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Perspective

Use of Weather Variables in SARS-CoV-2 Transmission Studies

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A B S T R A C T

The persistence and intensity of the current severe acute respiratory syndrome-coronavirus-2 (SARS-CoV-2) pandemic, and the advanced planning required to balance competing concerns of saving lives and avoiding economic collapse, may depend in part on whether the virus is sensitive to seasonal changes in environmental variables, such as temperature and humidity. Although multiple studies have sought to address possible effects of these variables on SARS–CoV-2 transmission, results of these studies have been varied. It is possible that at least some of the differing results are due to insufficient understanding of atmospheric science, including certain physical and chemical principles underlying selected meteorological variables, and how global seasons differ between tropical and temperate zones. The objective of this brief perspective is to provide information that may help explain some of the differing results of studies regarding the influence of environmental variables on transmissibility of SARS-CoV-2. This information may promote better variable selection and results interpretation in future studies of coronavirus disease 2019 (COVID-19) and other infectious diseases.

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Introduction

Severe acute respiratory syndrome-coronavirus-2 (SARS-CoV-2) is a novel virus that causes an acute highly contagious infection, which may result in death. Coronavirus disease 2019 (COVID-19) appeared in December 2019 in Wuhan, China, in patients exposed via that city's wet animal market (Xu et al., 2020). Human-to-human transmission was subsequently described and increased rapidly so that, by February 2020, there were over 77,000 laboratory confirmed infections reported globally (Shen et al., 2020). The World Health Organization (WHO) declared the situation a pandemic on March 11, 2020 (World Health Organization (WHO, 2020). COVID-19 was initially thought to be a respiratory illness, but it later became apparent that the disease was more than that. Like SARS-CoV-1, SARS-CoV-2 is acquired primarily via respiratory droplets. Unlike SARS-CoV-1, evidence now suggests that SARS-CoV-2 is vasculotropic, with respiratory symptoms due to effects on pulmonary vasculature resulting in poor gas exchange (Poor et al., 2020). SARS-CoV-2 has affinity for blood vessel endothelial cells in many anatomic locations, which could explain autopsy findings (Ackermann et al., 2020) and especially the variety of non-pulmonary findings (e.g., Pain et al., 2020).

Each SARS-CoV-2 virus particle has a diameter of 50–200 nm (Xu et al., 2020), includes a surrounding lipid envelope, and contains single-stranded positive-sense RNA. This envelope is a cell membrane hijacked from a previously infected cell, so its molecules are arranged with their hydrophobic ends on the internal surface and their hydrophilic ends on the external surface, making the virion soluble in liquid water. The virus adds club-shaped glycoprotein projections to this envelope to give it a characteristic crown-like (corona) appearance (Tyrrell and Myint, 1996). The most closely related human coronavirus to SARS-CoV-2 is SARS-CoV-1 (Wu et al., 2020). In an extensive review of the 2003 SARS-CoV-1 outbreak, Cheng et al. (2007) noted that genetic recombination in coronaviruses is common and that the presence of a large bat reservoir along with a local human culture of eating exotic animals that are kept alive and comingled until the point of sale is "a time bomb."

In lieu of a vaccine, perhaps the most effective public health measures are the so-called non-pharmaceutical interventions (NPI), which include self-isolation, social distancing, masks, closing non-essential businesses and schools, and quarantine. NPI have been implemented in many countries and regions to limit the spread of the disease (Flaxman et al., 2020). Adherence to NPI has proven very successful in reducing virus transmission (Markel et al., 2007; Ferguson et al., 2020). Because of economic impacts of NPI, governments are eager to know when and how to plan for a safe phased reduction in NPI. The duration of time that the current pandemic persists, and the advanced planning required to balance

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competing concerns (e.g., saving lives and avoiding economic collapse) (Anderson et al., 2020), depend in part on whether the virus is sensitive to seasonal changes. There has been much speculation as to whether higher temperatures arriving with the boreal summer might help flatten the epidemic curve. If so, specific regions may be impacted differently according to their respective seasonal climate changes. Furthermore, knowledge of COVID-19 seasonality would help prepare for the timing and degree of any resurgence of the epidemic during cooler months (Kissler et al., 2020).

Discussion

Exhaled viruses are encapsulated by liquid droplets, which then evaporate or grow based upon the water vapor content of the surrounding air, with the rate of evaporation increasing with increasing temperature (Nadykto et al., 2003). Droplet evaporation also depends on the velocity and dynamics of the exhaled cloud (Bourouiba, 2020). Droplets that grow large enough fall to the ground or on fomites, while those with diameter <10 μm can remain airborne for hours and are easily inhaled deeply into the respiratory tract (Blachere et al., 2009). Lower ambient temperature and higher atmospheric water vapor content tend to promote droplet growth, while higher temperature and lower water vapor content promote droplet evaporation.

When atmospheric temperatures fall below freezing, the liquid droplet changes phase to become an ice crystal. Because the liquid water surface vapor pressure is greater than the ice surface vapor pressure, liquid droplets shrink and ice crystals grow as water molecules escape more easily from liquid droplets than from ice crystals. The virion's lipid envelope becomes a gel at its freezing point, which varies with its chemical composition, but is at a lower temperature than that for water (Alberts et al., 2002). Jaakkola et al. (2014) found that influenza viruses, which also have a lipid envelope, remain infectious at temperatures near and below freezing. Florek et al. (2014) demonstrated stability of infectious human coronavirus NL63 (the main cause of croup) at temperatures around freezing. Temperature and humidity are the most common weather variables examined in studies of disease seasonality. Therefore, a detailed understanding of these variables is warranted.

There are a variety of measures of atmospheric water vapor content (e.g., Rogers and Yau, 1996). Relative humidity is perhaps the most common measure. However, relative humidity (RH) is not, as often assumed, relative to air's maximum capacity to hold water vapor (e.g., Bohren and Albrecht, 1998). Indeed, humid air is less dense than dry air occupying the same volume (e.g., Daidzic, 2019). If you took a clean smooth container of pure water vapor, you could create a relative humidity of over 300% before you would get condensation because air is mostly void. This phenomenon is used in studies of homogeneous nucleation (e.g., Hoppel and Dinger, 1973; Hamill and Toon, 1991; Hesson, 2012), and is also cited in college meteorology textbooks (e.g., Rogers and Yau, 1996). Most gases are indefinitely soluble in other gases (Ostwald, 1891). In an equilibrium state, the amount of vapor above a liquid depends almost entirely on the temperature of the liquid. John Dalton concluded that the vapor pressure of water in air is independent of the presence of dry gases in the air (Cardwell, 1968; Dalton, 1805).

Relative humidity is the ratio of the water vapor pressure in the atmosphere to the equilibrium vapor pressure over a hypothetical flat surface of pure water. The vapor pressure over a flat surface is different from that over water droplets in aerosols and clouds because the droplet curvature has an important effect (Kelvin effect) (e.g., Rogers and Yau, 1996). Equilibrium vapor pressure

means that the rates of condensation and evaporation are equal at the surface of pure water, so there is no net decrease or increase in the water vapor in the air above it. This equilibrium is dependent on temperature as described by the Clausius–Clapeyron equation (e.g., Rogers and Yau, 1996). This dependence means that relative humidity is not an absolute measure of humidity because it depends upon temperature. It is thus incorrect to assume that temperature and relative humidity are independent variables. Absolute humidity, specific humidity, and mixing ratio are alternative humidity measures that remove this temperature dependency (e.g., Rogers and Yau, 1996). Absolute humidity is water vapor density, defined as the ratio of the mass of water vapor present to the volume occupied by the moist air. Specific humidity is defined as the mass of water vapor per unit mass of moist air. Mixing ratio is defined as mass of water vapor per unit mass of dry air. However, there is an easily accessible direct water vapor measurement called *dewpoint*. Although dewpoint has a nonlinear relationship with mixing ratio and absolute/specific humidity, it is often used because it is measured directly. Dewpoint is more useful than relative humidity to meteorologists for predicting precipitation. Even if relative humidity reaches 100%, it does not mean precipitation will occur (e.g., Pruppacher and Klett, 2010). Therefore, dewpoint is commonly included in weather data and no further calculations are needed to obtain it. The value of dewpoint can be illustrated as follows. An atmosphere with both a temperature and dew point of 2 °C would have a relative humidity of 100%. If the temperature and dew point instead were 20 °C and 13 °C, respectively, the relative humidity would drop to 64%, even though there is actually a higher water vapor concentration in the air. Therefore, dewpoint is preferable to relative humidity because it is an absolute measure of water vapor content, is independent of temperature, and is readily available in weather data.

While there are papers (e.g., Graham, 2003) describing statistical pitfalls associated with assuming covariates are independent when they are not, a simple example may be helpful. Assume that the results of a regression analysis using daily temperature (T) and daily RH were described by the following equation:

Log(daily COVID cases) = Coefficient1 + Coefficient2*T + Coefficient3*RH

One would then interpret the atmospheric water vapor contribution to be described by Coefficient3. However, this assumption is not valid because RH is a function of temperature T. Therefore, Coefficient3 does not describe atmospheric water vapor impacts. In contrast, assume that the results of this analysis were described by the following equation:

Log(daily COVID cases) = Coefficient1 + Coefficient2*T + Coefficient3*Td

where Td is the dewpoint temperature. Now, Coefficient3 describes the contribution of water vapor content alone.

Evaporation is a phase change from liquid to vapor, while condensation is a phase change from vapor to liquid. In situations where evaporation dominates over condensation, evaporation removes heat from the air and cools the ambient temperature. This is evaporative cooling, which is most noticeable as the temperature drop immediately after a rain shower, perhaps contributing to tropical transmissibility of aerosolized viruses by reducing the temperature (Moura et al., 2009).

The Earth can be divided into three major climate zones (polar, temperate, and tropical) based upon sun angle, although the Köppen classification specifies many more based on vegetation (Kottek et al., 2006). The tropical zone is defined by where the sun can be directly overhead, which is between about 23.4 S and 23.4 N

latitude. Tropical climates usually occur within these latitudes, so these regions have at most two seasons (wet and dry) instead of the four typical of temperate zones. In tropical regions, weather changes are better correlated with dewpoint than temperature (Atkinson, 1991). Note that the dewpoints of tropical regions tend to stay above 15 °C, while temperate zones will more often have dewpoints below that value (e.g., Issa Lélé and Lamb, 2010; Minda et al., 2018). Hence, using dewpoint could take into account some of the differences between tropical and temperate locations.

Seasonal cyclicity is established in many infectious diseases (Martinez, 2018), including those caused by non-COVID-19 coronaviruses (Gaunt et al., 2010). As reviewed by Pica and Bouvier (2012), Tang and Loh (2014), Paynter (2015), and Otter et al. (2016), reported relationships between humidity and viral transmission have been varied, even for the same virus. Differences in reported results for humidity may be due to the different humidity variables used in these studies, especially when the chosen humidity variables are not independent of temperature. In addition, water vapor over land tends to have higher spatial and temporal variability compared with temperature (e.g., Hubbard, 1994; Robinson, 1998; Oke, 1987), which is one reason that it is more difficult to forecast fog than temperature for specific locations (Gultepe et al., 2007). As described earlier, water vapor has a more complicated relationship with aerosol size than temperature, in part due to its ability to change phase. This makes studies of relationships between water vapor and transmission more complicated than those between temperature and transmission.

In contrast to studies of humidity, the reviews mentioned above found higher temperatures associated with decreased transmission to be more consistently reported, with few exceptions. In terms of biological plausibility, Kampf et al. (2020) reviewed 22 human coronavirus studies and found that, while these viruses may remain infectious on inanimate surfaces from hours to days, this duration was reduced at higher temperatures and increased at lower temperatures. Among studies showing the opposite correlation were those by Xie and Zhu (2020). They used a multi-day moving average of daily mean temperatures between January 23 and February 29, 2020 for 122 cities in China. They concluded that daily mean temperature has a positive linear relationship with the number of COVID-19 cases when the temperature is below 3 °C. Breton (2020) performed a study to determine whether higher temperatures resulted in reduced rates of COVID-19 transmission across the 48 states in the continental USA between February 10 and March 10, 2020. This study concluded that the evidence was weak for any temperature effect. Note that these two studies used mean daily temperatures and were over a period of 1 month during the winter season. For temperature effects on virus transmissibility, daily minimum, rather than maximum or average, temperatures appear to be more important (Eggo et al., 2016). Using daily minimum temperatures captures lower bounds and longer durations of temperature effects, which could show a more consistent reduction in transmissibility than using daily mean, median, or maximum temperatures.

Proper understanding and use of information about seasonal effects on transmissibility could be used by governments and public health agencies in regional planning for phasing out NPI and phasing in a return to work, based in part on seasonal timing (e.g., as temperature increases differently geographically) in addition to many other factors (e.g., social distancing compliance, population age and comorbidities). While the most important determinant currently mitigating the pandemic remains population compliance with NPI, knowledge of probable seasonal environmental effects could offer additional guidance in forecasting and surge planning.

Disclaimer

The views expressed here are the opinions of the author and are not to be construed as official or as representing the views of the Johns Hopkins University or any of its institutions or departments.

Ethical Approval

Ethical approval was not required for this research.

Conflict of Interest

The author has no competing interests to declare.

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