Maximum Daily Temperature, Precipitation, Ultra-Violet Light and Rates of Transmission of SARS-Cov-2 in the United States

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Summary:

- Analyzed US data to investigate effects of temperature,precipitation and UV Index on community transmission of SARS-CoV-2 using Negative binomial regression modelling.
- Noted transmission declines with increasing temperature up until 52 F, but transmission still remains significant.

Abstract

Background: Previous reports have suggested that transmission of SARS-CoV-2 is reduced by higher temperatures and higher humidity. We analyzed case-data from the United States to investigate effects of temperature, precipitation, and UV Light on community transmission of SARS-CoV-2.

Methods: Daily reported cases of SARS-CoV-2 across the United States from 01/22/2020 to 04/03/2020 were analyzed. We used negative binomial regression modelling to investigate whether daily maximum temperature, precipitation, UV Index and the incidence 5 days later were related. We performed sensitivity analyses at 3 days, 7 days and 9 days to assess transmission lags.

Results: A maximum temperature greater than 52◦F on a given day was associated with a lower rate of new cases at 5 days[IRR: 0.85(0.76,0.96)p=0.009]. Among observations with daily temperatures below 52◦F, there was a significant inverse association between the maximum daily temperature and the rate of cases at 5 days [IRR 0.98(0.97,0.99)p=0.001]. The rate of new cases was predicted to be lower for theoretical states that maintained a stable maximum daily temperature above 52◦F with a predicted 23-fewer cases per-million per-day by 25 days of the epidemic. A 1-unit higher UV index was associated with a lower rate at 5 days [IRR 0.97(0.95,0.99)p=0.004]. Precipitation was not associated with a greater rate of cases at 5 days [IRR 0.98(0.89,1.08)p=0.65].

Conclusion: The incidence of disease declines with increasing temperature up until 52◦F and is lower at warmer versus cooler temperatures. However, the association between temperature and transmission is small and transmission is likely to remain high at warmer temperatures.

Key Words: Temperature, SARS-CoV-2, transmission rates

Introduction

Since the first case of SARS-CoV-2 was reported in Wuhan, China in December 2019 the disease has spread globally and on 11th March 2020 the World Health Organization declared SARS-CoV-2 a global pandemic. As of 21st May 2020, the SARS-CoV-2 virus has spread to more than 200 countries and affected over 5 million individuals globally. In the United States, the first case detected case of coronavirus was reported on 21st January 2020 (1) and COVID-19 has already caused greater than 80,000 deaths in the US (2). Various public health initiatives including social distancing have helped to slow the spread and there has been much speculation about seasonal effects of temperature and humidity on community transmission of SARS-CoV-2.

Seasonal trends in influenza are well-established but the relationship is less clear for previous coronavirus outbreaks such as SARS-CoV and MERS-CoV. Published in vitro data on temperature sensitivity on SARS-CoV-2 suggests that the virus survives for shorter duration at a higher temperature (3). Most studies looking at transmission of disease in the general population have noted reduction in transmission with increase in temperature and humidity **(Table 1)**. However, there is lack of consensus about the effects of temperature on transmission of SARS-Cov-2. In-vitro studies have also reported inactivation of SARS-CoV-2 with riboflavin and subsequent use of UV light (14). Previous studies on SARS-CoV and MERS-CoV have shown sensitivity of these viruses to UV light (15)(16).

To the best of our knowledge, no previous study has assessed the influence of temperature precipitation and UV light on SARS-CoV-2 transmission across the United States. Therefore, we investigated the potential relationship of daily on the incidence across the US. We analyzed case data from the United States to determine effects of temperature, precipitation and UV light on transmission of SARS-CoV-2 in the general population in order to determine if daily temperature and precipitation were associated with a subsequent change in the rate of new cases across the U.S.

Methods

Data Sources

We performed an observational analysis of the daily reported cases of SARS-CoV-2 and daily weather patterns across the US. Our null hypothesis is that there is no association between daily temperatures and SARS-CoV-2 disease spread. For the period 01/22/2020 to 04/03/2020, we accessed the number of new daily reported SARS-CoV-2 cases in each state from the Coronavirus COVID-19 Global Cases dashboard hosted by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (https://github.com/CSSEGISandData/COVID-19) and the COVID Tracking Project (https://covidtracking.com/api). US state population was obtained, and population density was calculated from the 2019 US Census Bureau population estimates. Case rates per million were calculated for each day. Daily temperature and precipitation data for each state capital was collected from the National Centers for Environmental Information repository and used as a proxy for daily weather in the state (https://www.ncei.noaa.gov). We identified other state-level characteristics and incorporated them into the analysis. Race, age and gender data was directly collected from 2018-American Community Survey (ACS), U.S. Census Bureau. State gross domestic product, median family income and rates of uninsured were obtained from Kaiser Family Foundation analysis of the U.S. Census Bureau's 2018-ACS. Graduation data was obtained from the US Department of Education and Obesity rates were obtained from the CDC's Behavioral Risk Factor Surveillance System.

Statistical Analysis

Negative Binomial regression models incorporating Generalized Estimating Equations (GEE), (robust estimators with exchangeable correlation matrix, clustering on U.S. state) were used to estimate associations between temperature, precipitation, and covariates relative to the number of new cases 5 days from a given date. We excluded days with fewer than 1 case per million in the population. Variables we considered in regression models included the baseline rate, calendar date, total tests performed per capita on day 5, the number of days from the initial cases in the state (including a squared term to consider that the effect may change with time), and the number of days before or after the initiation of stay at home orders. State-level factors were also considered including total population, population density, gross-domestic product, median family income, the proportion of uninsured, obesity rates, graduation rates, the proportion of African-Americans, and the proportion of older adults and children. All analyses were performed using Stata 14.2 software *(StataCorp, LP, College Station, TX)*.

Temperature was first modelled as a continuous variable. Based on prior literature and the distribution of our data, we evaluated a temperature threshold of 52° F (11° C) (4)(5). We also generated cubic splines with a knot at 52° degrees F to evaluate temperature as a continuous variable above and below that threshold. The use of cubic splines allows the analysis to evaluate the association with temperature separately below and above a certain threshold. Additionally, we categorized temperature as <30° F, 30-40° F, 40-50° F, 50-60° F, and ≥60° F. Quasi Information criterion was used to identify models with superior model fit.

Regression models were used to estimate the rates of new cases 5 days after the current date in each temperature category. Rates at 5 days were used to predict the subsequent new cases at 10 days and so on along with the other model parameters (including the days from initial cases and the interaction term). Figures were generated which represent an estimate of the daily reported cases over time that might be expected in a theoretical location that has a maximum temperature that is always within a single temperature category and is at the mean of all other state-level variables.

We defined our time to diagnosis as 5 days based on prior literature on incubation period of the disease (17). However, given potential variability in presentation and delays in testing, we performed sensitivity analyses assuming time to diagnosis of 3-days, 7-days and 9-days.

We also performed a number of other sensitivity analyses. For example, we generated cubic splines to account for different effects of time before and after the initiation of stay at home orders within each state and evaluated effects before the initiation of these orders (not shown). We explored the use of alternative correlation matrices in regression models such as independent and autoregressive functions. We also evaluated an alternative outcome of the change in new cases at 5 days and modeled this outcome using linear regression with GEE. Finally, in a subsample of states (N=33), with average temperatures available, we explored associations between average temperature and new cases at 5 days. We also categorized precipitation to evaluate whether more significant precipitation (>0.5 inches) was associated with the outcome.

Results

Fifty U.S. states and Washington D.C. were included in the analysis, with 974 eligible daily observations. The median maximum daily temperature was 50◦ F (inter-quartile range (IQR) 41-62 F). In basic models, there was a significant association between the daily rate of new cases and the daily rate 5 days later as well as the absolute change in the number of cases at 5 days **(Table 2)**. The number of days from the first identified cases (1 per million) was also associated with the cases at 5 days as well as a significant interaction term, which suggested a reduction in the effect of time over time.

Maximum daily temperature (per 1-degree F) was associated with the rate of new reported cases per million at 5 days [IRR: 0.994 (0.989, 0.999) p=0.02] when modeling temperature as a continuous variable. A daily maximum temperature greater than 52◦ F was also associated with a significantly lower rate at 5 days [IRR: 0.88 (0.80, 0.97) p=0.009]. Among observations with daily temperatures below 52◦ F, there was a significant inverse association between the maximum daily temperature (per 1-degree F) and the rate of cases at 5 days [IRR 0.987 (0.979, 0.994) p=0.001].

When broken into categories of temperature, there was a numerical trend towards higher rates of infection in lower temperature categories (**Supplementary Table 1**). For example, higher rates were observed for days where the maximum temperature was <30◦ F compared to a day where the maximum temperature was >60◦ F [IRR 1.59 (0.83, 3.06) p=0.16].

These results were similar when evaluating daily temperature as compared to subsequent case rates 3 days later (**Supplementary Table 2**). Specifically, a daily maximum temperature greater than 52° F was associated with a lower new case rate at 3 days [IRR 0.85 (0.75, 0.98) p=0.02] but not at 7 days [IRR: 0.95 (0.85, 1.06) p=0.40]. A maximum temperature >52° was associated with fewer new cases at 3, 7, and 9 days. A maximum temperature > 52° F was associated with lower rates at 5 days when limiting the analysis to time prior to the initiation of stay at home measures in each state [IRR: 0.87 (0.80, 1.00) p=0.051, N=794]. In 33 states with available data, a higher average daily temperature was associated with a lower rate of new cases [IRR: 0.99 (0.98, 0.997) p=0.004]. An average temperature >52◦ F was also associated with a lower rate at 5 days [IRR: 0.87 (0.76, 0.99) p=0.03].

Daily reported cases predicted from models for theoretical states that maintained a stable maximum daily temperature are shown in **Figure 1.** Cases per million were higher at 30 days among theoretical states with lower daily maximum temperatures. For example, based on these models, a hypothetical state that consistently had a maximum temperature less than 52° F would be expected to observe 23 cases per million more cases per day at the epidemic's peak compared to a hypothetical state with a maximum temperature consistently above 52° F. (**Figure 1A**). Similarly, a hypothetical state where the high temperature never went above 30◦ F would be expected to see approximately 110 additional cases per million at the peak of the epidemic compared to a state where the temperature did not drop below 60◦ F (**Figure 1B**).

In these models, a higher UV index on a given day was also associated with a lower rate of new infections at 5 days. In adjusted models, a 1-unit higher UV index was associated with a lower rate at 5 days [IRR 0.97 (0.95, 0.99) p=0.004].

The presence of precipitation on a given day was not associated independently with the rate of cases at 5 days [IRR 0.98 (0.90, 1.06) p=0.54].

The results were independent of state level factors such as state population, population density, gross-domestic product, median family income, the proportion of uninsured, obesity rates, graduation rates, the proportion of African-Americans, and the proportion of older adults and children.

Discussion:

We identified an association between temperature and SARS-CoV-2 case transmission in the United States. Specifically, the rate of cases presenting daily was inversely associated with daily temperature 5 days earlier up to a threshold of 52° F (11° C). In addition, rates were notably lower on days where the temperature was above 52° F 5 days earlier. These findings suggest that rates are likely to fall with the advent of warmer temperatures, however, the effect was relatively small. While these observations may be reassuring to some degree, it is likely that the transmission of disease will still occur at meaningful rates even at warmer temperatures during the coming summer months. We found no evidence that daily precipitation is associated with the rate of new cases independent of other factors.

The primary aim of this investigation was to understand the effect of temperature on SARS-CoV-2 disease spread in the United States. Our approach was motivated by previous work which suggested that temperature and humidity influence decrease spread. However, these previous studies considered case data from multiple countries, with varying health systems, and varied public health responses to the outbreak. Our study, focused on the United States alone, found a modest but important association between temperature and SARS-CoV-2 disease transmission. It is important to note that, while colder areas of the country may see attenuated transmission rates at warmer temperatures during the summer, this study does not support a dramatic decrease in case rates in areas that already have temperatures greater than 52° F as the climate transitions to even warmer temperatures in the summer.

Shortwave UV light (UVC) interacts with nucleic acids forming pyrimidine dimers that prevents the elongation of the nucleic acid chains and subsequently renders some viruses inactive. This is reported to be one of the major factors responsible for viral inactivation by UV light (18)(19). Interestingly, we also noted that a higher UV index was associated with a lesser increase in cases at 5 days. These data corroborate evidence that UV light may disrupt the integrity of the virus. The association of temperature and case increase was independent of the UV index. We also found no correlation between precipitation and the rate of case diagnosis. While the lack of association with precipitation might suggest a limited role of humidity in the rate of new cases, we did not directly study the role of humidity. Future studies may be needed to better characterize the relationship between humidity and case transmission independent of temperature.

Our findings suggest that the effects of temperature on SARS-CoV-2 transmission are modest and are unlikely to provide significant effect beyond current strategies for mitigation. In other words, although there is an association between daily temperature and subsequent case volume across the US, this relationship is small and it is likely that if containment measures are discontinued, the disease may continue to spread in the United States even in periods of warmer weather. We expect that if containment measures continue, we may see a more significant decline in cases in the warmer summer months across the US. Our findings also raise caution about a sudden increase in disease transmission in the United States in the fall and that countries in the Southern Hemisphere may soon start seeing higher rates of transmission as temperatures fall.

Several factors make this a difficult area of study. Countries across the world have had different rates of testing for SARS-CoV-2 and are using diagnostic tests with different test characteristics. In addition, different travel restrictions were placed by many countries at different stages of the pandemic and containment measures have varied considerably. These, among other factors have affected the quality of the information on the number of cases diagnosed in different regions of the world. Despite this variability in case data sources, most of the previous studies on SARS-CoV-2 transmission have noted that a rise temperature and humidity has slowed spread of SARS-CoV-2 (Table 1). In the study period, majority of the states in the US had not suspended free movement of people. The foreign travel restrictions were applied to the entire US at the same time (China 02/02/2020; Schengen countries 03/13/2020). Thus, even though testing for SARS-CoV-2 in the US has not been ideal and cases are under-reported, there are several strengths to this study.

The limitations of the current study include the potential for confounding by geographic areas. There has also been variation in containment strategies at different times across the country. It may be that states in warmer climates were more likely to employ measures to contain the virus or have other differences that are not assessed here. We did consider the timing of stay at home policies, though this does not fully account for differences in the response to the virus by geographic area. Temperatures registered at state capitals were extrapolated to the entire state, and more granular county-level data might provide more power for the study. Having found significant associations despite this lack of granularity in the exposure, we expect bias in this study may be toward the null. Furthermore, few days during the study period had maximum temperatures above 75° F, suggesting these data may be insufficient to fully evaluate the effect of higher maximum temperatures. The current study is limited in accurately defining the onset of symptoms and thus the likely time of exposure for new cases. Thus, while we used an incubation period of 5 days based on prior literature (14), we also performed sensitivity analysis at 3, 7 and 9 days to account for this uncertainty. While these sensitivity analyses largely corroborated the main findings, no association was noted with the assumption of a lag as long as 9 days. Finally, we did not directly assess humidity, but rather daily precipitation. Thus, while our data do not provide support for the hypothesis that the presence of precipitation is an important factor in the rate of transmission, we cannot rule out an important effect of humidity.

Conclusion

There is an association between temperature and rate of transmission of SARS-CoV-2 virus which may result in modest decline in the community transmission of SARS-CoV-2 with warmer weather. This effect is modest, however, and is unlikely to slow down disease spread if containment measures are relaxed.

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Conflicts of Interest

J.B. reports personal fees from Bristol-Myers Squibb, Gilead, and Burns-White LLC, outside the submitted work. All other authors have no potential conflicts.

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Tables

Table 1: Summary of available literature on meteorological data and SARS-CoV-2 transmission

Authors	**Title**	**Peer Reviewed (as of 04/12/20)**	**Countries Analyzed**	**Conclusion**
Sajadi et al (4)	Temperature, humidity, and latitude analysis to predict potential spread and seasonality for COVID-19	No	Multiple	Maximum disease spread with temperatures between 5 C – 11 C and low specific and absolute humidity
Notari (5)	Temperature Dependence of COVID-19 Transmission	No	Multiple	Peak Cases noted at 7.7 +/- 3.6 C
Luo et al (6)	The role of absolute humidity on transmission rates of the COVID-19 outbreak	No	China	Exponential growth and sustained transmission possible over a range of humidity conditions
Ficetola et al (7)	Climate Affects Global Patterns of Covid-19 Early Outbreak Dynamics	No	China	Growth rates peak noted at mean temperature of 5 C; suggest possibility of seasonal variation
Qi et al (8)	COVID-19 transmission in Mainland China is associated with temperature and humidity: a time-series analysis	No	China	Increase in average temperature in range of 5.04 - 8.2 C or increase in relative humidity led to a decrease in daily confirmed cases
Islam et al (9)	Temperature, humidity, and wind speed are associated with lower Covid-19 incidence	No	Multiple	Cold and dry environment are more favorable condition for virus survival
Wang et al (10)	High Temperature and High Humidity Reduce the Transmission of COVID-19	No	China	1 C increase in temperature and 1% increase in relative humidity lower significantly reduce transmission of COVID - 19
Martinez-Alvarez et al (11)	COVID-19 Pandemic in West Africa	Unknown	Multiple	Hypothesis that the virus will spread more slowly in countries with warmer climates not supported
Ma et al (12)	Effects of Temperature Variation and Humidity on Death from COVID-19 in Wuhan, China	Yes	China	Positive association of Diurnal temperature and negative association of humidity with COVID-19 deaths
Neher et al (13)	Potential impact of seasonal forcing on a SARS-CoV-2 pandemic	Yes	China, Sweden	Possible seasonal variation in temperate climates in the Northern Hemisphere

Table 2: Associations between baseline temperature, UV index, and precipitation and of rate of new cases per 1 million at 5 days using negative binomial regression with generalized estimating equations and with the change in number of new cases at 5 days using linear regression with generalized estimating equations.

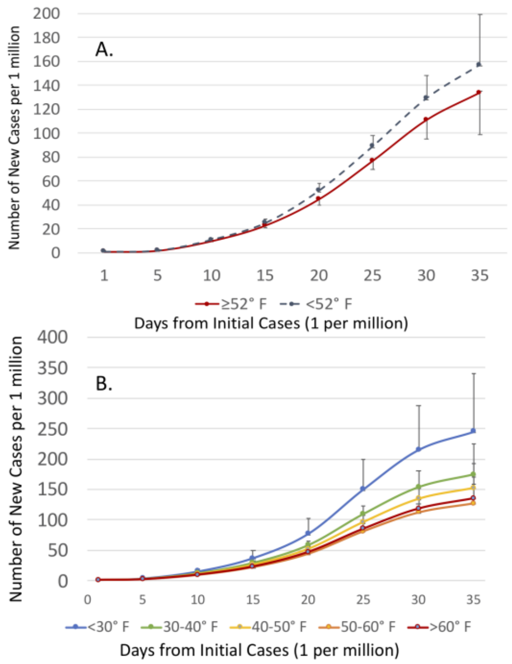
	Rate of New Cases at 5 days Groups=51; Observations=915		**Average Change in Case Number at 5 days (per 1 million)** Groups=51; Observations=915	
	IRR (95% CI)	P	β (95% CI)	p
Daily Tmax (per 1° F, below 52° F)	0.99 (0.98, 0.994)	0.001	-0.53 (-0.90, -0.16)	0.005
Daily Tmax (per 1° F, above 52° F)	1.00 (0.99, 1.00)	0.63	0.021 (-0.29, 0.33)	0.89
Any precipitation	1.00 (0.99, 1.02)	0.80	0.51 (-1.96, 2.97)	0.69
UV Index (per unit)	0.97 (0.94, 0.99)	0.007	-1,20 (-2.80, 0.42)	0.15
Current Rate (cases per 100 million)	1.00 (1.00, 1.00)	0.007	0.001 (-0.000, 0.003)	0.08
Days from Initial Cases (per 1 day)	1.25 (1.20, 1.31)	<0.001	1.27 (0.69, 1.85)	<0.001
Days from Initial Cases^2	0.996 (0.99, 0.998)	<0.001	--	
African American (per 1%)	1.05 (1.02, 1.08)	<0.001	1.11 (0.27, 1.94)	0.009
Older Adult (per 1%)	1.17 (0.997, 1.38)	0.054	4.94 (0.18, 9.70)	0.04

*Models also adjusted for population density, obesity rates (%), state GDP, total population, % child, median family income, % uninsured, graduation rates (%) (not shown). Also tested but not included in final model: calendar date, tests performed per day at 5 days, days from the stay at home order.

Figure Legend

Figure 1. Negative binomial regression predictions of the number of cases per 1 million population that hypothetical locations in the United States would experience at temperatures above or below 52° F.

Figure 1



A.
Number of New Cases per 1 million
200
180
160
140
120
100
80
60
40
20
0
1
5
10
15
20
25
30
35
≥52° F
<52° F
Days from Initial Cases (1 per million)
B.
Number of New Cases per 1 million
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
35
<30° F
30-40° F
40-50° F
50-60° F
>60° F
Days from Initial Cases (1 per million)