Science of the Total Environment 729 (2020) 139090

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Evidence that high temperatures and intermediate relative humidity might favor the spread of COVID-19 in tropical climate: A case study for the most affected Brazilian cities

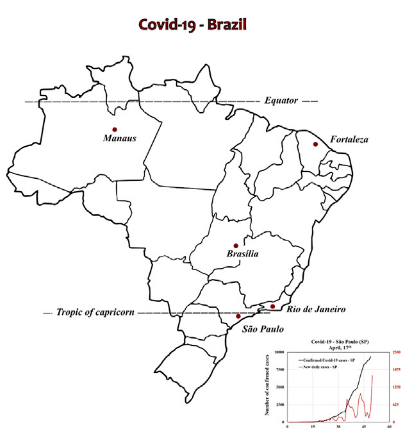
A.C. Auler [a], F.A.M. Cássaro [b], V.O. da Silva [c], L.F. Pires [b,*]

[a] Department of Soil Science and Rural Engineering, Federal University of Paraná, 80.035-050 Curitiba, PR, Brazil
[b] Laboratory of Physics Applied to Soils and Environmental Sciences, Department of Physics, State University of Ponta Grossa, 84.030-900 Ponta Grossa, PR, Brazil
[c] Chamber of Public Health, Federal University of Paraná, 83.260-000 Matinhos, PR, Brazil

HIGHLIGHTS

- This study attempts to model the effects of meteorological factors in COVID-19 spread in Brazil
- High mean temperatures influenced the COVID-19 transmission rate
- Intermediate relative humidity influenced the COVID-19 transmission rate
- Correlation of meteorological conditions with COVID-19 spread is presented for five Brazilian cities
- This study aims to support decision-makers to avoid deaths by the collapse of health-care systems

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 April 2020
Received in revised form 27 April 2020
Accepted 27 April 2020
Available online 28 April 2020

Keywords:
Air temperature
Humidity
Coronavirus
Meteorology
SARS-CoV2
Principal component analysis

ABSTRACT

This study aimed to analyze how meteorological conditions such as temperature, humidity and rainfall can affect the spread of COVID-19 in five Brazilian (São Paulo, Rio de Janeiro, Brasília, Manaus and Fortaleza) cities. The cities selected were those with the largest number of confirmed cases considering data of April 13. Variables such as number of cumulative cases, new daily cases and contamination rate were employed for this study. Our results showed that higher mean temperatures and average relative humidity favored the COVID-19 transmission, differently from reports from coldest countries or periods of time under cool temperatures. Thus, considering the results obtained, intersectoral policies and actions are necessary, mainly in cities where the contamination rate is increasing rapidly. Thus, prevention and protection measures should be adopted in these cities aiming to reduce transmission and the possible collapse of the health system.

* Corresponding author.
E-mail address: lfpires@uepg.br (L.F. Pires).

https://doi.org/10.1016/j.scitotenv.2020.139090

1. Introduction

In the first quarter of 2020, the novel coronavirus disease 2019 (COVID-19) spread rapidly around the world. The severe acute respiratory syndrome outbreak has hit severely several countries of Europe and the United States of America. The number of people infected by COVID-19, by April 26, 2020, was around 3 million cases and 204 thousand deaths reported globally (WHO, 2020). The COVID-19 transmission cases are posing a serious threat to the health systems of many countries (especially for the developing ones).

Some papers have described that the COVID-19 spread can be affected by a large number of factors, among them, climate conditions (Qi et al., 2020; Tosepu et al., 2020). It is known that the virus's survival and transmission by droplets are facilitated in dry and cold weather situations (Casanova et al., 2010). However, the number of reports about the virus dissemination and the influence of weather factors such as temperature and humidity in tropical countries is still limited. This kind of information is important to show whether tropical climates are less favorable to the spread of the virus.

Brazil is the fifth largest country in the world with an area of approximately 8.5 million km^2. The country has a wide range of meteorological conditions due to its large extension. According to Köppen's climate classification, 81.4% of the Brazilian territory comprises a tropical climate, 4.9% a semi-arid climate (northeast of the country) and 13.7% a subtropical climate, which is mainly located in the southern region (Alvares et al., 2013). As Brazil has a large area under tropical climate conditions, studying the COVID-19 spread in the country and its relationship to weather can bring important recommendations to support decisions related to this disease control.

A great number of studies modeling the effects of meteorological conditions on COVID-19 transmission from January to April 2020, were conducted in China (Liu et al., 2020; Xie and Zhu, 2020), Iran (Ahmadi et al., 2020), Europe and the United States of America (Bukhari and Jameel, 2020). The conclusions regarding the relationship of meteorological conditions and COVID-19 transmissibility are still controversial. Xie and Zhu (2020) investigated the relationship between daily mean temperature and newly confirmed COVID-19 cases in 122 cities from China (including Wuhan), between January 23 and February 29, 2020. Those authors highlighted no evidence supporting that COVID-19 case counts could decline when the weather becomes warmer. On the other hand, Liu et al. (2020) based on data from 130 Chinese cities, except Wuhan, between January 20 and March 2, 2020, emphasized that lower temperature and humidity are likely to favor the transmission of COVID-19.

Apart from the controversial results, we highlight that those findings might not be suitable to tropical regions due to the meteorological conditions of the temperate countries in the period of time of the studies. In Brazil up to now there is only one study about the influence of weather variables on COVID-19 spread (Coelho et al., 2020). Thus, our study intends to present new evidence of the influence of tropical weather conditions and epidemic transmission of the coronavirus in different Brazilian geographical regions.

This paper intends to analyze how meteorological conditions such as temperature, humidity and rainfall can affect the spread of COVID-19 in a tropical country. Five cities of Brazil (São Paulo, Rio de Janeiro, Brasília, Manaus and Fortaleza), which had the largest number of confirmed cases according to data of April 13, were selected for this study.

The results of this study aim at to present alternatives for predicting the COVID-19 pandemic trend and to support policymakers regarding choices on population mobility and human-to-human contact. A multivariate statistical method was employed for the analysis of the data.

2. Materials and methods

2.1. Study area, epidemiological and climate data

Epidemiological data between March 13 and April 13, 2020, were obtained from the following sources: Brazilian Federal District Health Office (Brasília), Rio de Janeiro State Health Office (Rio de Janeiro), "Prof. Alexandre Vranjac" Epidemiological Center (São Paulo) and Brazilian Ministry of Health (Manaus and Fortaleza) (CIIS-FMRB, 2020). As mentioned before, the selected cities were those with the largest number of confirmed cases by April 13, 2020 (São Paulo: 6418; Rio de Janeiro: 2322; Fortaleza: 1686; Manaus: 1106; Brasília: 641) (CIIS-FMRB, 2020). Number of cumulative cases, new daily cases and contamination rate were considered in this study. The latter was calculated per 100 thousand habitants.

These cities are located in the North (Manaus), Northeast (Fortaleza), Center-West (Brasília) and Southeast (São Paulo and Rio de Janeiro) regions of Brazil (Fig. 1). In 2019, the municipality of São Paulo had a population estimated in around 12.2 million people, Rio de Janeiro around 6.7 million people, Brasília around 3 million people, Fortaleza around 2.7 million people and Manaus around 2.2 million people (IBGE, 2019). All of these cities are capitals of their states and Brasília is the federal capital of Brazil.

The Köppen climate classification for São Paulo is Cfa (Humid Subtropical), Rio de Janeiro and Brasília is Aw (Tropical Savanna with dry winter), Fortaleza is As (Tropical Savanna with dry summer) and Manaus is Am (Tropical Monsoon) (Alvares et al., 2013). Table 1 presents the average data for some weather variables for the cities studied.

Weather data were obtained based on hourly meteorological observations from the "Instituto Nacional de Meteorologia" (INMET), the meteorological institute of Brazil, which is part of the Ministry of Agriculture, Livestock and Food Supply (INMET, 2020). For the cities with more than one meteorological station, cases of São Paulo and Rio de Janeiro, the one nearest to the city center was chosen. Mean, maximum and minimum daily temperatures and relative humidity and rainfall were selected for this study.

2.2. Statistical analysis

Regarding the statistical analysis, firstly, an exploratory analysis of the data was carried out for each city studied. The number of observations analyzed was 141 distributed among cities: 19 for Manaus (between March 25 and April 13), 29 for Fortaleza (between March 16 and April 13) and 31 for Brasília, Rio de Janeiro and São Paulo (between March 13 and April 13). After the application of the exclusion criterion, the meteorological variables (temperature, humidity and rainfall) were paired to the COVID-19 evolution variables (new daily cases, total number of cases and contamination rate).

Following the exploratory data analysis, the residual normality assumption was verified by the Shapiro-Wilk test (Shapiro and Wilk, 1965). After the assumption had been verified, the data of each variable studied were standardized (mean = 0 and variance = 1). This procedure was carried out for each city and considering the total number of observations ($n = 141$). Principal component analyses (PC) and canonical correlation were carried out based on the correlation matrix. In the present study, principal components were selected based on the fact that they explain at least 70% of the total variance of each data set. The significance level values ≤ 0.05 (p-value) for the χ^2 test were used to select the canonic pairs. The selection of the variables that comprise the canonic pair was determined when the coefficients were larger than 1 (Manly, 2004).

To simplify the multivariate statistical analysis, the absolute air humidity was calculated according to the Clausius-Clapeyron equation (Iribarne and Godson, 2012). This climate variable is interesting because it describes the actual amount of water vapor in the atmosphere, which depends on the air temperature. The absolute humidity has been used

Fig. 1. Map showing the locations with the highest number of confirmed COVID-19 cases in Brazil.

as a meteorological variable in studies of COVID-19 modeling (Liu et al., 2020; Xie and Zhu, 2020). Subsequently, linear regression analyses between the absolute humidity and the contamination rate were performed for each city and all cities together.

It is worth to mention that the multivariate as well as the linear regression analyses carried out for each city and all cities together, aimed to identify the micro climate condition specificities for each city and how these conditions are affecting the Brazilian COVID-19 spread. The R software (v. 3.6.1) primitive functions were used for the normality test and linear regression analysis and the package MVar.pt. for the multivariate analyses (R Core Team, 2019).

3. Results and discussion

3.1. Meteorological conditions

There was a wide variation of the weather conditions in the period of March 13 to April 13 for the five selected Brazilian cities (Figs. 2 and 3). These results were expected as they are located in different latitudes and altitudes (Alvares et al., 2013). Manaus and Fortaleza presented the highest temperature and amount of rainfall among the cities analyzed (Table 2). However, the highest relative humidity and the lowest temperatures were found in São Paulo (Table 2).

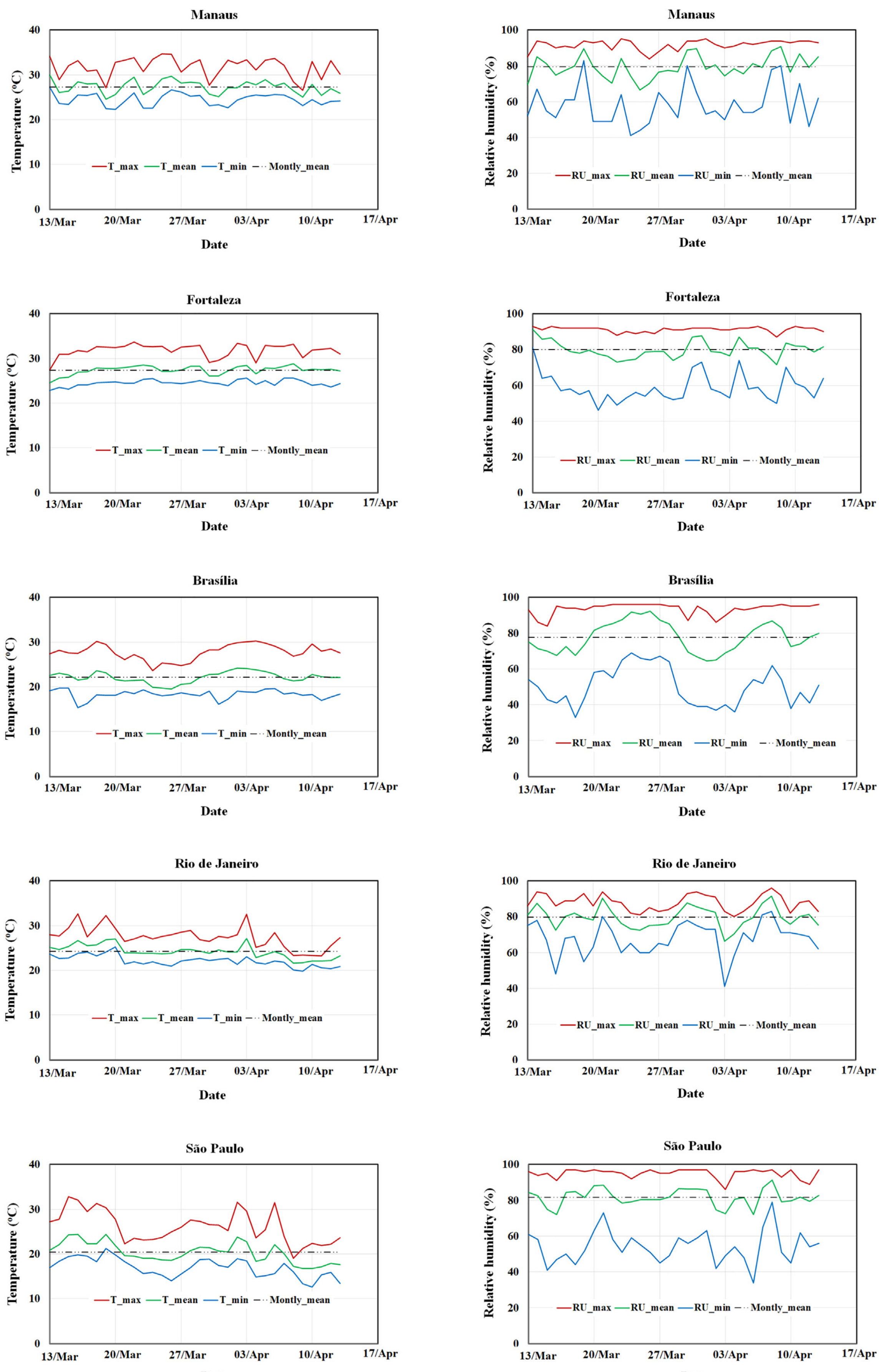
Brasília, unlike Manaus and Fortaleza, was characterized by intermediate rainfall associated with low temperatures (Table 2). The daily rainfall amount was also analyzed as it influences the air relative humidity (Vicente-Serrano et al., 2018) (Fig. 3). The number of rainfall events was irregularly distributed mainly in São Paulo and Rio de Janeiro (Table 2). The cumulative rainfall registered for each city was 412.8 mm (Manaus), 366.6 mm (Fortaleza), 225.2 mm (Brasília), 61.2 mm (Rio de Janeiro) and 35.4 mm (São Paulo), respectively.

Manaus presented higher rainfall than usual for March and April (323.3 mm). March is considered the driest month for this city (Table 1). Fortaleza had rainfall volumes close to the expected for this period of the year (339.6 mm). April is normally the driest month for this city (Table 1). Brasília had an accumulated rainfall volume higher than the usual for March and April (152.2 mm), while Rio da Janeiro and São Paulo had volumes lower than the usual for March and April (115.4 mm for Rio de Janeiro and 116.6 mm for São Paulo) (Weather-Atlas, 2020).

Table 1
Average temperature and rainfall in the Brazilian cities studied.

Cities	Temperature (°C)			Rainfall (mm)		
	Annual	Warmest	Coolest	Annual	Wettest	Driest
Manaus	27.2	September (28.3)	February (26.7)	2307.3	March (335.4)	August (47.3)
Fortaleza	26.6	December (27.3)	July (25.6)	1608.4	April (356.1)	November (11.8)
Brasília	20.6	September (21.7)	July (18.3)	1540.5	January (247.4)	June (8.7)
Rio de Janeiro	24.2	February (27.5)	July (21.0)	1069.2	January (137.1)	July (41.9)
São Paulo	20.6	February (23.9)	July (17.2)	1441.1	January (237.4)	August (39.6)

Values between parentheses represent average values of temperature and rainfall. Data of temperature were obtained from weatherbase.com and rainfall from weather-atlas.com


Manaus
Temperature (ºC)
T_max T_mean T_min Montly_mean
13/Mar 20/Mar 27/Mar 03/Apr 10/Apr 17/Apr
Date
Manaus
Relative humidity (%)
RU_max RU_mean RU_min Montly_mean
13/Mar 20/Mar 27/Mar 03/Apr 10/Apr 17/Apr
Date
Fortaleza
Temperature (ºC)
T_max T_mean T_min Montly_mean
Date
Fortaleza
Relative humidity (%)
RU_max RU_mean RU_min Montly_mean
Date
Brasília
Temperature (ºC)
T_max T_mean T_min Montly_mean
Date
Brasília
Relative humidity (%)
RU_max RU_mean RU_min Montly_mean
Date
Rio de Janeiro
Temperature (ºC)
T_max T_mean T_min Montly_mean
Date
Rio de Janeiro
Relative humidity (%)
RU_max RU_mean RU_min Montly_mean
Date
São Paulo
Temperature (ºC)
T_max T_mean T_min Montly_mean
Date
São Paulo
Relative humidity (%)
RU_max RU_mean RU_min Montly_mean
Date

3.2. COVID-19 spread

For the period selected for this study, São Paulo was the city that registered the highest number of new daily cases, mainly from March 31 onwards when the number of confirmed cases exhibited significant increases (Fig. 4). The variation of new daily cases was also high for São Paulo, which is probably related to the sub-notification cases of COVID-19 in Brazil. We came to this conclusion because this was the unique city that did not exhibit any statistical mode for the registration of COVID-19 new cases (Table 3).

The other cities had the following order of occurrence of new cases of COVID-19 from March 13 to April 13: Rio de Janeiro > Manaus > Fortaleza > Brasília (Table 3). The number of cumulative cases showed similar behavior to the new daily registered COVID-19 cases, except for Manaus and Fortaleza, which inverted their order in the trend of the highest number of cumulative cases (Fig. 4). On April 25, an update of the number of cumulative cases between the cities analyzed still exhibited the same tendency as April 13 (São Paulo: 13,098; Rio de Janeiro: 4481; Fortaleza: 4063; Manaus: 2481; Brasília: 956) (Table 3) (CIIS-FMRB, 2020).

The highest number of COVID-19 cases for the cities of São Paulo and Rio de Janeiro are related to the importance of these cities. São Paulo is the main economic destination for job seekers and investors and Rio de Janeiro is the most important tourist destination in the country. An analysis of the evolution of the COVID-19 transmission cases in these cities deserves special attention due to their economic relevance as well as their population density. Tosepu et al. (2020) have recently described the importance of the analysis of the meteorological conditions in the COVID-19 spread in very densely populated areas.

The increase in the number of cases in Fortaleza is confirmed when the contamination rate for this city is analyzed. It overcame the municipality of São Paulo on April 6. Regarding contamination rate, special attention has to be drawn to Manaus, which initially had almost 1/5 of the number of confirmed cases for São Paulo. Manaus started to present contamination rates similar to São Paulo between April 12 and April 13 (Fig. 4).

It is worth mentioning that the COVID-19 cases time series for Fortaleza and Manaus presented a delay when compared to the other cities. It means that the contamination rates in these two cities are probably more accentuated than in cities densely populated, such as São Paulo, Rio de Janeiro and Brasília. Thus, our results suggest that these cities might have a high risk of increasing the daily occurrence of new COVID-19 cases.

3.3. Multivariate analysis of COVID-19 spread

The analysis of the new daily cases, total number of cases and contamination rate and the meteorological data did not allow us to identify any type of tendency for the COVID-19 dissemination in Brazil. For example, São Paulo was the city with the highest number of confirmed and new daily cases and presented the lowest mean temperature and the highest relative air humidity. Nonetheless, Fortaleza and Manaus, cities characterized by higher temperatures, rainfall and intermediate relative humidity when compared to the other cities, had more significant increases in the contamination rate (Fig. 4 and Table 3). Thus, we decided to use the multivariate analysis to evaluate the effect of all the meteorological variables in the COVID-19 transmission in the Brazilian cities under distinct climate conditions.

Initially, principal component analysis was applied to identify the possible existence of any meteorological variable which is best correlated to the COVID-19 dissemination in Brazil between March 13 and April 13. The analysis was carried out for each city and all cities merged

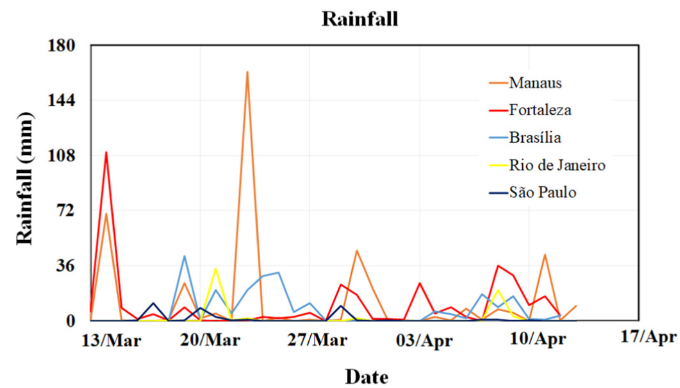


Fig. 3. Rainfall (mm) of the cities registered in the period between March 13 and April 13, 2020. The order of colors indicates the highest (red) to the lowest (blue) mean temperatures between cities. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to build a predictive model for Brazil. Chen et al. (2020) have recently presented a model to predict the COVID-19 spread rate based on different types of meteorological data. They observed that changes in a single meteorological factor (temperature or humidity) are not well correlated with the confirmed cases.

To verify the accuracy of any proposed model, correlations between meteorological variables and the evolution of COVID-19 number of cases were also carried out using the canonical correlation analysis. We also emphasize that our objective was to develop a simple model, such as a linear regression based on the multivariate analysis. As in Cássaro and Pires (2020), we adopted this strategy to facilitate the dissemination and understanding of the results and to reach a broader audience than just scientists.

Manaus, Fortaleza and Rio de Janeiro had the two first principal components (PC1 and PC2) explaining >70% of the total variance (σ^2) of the data sets; whereas, Brasília and São Paulo explained 68.4% and 67.9% of the total variance, respectively (Table 4). When all the cities were analyzed together three principal components were necessary to explain 76% of the total variance. In all cities, it was evident that meteorological data correlate better among themselves than with the COVID-19 evolution variables (Table 4).

PC1 for Fortaleza and Brasília was associated with the correlation between the meteorological variables that are negatively correlated to the air relative humidity as the temperature increases (mean, maximum and minimum), but relative humidity was positively correlated to rainfall. PC2 was composed of the combination of COVID-19 dissemination in which the contamination rate was highly relevant to explain the number of cumulative cases (Table 4).

Manaus was the city that best correlated meteorological variables and the evolution of the COVID-19 in PC1, although the meteorological variables explained most of the total variance (Table 4). Temperature was seen to affect negatively the contamination rate and the number of cumulative cases, while relative humidity had a positive influence.

Correlations between the climate variables and the COVID-19 evolution were also reported for Rio de Janeiro and São Paulo (Table 4). In both cities, in PC1 we observed that higher temperatures affected negatively the COVID-19 spread and PC2 was composed of a positive linear correlation between rainfall and relative air humidity.

The canonical correlation analyses (Tables 5 and 6) showed great correspondence with the principal component analysis. Manaus, Rio de Janeiro and São Paulo exhibited strong and significant correlations of the first canonical pair, while for Fortaleza and Brasília the correlations, even being high, were not significant. However, the greatest

Fig. 2. Temperatures (°C) and Relative humidity (%) – maximum (red line), mean (green line) and minimum (blue line) and monthly mean (black dashed line) – of the cities registered in the period between March 13 and April 13, 2020. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Descriptive analysis of the meteorological variables of the Brazilian cities with more cases of Covid-19.

Statistics	Temperature (°C)			Relative humidity (%)			Rainfall (mm)
	Mean	Max	Min	Mean	Max	Min	
Manaus							
Mean	27.3	31.7	24.5	79.4	91.8	58.2	12.9
Median	27.7	32.5	24.6	78.8	93.0	55.0	0.7
Mode	28.2	33.3	25.5	74.4	94.0	61.0	0.0
Minimum	24.6	26.6	22.3	66.5	84.0	41.0	0.0
Maximum	30.0	34.7	27.2	90.8	95.0	83.0	162.6
SD	1.5	2.2	1.3	6.3	2.8	11.0	31.8
Kurtosis	−0.9	−0.3	−1.0	−0.5	1.0	0.0	16.5
Asymmetry	−0.1	−0.8	0.0	0.1	−1.3	0.8	3.8
Fortaleza							
Mean	27.4	31.8	24.5	79.9	91.2	58.7	11.5
Median	27.6	32.5	24.6	79.0	92.0	57.0	3.9
Mode	28.3	32.7	24.6	78.9	92.0	53.0	0.0
Minimum	24.6	27.5	22.9	71.6	87.0	46.0	0.0
Maximum	28.8	33.7	25.6	91.3	93.0	81.0	110.0
SD	1.0	1.4	0.7	4.7	1.4	7.9	20.8
Kurtosis	1.1	1.5	0.1	−0.1	1.6	1.0	16.5
Asymmetry	−1.1	−1.3	−0.3	0.5	−1.3	1.1	3.7
Brasília							
Mean	22.1	27.8	18.3	77.7	93.5	50.1	7.0
Median	22.1	27.8	18.4	77.4	95.0	49.0	0.9
Mode	21.5	27.4	18.1	–	95.0	54.0	0.0
Minimum	19.5	23.6	15.4	64.5	84.0	33.0	0.0
Maximum	24.2	30.3	19.7	92.2	96.0	69.0	42.2
SD	1.2	1.7	1.0	8.3	3.3	10.5	11.0
Kurtosis	−0.3	−0.2	1.5	−1.2	2.4	−1.1	2.7
Asymmetry	−0.4	−0.5	−1.1	0.1	−1.8	0.3	1.8
Rio de Janeiro							
Mean	24.2	27.4	22.1	79.7	88.0	67.7	1.9
Median	24.0	27.6	22.0	79.9	88.0	69.0	0.0
Mode	23.8	28.0	22.7	87.5	93.0	75.0	0.0
Minimum	21.6	23.2	19.8	66.2	80.0	41.0	0.0
Maximum	27.1	32.6	25.2	91.5	96.0	83.0	34.4
SD	1.5	2.4	1.2	5.8	4.5	9.3	6.9
Kurtosis	−0.2	0.3	0.1	−0.1	−1.2	1.2	17.7
Asymmetry	0.3	0.3	0.4	0.0	0.0	−0.8	4.2
São Paulo							
Mean	20.4	26.1	16.9	81.6	95.0	54.2	1.1
Median	20.3	25.7	17.1	81.7	96.0	54.0	0.0
Mode	22.1	27.8	17.0	81.5	97.0	51.0	0.0
Minimum	16.8	19.1	12.6	72.0	86.0	34.0	0.0
Maximum	24.4	32.8	21.2	91.3	97.0	79.0	11.6
SD	2.3	3.6	2.1	4.8	2.7	9.3	2.9
Kurtosis	−0.9	−0.8	−0.7	−0.1	3.0	0.9	7.5
Asymmetry	0.2	0.3	−0.1	−0.3	−1.8	0.4	2.9

Max, Min and Cum stand for maximum, minimum and cumulative. SD is the standard deviation.

significance observed for both canonical pairs was reported when the effects of the meteorological variables of all cities were considered (Table 5).

Thus, considering the greater significance of the analysis for all cities, it is noteworthy that the COVID-19 contamination rate in Brazil is initially favored by higher mean temperatures as well as intermediate average relative humidity (Table 6), differently from the reports from colder countries or periods of time under cool temperatures (Araújo and Naimi, 2020; Bu et al., 2020; Cai et al., 2020; Luo et al., 2020; Qi et al., 2020). Yao et al. (2020) also reported that it is premature to consider that warmer weather can reduce the COVID-19 transmission.

It is also important to mention that the canonical correlation analysis of all cities together showed that extreme events, e.g. maximum and minimum temperature and relative humidity affected negatively the COVID-19 transmission rate (Table 6). This result can explain the lack of a significant correlation for Brasília, which had the largest number of days with the highest relative humidity associated with the lowest minimum temperatures (Fig. 2).

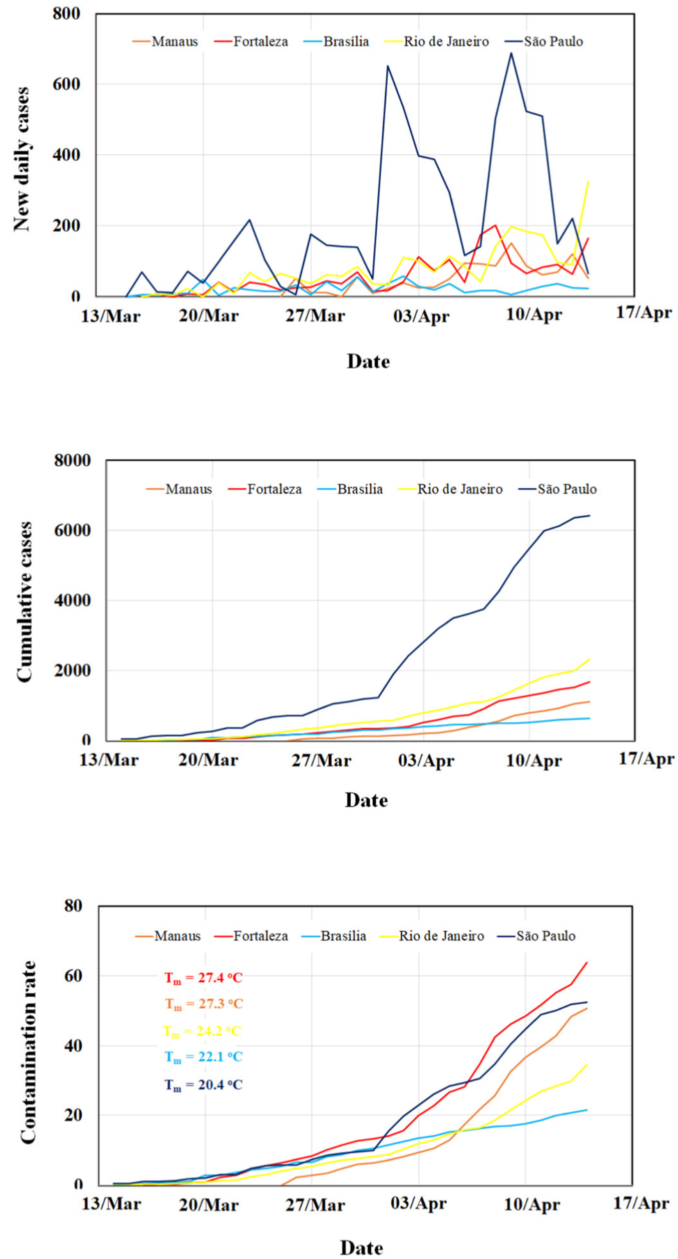


Fig. 4. Evolution of Covid-19 in Brazilian cities with higher records of new daily cases, cumulative cases and contamination rate in the period between March 13 and April 13, 2020. The order of colors indicates the highest (red) to the lowest (blue) mean temperatures (T_m) between cities. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.4. Linear regression analysis of the COVID-19 spread

Based on the individual and joint interpretations of the principal component analysis and canonical correlation, a new meteorological variable, absolute humidity, was calculated (Lowen and Steel, 2014).

Linear regressions between absolute humidity and the COVID transmission rate for the hottest cities (Manaus and Fortaleza) showed a positive correlation (Fig. 5). Thus, it can be inferred that the combination of relative humidity close to 79.6% and temperature of 27.3 °C favored the spread of COVID-19. It is also worth noting that the greatest significance was reported for Manaus. Although Brasília presented higher average relative humidity, close to 79.6%, it presented low average temperature (22.1 °C) (Table 2), then the conditioning variable absolute humidity did not justify the evolution of COVID-19 cases in the period (Fig. 5).

Table 3
Descriptive analysis of the evolution of Covid-19 in Brazilian cities.

Cities	Statistics							
	Mean	Median	Mode	Min	Max	SD	Kurtosis	Asymmetry
Manaus								
New daily cases	61.4	55.0	11.0	9.0	152.0	39.5	0.1	0.6
Cumulative cases	439.1	283.0	–	52.0	1106.0	363.5	−1.1	0.6
Contamination rate	20.1	13.0	–	2.4	50.7	16.7	−1.1	0.6
Fortaleza								
New daily cases	59.4	41.0	8.0	1.0	202.0	52.4	1.2	1.3
Cumulative cases	560.1	353.0	–	8.0	1686.0	529.0	−0.7	0.8
Contamination rate	21.2	13.4	–	0.3	63.8	20.0	−0.7	0.8
Brasília								
New daily cases	22.4	18.0	18.0	3.0	58.0	15.1	0.1	0.9
Cumulative cases	286.4	260.0	–	3.0	641.0	209.7	−1.4	0.2
Contamination rate	9.6	8.7	–	0.1	21.6	7.0	−1.4	0.2
Rio de Janeiro								
New daily cases	81.3	66.0	42.0	1.0	326.0	70.6	4.1	1.7
Cumulative cases	695.3	502.5	22.0	17.0	2322.0	674.7	−0.2	0.9
Contamination rate	10.3	7.5	0.3	0.3	34.6	10.0	−0.2	0.9
São Paulo								
New daily cases	227.0	143.5	–	5.0	689.0	209.8	−0.5	0.9
Cumulative cases	2174.8	1113.5	62.0	0.0	6418.0	2200.9	−0.8	0.8
Contamination rate	18.3	9.7	0.5	0.5	52.4	18.0	−0.9	0.7

Max and Min stand for maximum and minimum values, respectively. SD is the standard deviation.

Table 4
Principal components (PC) and its explained variance (σ^2) from individual and all cities considering meteorological variables and evolution of Covid-19 in the Brazilian cities.

Statistics	Eigenvalue	Eigenvectors									
		Temperature			Relative Humidity			Rain	NDC	Cum. cases	Cont. rate
		Mean	Max	Min	Mean	Max	Min				
Manaus											
PC 1	2.43	**0.39**	**0.35**	**0.32**	**−0.39**	**−0.33**	**−0.31**	−0.25	−0.18	**−0.29**	**−0.29**
σ^2 (%)	59.1	**15.5**	**12.1**	**10.1**	**15.0**	**10.9**	**9.8**	6.4	3.3	**8.5**	**8.5**
PC 2	1.42	0.09	0.27	0.07	−0.12	0.14	**−0.35**	**−0.35**	**0.49**	**0.45**	**0.45**
σ^2 (%)	20.3	0.7	7.4	0.5	1.4	2.0	**12.3**	**12.0**	**24.0**	**19.8**	**19.8**
Fortaleza											
PC 1	2.19	**0.39**	**0.40**	0.27	**−0.43**	−0.27	**−0.41**	**−0.37**	−0.04	−0.16	−0.16
σ^2 (%)	48.1	**15.2**	**16.1**	7.2	**18.9**	7.2	**16.4**	**13.8**	0.1	2.6	2.6
PC 2	1.64	0.23	0.11	0.13	−0.07	−0.10	−0.02	0.10	**0.52**	**0.56**	**0.56**
σ^2 (%)	26.8	5.4	1.3	1.6	0.5	1.0	0.0	1.0	**27.5**	**30.9**	**30.8**
Brasília											
PC 1	2.13	**0.45**	**0.43**	0.03	**−0.43**	−0.29	**−0.44**	**−0.34**	0.11	0.11	0.11
σ^2 (%)	45.2	**20.2**	**18.5**	0.1	**18.8**	8.3	**19.3**	**11.3**	1.1	1.2	1.2
PC 2	1.52	0.03	−0.05	0.10	−0.16	**−0.34**	−0.01	−0.03	**−0.35**	**−0.60**	**−0.60**
σ^2 (%)	23.2	0.1	0.3	1.0	2.4	**11.3**	0.0	0.1	**12.3**	**36.2**	**36.2**
Rio de Janeiro											
PC 1	2.22	**0.42**	**0.40**	**0.39**	−0.14	−0.06	−0.24	−0.12	**−0.35**	**−0.38**	**−0.38**
σ^2 (%)	49.4	**17.9**	**16.0**	**15.1**	2.0	0.3	5.6	1.4	**12.3**	**14.7**	**14.7**
PC 2	1.71	0.00	−0.08	0.06	**0.54**	**0.50**	**0.43**	**0.33**	−0.22	−0.23	−0.23
σ^2 (%)	29.1	0.0	0.6	0.4	**28.9**	**24.7**	**18.9**	**11.1**	4.7	5.3	5.3
São Paulo											
PC 1	2.07	**0.44**	**0.42**	**0.39**	−0.10	0.02	−0.17	0.15	−0.29	**−0.41**	**−0.41**
σ^2 (%)	42.8	**19.4**	**17.3**	**15.3**	1.0	0.0	2.9	2.3	8.2	**16.7**	**16.7**
PC 2	1.58	0.09	0.21	−0.13	**−0.59**	**−0.40**	**−0.48**	**−0.34**	0.01	0.19	0.19
σ^2 (%)	25.1	0.9	4.6	1.8	**34.7**	**16.1**	**23.1**	**11.4**	0.0	3.7	3.7
All cities											
PC 1	1.95	**0.45**	**0.44**	**0.41**	−0.26	−0.26	−0.12	−0.05	**−0.32**	**−0.38**	−0.20
σ^2 (%)	38.2	**20.6**	**19.4**	**16.7**	6.7	6.5	1.3	0.3	**10.4**	**14.1**	4.0
PC 2	1.46	0.10	−0.06	0.23	**0.54**	0.19	**0.52**	**0.48**	−0.19	−0.24	−0.08
σ^2 (%)	21.4	0.9	0.4	5.1	**29.6**	3.8	**27.5**	**22.6**	3.6	5.9	0.6
PC 3	1.28	0.31	0.17	**0.36**	0.04	−0.22	0.19	0.06	**0.37**	**0.38**	**0.61**
σ^2 (%)	16.4	9.6	2.8	**13.0**	0.2	4.9	3.7	0.3	**13.3**	**14.4**	**37.7**

Max and Min stand for maximum and minimum. Rain stands for rainfall. NDC, Cum. cases and Cont. rate stand for new daily cases, cumulative cases and contamination rate, respectively.

Table 5
Correlation, approximate chi-square (χ^2) and significance (p) of the first two canonical pairs (U1V1 and U2V2) from individual and all cities considering meteorological variables and evolution of Covid-19 in Brazil.

Statistics	Correlation	χ^2	p
Manaus			
U1V1	0.92	34.83	0.029
U2V2	0.68	10.75	0.551
Fortaleza			
U1V1	0.73	26.54	0.187
U2V2	0.54	9.37	0.671
Brasília			
U1V1	0.69	22.60	0.366
U2V2	0.47	6.86	0.867
Rio de Janeiro			
U1V1	0.84	38.89	0.010
U2V2	0.46	8.00	0.785
São Paulo			
U1V1	0.76	32.45	0.053
U2V2	0.49	10.06	0.611
All cities			
U1V1	0.72	123.09	<0.001
U2V2	0.36	24.73	0.016

Brasilia was also the city with the lowest COVID-19 contamination rate among the studied cities (Table 3). The statistical non-significance of the linear regression for Brasília demonstrates that the combination of higher temperatures and intermediate average relative humidity might favor the evolution of COVID-19.

On the other hand, Rio de Janeiro and São Paulo, cities with greater population densities (IBGE, 2019) and the highest number of total cases (Table 3), showed that the increase in absolute humidity reduced the contamination rate of COVID-19. The most significant reduction was found for São Paulo, which was directly affected by low average temperature, associated with high average relative humidity (Fig. 5 and Table 2). This result confirms the importance of the combination of temperature and average relative humidity to explain the dissemination of COVID-19 in Brazil. Thus, when all cities were combined, it was demonstrated that the increase in absolute humidity favors (high significance) the contamination rate of COVID-19 in Brazil (Fig. 5).

Our results contradict those presented by Wang et al. (2020), which analyzed data between January 21 and 23, 2020, of 100 Chinese cities with >40 confirmed cases of COVID-19. In this case, the mean temperatures reported for 3 and 5 days were 6 and 5.2 °C, respectively, with minimum and maximum of −20.8 °C (3 and 5 days) and 21 °C (3 days) and 18.5 °C (5 days), respectively. The average relative humidity was 78.4 and 77.5% for 3 and 5 days, respectively, but it ranged between 46.7 and 100% (3 days) and 49 and 91.8% (5 days). Thus, for the generalized linear model a range of temperature and relative humidity between −21 to 21 °C and 47 to 100%, for 3 or 5 days, was analyzed by Wang et al. (2020). In this way, the conclusion that high temperature and high humidity reduce the transmission of COVID-19 could not be applied to tropical regions with great transmission rates; where the minimum temperatures were almost constant and over 21 °C and relative humidity constant in values near 79% for 30 days.

4. Conclusions

Our paper demonstrates that meteorological factors affect the COVID-19 dissemination in different cities of Brazil. This is the first study that attempts to model the effects of meteorological factors in COVID-19 in tropical climate. Temperature and relative humidity deserve special attention. For the study period selected, the COVID-19 transmission rate in Brazil was initially observed to be favored by higher mean temperatures (27.5 °C) as well as intermediate relative humidity (near 80%).

However, it is important to mention that our study presents a preliminary analysis and has some limitations. A longer study period might better represent the relation between meteorological conditions and the COVID-19 transmissibility. So we encourage other researchers, but mainly epidemiologists and meteorologists, to repeat this study in the near future, considering other Brazilian cities or regions with a tropical climate.

Nonetheless, it is worth considering that in addition to meteorological conditions, several other factors are related to the COVID-19 spread. In this sense, the population's living and health conditions have, in their determination, a complex set of factors of individual and collective

Table 6
Coefficients of canonical variables (CV) of the first two canonical pairs from individual and all cities considering meteorological variables and evolution of Covid-19 in Brazil.

CV	Covid-19 variables			CV	Meteorological variables						
	NDC	Cum. cases	Cont. rate		Temperature			Relative humidity			Rain
					Mean	Max	Min	Mean	Max	Min	
Manaus											
U1	0.17	**−1377.43**	**1376.36**	V1	−0.09	**2.18**	−0.39	**−1.18**	−0.34	**2.79**	−0.11
U2	−0.74	**−4725.43**	**4726.05**	V2	−1.60	**−2.54**	0.98	**−2.33**	0.27	**−1.87**	0.37
Fortaleza											
U1	−0.13	**1220.83**	**−1219.76**	V1	**2.54**	−0.58	−0.81	**2.71**	**−1.04**	−0.84	0.38
U2	−1.33	**−1540.39**	**1541.34**	V2	**−2.03**	0.72	−0.09	**−2.26**	0.14	0.74	1.00
Brasília											
U1	−0.44	**−648.27**	**647.53**	V1	**−3.38**	**1.26**	**1.21**	**−3.81**	0.30	**1.68**	0.08
U2	0.86	**−988.73**	**988.20**	V2	**3.32**	**−3.58**	−0.79	0.66	0.28	**−1.18**	0.11
Rio de Janeiro											
U1	−0.16	**−1074.89**	**1075.97**	V1	0.84	**−1.16**	**−1.16**	**1.41**	−0.54	**−1.18**	−0.51
U2	−0.09	**3148.91**	**−3148.52**	V2	**−1.56**	−0.92	**1.55**	**3.49**	**−1.14**	**−3.66**	0.08
São Paulo											
U1	0.48	**−1037.52**	**1036.37**	V1	**5.48**	**−2.95**	**−2.18**	**1.03**	−0.11	−0.52	0.15
U2	**1.08**	**118.95**	**−119.10**	V2	**7.62**	**−4.54**	**−4.27**	**2.30**	**−1.06**	−0.99	0.04
All cities											
U1	0.04	**1.36**	**−1.01**	V1	**−1.65**	0.53	0.21	−0.22	−0.06	0.32	−0.36
U2	0.49	−0.30	**0.92**	V2	**8.54**	**−4.61**	**−4.51**	**3.23**	**−1.24**	**−2.63**	−0.11

Max and Min stand for maximum and minimum. Rain stands for rainfall. NDC, Cum. cases and Cont. rate stand for new daily cases, cumulative cases and contamination rate, respectively.

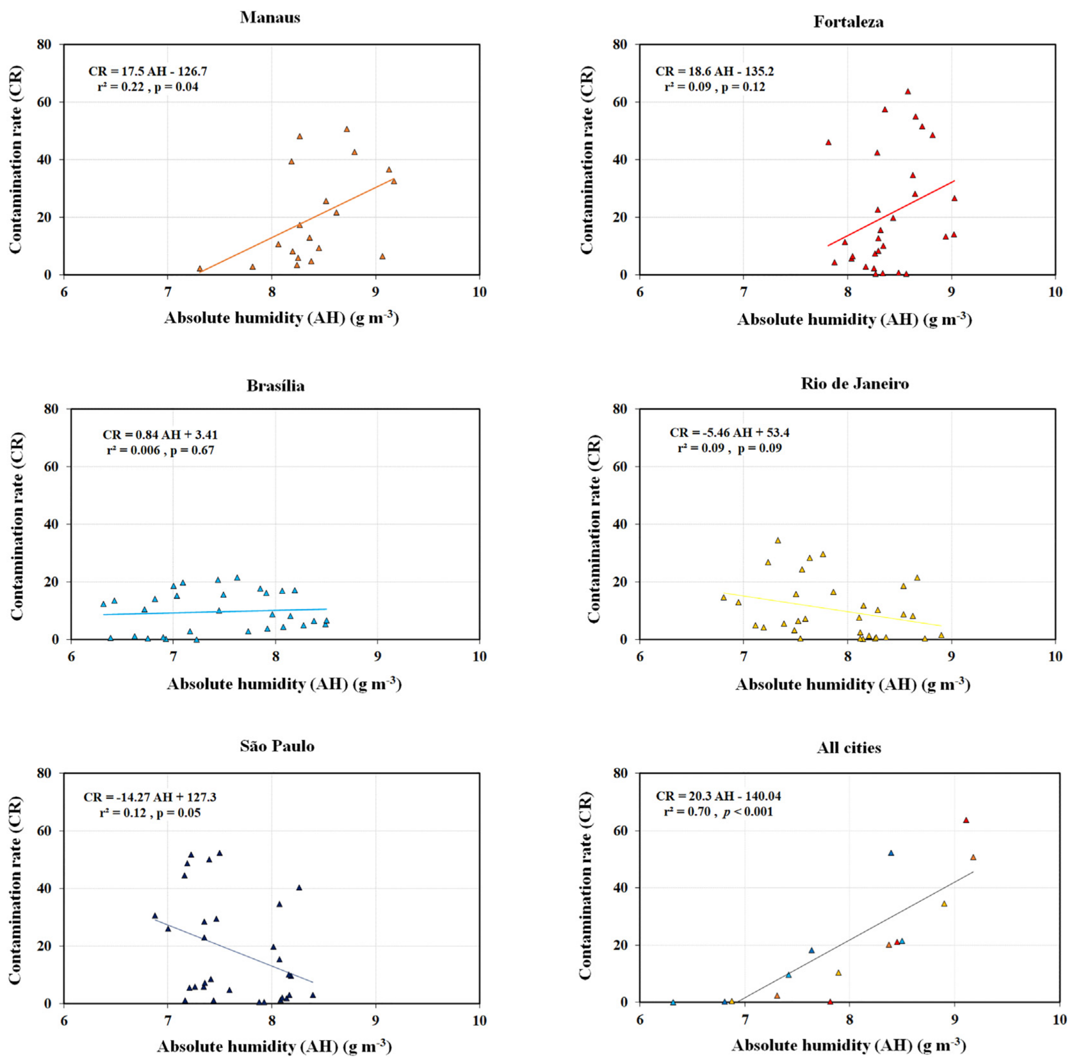


Fig. 5. Linear regressions between absolute humidity (g m^{-3}) and the Covid-19 contamination rate in Brazilian cities with the highest cumulative case records in the period between March 13 and April 13, 2020. The order of colors indicates the order from the highest (red) to the lowest (blue) mean temperatures between cities. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

coverage, such as political, social, economic and cultural conditions. Thus, considering the results obtained, intersectoral policies and actions are necessary, mainly in cities where the contamination rate has been increasing rapidly. Thus, prevention and protection measures should be adopted in these cities aiming to reduce transmission and the possible collapse of the health system.

We emphasize that other variables were not considered in our study due to the complexity of such analysis and the lack of updated information on these data, but the results presented here aimed to understand the role of tropical climate conditions in the transmission of COVID-19. Some suggestions for future research should focus on the issue of basic sanitation in these Brazilian cities, based on the evidence of virus survival in untreated wastewater. Other conditions that should be considered are the speed of the winds, presence of pollutants in the atmosphere and socioeconomic conditions of the population of the cities.

CRediT authorship contribution statement

A.C. Auler: Formal analysis, Data curation, Methodology, Writing - original draft. **F.A.M. Cássaro:** Writing - review & editing. **V.O. da Silva:** Writing - review & editing. **L.F. Pires:** Conceptualization, Data curation, Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Ahmadi, M., Sharifi, A., Dorosti, S., Ghoushchi, S.J., Ghanbari, N., 2020. Investigation of effective climatology parameters on COVID-19 outbreak in Iran. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2020.138705.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Spavorek, G., 2013. Köppen's climate classification map for Brazil. Meteorol. Z. 22, 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Araújo, M.B., Naimi, B., 2020. Spread of SARS-CoV-2 Coronavirus Likely Constrained by Climate. medRxiv preprint. https://doi.org/10.1101/2020.03.12.20034728.

Bu, J., Peng, D.D., Xiao, H., Yue, Q., Han, Y., Lin, Y., Hu, G., Chen, J., 2020. Analysis of Meteorological Conditions and Prediction of Epidemic Trend of 2019-nCoV Infection in 2020. medRxiv preprint. https://doi.org/10.1101/2020.02.13.20022715.

Bukhari, Q., Jameel, Y., 2020. Will Coronavirus Pandemic Diminish by Summer?. Available at SSRN 3556998. https://doi.org/10.2139/ssrn.3556998

Cai, Y., Huang, T., Liu, X., Xu, G., 2020. The Effects of "Fangcang, Huoshenshan, and Leishenshan" Hospitals and Temperature on the Mortality of COVID-19. medRxiv preprint. https://doi.org/10.1101/2020.02.26.20028472.

Casanova, L.M., Jeon, S., Rutala, W.A., Weber, D.J., Sobsey, M.D., 2010. Effects of air temperature and relative humidity on coronavirus survival on surfaces. Appl. Environ. Microbiol. 76, 2712–2717. https://doi.org/10.1128/AEM.02291-09.

Cássaro, F.A.M., Pires, L.F., 2020. Can we predict the occurrence of COVID-19 cases? Considerations using a simple model of growth. Sci. Total Environ. 728, 138834. https://doi.org/10.1016/j.scitotenv.2020.138834.

Chen, B., Liang, H., Yuan, X., Hu, Y., Xu, M., Zhao, Y., Zhang, B., Tian, F., Zhu, X., 2020. Roles of Meteorological Conditions in COVID-19 Transmission on a Worldwide Scale. medRxiv preprint. https://doi.org/10.1101/2020.03.16.20037168.

CIIS-FMRP, 2020. Monitoramento de casos confirmados de COVID-19 nos grandes centros populacionais. Faculdade de Medicina de Ribeirão Preto, Universidade de São Paulo Available from. https://ciis.fmrp.usp.br/covid19/analise-municipios-br/.

Coelho, M.T.P., Rodrigues, J.F.M., Medina, A.M., Scalco, P., Terribile, L.C., Vilela, B., Diniz-Filho, J.A.F., Dobrovolski, R., 2020. Exponential Phase of Covid-19 Expansion Is Not Driven by Climate at Global Scale. medRxiv preprint. https://doi.org/10.1101/2020.04.02.20050773.

IBGE, 2019. Instituto Brasileiro de Geografia e Estatística. Available from:. https://agenciadenoticias.ibge.gov.br/agencia-sala-de-imprensa/2013-agencia-de-noticias/releases/25278-ibge-divulga-as-estimativas-da-populacao-dos-municipios-para-2019.

INMET, 2020. Instituto Nacional de Meteorologia, Ministério da Agricultura, Pecuária e Abastecimento. Available from:. http://www.inmet.gov.br/portal/.

Iribarne, J.V., Godson, W.L., 2012. Atmospheric Thermodynamics. Springer, Netherlands.

Liu, J., Zhou, J., Yao, J., Zhang, X., Li, L., Xu, X., He, X., Wang, B., Fu, S., Niu, T., Yan, J., Shi, Y., Ren, X., Niu, J., Zhu, W., Li, S., Luo, B., Zhang, K., 2020. Impact of meteorological factors on the COVID-19 transmission: a multi-city study in China. Sci. Total Environ. 726, 138513. https://doi.org/10.1016/j.scitotenv.2020.138513.

Lowen, A.C., Steel, J., 2014. Roles of humidity and temperature in shaping influenza seasonality. J. Virol. 88, 7692–7695. https://doi.org/10.1128/JVI.03544-13.

Luo, W., Majumder, M.S., Liu, D., Poirier, C., Mandl, K.D., Lipsitch, M., Santillana, M., 2020. The Role of Absolute Humidity on Transmission Rates of the COVID-19 Outbreak. medRxiv preprint. https://doi.org/10.1101/2020.02.12.20022467.

Manly, B.F.J., 2004. Multivariate Statistical Methods: A Primer. Chapman & Hall/CRC, Boca Raton.

Qi, H., Xiao, S., Shi, R., Ward, M.P., Chen, Y., Tu, W., Su, Q., Wang, W., Wang, X., Zhang, Z., 2020. COVID-19 transmission in Mainland China is associated with temperature and humidity: a time-series analysis. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2020.138778.

R Core Team. R, 2019. A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Shapiro, S.S., Wilk, M., 1965. An analysis of variance test for normality (complete samples). Biometrika 52, 591–611. https://www.jstor.org/stable/2333709.

Tosepu, R., Gunawan, J., Effendy, D.S., Ahmad, L.O.A.I., Lestari, H., Bahar, H., Asfian, P., 2020. Correlation between weather and COVID-19 pandemic in Jakarta, Indonesia. Sci. Total Environ. 728, 138810. https://doi.org/10.1016/j.scitotenv.2020.138436.

Vicente-Serrano, S.M., Nieto, R., Gimeno, L., Azorin-Molina, C., Drumond, A., El Kenawy, A., Dominguez-Castro, F., Tomas-Burguera, M., Peña-Gallardo, M., 2018. Recent changes of relative humidity: regional connections with land and ocean processes. Earth Syst. Dyn. 9, 915–937. https://doi.org/10.5194/esd-9-915-2018.

Wang, J., Tang, K., Feng, K., Lv, W., 2020. High Temperature and High Humidity Reduce the Transmission of COVID-19. Available at SSRN 3551767. https://doi.org/10.2139/ssrn.3551767.

Weather-Atlas, 2020. Weather forecast and climate information. Available from:. https://www.weather-atlas.com/en.

WHO - World Health Organization, 2020. Situation report 89. Available from. https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200418-sitrep-89-covid-19.pdf?sfvrsn=3643dd38_2.

Xie, J., Zhu, Y., 2020. Association between ambient temperature and COVID-19 infection in 122 cities from China. Sci. Total Environ. 724, 138201. https://doi.org/10.1016/j.scitotenv.2020.138201.

Yao, Y., Pan, J., Liu, Z., Meng, X., Wang, W., Kan, H., Wang, W., 2020. No association of COVID-19 transmission with temperature or UV radiation in Chinese cities. Eur. Respir. J. https://doi.org/10.1183/13993003.00517-2020.