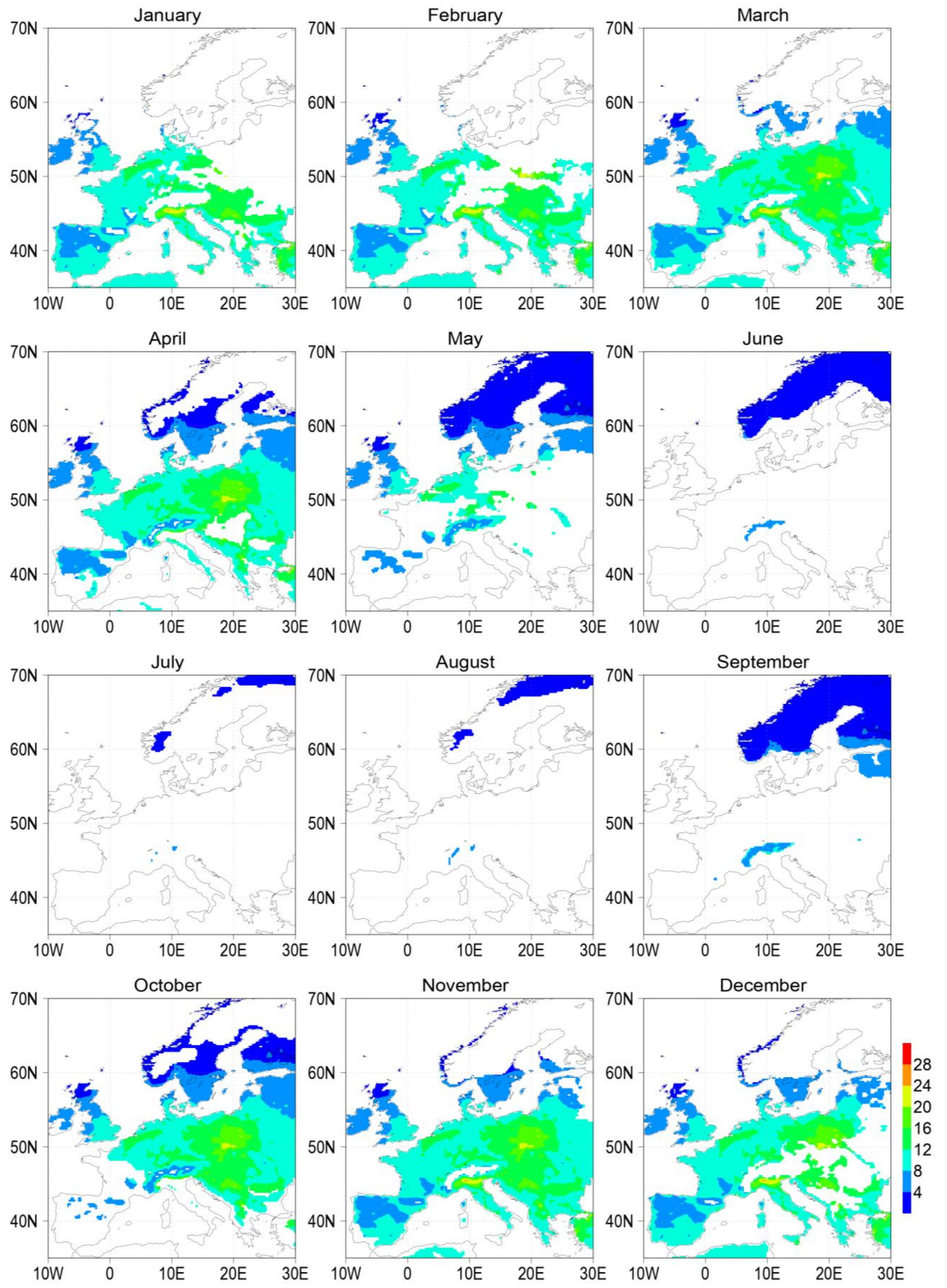


Figure 10. Average monthly NO_2 concentrations (μg/m^3) between 2015 and 2019 overlaid over areas where possibly favourable temperatures and humidity occurred at least once between 2000 and 2019.



The probability of the occurrence of potentially favourable climate conditions is estimated by counting the number of years from 2000 to 2019 when the mean monthly temperatures and humidity were within the values corresponding to major outbreaks in winter 2020 as shown in Figure 8. In order to account for the impact of global warming, the temperature trend is removed from the time series (Appendix 1). Figure 8 shows that there is a strong seasonal variability in the probability of occurrence of potentially favourable conditions in Europe. Areas with high probability cover most of Europe in February, March and April, while in May they are confined to Ireland, United Kingdom and Scandinavia. From June to September, only the northern parts and mountains in Scandinavia are characterised by potentially favourable temperatures and humidity. In October these areas cover United Kingdom, Sweden, Central and Eastern Europe and in November and December they spread over most of Europe.

We can also combine the favourable meteorological conditions with the hypothesis of an air pollution effect, Figure 9 shows a map of long-term averaged PM2.5 concentrations overlaid over areas where potentially favourable temperatures and humidity occurred at least once during the last 20 years. It shows that during several months from autumn to spring, areas characterised by high values of long-term fine particulate pollution in Northern Italy, Western, Central and Eastern Europe are located inside the area with the potentially most favourable climatic conditions for the outbreaks. A map of long-term averaged NO2 concentrations overlaid over areas with potentially favourable temperatures and humidity shows a similar distribution of regions with high pollution levels found in Northern Italy, Western, Central and Eastern Europe (Figure 10).

5 Conclusions

From the literature review covering a wide range of possible environmental impacts and methodologies used in the studies, early COVID-19 spread, mainly driven by close contact with infected persons and fomites, was statistically found to be linked to ambient outdoor solar radiation, temperatures and air humidity indicating direct or indirect relationship (in that increased solar radiation and temperatures also influence behaviour). A direct link is supported by laboratory studies that show that the virus survival rate on the surface and in aerosols is reduced by increasing solar radiation, temperature and humidity. Most of the statistical studies show that increasing sun radiation, temperature and humidity should reduce the spreading of the pandemic in the middle latitudes, but several studies find that the epidemic intensity may only be attenuated and does not disappear in summer in the middle latitudes and in areas with sub-tropical and tropical climate.

The role of air pollution in the transmission of the SARS-CoV-2 virus by aerosols is still under debate. Observations and laboratory experiments indicate that COVID-19 virus could be transmitted by aerosols in specific indoor conditions, but the relative importance of aerosols compared to droplets and fomites is not yet established. So far there are no observational or laboratory findings for outdoor conditions influenced by different levels of atmospheric pollution. Our conclusion from a simple aerosol dynamic modelling exercise is that in outdoor conditions, high ambient pollution levels produce similar atmospheric lifetime and respiratory track deposition efficiency of virus-laden particles, compared to clean continental conditions.

Indoor aerosol concentrations are strongly dependent on the availability and operation of ventilation and filtering installations. However, in the absence of details of actual ventilation and/or filtering effects, it is reasonable to assume that, different indoor ambient PM conditions produce similar airborne virus particle properties, either in terms of lifetime or inhalation efficiency.

So far studies statistically relating air pollution to the number of positive cases, deaths or mortality rate do not capture the complexity of the seeding and spreading dynamics sufficiently to allow the identification of any actual air pollution contribution. For this to be possible, further more comprehensive studies will be needed as suggested by the Italian Istituto Superiore di Sanitá ([10]).

In order to better understand of the relationship between air pollution and the mortality rate due to COVID-19, we estimated the maximum share of COVID-19 deaths with comorbidities attributable to long-term air pollution impacts by combining previously determined air-pollution morbidities, with Italian statistics on comorbidities in COVID-19 victims. This gives an upper bound to the possible impact of long-term air pollution exposure on the mortality rate from the COVID-19 pandemics of 6.6% in Europe and 11% in China.

In the report we further show monthly European maps of the probability of the occurrence of the environmental conditions that the current studies suggest potentially favour COVID-19, either directly or indirectly. Maps show that potentially favourable air pollution and climate conditions for COVID-19 may be found over large areas of Europe in Autumn and Winter.

The overview of available literature indicates that the relationship between environmental factors and the COVID-19 pandemic has not been fully established. It is, therefore, necessary to further investigate their relationship by developing uniform and internationally agreed protocols on the pandemic data collection and involving as much as possible multidisciplinary research teams combining statistical studies with laboratory and field experiments. The longer time series of data should further improve the robustness of the analysis and provide information on different stages of the pandemics evolution. If a reliable mathematical relationship can be shown to exist, it can be introduced in epidemiological models for improved monitoring and predicting the pandemics.

([10]) "It therefore seems necessary to plan and carry out studies characterised by adequate survey designs and protocols, and accompanied by analysis models that allow to understand the role played by the multiple variables involved in the phenomenon, also carrying out a comparative analysis on a larger scale, both European and international."

References

ACTRIS statement, Propagation du SARS-CoV-2 et Particules Atmosphériques, 2020, available at : https://www.actris.fr/propagationdusars-cov-2etparticulesatmospheriques/

Aldridge R. W., et al., Seasonality and immunity to laboratory-confirmed seasonal coronaviruses (HCoV-NL63, HCoV-OC43, and HCoV-229E): results from the Flu Watch cohort study. *Wellcome Open Res.*, 5:52, 2020, doi:10.12688/wellcomeopenres.15812.1

Anenberg, S. C., et al., Estimates of the global burden of ambient PM2.5, ozone, and NO2 on asthma incidence and emergency room visits. *Environ. Health. Perspect.* 126(10):107004, 2018, doi:10.1289/EHP3766.

Baker, R. E., Yang, W., Vecchi, G. A., Metcalf, C. J. E., and B. T. Grenfell, Susceptible supply limits the role of climate in the COVID-19 pandemic, *Science*, 2020, doi:10.1126/science.abc2535

Benedetti, A., et al., Aerosol analysis and forecast in the ECMWF Integrated Forecast System. Part II : Data assimilation, *J. Geophys. Res.*, 114, D13205, 2009, doi:10.1029/2008JD011115.

Benedetti, F., Pachetti, M. , Marini, B., Ippodrino, R., Gallo, R. C., Ciccozzi, M., and D. Zella Inverse correlation between average monthly high temperatures and COVID-19-related death rates in different geographical areas. Submitted to Journal of Translational Medicine, (2020), doi:10.21203/rs.3.rs-29039/v1

Biryukov, J., et al. Increasing temperature and relative humidity accelerates inactivation of SARS-CoV-2 on surfaces. *mSphere,* 5:e00441-20, 2020, doi:10.1128/mSphere.00441-20.

Booth, T. F., et al. Detection of airborne severe acute respiratory syndrome (SARS) coronavirus and environmental contamination in SARS outbreak units, *Journal of Infectious Diseases*, 191 (9), pp. 1472-1477, 2005, doi:10.1086/429634

Bukhari, Q., and Y. Jameel, Will Coronavirus Pandemic Diminish by Summer? 2020, doi:10.2139/ssrn.3556998.

Burnett, R., et al. Global estimates of mortality associated with longterm exposure to outdoor fine particulate matter, *Proceedings of the National Academy of Sciences of the United States of America*, 115 (38), pp. 9592-9597, 2018, doi:10.1073/pnas.1803222115

Burnett, R. and Cohen, A., Relative risk functions for estimating excess mortality attributable to outdoor PM2.5 air pollution: Evolution and state-of-the-art, *Atmosphere*, 11(6),589, 2020.

Cai, G., Cui, X., Zhu, X. and J. A. Zhou Hint on the COVID-19 Risk: Population Disparities in Gene Expression of Three Receptors of SARS-CoV. 2020, doi: 10.20944/preprints202002.0408.v1

Casanova, L.M., Jeon S., Rutala, W.A., Weber, D.J., and M. D. Sobsey, Effects of air temperature and relative humidity on coronavirus survival on surfaces. *Appl. Environ. Microbiol.*,76(9), 2712-7, 2010.

Chan, K. H., et al. The Effects of Temperature and Relative Humidity on the Viability of the SARS Coronavirus. *Advances in Virology*, 2011, 734690, 2011, doi:10.1155/2011/734690.

Chudnovsky, A., Letter to editor regarding Ogen Y 2020 paper: "Assessing nitrogen dioxide (NO2) levels as a contributing factor to coronavirus (COVID-19) fatality", *Science of The Total Environment*, 139236, 2020.

Coccia, M., Factors determining the diffusion of COVID-19 and suggested strategy to prevent future accelerated viral infectivity similar to COVID. *Science of the Total Environment*, 727, 138704, 2020, doi: 10.1016/j.scitotenv.2020.138704.

Coker, E., et al. The Effects of Air Pollution on COVID-19 Related Mortality in Northern Italy, Nota di Lavoro 6.2020, Milano, Italy: Fondazione Eni Enrico Mattei, 2020.

Cole, M.A., Ozgen, C., Strobl, E., Air Pollution Exposure and COVID-19, IZA DP No. 13367, 2020, Available at: http://ftp.iza.org/dp13367.pdf

Conticini, C., Frediani, B., and D. Caro, Can atmospheric pollution be considered a co-factor in extremely high level of SARS-CoV-2 lethality in Northern Italy?, *Environmental Pollution*, 261, 114465, 2020.

Cui, Y., et al. Air pollution and case fatality of SARS in the People's Republic of China: an ecologic study. *Environ. Health,* 2, 15, 2003, doi: 10.1186/1476-069X-2-15

Fattorini, D., and F. Regoli, Role of the chronic air pollution levels in the COVID-19 outbreak risk in Italy, Environmental Pollution, 264, 114732, 2020.

Ficetola, F., and D. Rubolini, Climate affects global patterns of COVID-19 early outbreak dynamics, 2020, doi: 10.1101/2020.03.23.20040501

Fragaszy, E. B., et al. Cohort Profile: The Flu Watch Study. *Int. J. Epidemiol.*, 46(2), e18, 2017, doi: 10.1093/ije/dyv370.

Gaunt, E. R., Hardie, A., Claas, E. C. J., Simmonds P., and K. E. Templeton, Epidemiology and Clinical Presentations of the Four Human Coronaviruses 229E, HKU1, NL63, and OC43 Detected over 3 Years Using a Novel Multiplex Real-Time PCR Method. *J. Clin. Microbiol.*, 48(8), 2940–2947, 2010, doi: 10.1128/JCM.00636-10

Gunthe, S. S., Swain, B., Patra, S. S., and A. Amte, 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. of Public Health: From Theory to Practice*, 2020, doi: https://doi.org/10.1007/s10389-020-01279-y

Halim, A. A., et al., Clinical characteristics and outcome of ICU admitted MERS corona virus infected patients, Egyptian Journal of Chest Diseases and Tuberculosis, 65(1), 85-87, 2016, doi: 10.1016/j.ejcdt.2015.11.011

Hersbach, H., Bell, B., Berrisford, P., Horanyi, A., Munoz-Sabater, J., Nicolas, J., Radu, R., Schepers, D., Simmons, A., Soci, C., and D. DeeGlobal reanalysis: goodbye ERA-Interim, hello ERA5. ECMWF Newsletter, 159, 17–24, , 2019, Available at: https://www.ecmwf.int/node/19027.

IAS statement, Informativa sulla relazione tra inquinamento atmosferico e diffusione del COVID-19, 2020 Available at: http://www.iasaerosol.it/attachments/article/96/Nota_Informativa_IAS.pdf

Liu, Y., et al. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. *Nature*, 582, 557–560, 2020, doi: 10.1038/s41586-020-2271-3

Kampf, G., et al., Persistence of coronaviruses on inanimate surfaces and their inactivation with biocidal agents. *Journal of Hospital Infection*, 104, 246 – 251, 2020, doi:10.1016/j.jhin.2020.01.022

Kifer, D., et al., Effects of environmental factors on severity and mortality of COVID-19, 2020, doi: 10.1101/2020.07.11.20147157

Kudo, E., Song, E., Yockey, L. J., Rakib, T., Wong, P. W., Homer, R. J., and A. Iwasaki, Low ambient humidity impairs barrier function and innate resistance against influenza infection. *Proceedings of the National Academy of Sciences,* 116(22), 10905–10910, 2019doi: 10.1073/pnas.1902840116

Kumar, S., Will COVID-19 pandemic diminish by summer-monsoon in India? Lesson from the first lockdown. 2020, doi: 10.1101/2020.04.22.20075499

Livadiotis, G., Statistical analysis of the impact of environmental temperature on the exponential growth rate of cases infected by COVID-19, 2020, doi: 10.1101/2020.04.21.20072405

Lowen, A. C., Mubareka, S., Steel, J., and P. Palese Influenza virus transmission is dependent on relative humidity and temperature. *PLoS Pathog.*, 3(10), e151, 2007, doi:10.1371/journal.ppat.0030151

Ma, Y. et al., Effects of temperature variation and humidity on the death of COVID-19 in Wuhan, China. *Science of The Total Environment*, 724, 138226, 2020, doi: 10.1016/j.scitotenv.2020.138226

Meier, R., et al., Differences in indoor versus outdoor concentrations of ultrafine particles, PM2.5, PM absorbance and NO2 in Swiss homes, *Journal of Exposure Science and Environmental Epidemiology*, 25 (5), pp. 499-505, 2020, doi: 10.1038/jes.2015.3

Merow, C., and M. C. Urban, Seasonality and uncertainty in COVID-19 growth rates, 2020, doi: 10.1101/2020.04.19.20071951

Morales, K. F., Paget, J., and P. Spreeuwenberg, Possible explanations for why some countries were harder hit by the pandemic influenza virus in 2009 – a global mortality impact modeling study. *BMC Infectious Diseases*, 17, 642, 2017, doi: 10.1186/s12879-017-2730-0

Morawska, L., Droplet fate in indoor environments, or can we prevent the spread of infection?, *Indoor Air*, 16 (5), pp. 335-347, 2006, doi: 10.1111/j.1600-0668.2006.00432.x

Morawska, L., and D. Milton, It is Time to Address Airborne Transmission of COVID-19. *Clin. Infect. Dis.*, 2020, doi: 10.1093/cid/ciaa939.

Moriyama, M., Hugentobler, W. J., and A. Iwasakiet, Seasonality of Respiratory Viral Infectionsal, *Annu. Rev. Virol.*, 7:2.1–2.19, 2020, doi: 10.1146/annurev-virology-012420-022445

Nicastro, F, et al., Modulation of COVID-19 Epidemiology by UV-B and -A Photons from the Sun., 2020, doi: 10.1101/2020.06.03.20121392

Notari, A., Temperature dependence of COVID-19 transmission, 2020, doi: 10.1101/2020.03.26.20044529

Ogen, Y., Assessing nitrogen dioxide (NO2) levels as a contributing factor to coronavirus (COVID-19) fatality. *Science of The Total Environment*, 726, 138605, 2020, doi: 10.1016/j.scitotenv.2020.138605

Otter, J.A., et al. Transmission of SARS and MERS coronaviruses and influenza virus in healthcare settings: the possible role of dry surface contamination. *J. Hosp. Infect.*, 92(3), 235-50, 2016.

Pisoni, E., and R. Van Dingenen, Comment to the paper “Assessing nitrogen dioxide (NO2) levels as a contributing factor to coronavirus (COVID-19) fatality”, by Ogen, 2020, *Science of The Total Environment*, 139853, 2020.

Prata, D. N., Rodrigues, W., and P. H. Bermejo, Temperature significantly changes COVID-19 transmission in (sub)tropical cities of Brazil. *Sci. Total Environ.,* 729, 138862, 2020, doi: 10.1016/j.scitotenv.2020.138862

Qi, H., et al., COVID-19 transmission in Mainland China is associated with temperature and humidity: A time-series analysis, *Science of the Total Environment*, 728, 138778, 2020, doi: 10.1016/j.scitotenv.2020.138778

Ratnesar-Shumate, S., et al., Simulated Sunlight Rapidly Inactivates SARS-CoV-2 on Surfaces. *The Journal of Infectious Diseases*, jiaa274, 2020, doi: https://doi.org/10.1093/infdis/jiaa274

Rissler, J., Nicklasson, H., Gudmundsson, A., Wollmer, P., Swietlicki, E. and Löndahl, J. A Set-up for Respiratory Tract Deposition Efficiency Measurements (15–5000 nm) and First Results for a Group of Children and Adults. *Aerosol Air Qual. Res*. 17: 1244-1255, 2017, doi: 10.4209/aaqr.2016.09.0425

Sajadi, M. M., Habibzadeh, P., Vintzileos, A., Shokouhi, S., Miralles-Wilhelm, F., and A. Amoroso, Temperature, humidity, and latitude analysis to predict potential spread and seasonality for COVID-19, *JAMA Network Open*, 3(6), e2011834, 2020, 2020, doi:10.1001/jamanetworkopen.2020.11834

Santarpia, J.L. et al., Aerosol and Surface Transmission Potential of SARS-CoV-2, 2020, https://doi.org/10.1101/2020.03.23.20039446.

Schuit, M., et al., Airborne SARS-CoV-2 is Rapidly Inactivated by Simulated Sunlight, *The Journal of Infectious Diseases*, jiaa334, 2020, doi:10.1093/infdis/jiaa334, 2020.

Setti, L., et al, SARS-Cov-2 RNA Found on Particulate Matter of Bergamo in Northern Italy: First Preliminary Evidence. *Environmental Research*, 188, 109754, 2020, doi: 10.1016/j.envres.2020.109754

Tellier, R., Li, Y., Cowling, B. J., and. Tang J. W., Recognition of aerosol transmission of infectious agents: a commentary, *BMC Infectious Diseases*, 19:101, 2019, doi: 10.1186/s12879-019-3707-y

Triplett, M., Evidence that higher temperatures are associated with lower incidence of COVID-19 in pandemic state, cumulative cases reported up to March 27, 2020, doi: https://doi.org/10.1101/2020.04.02.20051524 (no peer review)

van Doremalen, N., et al., Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1, *New England Journal of Medicine*, 2020, 10.1056/NEJMc2004973.

Wang, J., et al., High Temperature and High Humidity Reduce the Transmission of COVID-19, 2020, doi: 10.2139/ssrn.3551767

Wu, X., Nethery, R. C., Sabath, B. M., Braun, D., and F. Dominici, Exposure to air pollution and COVID-19 mortality in the United States: A nationwide cross-sectional study, 2020, doi: 10.1101/2020.04.05.20054502

Xiao, S., Li, Y., Wong T.-W., and D. S. C. Hui, Role of fomites in SARS transmission during the largest hospital outbreak in Hong Kong. *PLoS ONE*, 12(7), e0181558, 2017, doi: 10.1371/journal.pone.0181558

Yu, I. T.-S., Qiu, H., Tse, L. A., and T. W. Wong Severe acute respiratory syndrome beyond amoy gardens: Completing the incomplete legacy, *Clinical Infectious Diseases*, 58 (5), pp. 683-686, 2014, doi: 10.1093/cid/cit797

Zaki, A. M., van Boheemen, S., Bestebroer, T.M., Osterhaus, A. D., and R. A. Fouchier, Isolation of a novel coronavirus from a man with pneumonia in Saudi Arabia. *N. Engl. J. Med.*, 367, 1814–20, 2012.

Zhong, N.S., et al., Epidemiology and cause of severe acute respiratory syndrome (SARS) in Guangdong, People's Republic of China, in February, 2003, *Lancet*, 362 (9393), pp. 1353-1358, 2003, doi: 10.1016/s0140-6736(03)14630-2.

Zhu, Y., Xie, J., Huang F., and L. Cao, Association between short-term exposure to air pollution and COVID-19 infection: Evidence from China. *Science of the Total Environment*, 727, 138704, 2020, doi: 10.1016/j.scitotenv.2020.138704

List of abbreviations and definitions

ACTRIS	European Research Infrastructure for the observation of Aerosol, Clouds and Trace Gases
CAMS	Copernicus Atmospheric Monitoring Service
COPD	Chronic Obstructive Pulmonary Disease
COVID-19	Coronavirus Disease -2019
ECMWF	European Centre for Medium-Range Weather Forecasts
EEA	European Environmental Agency
ERA5	Fifth generation ECMWF atmospheric reanalysis
EU	European Union
FEEM	Fondazione Eni Enrico Mattei
GBD	Global Burden of Disease
IAS	Italian Aerosol Society
MERS-CoV	Middle East Respiratory Syndrome – Corona Virus
NCD	Non-communicable Disease
nm	nanometer
NO2	Nitrogen dioxide
PM	Particulate Matter
PM2.5	Particulate Matter having diameter below 2.5 micrometers
PM10	Particulate Matter having diameter below 10 micrometers
R0	Basic reproduction number
Rt	Reproduction number
SARS-CoV-1	Severe Acute Respiratory Syndrome – Corona Virus – 1
SARS-CoV-2	Severe Acute Respiratory Syndrome – Corona Virus – 2
SO2	Sulfur dioxide
USA	United States of America
UV	Ultraviolet
WHO	World Health Organization
μg	microgram
μm	micrometer
°C	degree Celsius

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Annexes

Annex 1. Meteorological conditions and air pollution data

Maps are based on meteorological variables and air pollution data from the Copernicus programme Climate Change Service. Climate data originate from the ERA5 reanalysis available at the horizontal resolution of 0.25 latitude/longitude degrees (Hersbach et al., 2019) in which in-situ and satellite observations are merged with model estimates by using a statistically optimal algorithm. Over highly populated areas with a large number of in situ observations like Europe, near-surface temperature and humidity fields are strongly influenced by observations. The area representing the most favourable climatic conditions is defined by temperatures between 3 and 11 0C and specific humidity between 3 and 5 g/kg. These values are estimated by Sajadi et al. (2020) and may represent possible favourable conditions for the epidemic. Other studies proposed slightly different favourable conditions, but it was found that the use of conditions proposed in some other studies did not produce qualitatively different maps (not shown).

Monthly averages of meteorological variables are obtained by averaging from 6 hourly fields from ERA5 starting in January 2000 and ending in December 2019. In order to account for the slow increase of temperatures due to global warming, monthly mean temperatures are detrended by adding the liner trend to values in years preceding 2019. Air humidity depends on temperature by the Clausius-Clapeyron relation, but here it is assumed that the temperature change due to global warming is small and does not impact humidity. In each point the percentage of occurrence of favourable conditions is then estimated form the percentage of years between 2000 and 2019 with favourable climatic conditions.

Concentrations of PM2.5 shown in Figure 2 are obtained from the Copernicus programme Atmospheric Monitoring Service global analysis by the CAMS model (Benedetti et al. 2009) available at horizontal resolution of 0.40. Long-term pollution in Europe (Figures 6 and 7) is estimated by near-surface PM2.5 and NO2 concentrations obtained as averages between 2015 and 2019 by the ENSEMBLE reanalysis from the Copernicus programme Atmospheric Monitoring Service available at horizontal resolution of 0.10. The reanalysis uses historical observations and combines them with air-quality models in order to produce statistically optimal estimates of air pollution fields. The ENSEMBLE reanalysis further combines the reanalysis made separately by several models.

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