Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
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, F.A.M. Cássaro, V.O. da Silva, L.F. Pires

Department of Soil Science and Rural Engineering, Federal University of Paraná, 80.035-050 Curitiba, PR, Brazil
Laboratory of Physics Applied to Soils and Environmental Sciences, Department of Physics, State University of Ponta Grossa, 84.030-900 Ponta Grossa, PR, Brazil
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

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.

© 2020 Elsevier B.V. All rights reserved.

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

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

https://doi.org/10.1016/j.scitotenv.2020.139090
0048-9697/© 2020 Elsevier B.V. All rights reserved.
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; Josepu 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 km². 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 in Chinese cities, except Wuhan, between January 20 and March 2, 2020, Brazil up to now there is only one study about the in

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 (Brasilia), 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; Brasilia: 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 inhabitants.

These cities are located in the North (Manaus), Northeast (Fortaleza), Center-West (Brasilia) 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. Brasilia 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 Brasilia is the federal capital of Brazil.

The Köppen climate classification for São Paulo is Cfa (Humid Subtropical), Rio de Janeiro and Brasilia 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 Brasilia, 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 χ² test were used to select the canonical pairs. The selection of the variables that comprise the canonical 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
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 specifics 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 a cumulative 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

| 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.
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 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 ($\sigma^2$) 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
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).

### 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 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 | 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 | 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 | 11.0 |
| 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.

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.)
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       |
|                 | 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       |
|                 | Contamination rate          | 21.2 | 13.4   | -    | 0.3  | 63.8 | 20.0  | -0.7    | 0.8       |
|                 |                             |      |        |      |      |      |       |         |           |
| Brasilia        | New daily cases             | 22.4 | 18.0   | 18.0 | 3.0  | 58.0 | 15.1  | 0.1     | 0.9       |
|                 | 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  | 0.1     | 0.7       |
|                 | 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| 141.5  | -    | 5.0  | 689.0| 209.8 | -0.5    | 0.9       |
|                 | 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 (σ²) from individual and all cities considering meteorological variables and evolution of Covid-19 in the Brazilian cities.

| Statistics | Eigenvector | 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 |
|            | σ² (%)      | 59.1 | -    | -    | 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 | -0.35 | 0.49  | 0.45  | 0.45  |
|            | σ² (%)      | 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 |
|            | σ² (%)      | 48.1 | 15.2 | 16.1 | 0.07 | 18.9 | 16.4 | 13.8 | 0.1   | 2.6   | 2.6   |        |
|            | PC 2        | 1.64 | 0.23 | 0.11 | 0.13 | -0.12 | -0.34 | -0.01 | -0.35 | -0.60 | -0.60 |        |
|            | σ² (%)      | 26.8 | 0.5  | 1.3  | 1.6  | 0.5  | 1.0  | 0.0  | 1.0   | 27.5  | 30.9  | 30.8  |
| Brasilia   | PC 1        | 2.13 | 0.45 | 0.43 | 0.03 | -0.43 | -0.29 | -0.44 | -0.34 | 0.11  | 0.11  | 0.11  |
|            | σ² (%)      | 45.2 | 20.2 | 18.5 | 0.1  | 18.8 | 19.3 | 11.3 | 1.1   | 1.2   | 1.2   |        |
|            | PC 2        | 1.52 | -0.05 | 0.10 | -0.16 | -0.34 | -0.01 | -0.35 | -0.60 |        |        |        |
|            | σ² (%)      | 23.2 | 0.1  | 0.3  | 1.0  | 2.4  | 11.3 | 0.0  | 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 |
|            | σ² (%)      | 49.4 | 17.9 | 16.0 | 15.1 | 2.0  | 5.6  | 1.4  | 12.3  | 14.7  | 14.7  |        |
|            | PC 2        | 1.71 | -0.08 | 0.06 | 0.54 | 0.50 | 0.43 | 0.33 | -0.22 | -0.23 | -0.23 |        |
|            | σ² (%)      | 29.1 | 0.0  | 0.6  | 0.4  | 28.9 | 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 |
|            | σ² (%)      | 42.6 | 19.4 | 17.3 | 15.3 | 1.0  | 2.9  | 2.3  | 8.2   | 16.7  | 16.7  |        |
|            | PC 2        | 1.58 | 0.09 | 0.21 | -0.13 | -0.50 | -0.40 | -0.48 | -0.34 | 0.01  | 0.19  | 0.19  |
|            | σ² (%)      | 25.1 | 0.9  | 4.6  | 1.8  | 34.7 | 16.1 | 23.1 | 11.4  | 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 |
|            | σ² (%)      | 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 |
|            | σ² (%)      | 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  |
|            | σ² (%)      | 16.4 | 0.9  | 2.8  | 13.0 | 0.2  | 4.9  | 3.2  | 13.3  | 14.4  | 14.4  | 14.4  |

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.
and evolution of Covid-19 in Brazil.

Thus, when all cities were combined, it was found 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 5
Correlation, approximate chi-square ($\chi^2$) 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 | $\chi^2$ | $p$  |
|------------|-------------|---------|------|
| 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|
| Brasilia   |             |         |      |
| 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|
| Sao 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 Brasilia 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 Sao 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 Sao 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).

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       | NDC  | Cum. cases | Cont. rate | CV       | Temperature | Relative humidity | Rain |
|----------|------|------------|------------|----------|-------------|--------------------|------|
|          | Mean | Max        | Min        | 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  |
| Brasilia |      |            |            |          |             |                    |      |      |      |
| 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  |
| Sao 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.
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., Spavares, 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/10.1101/2020.02.26.20029472.
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.
