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Coronavirus Pandemic

Relationship between temperature and relative humidity on initial spread of COVID-19 cases and related deaths in Brazil

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Abstract
Introduction: Climate conditions may influence the transmission of COVID-19. Thus, the aim of this study was to evaluate the impact of temperature and relative humidity on COVID-19 cases and related deaths during the initial phase of the epidemic in Brazil.
Methodology: An ecological study based on secondary data was conducted. Daily data on new COVID-19 cases, deaths, and climate indicators were collected from February 20 to April 18, 2020 (n = 59 days) for all state capital cities in Brazil and the Federal District (Brasília). The climate indicators included mean temperature, temperature amplitude, mean relative humidity, relative humidity amplitude, and percentage of days with mean relative humidity ≤ 65 %. Correlation and multiple linear regression analyses were performed for all cities and stratified by quintiles of the COVID-19 incidence rate.
Results: The mean daily temperature was positively correlated with the number of days until the first COVID-19 case was reported. A lower mean relative humidity was correlated with a lower number of cases and deaths in Brazil, especially when the relative humidity was ≤ 65 %. Higher temperatures and humidity amplitudes were correlated with lower COVID-19 mortality. Additionally, after controlling for humidity, cumulative cases of COVID-19 were inversely associated with temperature in cities with mean temperatures less than 25.8 °C.
Conclusions: Variations in temperature and humidity across the Brazilian territory may have influenced the spread of the novel coronavirus during the initial phase of the epidemic.

Key words: Temperature; relative humidity; COVID-19; Brazil.

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Introduction

Coronavirus disease (COVID-19) is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [1]. On March 11, 2020, the World Health Organization (WHO) categorized COVID-19 as a pandemic owing to the rapid increase in new cases and related deaths in different countries [2]. On April 1, 2020 there were more than one million confirmed cases and over 50,000 deaths worldwide [3]. Brazil declared COVID-19 a public health emergency on February 3, 2020, and the Brazilian Ministry of Health announced the first confirmed case on February 25, 2020 [4,5]. The first COVID 19 related death in Brazil was reported on March 17, 2020. Since then, the epidemic has rapidly spread countrywide, with more than 6,880 cases and 324 deaths per million as of April 1, 2020 [6].

Brazil is the largest country in South America, with a population of over 200 million [7]. Its territorial expanse is approximately 8.5 million km^2, with 93 % of its landmass lying in the Southern Hemisphere. According to Köppen's climate classification system, Brazil has three climate zones (tropical, subtropical, and semi-arid) and 12 different microclimates [8]. Most of the country's territory falls in the tropical climate zone (81.4 %), except in the south, which is mainly in the subtropical climate zone. As a result, Brazil exhibits a variety of climatic conditions—dry summers, dry winters, no dry season, hot summers, and temperate summers [8].

Climate conditions have been reported to influence the transmission of COVID-19 [9-28]. Upon comparing data on meteorological conditions of 166 countries worldwide, one study concluded that daily new cases and deaths due to COVID-19 may be partially suppressed with an increase in temperature and humidity [10]. Another study with data collected daily from several countries also indicated a negative correlation between the country's average temperature and the number of cases of SARS-CoV-2. An increase in the average daily temperature by one-degree Fahrenheit reduced the number of cases by approximately 6.4 cases/day [14]. Data from 30 provincial capital cities in China revealed that cities with low temperature, mild diurnal temperature range, and low humidity are more likely to favor transmission [11]. Finally, a systematic review including studies up to April 2020 concluded that cold and dry conditions were potential factors in spreading the virus [29]. However, recent studies have claimed that these associations are not linear [30,31]. Data from England suggests that daily ambient mean temperatures of approximately 11 °C to 13 °C pose a higher risk for COVID-19 cases compared with the risk-minimum at 22 °C, and relative humidity showed the highest risk at 61 % [31].

The majority of studies investigating climatic conditions and their impact on COVID-19 have been performed in the Northern Hemisphere [29,32]. Few have been conducted in countries located in the Southern Hemisphere, such as Brazil [9,33,34]. One study indicated that when the average temperature was below 25.8 ℃, a negative linear relationship was observed between temperature and the number of confirmed COVID-19 cases, although humidity was not considered [9]. Another case study on the most affected Brazilian cities concluded that high temperatures and intermediate relative humidity might favor the spread of COVID-19 [33].

The relationship between climatic conditions and COVID-19 transmission is unclear and warrants further investigation. There is lack of studies on COVID 19 in the Southern Hemisphere, including all Brazilian territories. Therefore, this study aimed to explore the impact of temperature and relative humidity on the initial spread of COVID-19 cases and deaths in the initial phase of the epidemic in Brazil. It was important to analyze the initial spread period to avoid the multiple factors involved in the COVID-19 pandemic, such as community transmission, public health policies, and new variants of SARS-CoV-2.

Methodology

Design and study area

We used an ecological study design based on secondary data. Data was explored from all 26 state capital cities in Brazil and the Federal District (Brasília). As shown in Figure 1, the cities are located in different regions of Brazil, with different climatic conditions.

Data collection

Daily data on new cases and deaths due to COVID-19 and climate indicators were collected from February 20 to April 18, 2020 (n = 59 days) for each state's capital city and the Federal District (Brasília). The daily cumulative number of newly confirmed cases, deaths, incidence, and mortality rates due to COVID-19 were collected from the official data reported by the Ministry of Health of Brazil (https://covid.saude.gov.br/) [35]. Additionally, data were also collected for the number of days between the start of follow-up (February 20) and the first case reported.

Daily climate data for each city, including mean, maximum, and minimum temperature (°C), and mean, maximum, and minimum relative humidity (%), were collected from the National Institute of Meteorology (http://www.inmet.gov.br/portal/). There was no climate data for the city of Porto Velho during the study period.

The temperature and relative humidity variables included the daily means and amplitudes (maximum–minimum). Additionally, two other variables were proposed based on the potential inactivation of the coronavirus at midrange humidity [36,37]: percentage of days with mean relative humidity ≤ 65% in the period (days with relative humidity ≤ 65%/59 × 100), and percentage of days with minimum humidity ≤ 65 % (days with minimum humidity ≤ 65%/59 × 100).

Statistical analysis

Descriptive analyses were performed for COVID-19 outcomes, and temperature and relative humidity data, using means and standard errors, amplitude (range), and relative frequencies. Variables were assessed for normality using the Shapiro-Wilk test, and Spearman's rank correlation coefficient was used to evaluate the correlations between the variables and outcomes. Correlation analyses were performed for all cities and stratified by quintiles of COVID-19 incidence rate utilizing cities from the medium and lowest quintiles as opposed to cities from the highest quintiles of incidence rate. Then, a sensitivity analysis was conducted to detect the potential heterogeneity in the results. The city of São Paulo was excluded from the analysis because it reported the first case of COVID-19 approximately 25 days earlier than the other cities.

Multiple linear regression analysis was also performed to investigate the relationship between daily mean temperature and daily cumulative cases of COVID-19, adjusting for daily mean relative humidity. This analysis was stratified by mean temperature in the period (< 25.8 °C vs. ≥ 25.8 °C). This cutoff, based on a previous finding, indicated that each 1 °C rise in temperature was associated with a decrease of 4.89% in the number of daily cumulative confirmed cases of COVID-19 when the average temperature was below 25.8 °C [9].

Data analysis was performed using the Statistical Package for Social Sciences (version 22.0; IBM Corp., Armonk, NY, USA). All tests were two-sided, and statistical significance was set at $p < 0.05$.

Results

Summary results for COVID-19 occurrence, temperature, and relative humidity in Brazilian state capitals and the Federal District (Brasília) from February 20 to April 18, 2020, are shown in Table 1.

Figure 1. COVID-19 cumulative cases (bubble size) in Brazilian state capitals and the Federal District (Brasília) from February 20 to April 18, 2020.

Table 1. Descriptive data for COVID-19 occurrence and the daily temperature and relative humidity in Brazilian state capitals and the Federal District (Brasília) from February 20 to April 18, 2020 (n = 59 days), according to the COVID-19 incidence rate.

	COVID-19					Temperature (ºC)		Relative humidity (%)			
Cities	Incidence rate[a]	Cumulative cases	Mortality rate[a]	Cumulative deaths	Days until first case (lapse)	Mean	Mean amplitude	Mean	Mean amplitude	% days mean ≤ 65[b]	% days min ≤ 65[c]
Fortaleza	729.00	2562.00	34.80	141.00	24	27.36	7.31	80.39	31.80	0.00	83.10
São Paulo	633.70	9428.00	45.50	686.00	5	20.88	9.24	70.69	41.14	27.00	91.50
Manaus	618.50	1593.00	42.10	134.00	21	27.52	7.23	78.25	34.80	0.00	86.40
Macapá	568.20	321.00	9.90	8.00	28	26.44	6.92	84.22	32.14	2.00	69.50
Recife	520.70	1255.00	37.70	106.00	21	27.58	8.79	77.29	37.27	0.00	96.60
São Luís	483.70	862.00	30.90	38.00	27	26.07	5.49	90.09	26.03	0.00	27.10
Florianópolis	413.20	221.00	6.00	3.00	22	23.35	9.06	69.18	38.05	25.00	94.90
Rio de Janeiro	374.90	3059.00	24.90	237.00	15	24.10	5.34	80.36	19.98	0.00	33.90
Vitória	372.80	224.00	16.60	9.00	28	25.32	8.14	78.92	39.27	0.00	91.50
Boa Vista	263.00	183.00	5.00	2.00	30	29.41	11.23	56.00	41.27	90.00	100.00
Porto Alegre	233.20	369.00	5.40	9.00	19	22.58	11.25	70.14	46.44	24.00	94.90
Brasília	226.20	762.00	5.60	24.00	16	21.25	8.78	80.20	40.34	3.00	86.40
Natal	193.40	236.00	5.70	5.00	21	27.87	6.21	81.07	27.47	0.00	54.20
Rio Branco	186.60	112.00	7.40	4.00	26	25.82	8.26	85.28	41.17	0.00	72.70
Belém	180.90	449.00	10.70	22.00	26	25.87	8.30	85.79	34.81	2.00	68.20
Salvador	180.70	759.00	5.20	19.00	22	27.32	5.87	80.54	23.61	0.00	39.00
Curitiba	157.80	346.00	3.60	8.00	20	19.17	11.20	68.16	54.53	36.00	94.90
Belo Horizonte	151.30	420.00	2.40	8.00	24	20.18	9.42	84.49	37.00	0.00	76.30
João Pessoa	142.10	148.00	17.30	17.00	27	27.81	7.31	76.90	32.90	0.00	91.50
Cuiabá	129.00	91.00	0.00	1.00	31	28.44	9.54	65.43	39.68	59.00	100.00
Goiânia	116.10	226.00	4.60	10.00	21	24.36	10.72	74.99	47.24	9.00	94.90
Porto Velho[d]	92.50	71.00	3.80	2.00	30	-	-	-	-	-	-
Teresina	72.80	94.00	5.80	5.00	31	26.88	9.14	81.64	38.27	0.00	94.90
Campo Grande	68.10	85.00	2.20	2.00	22	25.08	11.30	62.86	43.36	68.00	96.60
Maceió	64.80	107.00	2.90	6.00	33	27.31	7.19	79.11	30.95	0.00	88.50
Palmas	56.80	23.00	3.30	1.00	32	26.73	8.54	78.08	36.80	5.00	79.20
Aracaju	56.30	52.00	6.10	4.00	32	28.41	6.84	60.94	26.34	85.00	100.00

[a] Rate per million inhabitants; [b] Percentage of days in which the average of relative humidity was ≤ 65%; [c] Percentage of days in which the average minimum relative humidity was ≤ 65%; [d] Temperature and humidity data unavailable for Porto Velho, capital of Rondônia State.

The cumulative COVID-19 cases are displayed using bubble sizes in Figure 1. The cities in the highest quintile of incidence rates were located in the north and northeast regions, except for São Paulo, which is located in the southeast. By April 18, São Paulo and Rio de Janeiro, Brazil's most densely populated cities, showed a higher number of cumulative cases (9,428 and 3,059 cases, respectively). The highest incidence rate was observed in Fortaleza (729 per million inhabitants), with 2,562 cumulative cases. These results were consistent with the time-lapse between starting data collection (5, 15, and 24 days) and the first case reported in São Paulo, Rio de Janeiro, and Fortaleza. Using a longer time-lapse (≥ 32 days) until the first reported case resulted in lower incidence rates. The highest mortality rate (45.50 per million inhabitants) was observed in São Paulo.

The highest mean temperature in the period (29.41 °C) was observed in the northern region (Boa Vista), and the lowest mean temperature (19.17 °C) was observed in the southern region (Curitiba). The cities from the 5th quintile of the COVID-19 incidence rate showed a mean temperature of approximately 27 °C and a mean daily relative humidity greater than 77 %, except in São Paulo. Curitiba, Porto Alegre, Goiania, Campo Grande, and Boa Vista showed the largest daily temperature amplitude (approximately 11 °C) and the largest daily relative humidity amplitude. None of these capitals showed incidence rates belonging to the highest quintile.

Table 2 presents the correlation values for the relationship between COVID-19 occurrence, daily temperature, and relative humidity. We observed that the mean daily temperature was positively correlated with the number of days until the first COVID-19 case ($r = 0.513$; $p = 0.009$) and negatively correlated with mortality rate and cumulative deaths. The mean daily relative humidity was positively correlated with cumulative COVID-19 cases ($r = 0.414$; $p = 0.040$) and deaths ($r = 0.408$; $p = 0.043$). The measures of amplitude temperature ($r = -0.550$; $p = 0.004$) and humidity ($r = -0.473$; $p = 0.029$) were negatively correlated with COVID-19 mortality rates. Humidity amplitude was also negatively correlated with cumulative mortality ($r = -0.426$; $p = 0.034$). The percentage of days with mean humidity ≤ 65 % was negatively correlated with all COVID-19 measures. After stratification, some negative correlations were observed, such as humidity amplitude vs. time-lapse until the first case ($r = -0.517$; $p < 0.05$), while others showed more evidence for cities with medium and low COVID-19 incidence rates.

Linear regression coefficients were obtained for cumulative cases of COVID-19 stratified by the mean daily temperature (Table 3). We observed a linear and inverse relationship between COVID-19 cumulative cases and temperature among most cities with mean daily temperatures less than 25.8 °C. This association was evident even after adjusting for relative humidity. In São Paulo, the number of COVID-19 cumulative

Table 2. Correlation values for the relationship between COVID-19 occurrence and daily temperature and relative humidity in Brazilian state capitals and the Federal District (Brasília) from February 20 to April 18, 2020.

COVID-19	Temperature (ºC)		Relative humidity (%)			
	Mean	Mean amplitude	Mean	Mean amplitude	% days mean ≤ 65	% days min ≤ 65
All cities[a]						
Incidence Rate	-0.060	-0.253	0.266	-0.164	**-0.386***	-0.363
Mortality Rate	0.160	**-0.550*****	0.349	**-0.437*****	**-0.562*****	**-0.388***
Cumulative cases	-0.315	-0.247	**0.414*****	-0.269	**-0.613*****	**-0.558*****
Cumulative deaths	-0.170	**-0.426****	**0.408****	-0.364	**-0.702******	**-0.511*****
Days until first case[b]	**0.513****	-0.111	0.005	-0.190	0.192	0.195
Cities with medium and low incidence rates[c]						
Incidence Rate	-0.347	0.018	0.429	0.209	-0.296	**-0.491***
Mortality Rate	0.191	**-0.485***	0.385	-0.279	-0.287	-0.291
Cumulative cases	-0.459	-0.056	0.474	0.044	**-0.523****	**-0.556****
Cumulative deaths	-0.354	-0.121	0.342	-0.034	**-0.545****	-0.396
Days until first case[b]	0.623	-0.390	-0.001	**-0.517****	0.084	0.147
Cities with the highest incidence rate[d]						
Incidence Rate	-0.042	-0.115	0.285	-0.248	-0.225	-0.313
Mortality Rate	-0.079	-0.115	0.139	-0.164	-0.505	-0.276
Cumulative cases	-0.091	-0.224	0.188	-0.345	-0.519	-0.362
Cumulative deaths	-0.321	-0,297	0.236	-0.370	-0.505	-0.436
Days until first case[b]	0.439	0.091	0.140	0.195	0.230	0.142

[a] Except São Paulo. [b] Time-lapse in the number of days between the start of follow-up (February 20) and the first case reported. [c] Cities in 1st ,2nd, and 3rd quintiles of the COVID-19 incidence rate: Porto Alegre, Brasília, Natal, Rio Branco, Belém, Salvador, Curitiba, Belo Horizonte, João Pessoa, Cuiabá, Goiânia, Teresina, Campo Grande, Maceió, Palmas, and Aracaju. [d] Cities in 4th and 5th quintiles of COVID-19 incidence rate: Fortaleza, Manaus, Macapá, Recife, São Luis, Florianópolis, Rio de Janeiro, Vitória, and Boa Vista. **p = 0.05*, ***p < 0.05*, ****p < 0.01*, *****p < 0.001* for two-tailed Spearman's rank correlation coefficient. The capital of Acre State (Rio Branco) did not have complete temperature and relative humidity data for this period.

cases decreased by 713.27 for each 1 °C increase in temperature. However, this relationship was not observed for cities with a mean daily temperature greater than or equal to 25.8 °C.

Discussion

The aim of this study was to evaluate the possible contributions of temperature and relative humidity variations to the initial spread of COVID-19 cases and deaths in Brazil. Our results showed that the mean daily temperature was positively correlated with the number of days until the first COVID-19 case was reported. A lower mean relative humidity was correlated with a lower number of cases and deaths. Higher temperature and humidity amplitudes were correlated with lower COVID-19 mortality. Additionally, after controlling for humidity, cumulative cases of COVID-19 were inversely associated with temperature in cities with mean temperatures less than 25.8 °C.

In this study, the initial phase of COVID-19 spread in Brazil was from February 20 to April 18, 2020. The first day of data collection was the official start of the Carnival, the most popular holiday in the country. The festival brings together millions of people to celebrate in the streets, mainly in São Paulo, Rio de Janeiro, and Salvador, and attracts foreign tourists from Europe and North America. Even though the possibility that SARS-CoV-2 had already been circulating in the country, there was no official cancellation of the Carnival. Although the choice of the final data collection date was arbitrary, the aim was to control for potential variables in the analysis, such as the different public actions to combat COVID-19 in each city, differences in the healthcare system, and the possible changes in seasonal climates.

The Brazilian COVID-19 epidemic started in the three major cities of Brazil: São Paulo, Rio de Janeiro, and Brasília. These cities have a higher number of international flights. After 54 days of the epidemic, the five Brazilian capital cities with the highest COVID-19 incidence rates were identified in the north (Manaus and Macapá) and northeast regions (Fortaleza and Recife), with the exception of São Paulo [35]. The north and northeast capitals are characterized by tropical climate with the highest temperature and humidity in Brazil.

Our findings showed that a lower mean relative humidity was correlated with a lower number of cases and deaths. Previous studies have also explored this association [10,11,16,20,24,25,38-40]. However, some studies have shown an inverse relationship between

Table 3. Linear regression coefficients (Beta) for cumulative cases of COVID 19 in Brazilian state capitals and the Federal District (Brasília) from February 20 to April 18, 2020, according to mean temperature in the period.

Cities	β	SE	t	*p* value	Adjusted β[a]	SE	t	*p* value
Cities with mean temperature < 25.8 °C in the period[b]								
São Paulo	-531.71	162.88	-3.26	0.002	**-713.27**	**154.05**	**-4.63**	**< 0.001**
Rio de Janeiro	-276.75	76.27	-3.63	0.001	**-345.71**	**78.05**	**-4.43**	**< 0.001**
Porto Alegre	-31.69	4.27	-7.42	< 0.001	**-31.65**	**4.78**	**-7.41**	**< 0.001**
Curitiba	-25.15	5.18	-4.85	< 0.001	**-26.34**	**5.11**	**-5.15**	**< 0.001**
Florianópolis	-23.25	3.22	7.22	< 0.001	**-22.94**	**3.63**	**-6.31**	**< 0.001**
Goiânia	-13.17	5.73	-2.28	0.026	**-29.16**	**9.84**	**-2.96**	**0.004**
Belo Horizonte	-8.99	12.95	-0.69	0.490	-8.636	15.98	-0.54	0.591
Cuiabá	-7.50	1.94	-3.86	< 0.001	**-14.90**	**2.23**	**-6.66**	**< 0.001**
Vitória	-5.66	4.63	-1.22	0.227	**-12.53**	**4.77**	**-2.63**	**< 0.011**
Campo Grande	-5.16	1.12	-4.58	< 0.001	**-5.92**	**1.12**	**-4.58**	**< 0.001**
Brasília	-0.74	28.18	-0.026	0.979	-17.32	57.95	-0.29	0.766
Cities with mean temperature ≥ 25.8 °C in the period[b]								
Manaus	-140.62	41.78	-3.36	0.001	**-186.16**	**92.58**	**-2.01**	**0.049**
Recife	-81.50	47.66	-1.71	0.093	-57.75	87.93	-0.66	0.514
Fortaleza	-43.64	103.71	-0.42	0.675	153.7	231.68	0.66	0.510
Salvador	-42.73	28.22	-1.51	0.135	35.63	45.78	0.78	0.440
Macapá	-31.47	13.26	-2.37	0.021	-9.94	19.89	-0.50	0.619
São Luís	-17.96	32.26	-0.56	0.580	7.29	45.95	0.16	0.874
Boa vista	-10.98	7.23	-0.19	0.134	-4.90	9.31	-0.52	0.602
Natal	-9.41	8.90	-1.05	0.295	3.26	18.64	0.17	0.862
João Pessoa	-7.74	5.40	-1.43	0.157	-1.96	10.95	-0.18	0.858
Aracaju	-2.75	1.92	-1.43	0.158	2.94	3.16	0.93	0.355
Maceió	-0.46	1.43	-0.33	0.746	**7.31**	**2.57**	**2.84**	**0.007**
Belém	1.73	5.90	0.29	0.770	7.13	8.12	0.88	0.385
Teresina	7.80	2.28	3.42	0.001	8.05	5.81	1.38	0.172
Palmas	0.77	0.64	1.20	0.235	0.52	1.64	0.107	0.752

[a] Adjusted for daily mean relative humidity in the period. [b] This cutoff was based on a previous finding [9]. The capital of Acre State (Rio Branco) did not have complete temperature and relative humidity data for the period.

relative humidity and new cases and deaths [10,16,25,41]. Regarding the amplitudes of relative humidity, studies demonstrated that high epidemic transmission of COVID-19 is associated with a humidity range of 60-90 % [31,38]. This study included information from January 20 to March 11 for 430 cities and districts in China, 21 cities/provinces in Italy, 21 cities/provinces in Japan, and 51 other countries worldwide. Another study with Chinese data demonstrated that a humidity range of 50-80 % is conducive to the survival of the coronavirus [39], whereas data from England demonstrated that the highest risk was at approximately 61% relative humidity [31]. Based on our analysis, Brazilian cities with mean humidity ≤ 65 % had lower mortality rates, cumulative cases, and cumulative deaths. Additionally, the correlation between relative humidity and COVID-19 occurrences was more evident in cities with higher incidence rates up until April 18, demonstrating that this relationship was more important at the beginning of the epidemic.

Furthermore, our results revealed that higher humidity amplitudes were correlated with lower COVID-19 mortality rates. Restricting analysis only to capitals with medium and low incidence rates showed a negative correlation between humidity amplitude and time-lapse until the first case, exhibiting a complex relationship that requires further investigation. A laboratory study investigating how virus survival is affected by air temperature and relative humidity, revealed a potential inactivation of the coronavirus at midrange relative humidity (~50%), and a greater protective effect of the virus at low (20%) and high (80 %) relative humidity [36]. Therefore, higher humidity amplitude has a higher probability of including these extreme relative humidity values, leading to a greater potential for inactivating transmissibility.

Temperature also has an impact on the transmission of COVID-19. In our study, higher temperature showed a positive association with a larger time-lapse between the beginning of data collection and the first COVID-19 case reported. Studies using data from only Northern Hemisphere cities have shown that higher temperatures could reduce the spread of the virus [11,25,42]. Another study exploring data from 166 countries in all hemispheres demonstrated a negative linear correlation between temperature and COVID-19 cases [10]. However, this finding could be biased because the pandemic started during the coldest seasons of the year in the Northern Hemisphere. Consequently, these countries had a greater number of cases compared to Southern Hemisphere countries. Similarly, Wang *et al.* included data from China and the United States, and showed that every 1 °C increase in average temperature led to an increase of 0.83 in cumulative cases at lower temperatures. However, with higher temperatures in summer, this effect will probably decrease [16].

Previous data from a study in Brazil revealed a negative linear relationship between temperature and COVID-19 cases, but only when the mean temperature was below 25.8 °C [9]. This suggests a possible nonlinear dose-response relationship between the two variables, indicating that the effect of temperature on mitigating the spread of COVID-19 is limited to colder temperatures. Our results corroborate these findings because cumulative cases of COVID-19 were inversely associated with temperature only in cities with mean temperatures less than 25.8 °C.

In summer, higher temperature amplitudes were observed in subtropical climate cities in the South and Midwest regions of Brazil. In this study, cities with high amplitudes were negatively correlated with COVID-19 deaths (rate and cumulative). Previous studies have indicated that diurnal temperature range can affect COVID-19 transmission [11,25]. For example, in a study conducted in Wuhan, China a positive association with daily COVID-19 death counts was observed for the diurnal temperature range [25]. However, another study in China revealed that a 1 °C increase in the diurnal temperature range resulted in a decline in daily confirmed case counts [11]. This suggests that an environment with a small daily temperature range could be advantageous for virus survival. However, these effects were observed in cold climates without controlling for relative humidity.

In this study, cumulative cases of COVID-19 were inversely associated with temperature in cities with a mean temperature of less than 25.8 °C, after controlling for the association with humidity. In São Paulo, the number of COVID-19 cumulative cases decreased by 713.27 for each 1 °C increase in temperature. Our results indicated a significant interaction between temperature and humidity. Following this finding, a study in Hubei Province, China, reported a significant negative interaction between daily average temperature and relative humidity for COVID-19 incidence [20]. Every 1 °C increase in the daily average temperature led to a decrease in the daily confirmed cases by 36% to 57% when the relative humidity was in the range of 67-85.5%. Every 1 % increase in relative humidity led to a decrease in the daily confirmed cases by 11 % to 22 % when the daily average temperature was in the range of 5.04-8.2 °C [20]. A study in India also indicated some influence of the interaction between average temperature and average relative humidity on the incidence of COVID-19, but this finding is inconsistent throughout the study area [28]. Although the mechanism of this interaction remains unclear, regions with low temperatures and humidity are more affected by the virus, whereby meteorological factors can create ideal environmental conditions for virus attachment, replication, transmission, and survival.

Our study is the first to demonstrate how the combination of temperature and relative humidity can influence the initial spread of and mortality from COVID-19 in all Brazilian territories. We included several meteorological values for the temperature and relative humidity. Daily meteorological data were used to appropriately compare the effects of temperature and humidity on COVID-19 cases and deaths. Additionally, we evaluated this relationship during the initial period of the COVID-19 pandemic. To dismiss the possible effects of underreporting and city population density on the results, we adopted different outcome measures, including cases and deaths. However, some methodological considerations should be considered. First, as an ecological study, it has limitations in establishing causal relationships, as the association observed at a collective level does not necessarily represent the association that exists at an individual level. However, an ecologic analysis may be more appropriate than studies using individual data when investigating the determinants of infectious disease transmission with complex and nonlinear infection spread [43]. Second, we did not include ultraviolet radiation in the analyses, although recent studies have shown that ultraviolet radiation is associated with the incidence rates of COVID-19 [44,45]. Third, our goal was not to assess other determinants of the spread and mortality of COVID-19, such as social distancing strategies, health system structure, medical resources, people's endurance, and personal hygiene. These aspects should be examined in future studies. Fourth, we sought to explore data for all Brazilian state capitals and the Federal District from February 20 to April 18, 2020. We could not obtain meteorological data for Porto Velho, the capital of Rondônia State. Finally, further investigations in the rural cities of Brazil should be conducted to determine if a novel epidemic spread occurred. Replication of this investigation might lead to more conclusive results using data from the end of winter, especially for the southernmost cities.

Conclusions

Variations in temperature and humidity across the Brazilian territory may have influenced the spread of the novel coronavirus during the initial phase of the epidemic. Our study revealed that lower relative humidity was correlated with a lower number of cases and deaths in Brazil, especially when the relative humidity was ≤ 65 %. Higher temperature and humidity amplitudes were also correlated with lower COVID-19 cases and deaths. In addition, after controlling for humidity, cumulative cases of COVID-19 were inversely associated with temperature in cities with mean temperatures less than 25.8 °C. Although the large-scale implementation of public health control measures plays a considerable role in reducing COVID-19 cases and deaths, our results indicate that climate conditions independently contributed to the initial spread of COVID-19.

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