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The influence of climate factors and government interventions on the Covid-19 pandemic: Evidence from 134 countries

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ABSTRACT

This paper investigates at the world level the influence of climate on the transmission of the SARS-CoV-2 virus. For that purpose, panel regressions of the number of cases and deaths from 134 countries are run on a set of explanatory variables (air temperature, relative humidity, precipitation, and wind) along with control variables (government interventions and population size and density). The analysis is completed with a panel threshold regression to check for potential non-linearities of the weather variables on virus transmission. The main findings support the role of climate in the circulation of the virus across countries. The detailed analysis reveals that relative humidity reduces the number of cases and deaths in both low and high regimes, while temperature and wind reduce the number of deaths.

1. Introduction

This paper focuses on the meteorological factors and public policies that affect the SARS-CoV-2 virus propagation. It is interesting to note that wealthier countries, having greater education, greater health technologies, more trained physicians and nurses, and better equipped public and private hospitals, appeared very vulnerable during the successive Covid-19 waves. Even regions or states within each country had a different level of Covid-19 exposure, probably due to factors that are not limited to the efficiency of authorities (quality and timing of the strategy), the type of administrative organization (centralized vs. decentralized), or even the structural vulnerabilities (inequalities among people vs. among territories). The most common type of public health intervention has been a national/regional community containment (lockdown) to “flatten the curve” as a way to mitigate the burden on healthcare supply given the imbalance between supply and demand for medical care. The other important type of public health intervention is the supply of tests and vaccines in large-scale capacities. To that end, it is important to examine to what extent lockdowns, travel restrictions and anti-Covid-19 public health resources (tests and vaccines) play a role in controlling the epidemic. However, even if these public policies contribute to relieving the pressure on the hospitals, they did not explain why the virus transmission seems to differ from Winter to Summer.

The ongoing literature on SARS-CoV-2 shows that the virus transmission may depend on several environmental factors such as climatic conditions, socio-economic factors, demographic profiles, individual behaviors (hand-washing, mask-wearing, etc.), political factors (type of regime, type of administrative organization, type of interventions). Some are micro-factors (individual responsibility, socio-economic, etc.), others are macro-factors (weather, government intervention, demographic, geographic, etc.). Four studies survey the role of weather variables on SARS-CoV-2 circulation. Mecenas et al. (2020) show that there is some scientific evidence that warm and wet climates reduce the spread of Covid-19. Other studies that gave a particular focus on climate conditions confirm this result. Briz-Redon and Serrano-Aroca (2020) suggest that weather conditions (humidity, precipitations, radiation, temperature, and wind speed) could play a secondary role in the transmission of the disease, while at the same time, they notice that there are many contradictory findings. McClymont and Hu (2021) observe that temperature and humidity may be a significant factor in Covid-19 transmission whereas wind speed and rainfall may also contribute to transmission, although the evidence was not consistent across studies. Noormotlagh, Mirzaee, and Jaafarzadeh (2021) conclude that temperature and relative humidity are important factors in the survival of SARS-CoV-2.

Put all together, these surveys support the idea that meteorological

1. These restrictions encompass several forms: Stay at home orders (order for everyone to remain at home except for specific purposes), isolation (separation of sick people from the rest), quarantine (restriction of movements for people exposed to the virus to see if they become sick within 7–14 days) and curfew (restriction of movements after a specific time of the day).
conditions matter despite some conflicting results from the relevant literature. Therefore, it sounds logical to hypothesize that differences in average weather conditions, among countries, could significantly influence the virus circulation. Some studies have been exploring this side of the story. However, the results appear conflicting as put forward in the literature review. The existing studies are exposed to limitations due to the type of methodology (OLS based analysis or correlation-based analysis; mostly under a linear framework), the period (less than one year, i.e., not including all seasonal effects or more than one year), the type of data (global or local scale) and the lack of information on the nature of the data (balanced or unbalanced; the presence of unit root or stationarity).

The closest papers to this research are those that deal with a high number of countries. Chen et al. (2020) regress Covid-19 cases per million inhabitants in a country (among 117) against the country’s distance from the equator, where heat and humidity tend to be higher; they find that an increase in absolute latitude by one degree is associated with a 2.6% increase in Covid-19 cases per million inhabitants. Juni et al. (2020) use weighted random-effects regression to determine the association between the log ratio of Covid-19 and exposure variables from 144 geopolitical areas; they find no association of epidemic growth with latitude and temperature, but weak negative associations with humidity. Wu et al. (2020) use a generalized additive model to explore the effects of temperature and humidity on 166 countries (excluding China); they find that temperature and relative humidity were both negatively related to daily new cases and deaths. Yuan et al. (2021) use a generalized additive model and Spearman correlation analysis to analyze the relationship between Covid-19 and climate variables in 127 countries; they find that temperature, relative humidity, and wind speed are negatively correlated with daily new cases. Ficitola and Rubolini (2021) use linear mixed models to relate variation of Covid-19 growth rate across regions to weather (temperature and humidity) and socio-economic variables from 159 countries; they find that policy interventions can effectively curb disease spread irrespective of environmental conditions.

The novelty of this study lies in the comprehensive methodological approach to address some of the limitations in the existing studies combining linear and non-linear frameworks with a balanced dataset composed of transformed series. This study investigates the role of weather factors after controlling for governmental interventions on a global scale from January 1, 2020, to March 23, 2021. Given the heterogeneity in the data covering 134 countries, a set of panel linear regressions is implemented to analyze the role of temperature, relative humidity, and wind variables on the Covid-19 response variables.

2. The empirical model

Panel regressions of daily cases and daily deaths are considered, on weather variables along with control variables under three specifications: Pooled, fixed- and random-effects specifications. The model formulation is based on a literature review. Only relevant tables are displayed for discussion and non-reported tables are given upon request.

2.1. The pooled specification

Under this framework, given that OLS regression does not consider heterogeneity across groups or time, such a specification should not produce consistent estimates with our dataset because pooled regression may result in heterogeneity bias. The pooled specification is:

\[ y_{it} = \alpha + X_{it} \beta + \epsilon_{it} \]  

(1)

Where \( X_{it} \) is a column vector of the \( i^{th} \) country observed at day \( t \) of all the explanatory variables (weather variables) and control variables (government interventions, population size, and population density). \( \beta \) is a vector of unknown parameters while \( y_{it} \) is the response variable (new cases; new deaths) and \( \epsilon_{it} \) are the scalars representing the error variables. Moving away from OLS specification leads to selecting panel data models to examine fixed and/or random effects.

2.1.2. The fixed effect specification

The fixed effect (FE) general specification is:

\[ y_{it} = (\alpha + u_i) + X_{it} \beta + \epsilon_{it} \]  

(2)

Where \( u_i \) is a time-invariant fixed effect specific to a given country and errors \( \epsilon_{it} \) are independent identically distributed. The FE specification examines individual differences in intercepts with the assumption that slopes and variance remain the same across countries. Given the high number of countries in the data set, both “within” and “between” estimators are tested. The within estimation regresses deviations from group means of the dependent variable \( y_{it} - \bar{y}_i \) on the deviations from group means of the independent variables \( X_{i} \) on group means of independent variables \( \bar{X}_i \). This estimator reflects the cross-sectional information contained in the data. This simplification comes at the cost of dropping the intercept along with all other constants among the control variables. In contrast, the between estimation regresses group means of the dependent variable \( \bar{y}_i \) on group means of independent variables \( \bar{X}_i \). This estimator reflects the time-series country’s variation. The choice between both estimators depends on the study objective. This piece of research aims at exploring both estimators either to measure the variation of countries over time (within effect) or measure variation of the means across countries (between effect).

2.1.3. The random effect specification

The random effect (RE) general specification is:

\[ y_{it} = \alpha + X_{it} \beta + (u_i + \epsilon_{it}) \]  

(3)

Here \( u_i \) is a RE specific to individual countries and it is assumed that slopes and intercepts remain the same across countries. This signifies that the difference among countries lies in their specific errors and not in their specific intercept as in the case for the FE specification. Contrary to FE where the interest does not rely on the differences between countries, the RE is of interest when the variance between countries becomes
informative.

2.1.4. The panel threshold specifications

A set of panel threshold specifications are selected to account for non-linearity for the weather variables. This approach allows the slope parameters to vary with a regime change, which depends on the threshold variable, computed as a mean variable per country. Following Hansen (1999), the threshold regression model can be formally treated as a special case of a segmented regression. For the single threshold model, the specification is given by:

\[ y_{it} = a_i + x_{it}' \beta_{y} + w_{it} \theta_{1} + \gamma_{1} \delta_{1} + \epsilon_{it} \]

(4)

Where \( \gamma_{1} \) is the threshold that divides the equation into two regimes with coefficients \( \beta_{1} \) and \( \beta_{2} \) for the dependent weather variable. The threshold variable \( \mu_{i} \) is a scalar, and \( I_{(\cdot)} \) is an indicator function. \( w_{it} \) with subscripts 1, 2, or 3 corresponds to the three independent variables among the four weather variables and their respective coefficients \( \theta \). An iterative grid search takes this first threshold value as given and looks after a second threshold value that minimizes the sum of squared errors. For the double threshold model, the specification is given by:

\[ y_{it} = a_i + x_{it}' \beta_{y} + w_{it} \theta_{1} + w_{it} \theta_{2} + \gamma_{1} \delta_{1} + \gamma_{2} \delta_{2} + \epsilon_{it} \]

(5)

Where \( \gamma_{1} \) and \( \gamma_{2} \) are the thresholds that divide the equation into three regimes with coefficients \( \beta_{1} \), \( \beta_{2} \), and \( \beta_{3} \). The latter sequential procedure can be repeated for a third threshold and so on. For the triple threshold model, the specification is given by:

\[ y_{it} = a_i + x_{it}' \beta_{y} + w_{it} \theta_{1} + w_{it} \theta_{2} + w_{it} \theta_{3} + \gamma_{1} \delta_{1} + \gamma_{2} \delta_{2} + \gamma_{3} \delta_{3} + \epsilon_{it} \]

(6)

The thresholds are ordered so that \( \gamma_{1} < \gamma_{2} < \gamma_{3} \). According to Hansen (2000), the threshold variable may be an element of the regressor variable. In this study, the threshold variable is computed as the mean of the considered weather variable. It is equivalent to splitting the sample to examine the model if variable \( y \) is above or below its mean \( \mu_{i} \) for any given country \( i \) for the whole period.

3. The data description

3.1. Data construction

30 variables are pre-selected according to the relevant literature. Discarding redundant variables with strong correlation allows avoiding collinearity problems. After exploring the correlation matrix, only 14 variables are retained in the panel data set. The sample is arranged to obtain a balanced panel and to avoid missing data. This comes at the cost of reducing the number of observations. While the pandemic outbreak did not occur for all countries at the same time in January 2020, there has been a methodological choice to hold the same period for each country. Holding the same number of days for each country allows estimating the models on balanced panel data, which is a desirable feature. Weather data are calculated by averaging every day all the weather station observations for every single country. From January 3, 2020, to March 22, 2021, there are 134 countries in the final sample; each country covers 441 days which gives a total of 59,228 observations. Table 1 presents the data, their details, and their source while Fig. 1 displays the selected countries (color) and the non-selected countries (white).

Table 2 presents the correlation matrix among selected variables while Fig. 2 shows the corresponding correlation plot. Among the most correlated variables, we note first, TEMP and RH, and second, Testing. policy, Home.restrictions and International.restrictions. This is not surprising because the relative humidity is derived from the ratio of how much moisture the air is holding to how much moisture it could hold for a given temperature. Moreover, government interventions variables should be correlated among them and this correlation should be reflected through the coded government response (ordinal data) obtained from Oxford Covid-19 Government Response Tracker.

3.2. Data stationarity

Several tests are run to check for stationarity in the context of panel data where multiple time series are combined. The time series unit root tests (e.g., Dickey and Fuller, 1979; Kwiatkowski, Phillips, Schmidt, and Shin, 1992) may have limited power in such a context. In this study of relative micro panel data (large cross-section units N, small number of periods T), standard panel unit root tests can be applied. Most of these panel unit root tests are designed under the assumption of cross-section independence generally to set the normal limiting distribution as for the ADF test. Most of them test the null hypothesis of a unit root for each series in a panel (e.g., Im, Pesaran, and Shin, 2003) while few test the null hypothesis of stationarity (Hadri, 2000). Hadri statistics is a cross-sectional average of the KPSS stationarity test developed in the univariate context, while IPS statistics are based on the ADF unit root test averaged across groups. Given the existence of unit roots in several series, all of them are transformed except the ordinal data per construction.

3.3. Data presentation

Covid-19 series are transformed in growth rate. For instance, cases growth (daily new cases first difference divided by previous day cumulative cases); this variable allows computing the daily growth since the previous total number of cases; the same applies to deaths. Vaccines, Tests, and Hospitalization variables are transformed as simple growth rates (first difference divided by the previous day observation). Home. restrictions, International.restrictions, and Testing. policy variables are transformed as first differences. Population and Density variables are log-transformed as the unique non-governmental control variables; the population variable accounts for the size of the population, while the density variable accounts for the size of the population per square
kilometer. Weather variables are first-difference transformed.

- New.cases: Covid-19; case growth transformation
- New.deaths: Covid-19; death growth transformation
- TEMP: Climate variable; first difference transformation
- RH: Climate variable; first difference transformation
- PRCP: Climate variable; first difference transformation
- WDSL: Climate variable; first difference transformation
- Vaccines: Control variable (Government intervention); growth rate transformation
- Tests: Control variable (Government intervention); growth rate transformation
- Hospitalization: Control variable (Government intervention); growth rate transformation
- Home.restrictions: Control variable (Government intervention); no transformation
- International.restrictions: Control variable (Government intervention); no transformation
- Testing.policy: Control variable (Government intervention); no transformation
- Population: Control variable; log transformation
- Density: Control variable; log transformation

Table 3 presents the descriptive statistics for the transformed variables. Covid-19 data are skewed with a strong kurtosis. TEMP and overall RH and PRCP have a very high variance while PRCP has a strong kurtosis. Vaccines, Tests, and Hospitalization variables have a strong kurtosis. Notice that Covid-19 variables are regularly subject to modifications by local authorities, which can explain the abnormal higher-order moments. Table 4 presents the unit-root/stationarity tests for the transformed series. The stationarity hypothesis is accepted for the KPSS univariate test and the Hadri panel test. The unit root test is rejected for the ADF univariate test and the IPS test.

4. The empirical findings

The empirical results of the Panel linear models are displayed in Tables 5.1 and 5.2. Three empirical models are investigated: Model 1 considers climate variables only. Model 2 considers Government intervention variables only. Model 3 considers both climate and Government intervention variables. A one-day lagged New.cases variable is included for the New.deaths variable in Model 3. Given that weather variables can be subject to non-linearity with Covid-19 data, this analysis is extended with panel threshold regression models, which results are displayed in Tables 6.1 and 6.2. The empirical tests are implemented on Software R 4.0.3. Only the most relevant results are reported to save space.

4.1. Panel linear regression analysis

To decide which specification improves the goodness-of-fit, several diagnostic tests are run: Chow test of poolability, F-test (F), Breusch-Pagan (1980) Lagrange Multiplier test, and Hausman (1978) test. The testing procedures confirm that the data are not poolable; fixed and random effects are preferred over OLS. The Hausman (1978) test, under the null hypothesis, that the preferred model is random effects against the alternative fixed effects, is rejected for both variables. Fixed effects appear to be preferred to random effects. Among fixed effects, two estimators are examined: within and between.

The within estimator does not exhibit any significant impact of climate variables. Only Home_restrictions, International_restrictions, Testing_policy, and Tests variables are statistically significant for both reported cases and deaths. It means that the daily changes of such government policies are impacting the Covid-19 spread. Home_restrictions variable increases reported cases but decreases reported deaths. International_restrictions variable decreases both reported cases and deaths. However, not only climate variables are not statistically significant but the R-squared is below 1%, which means that the climate variation within countries across time seems not explaining the variance in the dependent variables.

Tables 5.1 and 5.2 display results for the between estimator. For Model 1, the RH variable is negative and statistically significant for both reported cases and deaths; the respective R-squared is 7.16% and 14.41% for New.cases and New.deaths.

For Model 2, the Testing_policy variable is positive and statistically significant for both reported cases and deaths. It is also the case for the Tests variable with reported cases and Home_restrictions variable with reported deaths; the R-squared is equal to 8.29% for New.cases and 8.00% for New.deaths.

For Model 3, RH and Density variables are respectively negatively and positively related to New.cases and also both statistically significant. TEMP, RH, and WDSL are negative and statistically significant for New.deaths. The lagged variable New.cases(-1) is positive and statistically significant for the New.deaths. The Population variable is positive and statistically significant for reported deaths. The R-squared raises to 13.77% for New.cases and 42.30% for New.deaths.

Fig. 4 displays the residuals from Model 3 of Tables 5.1 and 5.2. It shows the magnitude and the sign of the bias from the model for every single country. Hence, it determines for which country the model fits the best.

Regarding climate variables, we note that relative humidity reduces the number of cases and deaths, while temperature and wind reduce the number of deaths. For reported deaths, the WDSL variable is 2.53 times more impacting than TEMP and 5.56 times more than RH. Hence, wind seems to be the most influential variable for reported deaths, while relative humidity seems the most influential variable for reported cases.

Fig. 3 displays the New.cases and New.deaths variables according to the weather variables from the five geographical continents (Africa, Asia, Europe, Oceania, North America, South America). Only the statistically significant weather variables from Tables 5.1 and 5.2 are selected. It highlights the scale of the pandemic per continent according to the meteorological factor. As depicted in Fig. 3, Europe and South America appear as the most concerned regions by the epidemic.

Regarding government policies, we note that Home_restrictions and International_restrictions variables are not statistically significant contrary to the within estimator. It means that the government policies are influential on Covid-19 spread across time within each country, but not across countries. In clear, the difference in the level of restrictions among countries seems not likely to explain statistically the variation of reported cases and deaths. One potential explanation is that taken all together, these policies measures may induce mixed-effects (both positive and negative) on the aggregate number of cases and deaths; indeed, the within estimator reveals that the Home_restrictions variable increases the number of cases (probably due to home contamination), but decreases the number of deaths (probably because it flattens the curve for hospitalization in context of a limited number of hospital resources and physicians). Some results should be interpreted with caution. First, the fact that the Vaccines variable is not statistically significant should not be misinterpreted. Indeed, it is likely that this variable will turn out to be significant when most of the countries have administered sufficient vaccines and tests to most of their population. In clear, it might be significant for the few countries that have been in advance in their agenda and not significant for the majority of the countries that are lagging. Hence, at a global scale to date, it is not significant, but at a local scale, it might be significant. Second, the fact that the Testing_policy

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\[1\] I acknowledge the use of the following libraries: corrplot; gsdrr; plr; plm; tseries; rworldmap; urca.

\[2\] Results for within and random estimators are provided upon request.
variable increases the number of reported cases and deaths is only a statistical artifact, which only means that the number of individuals tested, raises the number of reported cases, which raises the number of reported deaths.

4.2. Panel threshold regression analysis

Linear panel analysis reveals that RH impacts New.cases, while RH, TEMP, and WDSR impact New.deaths. These climate variables are therefore selected to extend the previous analysis into the non-linear panel framework. This section discusses the existence of switching regimes for the climate variables that appeared statistically significant in the previous panel linear regression analysis. Results are presented in Tables 6.1 and 6.2: Panel A (New.cases on dependent variable RH), Panel B (New.deaths on dependent variable RH), Panel C (New.deaths on dependent variable TEMP), and Panel D (New.deaths on dependent variable WDSR). The thresholds are set equal to the mean of the respective weather variables for each country in the sample.

Table 6.1 reports the bootstrap value of the likelihood ratio F-statistic, along with the asymptotic estimate of the bootstrap p-value, the critical values, the sum of squared errors, the thresholds, and the 95% confidence region. The null hypothesis of no threshold is rejected if the p-value is smaller than the desired critical value. The F-test statistics along with their bootstrap p-value are presented only for the case of triple thresholds. The F-test is statistically significant for Panel A, B, and D, which means there is strong evidence of three thresholds in the regression relationship.

Table 6.2 displays the corresponding regression estimates for the panel threshold model. Regime-dependent and independent coefficients are reported along with their conventional and their White (1980)-corrected standard errors; one can note the comparable magnitude of both standard errors calculations, which is not in favor of an important presence of heteroskedasticity. Panel A and B show that the dependent-regime RH variable has both positive and negative coefficients that are statistically significant for both cases and deaths. Hence, relative humidity is a regime-dependent variable with triple thresholds that are statistically significant. In other words, relative humidity influences reported cases and deaths in both low and high regimes at the 5% significance level. No other weather variable shares this feature.

Panel D shows that the regime-dependent variable WDSR has only one positive coefficient that is close to being significant at the 5% significance level.

4.3. Summary

Empirical results can be summarized in three main findings.

First, panel regression analysis reveals that day-to-day weather variations do not influence Covid-19 reported cases and deaths, but instead, they do affect Covid-19 spread across countries. In contrast, government interventions do influence Covid-19 circulation only on a day-to-day basis but not across countries.

Second, panel regression analysis also reveals that relative humidity reduces the number of cases and deaths while temperature and wind reduce the number of deaths. In particular, relative humidity appears as the most influential variable for reported cases while wind appears as the most influential variable for reported deaths.

Third, panel threshold regression analysis reveals that relative humidity appears as the sole weather variable that is influential under both low and high regimes for both reported cases and deaths.

4.4. Discussion

The findings that climate variables are statistically significant and negatively related to Covid-19 reported cases and deaths seem consistent with some other articles, although this evidence seems not always homogeneous across studies as reported in the relevant literature. The existing results from the literature may be sensitive to several biases arising from various dimensions: the scope (global vs. local), the data (raw vs. transformed; missing values vs. no missing values), the model (panel vs. time-series or regression vs. correlation), the panel (a balanced database with lesser observations vs. unbalanced database with more observations) and the period (more than one year to capture the seasonal effect of weather variables vs. less than one year with less than four seasons). Put together, these biases may explain some conflicting results spotted in the relevant literature.

The results of this study highlight two important features. First, the role of the climate factor, in the SARS-CoV-2 transmission, is statistically observed across countries (between estimator), but not on a day-to-day basis (within estimator). It means that a country with a given climate is expected to have a different virus exposure than another country with a different climate. It means that different climates imply different risk exposures to SARS-CoV-2. Therefore, countries that share the same climate properties, such as countries that are geographically close, should have a comparable burden of Covid-19 cases and deaths, all other factors set equals (existence of clusters, government policies, population size, and population density, etc.). Notice that the fact it is not observed on a day-to-day basis, does not signify that it could not be observed on another frequency; for instance, it could be conjectured that sampling the data on a weekly frequency might induce a different outcome because weather variables might have a delayed effect on the Covid-19 due to delayed metabolic responses among other reasons. Second, the weather variables are generally negatively associated with Covid-19 contaminations and fatalities. To that end, among the prominent weather variables, relative humidity appears as the most influential since it affects Covid-19 diffusion under every single context (new cases/deaths; low/high regime). The other influencing weather variables (temperature and wind speed) have more effects on reported deaths than on confirmed cases. Contrary to temperature and relative humidity, studies on wind effect are rather scarce while it appears as the most influencing variable for reported deaths; to that end, it can be conjectured that wind speed reduces the virus concentration in the air, which explains its strong negative impact on virus mortality. On the contrary, living in an indoor environment that is poorly ventilated might increase the virus load in the air. This point relates to some extent to the density variable that is positively associated with the virus incidence.

4.5. Research limitation

This study tries to avoid several biases by employing standard methodology (panel linear regression, panel threshold regressions) on balanced transformed panel data. However, this study is also limited by two identified biases.

The first one corresponds to the problem of the omitted variables for which different alternative settings could have been investigated and provided different results. Recall that the variables have been selected based on the relevant literature and according to the degree of correlation between them. This bias is somehow limited by the selection of the most representative weather variables and control variables.

The second one corresponds to the Covid-19 related data. Government variables data are retrieved from Oxford Covid-19 Government Response Tracker. Most of them are highly correlated, and it is possible that the reported data worldwide may suffer from a lack of precision due to local authorities’ errors or omissions. Perhaps, using an alternative source of data might have produced different results. However, this problem applies also to the Covid-19 reported cases and deaths. For example, in some countries, there is information that officials were

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4. Results upon request for single and double thresholds where no F-test appears statistically significant.
censoring and modifying reported cases. In other countries, there are negative cases reported sequentially, which poses a problem for the data treatment; fortunately, discarding negative values on New.cases or New. deaths variables does not change either qualitatively or significantly the results.

5. Conclusion

This paper implements panel linear regressions and panel threshold regressions on the number of cases and deaths from 134 countries on a set of weather variables (air temperature, relative humidity, precipitation, and wind) and control variables (government interventions, total population, and population density) from January 1, 2020, to March 23, 2021.

The results for the panel linear regressions indicate that relative humidity reduces the number of cases and deaths while temperature and wind reduce the number of deaths. The wind appears as the most influential variable for reported deaths, while relative humidity is the most influential variable for reported cases. Public health policies are influential on Covid-19 spread overall across time within each country, but not across countries. The results for the panel threshold regressions highlight the prominent role of relative humidity in low and high regimes on both reported cases and deaths.

The main findings support the influence of climate in the circulation of the virus across countries, but not within each country on a day-to-day variation.

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

Table 1

Data Description

| Variable  | Description                                                                 | Source                                                                 |
|-----------|----------------------------------------------------------------------------|------------------------------------------------------------------------|
| New.cases | Number of confirmed cases.                                                  | https://github.com/CSSEG ISandData                                      |
| New.deaths| Number of deaths cases.                                                    | https://github.com/CSSEG ISandData                                      |
| TEMP      | Mean daily temperature converted to degrees C                              | https://www.nci.noaa.gov/                                              |
| RH        | Mean daily relative humidity                                               | https://www.nci.noaa.gov/                                              |
| PRCP      | Mean total precipitation reported during the day converted to millimeters  | https://www.nci.noaa.gov/                                              |
| WDSP      | Mean daily wind speed value converted to meters per second                 | https://www.nci.noaa.gov/                                              |
| Vaccines  | Cumulative number of doses administered                                    | https://github.com/OxCGRT                                               |
| Tests     | Cumulative number of tests.                                                | https://github.com/OxCGRT                                               |
| Hospitalization | Number of hospitalized patients on date                              | https://github.com/OxCGRT                                               |
| Home.restrictions | Stay home restrictions (0: No measures - 1: recommend not leaving house - 2: require not leaving house with exceptions for daily exercise, grocery shopping, and “essential” trips - 3: Require not leaving house with minimal exceptions) | https://github.com/OxCGRT                                               |
| International. restrictions | International movement restrictions (0: No measures - 1: Screening - 2: Quarantine arrivals from high-risk regions - 3: Ban on high-risk regions - 4: Total border closure.) | https://github.com/OxCGRT                                               |
| Testing.policy | (0: No testing policy - 1: Only those who both (a) have symptoms AND (b) meet specific criteria - 2: testing of anyone showing COVID-19 symptoms - 3: open public testing) | https://github.com/OxCGRT                                               |
| Population| Total population                                                           | https://github.com/OxCGRT                                               |
| Density   | Population density                                                        | https://ourworldindata.org                                             |

Note: This table presents the variables (name, details and source). There are 59,228 observations from January 1st, 2020 to March 22, 2021.
Fig. 1. World Map. Note: This figure presents the world map of the 134 selected country (color) and non-selected countries (white). There are 59,228 observations from January 1st, 2020 to March 22, 2021.

Table 2
Correlation Matrix

|                      | New cases | New deaths | TEMP | PRCP | RH | WDSP | Vaccines | Tests | Hospitalization | Home. restriction | International. restriction | Testing. policy | Population Density |
|----------------------|-----------|------------|------|------|----|------|-----------|-------|-----------------|----------------------|----------------------|----------------|-------------------|
| New.cases            | 1.0000    | 0.0505     | -0.0005 | -0.0039 | -0.0001 | 0.0022 | 0.0002 | -0.0226 | -0.0007 | 0.0170 | 0.0043 | 0.0196 | 0.0070 | 0.0158 |
| New.deaths           | 0.0505    | 1.0000     | -0.0036 | -0.0021 | 0.0006 | 0.0044 | 0.0005 | -0.0089 | -0.0004 | -0.0146 | -0.0325 | 0.0184 | 0.0245 | 0.0077 |
| TEMP                 | -0.0005   | -0.0036    | 1.0000 | -0.0968 | -0.2866 | 0.0934 | -0.0083 | -0.0012 | 0.0034 | 0.0012 | 0.0009 | -0.0089 | 0.0014 | 0.0002 |
| PRCP                 | -0.0039   | -0.0021    | -0.0968 | 1.0000 | 0.1697 | 0.0639 | -0.0001 | 0.0000 | -0.0044 | -0.0005 | 0.0006 | -0.0012 | -0.0001 | -0.0003 |
| RH                   | -0.0001   | 0.0006     | -0.2866 | 0.1697 | 1.0000 | -0.0645 | 0.0017 | 0.0054 | -0.0036 | 0.0000 | 0.0029 | 0.0017 | -0.0013 | -0.0015 |
| WDSP                 | 0.0022    | 0.0044     | 0.0934 | 0.0639 | -0.0645 | 1.0000 | -0.0034 | 0.0039 | -0.0018 | -0.0005 | -0.0015 | -0.0003 | 0.0000 | 0.0003 |
| Vaccines             | 0.0002    | 0.0005     | -0.0083 | -0.0001 | 0.0017 | -0.0034 | 1.0000 | -0.0005 | 0.0000 | 0.0071 | 0.0065 | -0.0003 | 0.0045 | -0.0045 |
| Tests                | -0.0226   | -0.0089    | -0.0012 | 0.0000 | 0.0054 | 0.0039 | -0.0005 | 1.0000 | 0.0001 | 0.0012 | 0.0082 | -0.0102 | 0.0044 | 0.0100 |
| Hospitalization      | -0.0007   | -0.0004    | 0.0034 | -0.0044 | -0.0036 | -0.0018 | 0.0000 | 0.0001 | 1.0000 | -0.0004 | -0.0009 | 0.0017 | -0.0035 | -0.0015 |
| Home. restrictions   | 0.0170    | -0.0146    | -0.0012 | -0.0005 | 0.0000 | -0.0005 | 0.0071 | 0.0012 | -0.0004 | 1.0000 | 0.4403 | 0.3300 | 0.2433 | 0.0176 |
| International.       | 0.0043    | -0.0325    | 0.0009 | 0.0066 | 0.0029 | -0.0015 | 0.0065 | 0.0082 | -0.0009 | 0.4403 | 1.0000 | 0.4750 | 0.1518 | -0.0928 |
| restrictions         | 0.0196    | 0.0184     | -0.0089 | -0.0012 | 0.0017 | -0.0003 | -0.0003 | -0.0102 | 0.0017 | 0.3300 | 0.4750 | 1.0000 | 0.0822 | 0.1161 |
| Testing. policy      | 0.0070    | 0.0245     | 0.0014 | -0.0001 | -0.0013 | 0.0000 | 0.0045 | 0.0044 | -0.0005 | 0.2433 | 0.1518 | 0.0822 | 1.0000 | 0.0108 |
| Population           | 0.0158    | 0.0077     | 0.0002 | -0.0003 | -0.0015 | 0.0003 | -0.0045 | 0.0100 | -0.0015 | 0.0176 | -0.0928 | 0.1161 | 0.0108 | 1.0000 |

Note: This table presents the correlation matrix among the variables. The transformed variables are: First difference divided by previous day cumulative observation (New.cases, New.deaths); First difference divided by the previous day observation (Vaccines, Tests, Hospitalization); First difference (TEMP, RH, PRCP, WDSP); Log (Population); Log(Density). The raw variables correspond to the ordinal variables (Home.restrictions, International.restrictions, Testing.policy).
Fig. 2. Correlation Plot. Note: This figure plots the correlation matrix among the variables. The transformed variables are: First difference divided by previous day cumulative observation (New.cases, New.deaths); First difference divided by the previous day observation (Vaccines, Tests, Hospitalization); First difference (TEMP, RH, PRCP, WDSP); Log (Population; Density). The raw variables correspond to the ordinal variables (Home.restrictions, International.restrictions, Testing.policy).

Table 3
Descriptive Statistics

| Variable    | Mean     | Standard Deviation | Minimum   | Maximum   | Skewness  | Kurtosis   |
|-------------|----------|--------------------|-----------|-----------|-----------|------------|
| New.cases   | -0.0022  | 0.0871             | -2.0000   | 4.5000    | 9.1275    | 509.5724   |
| New.deaths  | -0.0044  | 0.0647             | -1.0000   | 3.0000    | -2.7525   | 297.4977   |
| TEMP        | 0.0058   | 1.4828             | -19.9629  | 19.0250   | -0.3367   | 7.1987     |
| RH          | -0.0124  | 6.0498             | -51.3500  | 59.2500   | 0.1348    | 4.2867     |
| PRCP        | 0.0007   | 6.4939             | -239.0000 | 241.4500  | 0.2797    | 166.7368   |
| WDSP        | 0.0003   | 0.9269             | -11.7000  | 10.2295   | 0.1539    | 7.2238     |
| Vaccines    | 0.0076   | 10.5000            | 0.0000    | 2499.0000 | 229.4635  | 54341.7202 |
| Tests       | 0.0176   | 0.2368             | -0.2188   | 39.7778   | 115.8509  | 16534.7595 |
| Hospitalization | 0.0354 | 6.7087            | -0.9992   | 1628.0000 | 241.8508  | 58680.3696 |
| Population  | 16.1652  | 1.7752             | 11.0662   | 21.0545   | -0.1382   | 0.3546     |
| Density     | 4.2853   | 1.4966             | 0.6830    | 8.9766    | 0.0463    | 0.5648     |

Note: This table presents descriptive statistics of transformed variables (New.cases, New.deaths, Vaccines, Tests, Hospitalization, TEMP, RH, PRCP, WDSP; Population, Density). The raw variables correspond to the ordinal variables (Home.restrictions, International.restrictions, Testing.policy). There are 59,228 observations from January 1st, 2020 to March 22, 2021.

Table 4
Unit Root Tests

| Variables     | KPSS      | ADF        | HADRI         | IPS        |
|---------------|-----------|------------|---------------|------------|
| New.cases     | 0.086218  | -95.5130   | -0.5367 (0.7043) | -457.52 (0.000) |
| New.deaths    | 0.051132  | -87.7240   | -134.840      | -143.510   |
| TEMP          | 0.01228   | -134.840   | -143.510      | -143.510   |
| RH            | 0.012068  | -134.840   | -143.510      | -143.510   |
| PRCP          | 0.0008742 | -160.780   | -155.420      | -155.420   |
| WDSP          | 0.0033335 | -90.1880   | -90.1880      | -90.1880   |
| Vaccines      | 0.10072   | -90.1880   | -90.1880      | -90.1880   |
| Tests         | 0.11086   | -90.1880   | -90.1880      | -90.1880   |
| Hospitalization | 0.094746 | -99.2850   | -99.2850      | -99.2850   |
Note: This table presents the stationarity tests for the transformed variables (New_cases, New_deaths, Vaccines, Tests, Hospitalization, TEMP, RH, PRCP, WDSP). It includes univariate KPSS test with null hypothesis of non-unit root (automated lag detection) and the univariate ADF test with the null hypothesis of unit-root test (5 lags). It also includes the HADRI panel data test with the null hypothesis of non-unit root (5 lags) and the IPS panel data test with the null hypothesis of non-unit root (5 lags). For KPSS and ADF tests. The p-values are respectively 0.1 and 0.01 for each variable; for HADRI and IPS, p-values are in parenthesis.

Fig. 3. Covid-19 vs Meteorological Factors. Note: These figures present the Covid-19 data (daily growth rate) versus meteorological data (daily first difference) according to the five continents to which belong the 134 selected countries. The meteorological factors plotted are selected according to the statistically significant variables that appear respectively in Table 5.1 (RH) and Table 5.2 (RH, TEMP, WDSP). There are 59,228 observations from January 1st, 2020 to March 22 2021.

Table 5.1
Panel Linear Regression Models for New Cases

|            | Model 1               | Model 2               | Model 3               |
|------------|-----------------------|-----------------------|-----------------------|
| Intercept  | −0.0023*** (0.0006)   | −0.0046*** (0.0016)   | −0.0073*** (0.0023)   |
| TEMP       | −0.0549 (0.0427)      | −0.0306 (0.0429)      |
| RH         | −0.0348*** (0.0128)   | −0.0233** (0.0132)    |
| PRCP       | −0.0198 (0.0408)      | 0.0032 (0.0408)       |
| WDSP       | 0.0034 (0.1137)       | −0.0245 (0.1132)      |
| Vaccines   | 0.0005 (0.0009)       | 0.0005 (0.0009)       |
| Tests      | 0.0475* (0.0260)      | 0.0355 (0.0260)       |
| Hospitalization | 0.0005 (0.0014) | 0.0005 (0.0013) |

(continued on next page)
### Table 5.1 (continued)

| Model 1       | Model 2       | Model 3       |
|---------------|---------------|---------------|
| Home Restriction | −0.0005      | −0.0008      |     |
|               | (0.0008)     | (0.0008)     |     |
| International Restriction | −0.0005      | 0.0002       |     |
|               | (0.0008)     | (0.0008)     |     |
| Testing Policy      | 0.0019**     | 0.0010       |     |
|               | (0.0282)     | (0.0099)     |     |
| Density          | 0.0007**     | 0.0003       |     |
|               |              | (0.0003)     |     |
| **R^2**         | 0.0716       | 0.0830       | 0.1557 |

Note: This table presents the panel regression results for the “between” estimator for the New.cases. Model 1: Climate variables only. Model 2: Government intervention variables only. Model 3: Climate and Control variables (Government intervention and Density). Period: January 3 2020 to March 22 2021. Number of countries = 134; Number of days = 441; Number of observations = 59,228. The ***. ** and * denote respectively significance at the 1%, 5% and 10% level. The F-test for fixed effects (within; between) under the null is that no time-fixed effects needed is rejected (F = 1.471. df1 = 132. df2 = 58950. p-value = 0.0003; F = 321.5400. df1 = 58960. df2 = 122. p-value = 0.0000); fixed effects are preferred to OLS. The Breusch-Pagan (1980) Lagrange Multiplier test to check for the presence of individual and time effects in residuals under the null hypothesis of no panel effect is rejected (chisq = 16.6390. df = 10. p-value = 0.0827; chisq = 20.402. df = 11. p-value = 0.0401); fixed effects are preferred to random effects.

### Table 5.2

Panel Linear Regression Models for New Deaths

| Model 1       | Model 2       | Model 3       |
|---------------|---------------|---------------|
| Intercept     | −0.0046***    | −0.0070***    | −0.0170***   |
|               | (0.0003)     | (0.0011)     | (0.0025)     |
| TEMP          | −0.0456       | −0.0760**     |     |
|               | (0.0290)     | (0.0270)     |     |
| RH            | −0.0379***    | −0.0322***    |     |
|               | (0.0087)     | (0.0082)     |     |
| PRCP          | 0.0089        | 0.0034       |     |
|               | (0.0277)     | (0.0176)     |     |
| WDSR          | −0.1031       | −0.1791**     |     |
|               | (0.0772)     | (0.0772)     |     |
| Vaccines      | 0.0004        | 0.0003       |     |
|               | (0.0006)     | (0.0005)     |     |
| Tests         | 0.0116        | −0.0111      |     |
|               | (0.0184)     | (0.0154)     |     |
| Hospitalization | −0.0002     | −0.0005      |     |
|               | (0.0010)     | (0.0008)     |     |
| Home Restriction      | 0.0011*     | 0.0005       |     |
|               | (0.0006)     | (0.0005)     |     |
| International Restriction | −0.0003    | −0.0006      |     |
|               | (0.0005)     | (0.0005)     |     |
| Testing Policy     | 0.0011*     | 0.0005       |     |
|               | (0.0006)     | (0.0005)     |     |
| Population      | 0.0009***    | 0.0002       |     |
|               |              | (0.0002)     |     |
| New.cases(-1)   | 0.1874**     | 0.1874***    |     |
|               |              | (0.0526)     |     |
| **R^2**         | 0.1441       | 0.0801       | 0.4231 |

Note: This table presents the panel regression results for the “between” estimator for the New.deaths. Model 1: Climate variables only. Model 2: Government intervention variables only. Model 3: Climate and Control variables (Government intervention and Population). Period: January 3 2020 to March 22 2021. Number of countries = 134; Number of days = 441; Number of observations = 59,228. The ***. ** and * denote respectively significance at the 1%, 5% and 10% level. The F-test for fixed effects (within; between) under the null is that no time-fixed effects needed is rejected (F = 1.311. df1 = 132. df2 = 58815. p-value = 0.009621; F = 511.8800. df1 = 5882. df2 = 121. p-value = 0.0000); fixed effects are preferred to OLS. The Breusch-Pagan (1980) Lagrange Multiplier test to check for the presence of individual and time effects in residuals under the null hypothesis of no panel effect is rejected (chisq = 287.24. df = 2. p-value < 2.2e-16); random effect are preferred to OLS. The Hausman (1978) test under the null hypothesis that the preferred model is random effects against the alternative fixed effects (within; between) is rejected (chisq = 11.8760. df = 11. p-value = 0.0000; chisq = 81.82. df = 12. p-value = 1.853e-12); fixed effects are preferred to random effects.
Fig. 4. Residual Plot. Note: These figures present the residuals from Model 3 of Table 5.1 (New.cases) and Table 5.2 (New.deaths) for each of the 134 selected countries. The residuals are computed as the difference between the dependent variable (New.cases or New.deaths) and the fitted values from Model 3; they provide the sign and the magnitude of the model bias for each country. There are 59,228 observations from January 1st, 2020 to March 22, 2021.

Table 6.1
Tests for Threshold Effect

|                  | Panel A   | Panel B   | Panel C   | Panel D   |
|------------------|-----------|-----------|-----------|-----------|
| F1               | 12.9085*  | 14.5982***| 4.284596  | 10.14766**|
| P-Value          | 0.0650    | 0.0100    | 0.3850    | 0.050     |
| (10%. 5%. 1% critical values) | (10.6236, 13.6499, 30.7927) | (8.3911, 10.1531, 14.2247) | (8.4552, 11.1386, 16.1867) | (8.6091, 9.9305, 13.9152) |
| Sum of Squared Errors | 447.0556  | 246.5503  | 246.6075  | 246.5877  |
| Thresholds (γ1/γ2/γ3) | -0.1064   | -0.0470   | -0.0126   | -0.0096   |
|                  | 0.0229    | 0.0445    | 0.0216    | 0.0087    |
|                  | 0.0703    | 0.0368    | 0.03578   | 0.0027    |
| (95% Confidence Region) | (-0.0677, 0.0456) | (-0.1319, 0.0812) | (-0.011, 0.0358) | (-0.0096, 0.0102) |

Note: This table presents the tests for the threshold effects: Panel A (New.cases on dependent variable RH). Panel B (New.deaths on dependent variable RH). Panel C (New.deaths on dependent variable TEMP) and Panel D (New.deaths on dependent variable WDSP). These meteorological factors are selected according to the statistically significant variables that appear respectively in Table 5.1 (RH) and Table 5.2 (RH, TEMP, WDSP). The threshold is set equal to the mean of the climate variable of each country in the sample. Hansen (1999) implements a bootstrap approach to simulate the asymptotic distribution of the likelihood ratio test for which if the p-value for the F test under the null is smaller than critical value, the null hypothesis of no threshold effect is rejected. 200 bootstrap replications are used for each of the four tests. Period: January 3, 2020 to March 22, 2021. Number of countries = 134; Number of days = 441; Number of observations = 59,228. The ***. ** and * denote respectively significance at the 1%. 5% and 10% level.
### Table 6.2
Panel Threshold Regression Models

| Panel A: New Cases | Regime-dependent Coefficients | OLS Standard Errors | White Standard Errors | T-Statistics |
|-------------------|-------------------------------|---------------------|-----------------------|--------------|
| RH ($\beta_1$)    | 0.0011                        | 0.0005              | 0.0007                | 1.4423       |
| ($\beta_2$)       | -0.0001                       | 0.0001              | 0.0001                | -0.7211      |
| ($\beta_3$)       | 0.0005**                      | 0.0002              | 0.0002                | 2.1369       |
| ($\beta_4$)       | -0.0004**                     | 0.0002              | 0.0002                | -2.0850      |

| Panel B: New Deaths | Regime-dependent Coefficients | OLS Standard Errors | White Standard Errors | T-Statistics |
|---------------------|-------------------------------|---------------------|-----------------------|--------------|
| TEMP ($\theta_1$)   | -0.0001                       | 0.003               | 0.003                 | -0.2834      |
| PRCP ($\theta_2$)   | -0.0001                       | 0.0001              | 0.0000                | -1.6368      |
| WDSP ($\theta_3$)   | 0.0002                        | 0.0004              | 0.0004                | 0.4968       |

| Panel C: New Deaths | Regime-dependent Coefficients | OLS Standard Errors | White Standard Errors | T-Statistics |
|---------------------|-------------------------------|---------------------|-----------------------|--------------|
| TEMP ($\theta_1$)   | -0.0002                       | 0.002               | 0.002                 | -0.6414      |
| PRCP ($\theta_2$)   | -0.0000                       | 0.0000              | 0.0000                | -0.7196      |
| WDSP ($\theta_3$)   | 0.0003                        | 0.0003              | 0.0003                | 0.99128      |

| Panel D: New Deaths | Regime-dependent Coefficients | OLS Standard Errors | White Standard Errors | T-Statistics |
|---------------------|-------------------------------|---------------------|-----------------------|--------------|
| WDSP ($\beta_1$)    | -0.0015                       | 0.0013              | 0.0018                | -1.1068      |
| ($\beta_2$)         | 0.005*                        | 0.0020              | 0.0021                | 0.7982       |
| ($\beta_3$)         | 0.0009                        | 0.0006              | 0.0007                | 1.2290       |
| ($\beta_4$)         | -0.0011                       | 0.0009              | 0.0009                | -1.2303      |

Note: The table reports the panel threshold regression results of the four tests: Panel A (New cases on dependent variable RH), Panel B (New deaths on dependent variable RH), Panel C (New deaths on dependent variable TEMP) and Panel D (New deaths on dependent variable WDSP). These meteorological factors are selected according to the statistically significant variables that appear respectively in Table 5.1 (RH) and Table 5.2 (RH, TEMP, WDSP). It presents both the OLS standard errors and the White-corrected standard errors. Period: January 3 2020 to March 22 2021. Number of countries = 134; Number of days = 441; Number of observations = 59,228. The ***, ** and * denote respectively significance at the 1%, 5% and 10% level.
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