Does the morbidity of SARS-CoV-2 depend on climatic factors? A global-scale study using Structural Equation Modeling

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Research Article

Keywords: Covid-19, SARS-CoV-2, structural equation modeling, climate, solar irradiation, temperature, humidity

Posted Date: September 29th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-83741/v1

Abstract

Climate seems to influence the spread of SARS-CoV-2, but the findings of the studies performed so far are conflicting. To overcome these issues, we performed a global scale study considering 134,871 virologic-climatic-demographic data (209 countries, first 16 weeks of the pandemic). To analyze the relation between Covid-19, population density, and climate, a theoretical path diagram was hypothesized and tested using Structural Equation Modeling (SEM), a powerful statistical technique for the evaluation of causal assumptions. The results of the analysis showed that both climate and population density significantly influence the spread of Covid-19 ($p<0.001$ and $p<0.01$, respectively). Overall, climate outweighs population density (b-incidence=0.18, b-prevalence=0.11 *versus* b-incidence=0.04, b-prevalence=0.05). Among the climatic factors, irradiation plays the most relevant role, with a factor-loading of -0.77, followed by temperature (-0.56), humidity (0.52), precipitation (0.44), and pressure (0.073); for all $p<0.001$. An interesting outcome was the value of residual variance (ε-incidence=0.97, ε-prevalence=0.98) suggesting that other factors influence the transmission of the infection. In conclusion, this study demonstrates that climatic factors significantly influence the spread of SARS-CoV-2. However, demographic factors, together with other determinants, can affect transmission, and their influence may overcome the protective effect of climate, where favourable.

Introduction

SARS-CoV-2, a betacoronavirus responsible for Covid-19, has reached a global scale and, on March 11, 2020, the World Health Organization classified it as a pandemic. Still ongoing, Covid-19 has completely reshaped our world from all points of view, with dramatic social, economic, and psychological consequences.

Data provided by government and health organizations show a different distribution of the epidemic across countries [1], advocating a possible relationship between Covid-19 and climate factors. To address this issue, several studies have been carried out, but their results are mixed and conflicting [2–10].

The reasons for such contrasting findings are rooted in some intrinsic limitations, such as the absence of world-wide investigations (most of them considered only one or a few countries) [3,7], the short observation period (2-8 weeks) [4,9], and the low number of climatic variables considered [2,5]. Moreover, further unintentional biases have also led to other insidious pitfalls and to the consequent aforementioned discrepancy. One of these is the onset of outbreak. As the beginning of the infection did not occur simultaneously across the countries, if evaluated at the same time point, the countries whose outbreak started earlier tend to record higher prevalence of infection than the others. This requires a relative time scale, synchronizing the countries based on the beginning of the epidemic, prior to any statistical analysis.

Another pitfall is the single point of estimation. Climatic conditions across countries vary considerably from region to region. Data collection limited to a restricted area (e.g. the capital city) is not representative of the whole country, and this may cause misleading results. Therefore, more data collection points within the same country should be taken into account. A further pitfall is the lag interval. Incubation period, delayed testing from the onset of symptoms, as well as, late communication of test results, all contribute to a time shift between the infection exposure and the confirmation of diagnosis. Consequently, a lag time must be considered between the collection of covid-19 data and the acquisition of climatic data for the analysis.

Finally, interdependence of variables. Climatic variables are commonly considered as stand-alone factors. Instead, they interact with each other. Therefore, an integrative and specific analysis is necessary for a comprehensive understanding of their effects.

Altogether, these questions may account for the discrepancy among the numerous studies published, leaving the debate about the relationship between climatic factors and Covid-19 still open.

Surely, knowing the factors influencing the epidemic and understanding the dynamics of its spread is strategic and crucial. This would allow us not only to limit the contagion, but also to better calibrate the containment policies, thus reducing the psychological, social, and economic repercussions.

Starting from these considerations, we carried out an extensive and comprehensive analysis, based on as many as 134,871 data, using Structural Equation Modeling (SEM), a statistical technique for testing the relationships between observed variables and latent variables, based on statistical data and causal qualitative hypothesis [11,12]. Applied for the first time in the 70s in the field of social sciences with variables that could not be directly observed or measured, the SEM later spread among the scientific community, thanks to both its flexibility and rigorous approach. One of the main advantages of SEM is the possibility to take into consideration several dependent variables simultaneously.

Flexibility and potential of this analysis were key for the evaluation of climatic factors and their role in the outbreak of SARS-CoV-2, trying to overcome the limitations and the pitfalls above-mentioned. In addition, since Covid-19 seems to spread more widely in highly populated areas, we also investigated the influence of some socio-demographic variables (such as population density) over the incidence of the disease.

Results

The morbidity of pandemic differs among the climatic zones and by population density

Table 1 shows summary statistics of meteorological variables, population density, weekly incidence and prevalence of SARS-CoV-2, by climatic zones. All data are relative to the first 16 weeks of infection in the 209 countries considered in this study. The warm temperate zone showed the highest values of incidence ($\mu \pm \sigma = 24.68 \pm 46.33$) and prevalence ($\mu \pm \sigma = 94.82 \pm 216.56$), as well as of population density ($\mu \pm \sigma = 564.38 \pm 2986.82$), a relevant factor in virus transmission through both respiratory droplets and contact routes. In contrast, low values of incidence and prevalence were recorded in the equatorial ($\mu \pm \sigma = 4.28 \pm 12.89$ and $\mu \pm \sigma = 11.84 \pm 35.67$, respectively) and arid zone ($\mu \pm \sigma = 10.77 \pm 34.01$ and $\mu \pm \sigma = 27.78 \pm 95.75$), areas with the hottest temperature and greater solar irradiation.

The non-parametric k-sample test for median equality confirmed the different spreading dynamics of Covid-19, showing statistically significant differences in incidence and prevalence among the various geoclimatic zones (incidence, Chi square = 309.0387 $p < 0.001$; prevalence, Chi square = 317.6152 $p < 0.001$).

Table 1

Climatic zone	Variable	Mean	Std. Dev.	Min	Max
Cold temperate	Precipitation	2.61	2.68	0.00	18.15
	Humidity	77.46	10.15	32.68	97.40
	Pressure	96.97	5.93	78.87	102.70
	Temperature	5.85	6.11	-15.16	25.64
	Wind	2.80	1.62	0.28	11.59
	Solar irradiation	13.80	5.43	0.79	29.06
	Population density	58.83	62.51	3.00	284.00
	Weekly incidence	23.13	34.38	0.00	205.08
	Weekly prevalence	74.29	133.73	0.00	856.62
Warm temperate	Precipitation	2.70	3.17	0.00	21.64
	Humidity	74.46	11.16	23.04	97.12
	Pressure	97.62	4.54	76.36	102.96
	Temperature	11.72	6.41	-11.21	32.64
	Wind	2.58	1.60	0.22	13.02
	Solar irradiation	15.58	5.38	1.17	29.23
	Population density	564.38	2986.82	12.00	26337.00
	Weekly incidence	24.68	46.33	0.00	342.91
	Weekly prevalence	94.82	216.56	0.00	1502.94
Arid	Precipitation	1.58	3.76	0.00	47.56
	Humidity	54.37	18.42	8.22	89.43
	Pressure	93.93	7.99	75.22	102.37
	Temperature	19.42	8.78	-12.36	36.95
	Wind	2.99	1.69	0.61	16.84
	Solar irradiation	20.15	4.47	4.09	30.69
	Population density	113.59	328.88	2.00	2239.00
	Weekly incidence	10.77	34.02	0.00	425.64
	Weekly prevalence	27.78	95.75	0.00	1231.56
Equatorial	Precipitation	5.68	7.90	0.00	61.27
	Humidity	77.07	10.00	39.34	95.85
	Pressure	98.10	4.49	83.64	101.82
	Temperature	26.18	3.03	13.30	33.25
	Wind	2.69	1.66	0.25	8.16
	Solar irradiation	19.54	4.32	0.77	28.37

	Population density	351.20	1082.77	8.00	8358.00
	Weekly incidence	4.28	12.89	0.00	115.40
	Weekly prevalence	11.84	35.67	0.00	343.64

Table 1. Summary statistics of meteorological variables, *weekly incidence* and *weekly prevalence* of SARS-CoV-2, population density, by climatic zone, in the first 16 weeks of the infection, in 209 countries.

A bivariate approach on morbidity of SARS-CoV-2 and its determinants can hide more complex relationships?

To evaluate a two-way association between incidence, prevalence, population density and meteorological variables, Spearman correlation coefficient was calculated. According to the latter, only moderate concordance between solar irradiation and temperature ($r=0.58$; $p<0.05$) and a significant (albeit low) negative correlation of temperature with incidence and prevalence ($r = -0.37$ and $r = -0.34$, respectively) exists (table 2).

Indeed, the weak correlations detected is likely due to the heterogeneity of the climatic conditions of the countries considered. In these cases, a simple bivariate approach (such as the Spearman's rank correlation coefficient) cannot reveal complex relationships. A more relevant analysis, where variables can be considered simultaneously and in an integrated way, is therefore needed.

Table 2

	Precipitation	Humidity	Pressure	Temperature	Wind	Solar irradiation	Population density	Incidence	Prevalence
Precipitation	1.00								
Humidity	0.55*	1.00							
Pressure	-0.11	0.15*	1.00						
Temperature	-0.02	-0.16	0.22*	1.00					
Wind	-0.19	-0.03	0.41*	0.09*	1.00				
Solar irradiation	-0.38	-0.50	0.05*	0.58*	0.02	1.00			
Population density	-0.04	0.01	0.22*	0.13*	0.05*	0.11*	1.00		
Incidence	0.05*	0.09*	0.07*	-0.37	-0.01	-0.15	-0.01	1.00	
Prevalence	0.04	0.06*	0.07*	-0.34	-0.02	-0.08	0.01	0.95*	1.00

Table 2. Spearman's rank correlation coefficient between meteorological variables, *weekly incidence* and *weekly prevalence* of SARS-CoV-2, and *population density*. *$p<0.05$.

SEM reveals a significant effect of the climate and density of population on SARS-CoV-2, overcoming the bivariate approach and integrating the effects of weather variables into climate variable

In light of the above, the use of SEM is appropriate, as it allows for further investigation of the relation between SARS-CoV-2 incidence and prevalence with population density and meteorological variables. A theoretical path diagram has been drawn up (figure 1) and tested by SEM.

The results of the analysis showed a clear causative role of climate. The integrated effects of meteorological factors, measured at two-week lag and expressed by a single latent variable (climate), resulted to be significantly ($p<0.001$) linked to incidence and prevalence by a standardized positive path coefficient ($b = 0.18$ and $b = 0.11$, respectively) (figure 2).

In turn, the different climatic factors were found to be correlated with climate in a different way. Specifically, solar irradiation and temperature were negatively correlated, with a factor loading of -0.77 ($p < 0.001$) and -0.56 ($p < 0.001$), respectively. While, relative humidity, precipitation and pressure showed a positive correlation, with factor loading of 0.52, 0.44, and 0.073, respectively (for all, $p < 0.001$). Wind was negatively correlated (-0.046) but without a significant p-value.

Also, population density resulted to be linked to incidence and prevalence by standardized positive path coefficients ($b = 0.043$, $p < 0.01$ and $b = 0.051$, $p < 0.01$, respectively), although to a lesser extent than those exhibited by climate. The variables, incidence and prevalence observed, being by their nature closely related, showed a high covariance between errors of 0.96 ($p < 0.001$).

An interesting outcome is given by the residual variance of the observed variables ($\varepsilon 1=0.97$ for incidence and $\varepsilon 2=0.98$ for prevalence). This parameter represents the unmeasured factors affecting incidence and prevalence. Basically, this parameter indicates that factors other than climate and population density affect SARS-CoV2 incidence and prevalence.

Finally, the goodness of fit of the model was tested, and the results of the evaluation showed an overall good fit (CD=0.826, RMSEA=0.088, SRMR=0.078). This demonstrates that SEM adequately confirms the theoretical path diagram of Figure 1, indicating the strength and direction of association between incidence and prevalence of SARS-CoV-2, climatic variables, and population density.

Overall, the results of the analysis demonstrated that a) climate has a relevant impact on incidence and prevalence of SARS-CoV-2 (at least in the first 16 weeks), stronger than that exhibited by density of population; b) among the climatic variables, solar irradiation proved to be the most influential factor, followed (but in the opposite direction) by relative humidity, and by temperature (in the same direction of solar irradiation).

Discussion

Covid-19 pandemic represents a serious threat for people worldwide, with an alarming day-by-day increasing number of infections and death cases. Consequently, the scientific community worldwide is constantly seeking for new and useful knowledge aimed at contrasting the spread of SARS-CoV-2.

Climatic factors seem to play a role in the epidemiology of the infection. However, results of recent studies on the subject are mixed and conflicting.

In this paper, we have carried out an extensive and comprehensive analysis to determine the role of climate and some demographic factors in the spread of COVID-19. For this purpose, we used a particular and powerful statistical technique (the Structural Equation Modeling), for the evaluation of causal assumptions, taking into consideration several dependent variables at the same time (weekly incidence and weekly prevalence).

The key objective of this study was to overcome the limitations of previous investigations. In this view, we have a) conducted research on a global scale (on all countries in the world), b) carried out observation over a long period of time (the longest among the studies published so far), c) considered not some but all the main six climatic factors, d) used a relative time scale, synchronizing the countries based on the beginning of the epidemic, e) took into account not a single point but multiple points of evaluation for climatic variables for each country, f) considered a lag interval between the collection of covid-19 data and the acquisition of climatic data for the analysis, g) did not consider the variables as stand-alone factors but kept into account their interdependence and used an integrative statistical investigation to evaluate their effects.

This approach helped build a more comprehensive and robust analysis, with more solid and reliable findings. The findings of this investigation, relative to the first 16 weeks of the pandemic, were highly consistent with the hypothesis that both climate and population density have significantly influenced the spread of Covid-19. Overall, climate outweighs population density, and, in this context, solar irradiation, plays the most relevant role.

This is in line with the results of some epidemiological reports [10] and with a recent experimental investigation demonstrating that UV radiation, in very small doses, is able to inactivate SARS-CoV-2 [13]. Although to a lesser extent, temperature, humidity, and precipitation also resulted to significantly influence SARS-CoV2 incidence and prevalence. The role of wind, instead, was demonstrated to be small, while that of pressure was not relevant. Overall, these findings may account for the different initial distribution of the epidemic across the countries, with the cold countries being affected more quickly and more intensely than the hot ones.

Similarly, the aforementioned results provide support to the common opinion that the climate is a determining factor in the spread of the pandemic. They also provide grounds for recent clusters of infections that have developed in different European working places, all characterized by a lack of solar irradiation and low temperature (i.e. a sausage factory in Mantova, Italy; a slaughterhouse in Gütersloh, Germany; a slaughterhouse in Tipperary, Ireland).

However, the significant increase in new cases observed in the last weeks in Brazil, India, and the USA seems to contradict the conclusions drawn in the present study, as this recent outbreak of pandemic occurred in countries with high temperature and good solar irradiation. In fact, since SEM has shown that SARS-CoV-2 incidence and prevalence is certainly influenced by climate but that it also depends on population density (very high in the three countries mentioned), if accurately interpreted, the findings of the present study may explain this apparent paradox.

In addition, a closer look at the SEM diagram reveals another intriguing detail. The residual term (i.e. the coefficient in the circles near incidence and prevalence) is quite high. This indicates that other factors influence the spread of SARS-CoV-2 too (severity and observance of containment measures, intensity of trade and human contact, hygiene measures, etc.).

All these variables, not considered in the present paper, may account for the residual effect on both incidence and prevalence and they are currently under evaluation by our research group.

In conclusion, the present study demonstrates that climatic factors significantly affect the spread of SARS-CoV-2 (probably and especially by influencing the air transmission through respiratory droplets). Among the variables investigated, solar irradiation proved to be the most influential factor, followed by temperature, humidity, precipitation, and, with a minimal or non-significant impact, pressure, and wind. However, demographic factors, together with other determinants, can affect the transmission (probably and especially through direct contact routes), and the influence of these can be such that they may overcome the protective effect of climate in some countries.

Methods

Data sources

Data regarding Covid-19 were collected from Johns Hopkins GitHub repository Systems Science and Engineering [14]. The information on governmental measures (school and university closures) were acquired from the UNESCO database [15].

The climatic parameters reported were taken from the dataset of the NASA Langley Research Center (LaRC) POWER Project [16].

The demographic estimates (population size, land area, population density) were obtained from the United Nations population estimates and from the World Factbook of Central Intelligence Agency (CIA) [17].

Geoclimatic categories

In order to evaluate the relation of Covid-19 with geo-climatic environment, the world has been divided into five geoclimatic zones, according to the updated Koppen-Geiger classification: polar, cold-temperate, warm- temperate, arid, and equatorial [18].

Countries considered

For SARS-Cov-2 analysis, all the UN 193 countries have been taken into account. Among these, 16 small countries, with a population below one million and a density of less than 100 people/km2, as well as 18 countries with insufficient data on Covid-19 have been excluded. Conversely, all 50 states of the United States of America have been considered individually. Therefore, a total of 209 Countries have been included in the present study.

Data acquisition

A total of 134,871 data were acquired from the sources mentioned above and inserted in a Microsoft Excel spreadsheet (Supplementary table S1). Fifteen variables have been considered for the analysis and organized into the 3 groups herein reported.

1) Demographic: population size (number of people), land area (Km2), population density (people/Km2).

2) Climatic: climatic zone (one to five), temperature at two meters (°C), solar irradiation (MJ/m2/day), relative humidity (%), wind speed at two meters (m/sec), surface pressure (KPa), precipitation (mm/day).

3) Covid-19: date of the first confirmed case, number of new weekly cases, number of active weekly cases, weekly incidence (number of new weekly cases /population size per 100,000) and weekly prevalence (number of active weekly cases/population size per 100,000).

Data processing

To ensure that the data collected met the purposes of the study, a set of specific criteria was established for the selection of the appropriate sample, and separate studies were performed to confirm the appropriateness of these choices. In particular:

1) Data on weekly new cases and active cases of SARS-CoV-2 infection were collected for a period of 16 weeks. Since the beginning of the infection did not occur simultaneously across all the countries, the data collected start from the first documented case in each country.

2) To evaluate the relationship between Covid-19 and climatic factors, matching epidemic and climatic data was found to be of importance. In each country, climatic conditions vary considerably across regions. Therefore, one to four cities, one for each of the regions most affected by Covid-19, were chosen for each country. Then, the weekly average was calculated for all the six climatic variables. Finally, the weekly means of all the cities were averaged to get the six total national weekly values. The process was repeated for all the weeks considered.

3) To evaluate the relationship between Covid-19 and climatic factors, a shift time between the collection of virologic data and the acquisition of climatic data had to be taken into consideration. In fact, the incubation period, the delay between symptom onset and testing, and the delay due to the communication of the result, contribute to a time shift between the infection exposure and the publication of the virologic data. Consequently, it is necessary to take into account a lag time between the collection of virologic data and the acquisition of climatic data for the analysis. According to the literature data [19–21], a lag time of two weeks was considered in the present study.

Data analysis

Data relative to SARS-CoV-2 were collected into a balanced panel dataset of 209 countries, starting from the first week of outbreak, until the sixteenth week. Due to data skewness (i.e. data with a non-Gaussian distribution), logarithmic transformation was applied to the analyzed variables. To evaluate two-way association between incidence, prevalence, population density, and meteorological variables, Spearman's rank correlation coefficient was calculated, considering a lag of two weeks between climatic data collection and virologic data acquisition.

In order to analyze the relation among the above-mentioned variables simultaneously, a theoretical path diagram was presumed (figure 1). In this theoretical path, meteorological factors were hypothesized to be correlated to each other and related to an unobserved variable, indicated by climate label. In addition, it is supposed that climate and population density are regressors on incidence and prevalence, whose covariation is expressed by an arc.

To test this theoretical path and convert it into a set of equations, the authors applied the SEM, a broad and flexible statistical technique for modeling causal chain of effects simultaneously. Using a confirmatory approach (hypothesis-testing), this technique, examines the relationships between observed variables and not observed (latent) variables, in turn linked to observed variables, their indicators.

The SEM graphical representation is given by a path diagram, a kind of flow-chart that uses boxes and ellipses linked via arrows. Observed variables are represented by a box, and latent variables by an ellipse. Straight single-headed arrows express causal relations and double-headed curved arrows express correlations or covariance (without a causal interpretation). The values on the straight arrows between latent and observed variables and those between latent and observed indicators, represent the standardized path coefficients and the factors loading, respectively. The circles with short arrows to their respective measured variables define random error and residual terms (sources of systematic variance not due to the variable).

To evaluate the adequacy of the model, the following fit indices were considered [22]: a) coefficient of determination (CD) (similar to the R-squared value, ranging 0-1, good fit for values close to 1); b) root mean square error of approximation (RMSEA) (good fit for RMSEA < 0.08), and c) standardized root mean square residual (SRMR) (adequate fit for SRMR < 0.08).

SEM was fitted by maximum likelihood estimation (MLE) method and p-value less than 0.05 was considered as statistically significant. All of the statistical analysis was performed using STATA 14.0 (STATA Corp, College Station, TX) [23].

Declarations

Author contibutions: All authors contributed to the study conception and design. Data collection was performed by Agorà Covid-19 Task Force, under the supervision of P.P.C., N. C., V. T., M. C. and R. I.. The statistical analyses were chosen and performed by A. S. and F. A. T.. The first draft of the manuscript was written by A. U. and A. T. and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding: None

Conflict of interests: None

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Figures

Figure 1

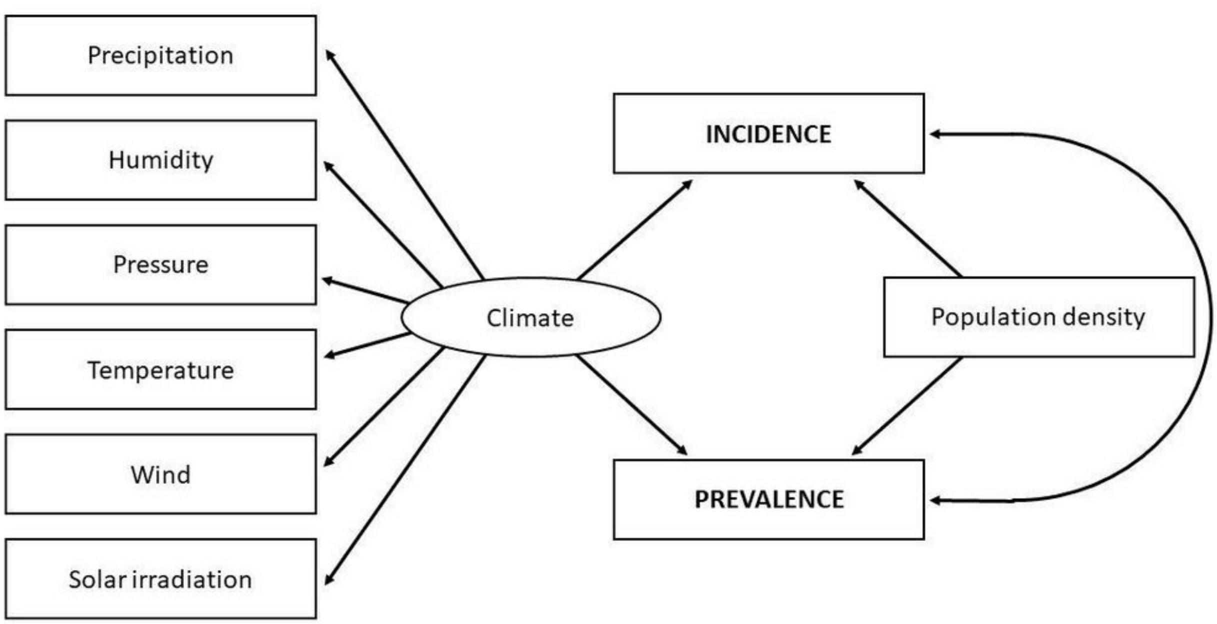

Figure 1. Theoretical path diagram used to analyze the effects of climate and population density on the spread of SARS-CoV-2

Figure 1

Theoretical path diagram used to analyze the effects of climate and population density on the spread of SARS-CoV-2

Figure 2

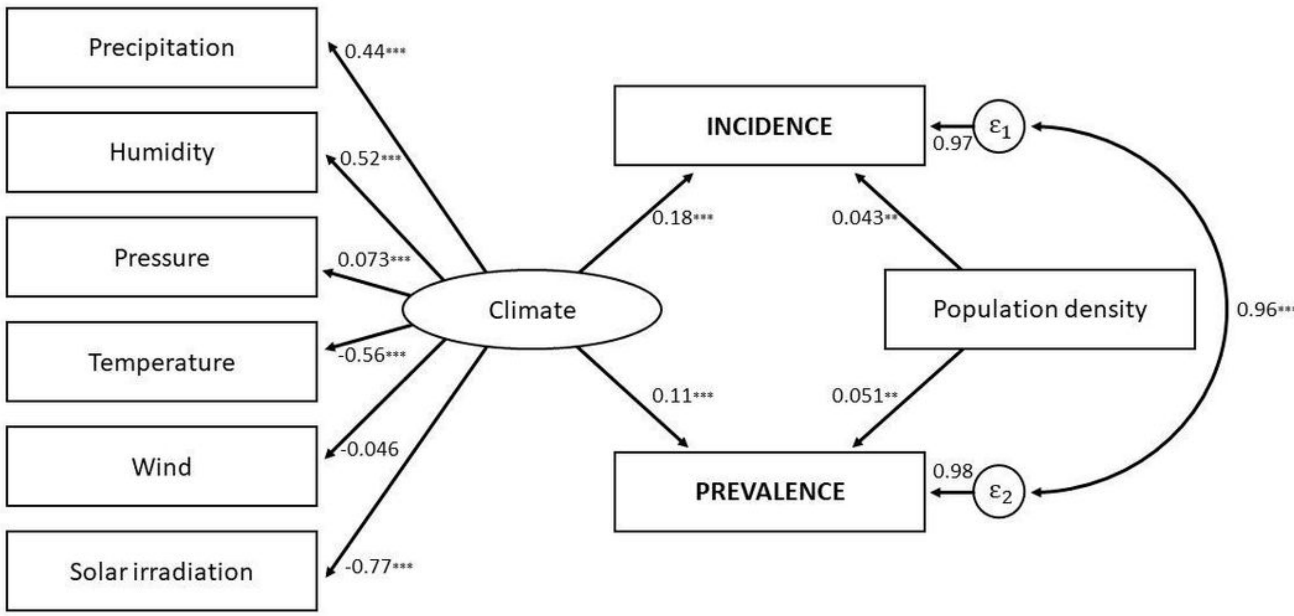

Figure 2. SEM path diagram for the effects of climate and population density on the spread of SARS-CoV-2. *** p<0.001; **p<0.01.

Figure 2

SEM path diagram for the effects of climate and population density on the spread of SARS-CoV-2. *** p<0.001; ** p<0.01

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryTableS1.xlsx