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The effect of human settlement temperature and humidity on the growth rules of infected and recovered cases of COVID-19

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ABSTRACT

This study investigated the impact of humidity and temperature on the spread of COVID-19 (SARS-CoV-2) by statistically comparing modelled pandemic dynamics (daily infection and recovery cases) with daily temperature and humidity of three climate zones (Mainland China, South America and Africa) from January to August 2020. We modelled the pandemic growth using a simple logistic function to derive information of the viral infection and describe the growth of infected and recovered cases. The results indicate that the infected and recovered cases of the first wave were controlled in China and managed in both South America and Africa. There is a negative correlation between both humidity ($r = -0.21; p = 0.27$) and temperature ($r = -0.22; p = 0.24$) with spread of the virus. Though this study did not fully encompass socio-cultural factors, we recognise that local government responses, general health policies, population density and transportation could also affect the spread of the virus. The pandemic can be managed better in the second wave if stricter safety protocols are implemented. We urge various units to collaborate strongly and call on countries to adhere to stronger safety protocols in the second wave.

1. Introduction

The coronavirus disease scientifically reclassified COVID-19 is an infectious disease caused by the coronavirus (SARS-CoV-2). Globally, as of 3:40pm CEST, 9 October 2020, there have been 36,754,395 confirmed cases, including 1,064,838 deaths, reported by WHO since the virus started from Wuhan in December 2019. The World Health Organization (WHO) declared COVID-19 a global pandemic on March 11, 2020 (WHO, 2020). As spread of the virus intensified, many virologists likened its characteristics to influenza whose behaviour invoked an epidemiological hypothesis, asserting that, cold and dry (low humidity) environments favour the survival and spread of droplet-mediated viral diseases (Liu et al., 2020; Zhu et al., 2020; Azuma et al., 2020; Casanova et al., 2010; Sarkodie and Owusu, 2020; Sizun et al., 2000; Redding et al., 2020). Several studies investigated the relationship between temperature and humidity on the spread of the...
virus. However, these studies have not been able to confirm with strong scientific evidence that temperature and humidity have significant effect on the spread of the virus. Commonly, previous studies have not tested sufficiently wide sample geographic locations to make this assertion.

SARS-CoV-2 virus is transmitted from person to person through respiratory (aerosol and droplet) and contact media (Rothen and Byrareddy, 2020; Rahimi et al., 2021; Wang et al. 2020a, 2020c). Transmission can either be direct through droplet and person-to-person or indirectly through contaminated objects/airborne to infect the respiratory system. If droplets and bioaerosols containing the virus enter the body, they may cause infection while an unprotected contact with a contaminated object is a potential risk of infection. The risk of transmission is highest when people are in close proximity (within 2 m). Van Doremalen et al. (2020) studied aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV in China and concluded that SARS-CoV-2 could suspend in the air much longer. Airborne transmissions intensify in poorly ventilated indoor spaces where people are in close proximity (Rosario et al., 2020; Coccia, 2020a, b; Travaglio et al., 2020). Airborne transmissions can also occur in health settings that generate aerosols to support SARS-CoV-2 treatments.

Meteorological weather conditions including humidity, temperature, air pollution (particulate matter (PM) and gas-based pollutants) and wind speed intensify the transmission of SARS-CoV-2 (Coccia, 2020a, 2020b; Rahimi et al., 2021, Han et al., 2021). For example, Wei et al. (2020) discovered that in the presence of accumulated PM 2.5, PM10 and other pollutants, microorganism attach themselves for anchorage and nutrients to enhance their toxicity. Groulx et al. (2018) and Zhang et al. (2019) discovered that microorganisms mix with particulate matter (PM) and air pollutants and strive better under such conditions. Wu et al. (2020) found positive association between COVID-19 infection cases and particulate matter concentration in 3000 states in the United States. Wang et al. (2020a), Travaglio et al. (2020) and Yongjian et al. (2020) found a positive relationship between air pollution and COVID-19 mortality rate. Coccia (2020b) discovered that cities with atmospheric turbulence (higher wind speed) and lower levels of air pollution had lower COVID-19 infection rates. Studies conducted in Italy and California suggest that colder weather and air pollutants are associated with increased COVID-19 incidence (Bashir et al., 2020; Fattorini and Regoli, 2020), while studies conducted in Iran and Spain suggest that there is a correlation between temperature and COVID-19 (Briz-Redon and Serrano-Aroca, 2020; Ahmad et al., 2020). Yang et al. (2020) observed that decreased relative humidity and maximum temperature and increased air pollution incidences interacted during the summer to cause increased incidence rates in arid inland cities. Wang et al. (2020f), Roy and Kar (2020), and Nazari Harmooshi et al. (2020) argued that decreased transmissibility ensues when outdoor temperatures and humidity are higher. Other studies by Ma et al. (2020); Bypass (2020); Xie and Zhu (2020) and Al-Rousan and Al-Najar (2020) confirmed that temperature affects the transmission of the virus.

Comparing the current SARS-CoV-2 to the previous SARS-CoV-1, Fagbo et al. (2017), Lowen et al. (2007) and other studies drew a parallel analysis and concluded that since there exist an inverse relationship between warm temperatures and viral infections (including influenza, MERS-CoV and other coronaviruses), the activity of SARS-CoV-2 would subside when the climate becomes warmer. However, their comparison lacked mathematical and statistical connectedness as well as an in-depth exposition of socio-cultural dynamics on viral growth rules. Therefore, contrasting the observed cases of SARS-CoV-2 continued to increase in warm climate countries including Egypt, India, Iran, and Brazil, counterverting the hypothesis (Zhao et al., 2020). Cultural hegemony, religious dogma, government responses and geo-political ambiances could interrupt the scientific hypothetical argument but previous studies have not examined sufficiently wide sample locations. In temperate countries like England, increased temperature could result in increased outings due to warm weather, resulting in increased person-to-person contact and a possibility of increased atmospheric viral concentrations. On the other hand, in some tropical zones (especially developing countries with warmer temperatures), increased temperature will result in the opposite as people will rather limit movement to seek shelter from the sun. Increased rainy days in most tropical African countries will withdraw people to their homes and decrease person-to-person contact.

To attain a comprehensive summary of the findings of previous studies, we conducted a brief bibliometric review. The review was done to categorise the scope of studies into two groupings: (i) studies which correlate COVID-19 positively with temperature or humidity and, (ii) studies which correlate negatively with temperature or humidity. As a result, we did a brief keyword concurrence search to analyze the general status of the research field and identify current studies as well as hotspot areas. The studies are summarised in Table 1 and a keyword concurrence shown in Fig. 1. Note that the term ‘climatic variables’ is sometimes used as a larger domain for temperature and humidity for the purposes of literature review which requires the mention of a larger set to which temperature and humidity belong. From Table 1, eight of the studies used data from China while the rest examined various parts of the world. Only one of the studies from China showed a negative correlation between temperature and COVID-19 (i.e. every unit increase in temperature was associated with decreasing COVID-19 cases). Ten (10) studies were done outside China: six (6) of that reported a strong correlation between temperature and humidity, and spread of the virus; three (3) showed no/weak correlation, while one (1) was uncertain. Note the stars bullet pointing the articles: the red star bulleted articles indicate studies that drew no or weak correlation with temperature. The green star indicates studies that drew a strong correlation with temperature, while the yellow star indicates studies with uncertain outcomes. Some studies reported a positive relationship between the spread of the virus with temperature (Wu et al., 2020; Bashir et al., 2020; Tosepou et al., 2020; Sobral et al., 2020; Prata et al., 2020, Xie and Zhu, 2020). Others reported a negative relationship (Haque and Rahman, 2020; Rosario et al., 2020). Some reported no, or weak correlation between temperature and spread of the virus (Ma et al., 2020; Demongeot et al., 2020; Iqbal et al., 2020; Jiang et al., 2020; To et al., 2021). While others suggested an optimum temperature from 5 °C to 15 °C, as ideal for the transmission of the virus (Gunthe et al., 2020; Sajadi et al., 2020). The presence of mixed and contrasting evidence among observational studies warrant the need for further investigation into this scientific issue.

Majority of previous studies have not sampled wider zones with varying cultural hegemony, different religious dogma, government responses and varied geo-political ambiances. Furthermore, previous studies included less than four months of data in their analyses, and largely not including the main effects in Africa and South America. Additionally, several manuscripts of previous studies were not peer reviewed (Araujo and Naimei, 2020; Al-Rousan and Al-Najar, 2020; Bannister-Tyrell et al., 2020; Luo et al., 2020; Oliveira et al., 2020; Poirier et al., 2020; Sajadi et al., 2020; Wang et al., 2020a; Bhattacharjee 2020, Gupta, 2020; Khattabi et al., 2020; Shi et al., 2020), due to the urgency of publication on the topic. This study covers a wider period encompassing all the seasons of the calendar year (summer, winter, autumn and spring). The objective of the study is to confirm or debunk the hypothesised rule whether temperature and humidity have an impact on COVID-19 spread. We also seek to do a brief literature summary on findings of previous studies to be able to juxtapose our findings in the context of other studies and present a conclusive recommendation. Understanding the true relationship between climatic conditions and COVID-19 after almost a year of its existence is necessary to inform management about their true relation.

2. Methods

We used a simple logistic model to describe the growth rules of infected and recovered cases of COVID-19 and draw their association with temperature and humidity by doing a parametric statistical test (t-test) and comparing growth rates with temperature and humidity using
3

Table 1
Summary of previous studies and their role on COVID-19 association with climatic weather conditions.

| Title of Article | Authors | Journal | City/Location | Summary of findings | URL |
|------------------|---------|---------|---------------|---------------------|-----|
| Impact of climate and ambient air pollution on the epidemic growth During COVID-19 outbreak in Japan. | Kenichi et al. | Environ Research | Japan | Growth of COVID-19 is significantly associated with increase in daily temperature, and or sunshine hours. | Environ Research: 10.1016/j. enrres.2020.110042. |
| Impact of meteorological factors on COVID-19 pandemic: Evidence from Top 20 countries with confirmed cases. | Sarkodie and Owusu | Environ Research | 20 countries | There is strong correlation between temperature relative humidity on COVID-19 cases. | Environ Research: 10.1016/j. enrres.2020.110101 |
| Correlation of ambient temperature COVID-19 incidence in Canada | ToF et al. | Sci. Total Env. | Canada | There is no correlation between temperature and COVID-19. | TBA |
| Investigation of effective climatology, Parameters on COVID-19 outbreak in Iran. | Ahmadi M et al. | Sci. Total Env. | Iran | There is no correlation between air temperature and COVID-19 cases. | Sci. Total Env. 10.1016/j. scitotenv.2020.138811 |
| A spatio-temporal analysis for exploring the effect of temperature on COVID-19 early evolution in Spain. | Briz-Redon & Serrano-Arocá | Sci. Total Env. | Spain | No significant evidence of relationship | Sci. Total Env. 10.1016/j. scitotenv.2020.138811 |
| Effects of Temperature Variation and humidity on the death of COVID-19 in Wuhan, China | Ma Y et al. | Sci. Total Env. | China | 1 unit increase in temperature and humidity resulted in COVID-19 death in lag 3 and 5 with significant decreases in lag 3 and 5, and significant contain or slow down new COVID-19 infections. | Sci. Total Env. 10.1016/j. scitotenv.2020.138201. |
| Eco-epidemiological Assessment of the COVID-19 epidemic January–February 2020 | Bypass P | Global Health Action | China | Adjusted incidence rate ratios suggested brighter, warmer and drier conditions were associated with lower incidence. | Glob Health Act. 10.1080/ 16549716.2020.1760490 |
| Association between ambient Temperature and COVID-19 Infection in 122 cities from China | Xie J et al. | Sci. Total Env. | China | Below 3 °C mean temperature each 1 °C rise was associated with a 4.861% increase in daily COVID-19 cases. | Sci. Total Env. 10.1016/j. scitotenv.2021.38201. |
| The correlation between the Spread of COVID-19 infections And weather variables in 30 Chinese provinces and the impact Of Chinese government mitigation Plans | Al-Rousan N et al. | Eur Rev Med Pharmacol Sci | China | Weather conditions (temperature) and short-wave radiation increases the number of confirmed fatal and recovered cases | Eur 10.26355/eurrev_202004, 212042 |
| The nexus between COVID-19, Temperature and exchange rate in Wuhan City: New findings from partial And multiple wavelet coherence | Iqbal N et al. | Sci. Total Env. | China | Increase in temperature does not significantly contain or slow down new COVID-19 infections. | Sci. Total Env. 10.1016/j. scitotenv.2020.138916 |
| Effect of ambient air pollutants and Meteorological variables on COVID-19 Incidence | Jiang Y et al. | Infect Control Epidemioi | China | The relative risk of temperature and COVID-19 cases was 0.738–0.969 but may not be independent of PM10. | Infect Control Hosp Epidemiol. 10.1017/ ice.2020.222 |
| Temperature significantly changes COVID-19 transmission in (sub) tropical Cities of Brazil | Prata DN et al. | Sci Total Env. | Brazil | A 1 °C rise in temperature was associated with a −4.895% (t = −2.29, p = 0.0226) decrease in number of daily cumulative confirmed cases of COVID-19. | Sci. Total Env. 10.1016/j. scitotenv.2020.138862. |
| Temperature Decreases Spread Administrative Parameters of the COVID-19 case dynamics | Demongeot J et al. | Biology | 21 French regions | High temperatures diminish initial contagion rates but seasonal temperature effects at later stages of epidemic cannot be proven | Biology (Basel). 10.3390/ biology9050094. |
| Effects of temperature variation and Humidity on the death of COVID-19 in Wuhan, China. | Ma Y et al. | Sci. Total Env. | China | A unit increase in temperature and humidity resulted in decrease COVID-19 deaths in the 3rd and 5th lag. | Sci Total Env. 10.1016/j. scitotenv.2020.138226. |
| Association between climate variables And global transmission of SARS-CoV-2 | Sobral MFF et al. | Sci. Total Env. | Global | A 1% increase in daily temperature reduced the number of cases by 6.4 per day. | Sci Total Env. 10.1016/j. scitotenv.2020.138997 |
| Correlation between weather and Covid-19 pandemic in Jakarta Indonesia. | Tosepu R et al. | Sci. Total Env. | Indonesia with Covid-19 | Temperature significantly correlates | Sci. Total Env. 10.1016/j. scitotenv.2020.138436. |
| Correlation between climate Indicators and COVID-19 pandemic In New York USA. | Bashir MF et al. | Sci Total Env | New York City | Minimum temperature, average temperature and air quality were significantly associated with COVID-19. | Sci. Total Env. 10.1016/j. scitotenv.2020 |
| Effects of temperature and humidity On the daily new cases and deaths of China COVID-19 in 166 countries | Wu Y et al. | Sci. Total Env | 166 countries | A 1 °C increase in temperature resulted in 3.08% (95% CI: 1.53%, 4.63%) reduction in daily new cases and a 1.19% (95% CI: 0.44%, 1.95%) reduction in daily deaths. | Sci. Total Env. 10.1016/j. scitotenv.2020 |

Note: ✿ Green star articles concluded that there is strong correlation between climatic variables and COVID-19. ✿ Red star variables means there is no, or a weak correlation between climatic variables and COVID-19. ✿ Yellow star articles were uncertain about the correlation between climatic variables and COVID-19. ✿ Pearson’s correlation.

2.1. Brief bibliometric review

To provide a comprehensive overview of the stage of knowledge in the area, we conducted a brief bibliometric analysis. The analysis was also to identify the milestones chalked in the field by analysing the most cited studies and categorising them into groups based on findings on the subject matter. We explored Web of Science Core Collection Database in advanced search page, using Boolean Logic to search TS = (COVID-19 OR SARS-CoV-2 OR Impact of COVID-19 on climatic weather variables OR Impact of SARS-CoV-2 on climatic weather variables) in which the subject contains “SARS-CoV-2 Impact on temperature and humidity “and “COVID-19 Impact on climatic weather variables”. We searched for articles from 2019 to 2020. The initial screening identified 517 articles. After examining the full texts, 19 studies were shortlisted manually. We observed great homogeneity in the findings regarding the effect of climatic weather variables on the transmissibility of COVID-19. Cold and
dry conditions were potential factors affecting the spread of the virus.

2.2. Research settings, sample and data

To ensure that our sample settings cover a wider scope geo-political ambience, we compared cases from three continents including selected countries in Africa, South America and China (Appendix 1 shows list of countries selected for the study) with varying meteorological weather conditions and different government responses to the pandemic. Previous studies largely excluded Africa and South America, which display major variations in meteorological weather conditions. The success of China in keeping initial growth rates down sets it as an ideal control to compare other countries. Another reason for selecting these countries was the great variation in intranational and intracontinental meteorological weather conditions. The cumulative confirmed and recovered cases of COVID-19 in China as well as African and South American countries from January to August 2020 was obtained from the John Hopkins COVID-19 real-time data (Lauren, 2020). Data for humidity and temperature from January to August 2020 was obtained from NASA’s datasets at www.disc.gsfc.nasa.gov/datasets/GLDAS_CLSM025_DA1_D_EP_2.2/summary. We modelled confirmed and recovered cases of COVID-19 in China as well as African and South American countries while a Pearson correlation was used to compare the relationship between model parameters in China and selected African and South American countries while a Pearson correlation was used to compare the relationship between environmental indexes and model parameters.

2.3. Measures of variables of the study

Temperature and humidity were measured and compared with the epidemic growth rules in the selected countries. A parametric statistical test (t-test) was done to compare the difference between model parameters in China and selected African and South American countries while a Pearson correlation was used to compare the relationship between temperature and humidity with model parameters.

2.4. Data analysis procedure and epidemic curve modelling

We adopted the ‘logistic function’ as used in previous epidemic studies including COVID-19 (Han et al., 2020; Huang et al., 2003; Wang and Liu 2005). Based on the logistic function, we modelled the epidemic information of the viral infection cases in a typical logistic form equation (Eq. (1)):

\[ N(t) = \frac{A}{1 + e^{-kt_0}} \]  

(1)

Where \(N(t)\) indicates the general form of the cumulative number of infected or recovered patients at time; \(A\) denotes the maximum number of infections or recoveries; \(k\) is the logistic growth rate, and \(t_0\) is the semi-saturation period (SSP), which is the inflection point of the sigmoid curve. Before we applied this model in this study, we tested it on SARS data for China for 2003 and also confirmed with simulation results of China done by Han et al., (2020). We then further confirmed it with the infected, death, and recovered cases of COVID-19 in this study. With the infected cases, there are three parameters \(A, k, t_0\) in the model, while in dealing with the recovered cases, we fixed \(A\) to the difference between the maximum number of cumulative infections and deaths, based on biological fact. In our model, \(t_0\) is the mathematically defined inflection point. In this study, we assume that \(t_0\) is the time of inflection of the epidemic dynamics in a region. We processed the data and modelled them with custom scripts on MATLAB (the Math Works). The nonlinear least square (NLS) algorithm was adopted for data fitting and parameter estimation. We used the MATLAB function “nlinfit” to minimize the sum of squared differences between the data points and the fitted values.

2.5. Statistical comparison of covid-19 infection growth rules with temperature and humidity

A parametric statistical test (t-test) was done to test the difference between model parameters in China and selected African and South American countries while a Pearson correlation was used to compare the relationship between environmental indexes and model parameters.

3. Results

The first phase of the epidemic situation was controlled in China (Fig. 2) with a recovery rate of 94.5% (CCDC 2020). The time series of infected and recovered cases and their fitted curves for mainland China are shown in Fig. 2. Since China was the first country to control the pandemic successfully, this study first modelled cases in China separately, and also compared with other countries. In Fig. 2, each red line represents the time series of infected cases of a province while each blue line represents the time series of recovered cases of a province in China’s mainland.

Based on this simulation, we applied the descriptive model to fit the data for the cumulative number of infected cases in some selected African and South American countries (Fig. 3). See the full list of countries in appendix 2.

In Fig. 3 and appendix 2, all data series for infected growth cases are explained in the diagrams. Finally, we plotted all the fitted curves for China, Africa and South America to compare the intrinsic growth rules of these zones (Fig. 4). The black dots represent Chinese provinces, the blue dots represent selected African countries and the red dots represent
selected South American countries. We noticed that, apart from China (Fig. 4A), the logistic growth rate of all African and South American countries does not show a significant difference between saturation point and infection rate.

We compared temperature and humidity with growth rates and saturation points of the pandemic. Fig. 5 presents time series of humidity and temperature for provinces in China and some selected African countries. In Fig. 5A and B, each line indicates a province.

Fig. 2. Fitted time series of first phase of COVID-19 infected and recovered cases in China’s mainland.

Fig. 3. Intrinsic growth rules of patients infected with COVID-19 in African and South American countries.
Table 2 summarises results of the association between temperature, humidity, and the pandemic growth. There is a negative correlation between mean humidity ($r = -0.21; p = 0.27$) and temperature ($r = -0.22; p = 0.24$) with spread of the virus. There is also a negative correlation between humidity ($r = -0.18; p = 0.36$) and temperature ($r = -0.13; p = 0.51$) with saturation of the virus. This means that the virus strives faster in colder humid regions. A scatter plot explains this association in Appendix 2.

The relationship between temperature, humidity, and the epidemic growth rate were further compared for China, Ghana and Argentina in Table 3 and shown in Appendix 4.

4. Discussion

The results of this study indicate that the survival and spread of SARS-CoV-2 is influenced by temperature and humidity. Colder, less humid regions support the growth of the virus. This result supports findings of several studies mentioned earlier and confirms the hypothesis that cold and dry (low humidity) environments favour the survival and spread of droplet-mediated viral diseases including SARS-CoV-2 (Chan et al., 2011). SARS-CoV-2 is not temperature resistant and starts to break down at higher temperatures. Wang et al. (2020f), Roy and Kar (2020) and Nazari Har-mooshi et al. (2020) presented a broader perspective that confirms that there is decreased transmissibility of COVID-19 in higher outdoor temperatures and humidity. In the same regard, Biktasheva (2020) affirmed that there is a higher infection rate and respiratory sensitivity for some viruses in extreme low temperature and humidity conditions. Xu et al. (2020) found that in specific situations, meteorological parameters might affect the reproduction of SARS-CoV-2. Otter et al. (2016) confirmed that SARS-CoV-1 is affected by relative humidity and ambient temperature. Studies done in 122 Chinese cities confirm cases to decline by 4.9% when temperature increases by 1°C (Xie and Zhu, 2020). Qi et al. (2020), suggest that when average temperature is in the range 5.04°C-8.2°C COVID-19 cases dropped 11%–22%. Casanova et al. (2010) reported that coronaviruses last longer on non-living objects in low temperatures compared to higher temperatures. Though a few studies (Ma et al., 2020; Demongeot et al., 2020; Iqbal et al., 2020; Jiang et al., 2020; To et al., 2021) reported ‘uncertain’ or ‘no relationship’ between COVID-19 spread with temperature and humidity, overall, great homogeneity was observed among statistical results, hence, we maintain our position that lower temperature favours the growth and spread of the virus while increasing temperatures inhibit the growth and spread of the virus.

With a parallel comparison with SARS-CoV-1 and MERS, as well as considering existential limitations to fully encompass the influence of socio-cultural factors such as containment measures, local health policies, government responses, population density, cultural aspects which have not been fully included to maximum unit of influence, this study however cannot wholly associate the spread of the virus to climatic weather variables alone. Based on comparative statistical analysis of infections rates done on the three climate zones of study (Africa, China and South America), and comparing their government responses vis-a-vis viral infection rates, we agree with Oliveiros et al. (2020) that though temperature and humidity contribute significantly to the spread of the virus, other atmospheric conditions and socio-cultural factors including government responses, general health policies, population density and transportation also contribute to the spread of the virus. Studies done in China by Al-Rousan and Al-Najjar (2020), Bhattacharjee

Fig. 4. Fitted curves for china, Africa and South America compared.
Suggests that a major part of China’s success story is attributed to effective response mechanisms popular with actual lockdown and the wearing of mask. We recommend the international community to return to effective social distancing, isolation of infected persons and the effective wearing of mask.

To further put our arguments in a proper demonstrably context, we can say, for example, that though South Africa (a cooler climate country comparative to Ghana) is recording higher cases than Ghana (a hotter climate country), the higher cases in South Africa are not necessarily resulted from the cooler climate there but could result from other factors. Higher number of tourists received across South Africa, Egypt, Brazil and India could contribute to increased incidence rates in these countries (Babuna et al., 2020). Similarly, the present second wave of recorded cases in Europe cannot solely be blamed on the approaching winter without considering increased person to person contact during the past summer holidays. Consequently, this study asserts that socio-cultural variables are also significant factors as meteorological variables. We hence encourage various countries to augment their public health interventions to contain viral spread at manageable levels while the world awaits the discovery of a vaccine. It is only with proper planning and adherence to safety protocols that unnecessary damage could be averted.

Other studies discussed another hypothesis to explain the recorded lower infection cases in some tropical countries, especially, in Africa and parts of South America (Bukhari and Jameel, 2020). Bukhari and Jameel (2020) argued that less mass testing in underdeveloped countries as a result of weaker health care systems could be the reason for lower recorded cases. Though this argument seems rational, lower number of death cases recorded in these underdeveloped countries does not support this hypothesis. Tropical zones especially sub-Saharan African countries recorded some of the lowest death rates and higher recovery rates. As a result, we recommend immunology studies on covid-19 survivors in the near future.

The findings of this study have policy implications for preventing the spread of the virus. The present ongoing second wave should be taken seriously. Having gone through the first wave, humanity is in a better position to reduce infections if proper safety protocols are adhered. The practice of social distancing; staying home; applying 70% alcohol-based sanitizer; avoiding handshakes; using face masks; handwashing with soap and running water, will help reduce the spread of the virus.

### 4.1. Limitations of the study

This study could not include other meteorological variables such as air pressure, ultraviolet, wind speed, atmospheric particles, and only discussed social factors such as government response and migration from observational knowledge. The inclusion of such factors would have

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**Table 2**

Summary of correlation results between temperature, humidity and spread of COVID-19.

| Humidity (Chinese Provinces) | Temperature (Chinese provinces) |
|-----------------------------|-------------------------------|
| $K$                         | $r = 0.21, p = 0.27$          |
| $\tau_0$                    | $r = 0.18, p = 0.36$          |

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**Table 3**

Summary of relationship between dynamics of epidemic and environment indices for China, Ghana and Argentina.

| Humid (Ch) | Humid (Gh) | Humid (Arg) | Temp. (Ch) | Temp. (Gh) | Temp. (Arg) |
|-----------|------------|------------|-----------|-----------|------------|
| Mean      | 0.0056     | 0.0137     | 0.007     | 2.47      | 28.57      | 16.11      |
| Std       | 0.0022     | 0.0007     | 0.002     | 3.52      | 2.07       | 6.32       |
| $k$ (Ch provinces) | $k$ (Gh) | $k$ (Arg) | $\tau_0$ (Ch provinces) | $\tau_0$ (Gh) | $\tau_0$ (Arg) |
| Mean      | 0.26       | 0.04       | 0.05      | 34.18     | 205.91     | 224.51     |
provided a higher level of accuracy. Data especially on meteorological factors was hard to get for some African countries.

5. Conclusion

To determine the correct position on the current debate on impact of temperature and humidity on the viral spread of COVID-19, we tested three climate zones including Africa, South America and Mainland China using daily data from January to August 2020. Based on sufficient evidence, we found that temperature and humidity correlate negatively with spread of COVID-19. SARS-CoV-2 dies under very high temperatures but that alone is not a sufficient factor to explain the slow spread of the virus in some lower temperature climates. With greater influence from socio-cultural factors including public health interventions, local culture and transport, countries must attach more seriousness to implementing safety protocols. Countries could take a cue from China and other countries who implemented strict lockdown of cities and provinces, limiting the movement of people and closing down borders until such a time an efficient vaccine is discovered for entire global vaccination.

It takes the strong collaboration of various units, and discipline from people to manage COVID-19 below pandemic. Future research should investigate immunological aspects, age of population, herd immunity, migration patterns, population density and socio-cultural dynamics. Furthermore, the impact of humidity and temperature on the rate of quantitative and qualitative progression of the pandemic should be estimated, especially in the advent of the arrival of the second wave particularly in Europe and the northern hemisphere.

Author contribution

Pius Babuna and Chuanliang Han: Conceptualization, Formal analysis, Methodology, Software, Validation; Visualization, Writing - review & editing. Mejia Li, Doris Awudi, Roberto Xavier Supe Tulcan, Amatus Gyilbag, Jian Dehui. Writing - review & editing, Data curation. Xiaohua Yang. Conceptualisation, Review and Funding. Saini Yang. Conceptualisation Review and Funding. Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2021.111106.

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