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Original Research

Effect of environmental factors on SARS-CoV-2 infectivity in northern hemisphere countries: a 2-year data analysis

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ABSTRACT

Objective: The COVID-19 pandemic that emerged in December 2019 brought human life to a standstill. With over 2-year since the pandemic originated from Wuhan, SARS-CoV-2 has caused more than 6 million deaths worldwide. With the emergence of mutant strains and COVID-19 surge waves, it becomes critically important to conduct epidemiological studies that allow us to understand the role of various environmental factors on SARS-CoV-2 infectivity. Our earlier study reported a strong negative correlation between temperature and COVID-19 incidence. This research is an extension of our previous study with an attempt to understand the global analysis of COVID-19 in northern hemisphere countries.

Study design: This research aims at achieving a better understanding of the correlation of environmental factors such as temperature, sunlight, and humidity with new cases of COVID-19 in northern hemisphere from March 2020 to February 2022.

Methods: To understand the relationship between the different environmental variants and COVID-19, a statistical approach was employed using Pearson, Spearman and Kendall analysis.

Results: Month-wise univariate analysis indicated a strong negative correlation of temperature and sunlight with SARS-CoV-2 infectivity, whereas inconsistencies were observed in correlation analysis in the case of humidity in winter months. Moreover, a strong negative correlation between average temperature of winter months and COVID-19 cases exists as evidenced by Pearson, Spearman, and Kendall analyses. In addition, correlation pattern between monthly temperature and COVID-19 cases of a country mimics to that of sunlight of a country.

Conclusion: This pilot study proposes that low temperatures and low sunlight might be additional risk factors for SARS-CoV-2 infectivity, mostly in northern hemisphere countries.

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Introduction

The end of 2019 witnessed the emergence of a novel virus in Wuhan, China, which was later identified as severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2).¹ The spread of the virus accelerated to such an extent that the COVID-19 was declared as a pandemic on March 11 by the World Health Organization. Since then, governments all around the world have imposed major lockdowns and travel restrictions to contain the spread of the disease. As of May 2021, 161, 080, 581 confirmed cases have been identified, with more than 3,345,018 deaths worldwide. The SARS-CoV-2 is

reported to develop pneumonia-like symptoms, such as sore throat, fever, cough, shortness of breath, loss of smell and taste, muscle ache, and dry mouth.^{2,3} World Health Organization specifies six pandemic phases wherein previous pandemics such as influenza have reported—“waves of infection spread over months.”⁴ In a matter of the first year, COVID-19 reports a similar pattern with most countries experiencing a two-wave surge of COVID cases. The second wave has been observed in the winter season in most parts of the world, especially in the European countries, including Italy, Germany, Poland, Russia, and France, suggesting a possible link between temperature and COVID-19 incidence. Earlier outbreaks of other respiratory diseases, such as the influenza pandemic (1918), also reported a lethal second wave, which was responsible for the majority of deaths in the United States due to the pandemic.⁵ To understand the role of environmental temperature in the SARS-CoV-2 infectivity, we published data at the beginning of the pandemic, which reported a strong negative correlation relationship between

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environmental temperature with SARS-CoV-2 infection rates in various countries worldwide.⁶ Since then, several studies have been reported that support our findings, thus depicting high COVID-19 incidence, particularly in colder areas.^{7–9} A study by Chen et al. reported a 5.4% decrease in COVID-19 cases with 1°C increase in temperature.¹⁰ However, certain scattered did not observe positive or no correlation between temperature with COVID-19 cases.^{11–13} Although some studies have focused on a single country, other studies have focused on a particular province incorporating such biasness in the analysis. A consequence of such limited data led to a low range of temperature being considered for each study. Also, migration of people was obstructed between the countries in the first place when international travel restriction was imposed. Having said that, it was post lockdown when migration within a country was limited, influencing the spread of infection of COVID-19. Thus, such studies could not find an association between temperature and COVID-19 cases. However, since the data at the time of our previous study was quite dynamic, we have validated our previous study by performing an extended global data analysis from March 2020 to February 2022. Owing to the discrepancies observed in understanding the role of temperature in SARS-CoV-2 infectivity, we have considered that temperature might not be an alone factor. The study has also considered additional environmental factors, such as sunlight and humidity. Our present study focuses on detecting the role of different environmental factors on COVID-19 incidence in northern hemisphere countries. Previously reported epidemics offer epidemiological studies that can help researchers to understand how COVID-19 might unravel with time. Such studies will allow local and global authorities to formalize optimized measures to curtail the frightening spread of this respiratory infection.

Methods

Data collection

The data for COVID-19 from March 2020 to February 2022 was collected from the <http://ourworldindata.org/coronavirus> website. In our study, we have considered new cases of COVID-19 as our variable of interest. The data for new cases for each country were calculated by deducting total cases per million of the previous month's data with later month data. As gathering data for environmental factors for every location of a single country was difficult, the data for the capital of each country were taken into consideration representing the data for the entire country. The data for the maximum and minimum temperature were retrieved from *climatestotravel* site, and the monthly average temperature was calculated for all the countries.⁶ The data for sunlight were obtained in terms of insolation (kWh/m²/day) for capital of each country from *giasma.com* site. The humidity data in terms of relative humidity of different countries were collected from *climate-data.org*. In this study, infectivity of SARS-CoV-2 has been studied in northern hemisphere countries alone, given the fact that the northern hemisphere countries experience winters in December and southern hemisphere countries experience it in the month of June. The data were divided into two sets—winter and summer. The data from November to February were considered for winter months, whereas the data from June to September were considered for summer months.

Statistical analysis

Univariate analysis was performed using Pearson, Spearman, and Kendall methods to determine the relationship between new cases of COVID-19 for each month and environmental factors, described previously.^{6,14–17} The statistical analysis was considered significant for P-value <0.05. The univariate analysis for each factor

was performed using the software GraphPad prism 6.0. The three-dimensional plot was generated using R Studio (Package ggplot2 of statistical software RStudio, version 1.4.1106).

Results

Association between new cases of COVID-19 and temperature and sunlight in northern hemisphere countries in the months of winter and summer

Our previous publication reported strong negative correlation between monthly average environmental temperature and COVID-19 cases. Following that, several studies have been performed to understand the role of temperature in SARS-CoV-2 infectivity and have also reported contradictory results in some cases. To understand the dependence of COVID-19 incidence on different seasons, we divided our data into two sets—winter and summer. The data from November to February were considered for winter months, whereas the data from June to September were considered for summer months. Also, the line of 0° latitude divides the Earth into the northern and southern hemispheres, each experiencing different temperatures at the same time of the year. We have considered only northern hemisphere countries for our analysis. We conducted univariate analysis using Pearson method between monthly average temperature and new cases of COVID-19 for summer and winter months of a country and observed strong negative correlation with statistical significance in winter months. To verify our findings, we further performed correlation using the Spearman univariate method as well as Kendall univariate method. Similar to the Pearson method, we observed a negative association between temperature and new cases of COVID-19 in winter months from November 2020 to February 2021 (Table 1). Hence, our findings suggested that cold temperature might influence SARS-CoV-2 infectivity. To validate our findings, we chose sunlight as another factor for our study. Univariate analysis using Pearson method for northern hemisphere countries depicted a strong negative correlation with statistical significance in winter months. Spearman and Kendall's statistical analyses also found a strong negative correlation in the winter months from November 2020 to February 2021 (Table 2 and Supplementary Fig. S1). Similar univariate analysis was conducted with summer and winter months' data for the year 2021 shown in Supplementary Tables S1 and S2. Thus, the elimination of southern hemisphere countries also reported a similar finding as mentioned earlier, indicating that cold temperature influences SARS-CoV-2 infectivity.

Month-wise univariate analysis to study the relationship between new cases of COVID-19 and different environmental factors in northern hemisphere countries

The general tendency of our data depicted a strong negative correlation between temperature and sunlight on SARS-CoV-2 infectivity in winter months and a slight negative correlation between humidity and new cases of COVID-19 in summer months. Hence, we performed month-wise univariate analysis of each factor to further understand the conjugative relationship between these factors and new cases of COVID-19. The univariate analysis between temperature with new cases of COVID-19 has been shown in Table 3. Pearson statistical analysis found a negative correlation between temperature and new cases of COVID-19 in March and April with statistical significance. However, from May to September, we observe that this relation is quite weak and not much significant. However, from October 2020 to April 2021, we reported strong negative correlation, thus supporting our previous finding. To further verify our findings, we performed correlation using the Spearman method as well as Kendall method and

Table 1
Relationship between average new cases of COVID-19 and average environment temperature in summer months and winter months of a country: northern hemisphere.

New cases of COVID-19 vs average environment temperature						
Characteristics	Pearson		Spearman		Kendall	
	Summer months	Winter months	Summer months	Winter months	Summer months	Winter months
Correlation coefficient	0.1393	−0.5307	−0.1361	−0.5858	−0.0967	−0.4125
P-value	0.0790	<0.0001	0.0861	<0.0001	0.0698	<0.0001
No. of countries	160	148	160	148	160	148

Table 2
Association between average new cases of COVID-19 and average sunlight in northern hemisphere countries in the months of winter and summer.

New cases of COVID-19 vs average sunlight						
Characteristics	Pearson		Spearman		Kendall	
	Summer months	Winter months	Summer months	Winter months	Summer months	Winter months
Correlation	0.2441	−0.6310	0.1614	−0.6737	0.1100	−0.4712
P-value	0.0013	<0.0001	0.0355	<0.0001	0.0332	<0.0001
No. of countries	170	158	170	158	170	158

Table 3
Month-wise univariate analysis to study the relationship between average new cases of COVID-19 and average monthly temperature in northern hemisphere countries.

New cases of COVID-19 vs average environment temperature							
Characteristics	Pearson		Spearman		Kendall		Number of countries
	r	P-value	rho	P-value	tau	P-value	
2020							
March	−0.2536	0.0013	−0.5381	<0.0001	−0.3699	<0.0001	159
April	−0.3395	<0.0001	−0.4782	<0.0001	−0.3349	<0.0001	160
May	0.1537	0.0524	−0.2044	0.0095	−0.1420	0.0085	160
June	0.2622	0.0008	−0.0425	0.5934	−0.0296	0.5847	160
July	0.1716	0.0300	−0.1042	0.1897	−0.0717	0.1861	160
August	0.0807	0.3107	−0.1099	0.1664	−0.0766	0.1574	160
September	0.0298	0.7085	−0.1836	0.0202	−0.1333	0.0136	160
October	−0.3272	<0.0001	−0.4576	<0.0001	−0.3096	<0.0001	160
November	−0.4333	<0.0001	−0.5388	<0.0001	−0.3813	<0.0001	160
December	−0.5470	<0.0001	−0.6222	<0.0001	−0.4441	<0.0001	148
2021							
January	−0.3850	<0.0001	−0.5017	<0.0001	−0.3333	<0.0001	148
February	−0.3717	<0.0001	−0.4568	<0.0001	−0.3073	<0.0001	148
March	−0.3267	<0.0001	−0.4836	<0.0001	−0.3348	<0.0001	162
April	−0.4243	<0.0001	−0.4461	<0.0001	−0.3105	<0.0001	157
May	−0.2536	0.0013	−0.5381	0.0000	−0.3699	0.0000	159
June	−0.3395	0.0000	−0.4782	0.0000	−0.3349	0.0000	160
July	0.1537	0.0524	−0.2044	0.0095	−0.1420	0.0085	160
August	0.2622	0.0008	−0.0425	0.5934	−0.0296	0.5847	160
September	0.1716	0.0300	−0.1042	0.1897	−0.0717	0.1861	160
October	0.0807	0.3107	−0.1099	0.1664	−0.0766	0.1574	160
November	0.0298	0.7085	−0.1836	0.0202	−0.1333	0.0136	160
December	−0.3272	0.0000	−0.4576	0.0000	−0.3096	0.0000	160
2022							
January	−0.4333	0.0000	−0.5388	0.0000	−0.3813	0.0000	160
February	−0.5470	0.0000	−0.6222	0.0000	−0.4441	0.0000	148

observed similar results with strong negative correlation mostly in the winter months. We had further performed month-wise univariate analysis between sunlight and new cases of COVID-19. Pearson, Spearman, and Kendall statistical analyses observed strong negative correlation in the month of March and April. The univariate analysis between sunlight with new cases of COVID-19 has been shown in Table 4. We observed that sunlight follows a similar pattern such as temperature with strong negative correlation from October 2020 to April 2021. Similar to this, we observed strong negative correlation in the months of December 2021 to February 2022. Our findings with both temperature and sunlight indicated that cold temperatures escalate SARS-CoV-2 infection rates. To visualize our data more constructively, we squared the

values of correlation coefficient of temperature and sunlight obtained from Pearson method and plotted against the months. Squaring of the values was done to eliminate the negative values of the correlation coefficient. Graph of square of correlation coefficient against months has been shown in Fig. 1 and Supplementary Fig. S2. The graphical pattern of correlation coefficient of average temperature mimics to the pattern of average sunlight with new average COVID-19 cases in each month. These findings suggest that the sunlight and environment temperature may have similar influence on estimator COVID-19 cases. Humidity was another variable included in our study. As the air temperature changes, relative humidity also changes, which is why month-wise correlation analysis was performed. The month-wise analysis of humidity and

Table 4 Month-wise univariate analysis to study the relationship between average new cases of COVID-19 and average monthly sunlight in northern hemisphere countries.

Characteristics	New cases of COVID-19 vs average sunlight						No. of countries
	Pearson		Spearman		Kendall		
	r	P-value	rho	P-value	tau	P-value	
2020							
March	-0.3113	0.0001	-0.5638	0.0000	-0.3902	<0.0001	159
April	-0.3345	<0.0001	-0.4001	0.0000	-0.2663	<0.0001	170
May	0.1272	0.0984	-0.0566	0.4632	-0.0362	0.4851	170
June	0.2134	0.0052	0.1278	0.0969	0.0847	0.1021	170
July	0.1562	0.0420	0.1521	0.0477	0.1070	0.0388	170
August	0.2359	0.0020	0.2026	0.0081	0.1425	0.0059	170
September	0.1144	0.1374	-0.0541	0.4836	-0.0430	0.4057	170
October	-0.3260	<0.0001	-0.4360	<0.0001	-0.2948	<0.0001	170
November	-0.4825	<0.0001	-0.5761	<0.0001	-0.4067	<0.0001	170
December	-0.6352	<0.0001	-0.7238	<0.0001	-0.5152	<0.0001	158
2021							
January	-0.5011	<0.0001	-0.6072	<0.0001	-0.4254	<0.0001	158
February	-0.4450	<0.0001	-0.5327	<0.0001	-0.3663	<0.0001	158
March	-0.3268	<0.0001	-0.4549	<0.0001	-0.3233	<0.0001	168
April	-0.3507	<0.0001	-0.4087	<0.0001	-0.2828	<0.0001	169
May	-0.3113	0.0001	-0.5638	0.0000	-0.3902	0.0000	159
June	-0.3345	0.0000	-0.4001	0.0000	-0.2663	0.0000	170
July	0.1272	0.0984	-0.0566	0.4632	-0.0362	0.4851	170
August	0.2134	0.0052	0.1278	0.0969	0.0847	0.1021	170
September	0.1562	0.0420	0.1521	0.0477	0.1070	0.0388	170
October	0.2359	0.0020	0.2026	0.0081	0.1425	0.0059	170
November	0.1144	0.1374	-0.0541	0.4836	-0.0430	0.4057	170
December	-0.3260	0.0000	-0.4360	0.0000	-0.2948	0.0000	170
2022							
January	-0.4825	0.0000	-0.5761	0.0000	-0.4067	0.0000	170
February	-0.6352	0.0000	-0.7238	0.0000	-0.5152	0.0000	158

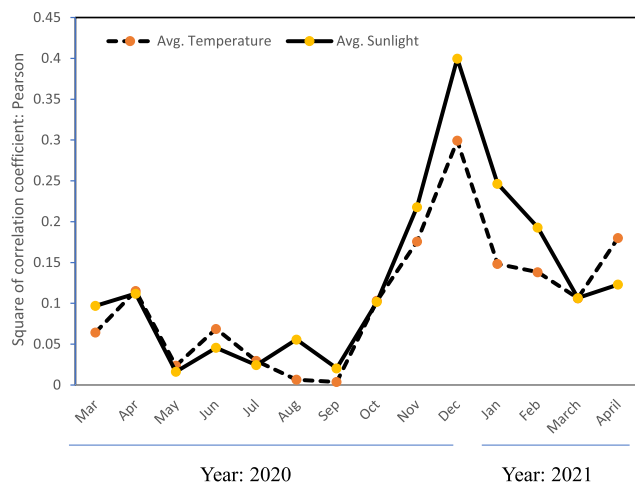


Fig. 1. Pattern of correlation coefficients of COVID-19 cases with monthly average sunlight and monthly average temperature of country in the month March 2020–April 2021 in northern hemisphere countries: Pearson analysis.

new cases of COVID-19 using Pearson, Spearman and Kendall method reported certain inconsistencies with positive value of R² in some months, whereas negative value in others. The univariate analysis between humidity with new cases of COVID-19 from March 2020 to April 2021 has been shown in Table 5.

Discussion

The world is in a pandemic mode for more than 2 years now and the novel SARS-CoV-2 continues to spread at an alarming rate. With the emergence of more contagious mutant strains, infection rates all over the world have been reported to increase rapidly. Despite various attempts by governments all over the world to limit the

spread of SARS-CoV-2 through several precautionary measures such as social distancing, wearing masks, restricting gatherings, imposing night curfew, performing vaccinations, and practicing hand hygiene, the infectivity of this virus continues to be irrepressible. With most countries currently preparing to encounter the third wave of the deadly SARS-CoV-2, it becomes important to understand the seasonality of the virus to be able to predict infection waves beforehand and ensure rigorous public health mitigation strategies. Former studies that focused on major infectious outbreaks examined various factors that could influence the infectivity of viruses. Respiratory viruses such as influenza viruses and other coronaviruses (SARS and MERS-CoV) have been reported to depend upon environmental factors such as temperature.^{18–20} Several studies conducted on influenza and SARS coronavirus reported high sensitivity of these viruses to increased temperatures. A study conducted in 2006 reported significant decrease in SARS-CoV infectivity, as the rise in temperature from 15°C to 29°C was observed. Considering such findings, we conducted a study to understand the link between temperature and COVID-19 incidence at the beginning of the pandemic. Our study observed higher COVID-19 cases in countries that were located in the higher latitudes of the globe. Thus, we performed a detailed correlation study that suggested a strong negative correlation between temperature and COVID-19 cases in March and April 2020. Since then, several studies were reported, which were in agreement with our findings,²¹ and negative influence of temperature on COVID-19 cases was observed. A study conducted by Sobral et al. reported that 1°F increase in temperature led to a decrease of 6.4 cases per day.²² However, some studies claimed positive correlation between temperature and COVID-19 cases.^{11,12,23} Also, research conducted in 127 countries by Yuan et al. reported unclear link between COVID-19 incidence and humidity >70%.¹³ Another study reveals insignificant relationship between relative humidity and spread of COVID-19.²⁴

Table 5
Month-wise univariate analysis to study the relationship between average new cases of COVID-19 and average humidity in northern hemisphere countries.

Characteristics	New cases of COVID-19 vs average humidity						Number of countries
	Pearson		Spearman		Kendall		
	r	P-value	rho	P-value	tau	P-value	
2020							
March	0.1925	0.0141	0.4706	0.0000	0.3249	0.0000	162
April	0.2041	0.0076	0.3877	0.0000	0.2650	0.0000	170
May	-0.0565	0.4643	0.0744	0.3350	0.0533	0.3097	170
June	-0.1547	0.0439	-0.1481	0.0540	-0.1059	0.0436	170
July	-0.1622	0.0346	-0.1874	0.0144	-0.1329	0.0110	170
August	-0.0396	0.6078	-0.1817	0.0177	-0.1291	0.0134	170
September	-0.0681	0.3776	-0.2776	0.0002	-0.1902	0.0003	170
October	-0.2089	0.0062	-0.4016	<0.0001	-0.2650	<0.0001	170
November	-0.0233	0.7630	-0.3356	<0.0001	-0.2228	<0.0001	170
December	0.1171	0.1442	-0.1211	0.1308	-0.0654	0.2311	157
2021							
January	0.2075	0.0091	0.2732	0.0005	0.1888	0.0005	157
February	-0.0477	0.5527	0.3264	0.0000	0.2181	0.0001	157
March	0.2701	0.0004	0.2975	0.0001	0.2023	0.0001	170
April	0.2359	0.0021	0.1744	0.0242	0.1278	0.0160	167

Hence, in this study, we conducted a global 2-year analysis to identify the association of temperature and humidity with SARS-CoV-2 infectivity. To verify our finding that cold temperature augments COVID-19 infection, we performed correlation analysis for winter and summer months separately and observed negative correlation in winter month. Our present study has majorly focused on COVID-19 incidence in northern hemisphere countries. To further reconfirm that low-temperature influences SARS-CoV-2 infectivity, we included sunlight as another factor and performed univariate statistical analysis. Similar negative relationship between sunlight and new cases of COVID-19 was detected, with value of correlation coefficient near to 0.7 in the month of December. All these observations strongly suggested that cold temperature aggravates COVID-19 incidence. Three-dimensional representation of relationship between temperature, sunlight, and new cases of COVID-19 is depicted in Fig. 2. Various studies have reported several hypotheses that explain this relationship between air temperature and viral seasonality. Warmer temperature possibly affects the ordering of phospholipids, thus decreasing the stability of enveloped viruses such as SARS-CoV-2.²⁵ Seasonal fluctuations in temperature have also been reported to influence the airway defense at diverse levels. Low temperature can promote dry breathing that immobilizes the cilia, allowing the virus to elude mucous layer and attack the host cell easily.²⁶ Temperature is also known to suppress immune responses allowing the virus to

replicate in host cells faster at low temperature.²⁷ The second finding of our study indicated that humidity is weakly associated with SARS-CoV-2 infectivity, and major inconsistencies were observed in the correlation analysis between the two factors.

The end of 2020 and beginning of 2021 witnessed many countries such as the United States, France, Russia, the United Kingdom, Italy, and Spain experiencing the second wave of COVID-19 pandemic, thus supporting the fact that cold temperature augments SARS-CoV-2 infectivity. Ours is the first global study that has focused on 2-year data from March 2020 to February 2022 and has taken into account all countries affected by COVID-19. With the uncertainties associated with novel mutant strains and upcoming third COVID wave, understanding the role of different environmental factors in the infectivity of this virus will help formulate optimized public health measures. Despite the novelty of SARS-CoV-2 virus, it is highly anticipated that this virus would possibly follow infectivity pattern similar to other respiratory viruses such as influenza virus and other coronaviruses.

Our study indicates a negative correlation between temperature, sunlight, and the number of COVID-19 cases, specifically in the northern hemisphere countries. However, the plausibility of this infectious virus also depends on age, sex, and ethnicity, the prevalence of different diseases in the population, as well as the prevalent antibodies in an individual (naturally or artificially acquired). Also, our findings take into account the atmospheric temperature on COVID-19 cases; how indoor temperature might affect infection rate remains unclear. Our study takes into account a comprehensive approach in understanding the role of temperature and sunlight in infection rates of the virus and takes into account the fluctuations observed in a single country. Moreover, with the emergence of SARS-CoV-2 mutant strains, the future trail of SARS-CoV in affecting the infection rate remains dubious. Although the pattern of infection by the virus may differ in the near future due to our growing knowledge of treatment and an improved understanding of the SARS-CoV-2 virus infectivity, a holistic approach on understanding how environmental factors affect the rate of infectivity will help formulate possible public measures to curb the infection rate in near future. Our study does not implicate those warm temperatures will be enough to curb the spread of the virus but rather emphasizes that more vigilant quarantine measures should be taken to avoid the dramatic spread of SARS-CoV-2. Our recent study has also suggested a combinatorial influence of environment temperature and other metabolic diseases such as obesity and high cholesterol on SARS-CoV-2 infectivity.²⁸ Future studies should also focus on

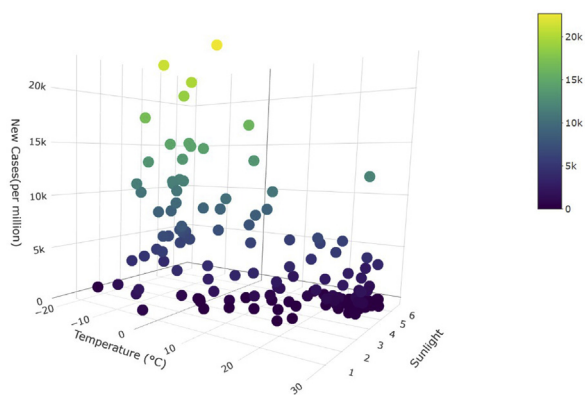


Fig. 2. Three-dimensional representation of relationship between average COVID-19 cases, average temperature, and average sunlight in winter months from November 2020 to February 2021.

other factors such as public health policies, healthcare structures, and healthcare quality to understand the upsurge in COVID-19 cases in some countries compared with others.

Our 2-year data analysis further proposes that cold temperature could aggravate COVID-19 incidence, especially in the northern hemisphere countries. This research provides important pattern of COVID-19 infectivity and suggests that warmer temperature could limit the COVID-19 infection if the other precautionary measures are vigilantly followed.

Author statements

Author contribution

V.T. collected information, prepared tables and figures, and drafted the article. R.B. analyzed data and participates in writing the article. C.C.M. formulated study and written article.

Ethical approval

Not required.

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Competing interests

All authors declare that they have no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.puhe.2022.04.011>.

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