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Article

The Contribution of Meteorological Parameters and the COVID-19 Partial Lockdown on Air Quality in Rio de Janeiro, Brazil

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This study evaluated the pollutant levels (NO_2, SO_2, CO, and O_3), air quality index (AQI) and the influence of meteorological variables and coronavirus disease (COVID-19) pandemic on the air quality in Rio de Janeiro. The data set used comprises periods before (March-April, 2019) and during pandemic (March-April, 2020). According to the AQI results, on most days, the air quality was ranked as "good". Brazilian air quality standards for SO_2, O_3, and NO_2 were not exceeded in any of the monitoring stations during partial lockdown, while CO exceeded in all periods in one site due to industrial emission. Comparing both periods, descriptive statistics for the meteorological parameters presented no differences, which suggests similar conditions. However, when evaluated week by week in 2020, weather conditions presented some differences that probably affected pollutant concentrations. The correlations between O_3 and NO_2 and some meteorological parameters indicate that variations in both favored ozone formation, since it is a photochemical process favored by temperature and solar radiation and that, in Rio de Janeiro, low NO_2 concentrations lead to increased O_3. The improvements on air quality during the partial lockdown may be attributed mainly to a reduction on emission sources rather than weather conditions.

Keywords: air quality, AQI, meteorological variables, COVID-19

Introduction

COVID-19 is a disease caused by coronavirus pathogen that quickly spread around the world at the beginning of 2020. In an attempt to contain the spread of the disease, governments decreed lockdown in many cities. In Brazil, the first decree (March 16th, 2020) was in Rio de Janeiro, establishing a partial lockdown, which included the closure of schools, universities, cinemas and theaters, suspension of shows, parties, sport events and reduction of public transportation by 50%. After that (March 19th, 2020), restrictions increased and beaches, bars, restaurants and shopping malls were closed, in addition, the circulation of public transport between the metropolitan region and the capital was stopped.[1]

As in other cities on the world, the people circulation on the Rio de Janeiro streets had decreased. Social isolation

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reached 85% in the first two weeks of the partial lockdown (March 16th-27th, 2020), according to the Rio Operations Center.[2,3] Besides, satellite images and air quality monitoring networks recorded a reduction in the concentration of atmospheric pollutants around the world during this period.[4-7]

Air pollutant levels are highly dependent of the emission sources and meteorological conditions.[8,9] If the regional atmospheric emissions are roughly stable in a particular period, meteorological conditions may be the determining factor for the occurrence of air pollution.[10] In Brazil, a study conducted in São Paulo compared 90 days of partial lockdown with a period of 2019 that had the same meteorological characteristics and concluded that social isolation contributed to air quality improvements.[11] Once meteorological factors play significant roles in air pollution formation, transport, and dispersion, researchers should be cautious when directly attributing air quality improvement to control measures if the effects of meteorological variations are not accounted for.[12-16]

Rio de Janeiro has a subtropical climate, characterized by intense solar radiation, consequently, high temperatures, favoring pollutants formation by photochemical processes.[17-19] Due to the geographic differences in the city terrain, the weather can vary according to the proximity to the sea or massifs.[20] The proximity to the sea allows for ocean-continent exchanges that favor ventilation, contributing to the dispersion of pollutants.[17] However, the mountainous topography makes it difficult for pollutants to spread towards the continent, causing an increase in pollutant concentrations.[19]

Studies[21-26] conducted in Rio de Janeiro highlight that the main source of air pollutant emissions are the vehicles, whose fleet grows every year. However, the metropolitan region of Rio de Janeiro also has some industrial complexes located in different cities that have varied emission profiles, but which contribute mainly to the concentration of criteria pollutant.[27,28] Construction works can be considered an important source of air pollutant emissions, since the metropolis has undergone several structural changes in recent years.[26,29-31]

Considering the complex meteorological characteristics of Rio de Janeiro and changes caused by social isolation, this study aims to assess the influence of meteorological parameters and the partial lockdown on air quality. Meteorological variables such as wind speed (WS) and direction (WD), temperature (T), relative humidity (RH), rainfall (RF), solar radiation (SR) and atmospheric pressure (AP) will be considered, as well as pollutant concentrations obtained from monitoring stations located in the metropolitan region of Rio de Janeiro from March 1st to April 12th, 2020. A comparison with the same period of 2019 was also made.

Experimental

Study area

The study was performed in the metropolitan region of Rio de Janeiro (MRRJ), Brazil. A condensed study[32] focused on weekly air quality assessment describes the study area in detail. Four air quality and meteorology monitoring stations located in urban and industrial areas with a large circulation of vehicles were selected. Two of these stations were located in Rio de Janeiro City (Manguinhos (MG) and Largo do Bodegão (LB)), the third is in Duque de Caxias City (São Luiz (SL)) and the fourth in Itaguaí City (Monte Serrat (MS)). The parameters measured at the stations and the geographical coordinates are described in Table 1.

Table 1. Description of the location, monitored parameters, and number of observations (n) of the air quality monitoring stations located in the metropolitan region of Rio de Janeiro (MRRJ), Brazil

Sampling site	Meteorological parameters	2019 (n)				2020 (n)			
		SO_2	NO_2	CO	O_3	SO_2	NO_2	CO	O_3
São Luiz (SL) Duque de Caxias (22.78 S, 43.29 W)	WS, WD, T, RH, RF, SR, AP	948	946	1032	926	1032	1025	1030	1030
Manguinhos (MG) Rio de Janeiro (22.88 S, 43.24 W)	WS, WD, T, RH, RF, SR, AP	1013	984	1032	1005	1032	986	964	959
Largo do Bodegão (LB) Rio de Janeiro (22.93 S, 43.69 W)	WS, WD, T	746	746	0	0	829	877	0	0
Monte Serrat (MS) Itaguaí (22.83 S, 43.77 W)	WS, WD, T	1015	657	0	1015	1015	1039	0	1038

WS: wind speed; WD: direction; T: temperature; RH: relative humidity; RF: rainfall; SR: solar radiation; AP: atmospheric pressure.

Air quality data

The pollutants SO_2, NO_2, CO and O_3 were measured according to the methodologies described in the Technical Guide for Monitoring Air Quality, published by the Ministry of Environment.[33] Sulfur dioxide (SO_2) was monitored by the ultraviolet (UV) fluorescence methods, nitrogen dioxide (NO_2) was measured by the chemiluminescence method, carbon monoxide (CO) was measured by infrared method and tropospheric ozone (O_3) was measured by the infrared method absorption of ultraviolet light. Data were obtained each 15-min interval by the automatic monitoring stations, calibrated monthly, using standard methods and types of equipment (Horiba, Kyoto, Japan and Ecotech, Knoxfield, Australia). The values were organized in 1-h data means for each day including nighttime observations.

Air quality and meteorological parameters were obtained from three periods: (*i*) March 1st to April 12th, 2019, (*ii*) March 1st to 15th, 2020 classified as "before lockdown" and (*iii*) March 16th to April 12th, 2020 classified as "lockdown".

Meteorological data

Rainfall (RF, in mm), temperature (T, in °C), solar radiation (SR, in W m^{-2}), relative humidity (RH, in %), atmospheric pressure (AP, in mbar), wind speed (WS, in m s^{-1}), and wind direction (WD, in degrees) were used in the study. The meteorological variables were monitored every 15-min by automated analyzers (Met One Instruments, Washington, TX, USA) at surface meteorological stations located on the sampling sites installed at a height of 10 m above the ground. The values were organized in 1-h data means for each day.

Statistical analyses

The Mann-Withney test with a confidence level of 95% was applied to statistically verify the mean values from different periods for the meteorological variables of each of the four studied sites assuming different variances. For data collected in 2020, all sites were evaluated weekly (W), with the first two weeks (W1 and W2) corresponding to before the partial lockdown (March 1st-15th), whereas the following four weeks (W3, W4, W5, and W6) denoting during the partial lockdown period (March 16th-April 12th).

The language and environment for statistical computing R[34] was applied for some statistical analysis. Correlation matrices were used to evaluate the degree of relationship between regulated pollutant concentrations (NO_2, SO_2, O_3, and CO) against meteorological variables. Pearson correlations were considered for $p < 0.05$ and the Bryman and Cramer[35] criterion was used to assess the intensity of the correlations. As this evaluation included many variables, a hierarchical cluster analysis (HCA) was carried out in order to group variable. The package Openair[36] was applied to make the correlation plots associated with cluster.

Pollution roses were elaborated to evaluate the predominant direction of the pollutant concentrations measured in the monitoring stations. Hourly data of wind direction and speed correlated with the hourly data of each pollutant concentration were used to build them. The pollution rose shows the frequency distribution of a specific pollutant on a wind intensity, in classes, for each wind direction. The roses help identifying the direction associated with higher or lower concentrations.[37] The function pollutionRose was used via the R package Openair.[36]

Air quality index (AQI)

To standardize and simplify the air quality assessment, the computation of the air quality index (AQI) was carried out for each pollutant, according to the equation 1 following the recommendations of the Brazilian Ministry of Environment.[33] Depending on the index obtained, the air quality score could be ranked with good, regular, poor, very poor, or terrible.

$$\text{AQI} = I_{ini} + \frac{I_{fin} - I_{ini}}{C_{fin} - C_{ini}} \times \left(C - C_{ini}\right) \quad (1)$$

where, I_{ini} is a value that corresponds to the initial concentration of the range, I_{fin} is a value that corresponds to the final concentration of the range, C_{ini} is the initial concentration of the range in which the measured concentration is located, C_{fin} is the final concentration of the range in which the measured concentration is located and C is the measured pollutant concentration.

According to CONAMA (Conselho Nacional do Meio Ambiente) Resolution 491/2018,[38] the concentration values that classify quality as "good" are the values recommended by the World Health Organization (WHO) as being the safest for human health for short-term exposure and are related to the final standards of air quality. The other AQI ranges represent different levels of health effects associated with increased pollution. The daily AQIs are calculated based on the 24-h average concentration of SO_2, daily average 1-h maximum concentration for NO_2 and the daily average 8-h maximum concentrations for CO and O_3. According to the Brazilian legislation[38] and Brazilian air quality guideline,[33] the ranges of AQI values related to air quality can be classified into five classes as presented in Table 2.

Table 2. Air quality index (AQI) range and air classification according to index values

Class	AQI range	Air classification	Color identification
I	0-40	good	green
II	41-81	moderate	yellow
III	81-120	poor	orange
IV	121-200	very poor	red
V	201-400	terrible	purple

Hybrid single-particle Lagrangian integrated trajectory

To evaluate air mass origins, a hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) model implemented by Air Resources Laboratory-National Oceanic and Atmospheric Administration (NOAA) was used to simulate and cluster backward trajectories for the period between March 1st and April 12th, 2020.[39,40] The simulation was done directly on the site of the Air Resources Laboratory-NOAA considering 120 h for backward trajectories of one day of each week.

Results and Discussion

Pollutant concentrations and Brazilian air quality standards

During 2019, urban centers were on a routine scenario, thus, the period between March and April, 2019 will be compared with the same period of 2020, considering the partial lockdown measures. Boxplots with pollutants concentration in three periods considered are presented in Figure 1.

The daily SO_2 concentrations in MRRJ ranged from 0.87 to 26.60 µg m^{-3} from March 1st to April 12th, 2019. During 2020, the concentrations ranged from 3.26 to 52.46 µg m^{-3}, before the partial lockdown; while during the partial lockdown were 2.63 to 115.99 µg m^{-3}. The daily air quality standard established for SO_2 by CONAMA (125 µg m^{-3}) was not exceeded in any locations before and during the partial lockdown. Overall, SO_2 concentration was found in similar values for both years in sites, except for Largo do Bodegão. A significant increase in SO_2 concentrations in Largo do Bodegão on the first partial lockdown week may be attributed to industrial emission. During this week, SO_2 average concentration increased by 250% in relation to the previous period at this site. In Largo do Bodegão, an average reduction of 89% in SO_2 concentrations were observed in April, compared to the first partial lockdown weeks; and 65% in relation to the beginning of March. At the other monitored sites, reductions of 14% at Manguinhos, 26% at São Luiz, and 7% at Monte Serrat were observed in the first weeks of partial lockdown compared to the beginning of March.

The daily NO_2 concentrations during 2019 ranged from 3.14 to 41.59 µg m^{-3}; before partial lockdown ranged from 3.71 to 40.58 µg m^{-3} and from 0.28 to 39.60 µg m^{-3} after the partial lockdown decree. The Brazilian air quality standard for NO_2 (260 µg m^{-3}, 1-h) was not exceeded in any monitoring site. NO_2 was found in lower concentration in 2020, mainly in Largo do Bodegão and Monte Serrat, where NO_2 concentration decreased significantly after the lockdown decree, and remained low during all the evaluated period. Once NO_2 is generally associated with traffic emission, lower NO_2 concentrations were expected due to the severe traffic reduction. In the first partial lockdown weeks, NO_2 concentration reduced about 20 and 14% at Largo do Bodegão and Monte Serrat, respectively. In April, the NO_2 concentration decreased 65% at Largo do Bodegão. Alternatively, Manguinhos and São Luiz presented an increase of 31 and 4% in the first partial lockdown weeks; however, reductions were recorded in April (3 and 14%, respectively). Those last two sites are close to oil refineries and important roads that connect Rio de Janeiro City and neighboring cities, where vehicle traffic is intense. The prohibition of intercity public transport circulation on March 21st may be the explanation for the decrease in the NO_2 levels in last week of March.

The daily O_3 concentration ranged from 11.75 to 115.74 µg m^{-3} from March 1st to April 12th, 2019. In 2020, it ranged from 8.98 to 32.38 µg m^{-3} before partial lockdown and from 0.60 to 48.63 µg m^{-3} during the partial lockdown. The O_3 Brazilian air quality standard (140 µg m^{-3}, 8-h rolling mean) was not exceeded at any time. O_3 were at lower concentration in 2020 in all monitored sites. A similar trend on O_3 concentration was observed for Manguinhos, Monte Serrat and São Luiz, which indicates that O_3 is under the same formation conditions. Peaks of concentration were observed at the beginning of partial lockdown (March, 16th, 2020) and on the second week of April. The decrease in primary pollutants in the first partial lockdown week may have contributed to increasing the O_3 concentration, once NO_2 may participate on O_3 depletion. Monte Serrat presented the highest O_3 concentration on the first partial lockdown week, 25% higher than previous weeks. Although O_3 concentration decreased as days goes by, it remained 18% higher than at the beginning of March. Manguinhos and São Luiz presented similar O_3 concentrations that increased about 30% in the first partial lockdown weeks. In April, while Manguinhos recorded decreasing on O_3 concentration, 12% lower than before partial lockdown, in São Luiz O_3 continued to increase, reaching values 34% higher than before partial lockdown.

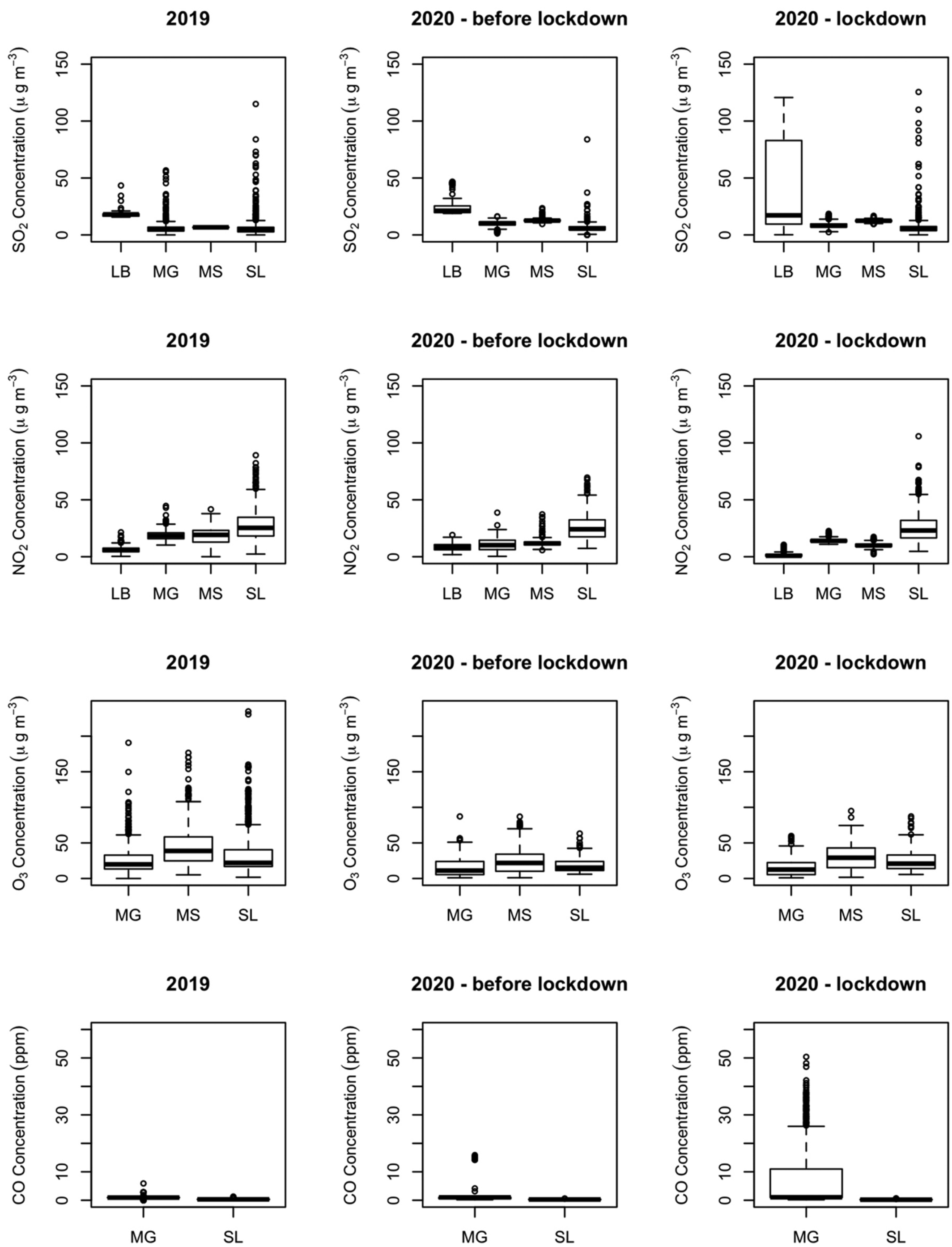

Figure 1. Boxplot with the distribution of the concentrations of SO_2, NO_2, and O_3 and CO for Largo do Bodegão (LB, Rio de Janeiro), Manguinhos (MG, Rio de Janeiro), São Luiz (SL, Duque de Caxias) and Monte Serrat (MS, Itaguaí) stations in the three periods: (*i*) March 1st to April 12th, 2019, (*ii*) March 1st to 15th, 2020 classified as "before lockdown" and (*iii*) March 16th to April 12th, 2020 classified as "lockdown". The boxes cover the 1st quartile to the 3rd quartile. The lines in the boxes represent the median values.

The data obtained in this study showed a certain similarity with other studies that evaluated air pollutants during the lockdown adopted due to the new coronavirus. The highest concentration was observed in the first weeks of lockdown, followed by a slight decrease in the following weeks, but the values remained higher than in the weeks before the lockdown. In Rio de Janeiro City, high concentrations of O_3 can be attributed to the transport of pollutants and low concentrations of NO_2, which can be triggered by high temperatures and solar radiation.[14,26] In Monte Serrat, where the highest concentrations of ozone were observed, negative correlations were found between NO_2 and O_3, both before and during partial lockdown (–0.50 and –0.66, respectively). These negative correlations indicate that NO_2 is participating in the consumption of tropospheric O_3, which explains the increase in O_3 during the partial lockdown when the NO_2 concentration decreased. In Manguinhos, the correlation between NO_2 and O_3 was also negative during the partial lockdown (–0.53). The 30% increase in NO_2 concentration at this station may have contributed to a smaller increase in the concentration of O_3 at that station (3%), compared to the other stations.

The daily CO concentrations ranged from 0.09 to 2.25 ppm in 2019; in 2020 ranged from 0.19 to 15.10 ppm before partial lockdown and from 0.11 to 35.37 ppm during lockdown. CO presented similar values for both years in São Luiz, but in Manguinhos increased significantly. The air quality standard established for CO by Brazilian legislation (9 ppm or 10,0000 µg m^{-3}, 8-h rolling mean) was exceeded in Manguinhos in 2020, both before and during the lockdown. In São Luiz, a decrease trend can be observed on the first lockdown week, which may be related to the prohibition of intercity public transport circulation. As CO is formed by incomplete combustion, vehicle emission is one of the main sources of this pollutant. The decrease in vehicle traffic near São Luiz, through which a major highway passes, may have led to a decrease in the concentration of CO. On this site, a reduction of 13% was recorded on the first lockdown week and 22% in April. The increase in CO concentration recorded at Manguinhos (7%) in first weeks of partial lockdown may be attributed to industrial emissions. In April, CO concentration reduced 92% in relation to beginning of March. Vehicle emissions are considered the main source of this pollutant in the MRRJ, with the largest contribution (75%) attributed to light vehicles and motorcycles.[41] However, it has been found that in regions near oil refineries, concentrations up to 50 higher than routine concentrations can eventually be recorded.[42]

Air quality index (AQI)

The AQI was calculated for SO_2, CO, O_3, and NO_2. For both years and for all stations, NO_2 presented AQI values lower than 40, which is classified as "good" 100% of the time in all sites (Figure S1, Supplementary Information (SI) section). NO_2 concentrations were at least 7 times lower than the limit established by the Brazilian legislation.[38] The AQI for O_3 was also ranked as "good" in most days of the evaluated period. In a few random days in both years, the air quality was classified as "moderate" to "poor" (Figure S2, SI section). Concentrations obtained in 2020 were slightly lower than in 2019, indicating a better air quality. Some days during the partial lockdown presented higher O_3 concentrations than early March, which is related to the increase in O_3 concentration induced by the decrease in primary pollutant that participate in tropospheric ozone formation, as discussed above.

Overall, the air quality index ranged from "moderate" to "good" for all stations. Some exceptions were observed for SO_2 (Figure S3, SI section) and CO (Figure S4, SI section). São Luiz station presented "good" air quality for almost all days, in both years and for both pollutants. The exceptions were in some days during the partial lockdown for SO_2. In Largo do Bodegão, SO_2 index was "good" for April-2019, April-2020 and for many days in March-2020. However, during the partial lockdown days (March-2020) the index ranged from "moderate" to "poor". This station is located in a populated area, near a huge industrial complex and highways with intense traffic. Therefore, the industrial activities, which were not paralyzed during the partial lockdown, could be the reason of the poor air quality. Added to that, in the region the traffic was reduced only 25% during the partial lockdown.[43]

Regarding CO, São Luiz station presented "good" air quality for both years. In contrast, Manguinhos presented the worst air quality because of the increase (20-30%) in CO concentrations during the partial lockdown. On some days the air quality was ranked as "terrible", since the concentrations were 1.5-4.3 times greater than the CONAMA limit.[38] During this period, CO concentration did not present daily peak values, which indicates that the industrial emission contributed to those high concentrations. The AQI obtained for Manguinhos and Monte Serrat regardless of SO_2 indicated good air quality all days from both periods evaluated.

In some days of the evaluated period, data collection failed or they were invalidated due to the monitoring station maintenance, therefore the AQI was not performed and the days are not filled in calendar plots (Figures S1-S4). In general, the days in which the air quality were not considered "good" occurred in the period before the partial lockdown, except Manguinhos, which presented days with "terrible" air quality in the second week of the partial lockdown. A previous study[32] about time variation of pollutants showed that in the weeks immediately following the lockdown decree the concentration of pollutants reduced, contributing to improved air quality.

These AQI results are in agreement with studies carried out in other cities in the world. In India, the air pollution decreased after the second week of lockdown and the AQI for a total of 91 cities was rated as "good" and "satisfactory", and no city was classified as "poor".[44] The AQI for three cities in China (Wuhan, Jingmen, and Enshi) showed that 88% of the days were classified as "moderate" or "good" during the lockdown, while before the lockdown the percentage of the days was 66%.[45]

Statistical analysis of meteorological parameters

Table 3 presents the descriptive statistics for meteorological parameters before and during the partial lockdown for all monitoring stations in 2019 and 2020. In order to verify changes in meteorological conditions between the years, the Mann Withtney test ($p < 0.05$) was applied. No statistical difference was observed between the periods. This observation indicates that in 2020, Rio de Janeiro was under a similar meteorological condition as in 2019, suggesting that pollutant concentrations variations were probably due to changes in emission sources. All monitoring sites presented similar meteorological conditions, but São Luiz recorded WS at least 2 times (1.6-2.3 m s^{-1}) greater than the others (0.1-1.0 m s^{-1}). According to the National Institute for Meteorology (INMET),[46] WS less than 2.0 m s^{-1} does not favor atmospheric dispersions. Because of higher WS values in São Luiz, air circulation at this site affected air masses circulation, which promotes stronger pollutants dispersion.

Considering that the weather conditions change frequently, the Mann-Whitney test was applied to evaluate how meteorological parameters (WS, T, SR, RH, and AP) varied over the weeks in the four MRRJ monitoring stations in 2020 (Table S1, SI section). In the first week of March, 2020 (W1), two weeks before the partial lockdown, a cold front arrived at Rio de Janeiro, increasing air humidity (up to 93%) and cloud cover, reducing solar radiation (167 W m^{-2}) and average temperature (27 °C). Heavy rain (117 mm *per* week) also occurred during this week, which improved the air quality as a result of the wash-out effect. However, in the middle of the second week of March (W2), a high-pressure system reached the MRRJ, which made the atmosphere more stable, with higher T (26-34 °C) and lower RH (67-87%) averages, and without rain. The high-pressure system produced a wind barrier, which favors the increase in pollutant concentrations. These conditions probably contributed to rise SO_2 average concentrations from 12 (W1) to 14 µg m^{-3} (W2).

Changes in some meteorological conditions were also observed in the third week (W3), first partial lockdown week, compared to the W2 (Table S1). In the W3 was sunny days, with temperatures around 40 °C and low RH (31%). Due to high temperatures, ozone hourly concentration reached 142 µg m^{-3}. At the end of W3, another cold front arrived at MRRJ, decreasing temperature (19 °C), and bringing humid winds from the ocean to the continent. This system produced atmospheric instability resulting in the rain (69 mm *per* week), which decreased pollutant levels.

In the fourth week (W4), during the partial lockdown, a high-pressure system was predominant. In this week, drops of rain (3.2 mm *per* day), high T (39 °C) and the highest levels of SR (1042 W m^{-2}) were registered. Due to these conditions, a high hourly O_3 concentration reached (up to 74 µg m^{-3}). In the fifth week (W5) the weather conditions were quite similar to W1, under high atmospheric pressure system followed by a cold front.

Due to the instability in the weather conditions, the hypothesis test was applied to identify similarities and

Table 3. Descriptive statistics of meteorological variables before and during the partial lockdown in 2020 and in the same period in 2019

Variable	WS / (m s^{-1})	RF / mm	T / ºC	SR / (W m^{-2})	RH / %	AP / mbar
			March-April 2019			
Max	6.5	46.2	45.8	1050	99.0	1023
Min	0.0	0.0	16.9	0.0	32.0	1000
Mean	0.9	0.4	26.6	214.6	79.6	1011
Median	0.6	0.0	25.8	8.5	83.0	1010
			2020-Before the COVID-19 lockdown			
Max	5.1	80.2	43.6	1027	99.0	1018
Min	0.0	0.0	15.7	0.0	37.0	996.0
Mean	0.9	8.9	27.5	229.7	80.3	1007
Median	0.7	0.0	25.3	7.2	85.0	1007
			2020-Before the COVID-19 lockdown			
Max	6.3	37.8	43.3	1042	98.0	1021
Min	0.0	0.0	10.1	0.0	31.0	991.0
Mean	0.9	2.8	27.2	216.8	78.2	1007
Median	0.6	0.0	25.1	7.8	82.3	1008

WS: wind speed; T: temperature; RH: relative humidity; RF: rainfall; SR: solar radiation; AP: atmospheric pressure: Max: maximum; Min: minimum.

differences among weeks. In Largo do Bodegão and Monte Serrat stations meteorological parameters were different between W3 and W4, as well as between W4 and W5. In the other monitoring stations, some meteorological variables were similar (WS, SR, RH) while others were different (T, AP). The W3 and W5 presented the lowest AP average (1005 and 1004 mbar), while W4 presented the highest AP average (1010 mbar).

In the sixth week (W6), the meteorological parameters were different from the W5, both during the partial lockdown, for all sites, except for WS in Largo do Bodegão station. W6 was characterized by low T (25 °C) and SR (120.2 W m^{-2}) averages, while W5 was predominantly influenced by a high-pressure system, with higher T (28 °C) and SR (204 W m^{-2}), which favored O_3 maximum concentrations (73.2 µg m^{-3}) in W5. However, in both weeks, the accumulated rainfall volumes did not exceed 5 mm *per* day, nor 14 mm in the week.

Correlation between pollutants and meteorological parameters

Pearson correlations (r) and grouping by HCA were carried for the evaluation of meteorological variables and pollutant concentrations (Figure S5, SI section). In 2020, a moderate to strong positive correlation between O_3 and T was obtained for all monitoring stations, which is expected once this pollutant formation occurs throughout the photochemical process. O_3 was also positively correlated with WS at all monitoring stations, which indicates that pollutants from other regions contributed to its formation. These correlations have also been observed in Rio de Janeiro City by Gioda *et al.*[18] and Geraldino *et al.*[47] A moderate negative correlation between O_3 and RH was verified in Manguinhos which may be explained by the SR limited availability and low photochemical activity, as a result of high cloud coverage.[26]

A negative correlation between NO_2 and O_3 indicates that NO_2 participates in O_3 formation, as mentioned above. A negative correlation between NO_2 and WS suggests that wind participates in its dispersion. Considering correlations between WS with NO_2 and O_3, it is possible to conclude that wind acts on NO_2 dispersion, transporting this pollutant to the region where it participates in ozone formation. A wide group including T, WS, O_3 and NO_2, mainly at Largo do Bodegão, corroborates the idea that NO_2 from other regions participate in complex processes of O_3 formation and depletion.

For SO_2 only weak correlations with meteorological variables were found, highlighting the correlation observed in 2020 with WS in Largo do Bodegão at (r = –32), with WD in Monte Serrat (r = –24), São Luiz (r = –18) and Manguinhos (r = –11). At most of these sites the cluster grouped SO_2 and the wind-related variables. The negative correlations are an indication that wind action is one of the factors contributing to the dispersion of pollutants.

At São Luiz, moderate correlation between CO and NO_2 (r = 0.56) and the grouping of NO_2, CO, and SO_2 were verified. Those observations indicate that industrial complexes are the main factor for the concentration of pollutants. It may be corroborated by the fact of the same behavior has been observed both before and during the partial lockdown. In other words, the traffic affects pollutant emission less than industrial activities in this site.

Following Bryman and Cramer[35] criteria, it was found, in general, weak to moderate correlations ($0.1 < r < 0.7$) were found between meteorological variables and NO_2, SO_2 and CO. Thus, these pollutants were less influenced by the meteorological conditions of the monitoring sites. However, O_3 showed moderate to strong correlations ($r > 0.6$) with meteorological variables ($r > 0.6$).

Pearson correlations obtained for data collected between March 1st and April 12th, 2019, were similar to those observed for 2020. Largo do Bodegão did not present any important correlation, however, some parameters were not monitored in this year. Manguinhos presented a correlation between O_3 and meteorological paramenters. Monte Serrat presented a negative correlation between O_3 and SO_2 (r = –0.40). São Luiz presented a moderate correlation between NO_2 and CO (r = 0.57) also observed in 2020.

An extrapolation of the correlation between pollutants and meteorological variables data obtained in 2020 was made considering the territory of Rio de Janeiro State. Only O_3 correlated with meteorological conditions. Positive correlations were observed between T and WS and negative between T and RH, which was already expected due to ozone photochemical formation.

Backward trajectories calculated by HYSPLIT model for the period between March 1st and April 12th, 2020 (Figure S6, SI section), indicate that air masses that reach Rio de Janeiro State during the partial lockdown period were from the Atlantic Ocean. The maritime origin may contribute to lower temperatures in the coastal regions than the interior. Besides of that, sea breeze may contribute to transport pollutants on the coast.

Pollution roses

Pollution rose plots (Figures 2-5) show the relationship between WD and WS, and pollutants concentration at monitoring stations. The left panel shows pollutant concentrations before the lockdown, while the right panel pollutant concentrations during the partial lockdown.

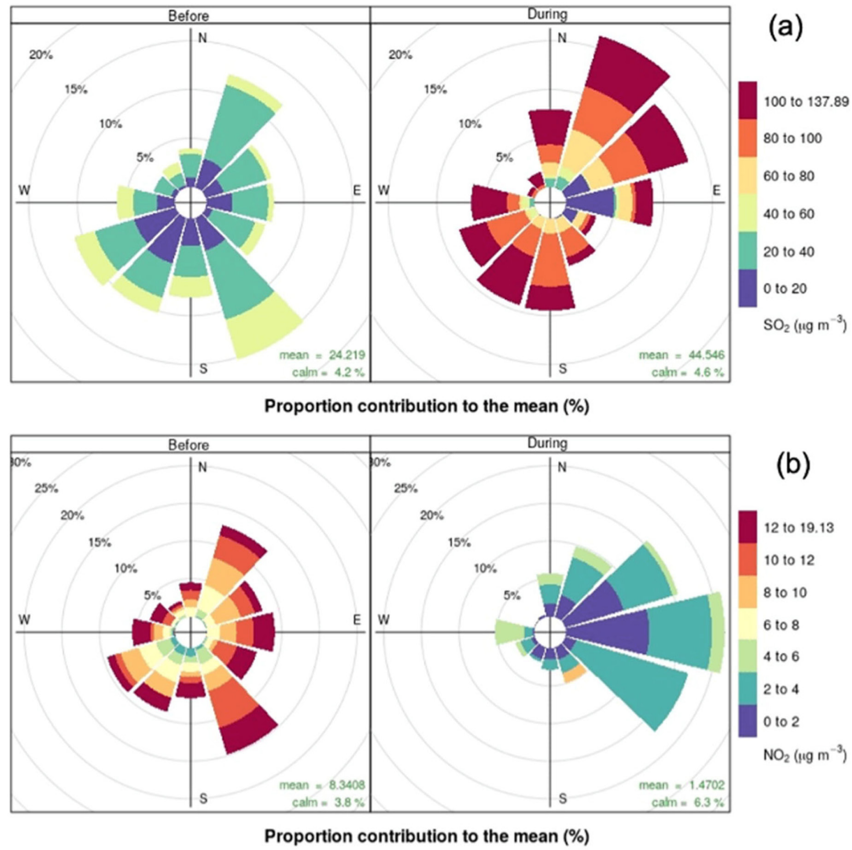

Figure 2. Pollution rose plot to show the relation between wind direction and pollutant concentrations at Largo do Bodegão monitoring station: (a) SO_2 and (b) NO_2. Before: March 1st to 15th, 2020 and during: March 16th to April 12th, 2020.

Largo do Bodegão

Figure 2 shows the pollution roses for SO_2 and NO_2. The SO_2 increase may be related to those facilities located to east and northeast of this monitoring station that continued to work, which includes metallurgical industry and concrete factory. In addition, the Santa Cruz train station is also located in this direction. In the southwest, from where a considerable contribution to the SO_2 concentration was also observed, is located the Santa Cruz area base, the largest in the country and which was a strategic point for the logistics of material distribution during the pandemic. The NO_2 concentration was influenced by industrial facilities located to the southeast and northeast of this monitoring station. Likewise, decreasing in NO_2 concentration may be related to movement restrictions and greater average WS.

Manguinhos

The SO_2, NO_2, O_3, and CO pollution roses for Manguinhos is presented in Figure 3. SO_2 decreasing may be ascribed to greater average wind speed. NO_2 concentrations were influenced by industrial facilities and traffic pollution located to the northeast of this monitoring station. Likewise, the decreasing NO_2 concentration during the partial lockdown may be attributed to movement restrictions put in place by the government and more intense average wind speed. Before partial lockdown, O_3 concentrations were mainly from east and northeast, while during the partial lockdown came from north and northeast. O_3 concentration was influenced by industrial facilities located to the north and northeast of the monitoring station. The low CO concentration before the partial lockdown, came mainly from northeast and east, while for during the partial lockdown, high CO concentration came from the northwest and northeast. CO increasing may be related to heavy traffic in the regions located between northwest and northeast.

Monte Serrat

The pollution roses for Monte Serrat are presented in Figure 4. Calm wind was representative in both periods, indicating local sources of this pollutant. As well as SO_2 concentration, the NO_2 concentration before and during the partial lockdown came mainly from the southeast with calm winds. Therefore, NO_2 is source-specific and generated near the station, which is surrounded by the highway and heavy traffic.

Southeast and east directions were predominant in the O_3 concentration in both periods. The calm wind was representative for both periods. O_3 is source-specific

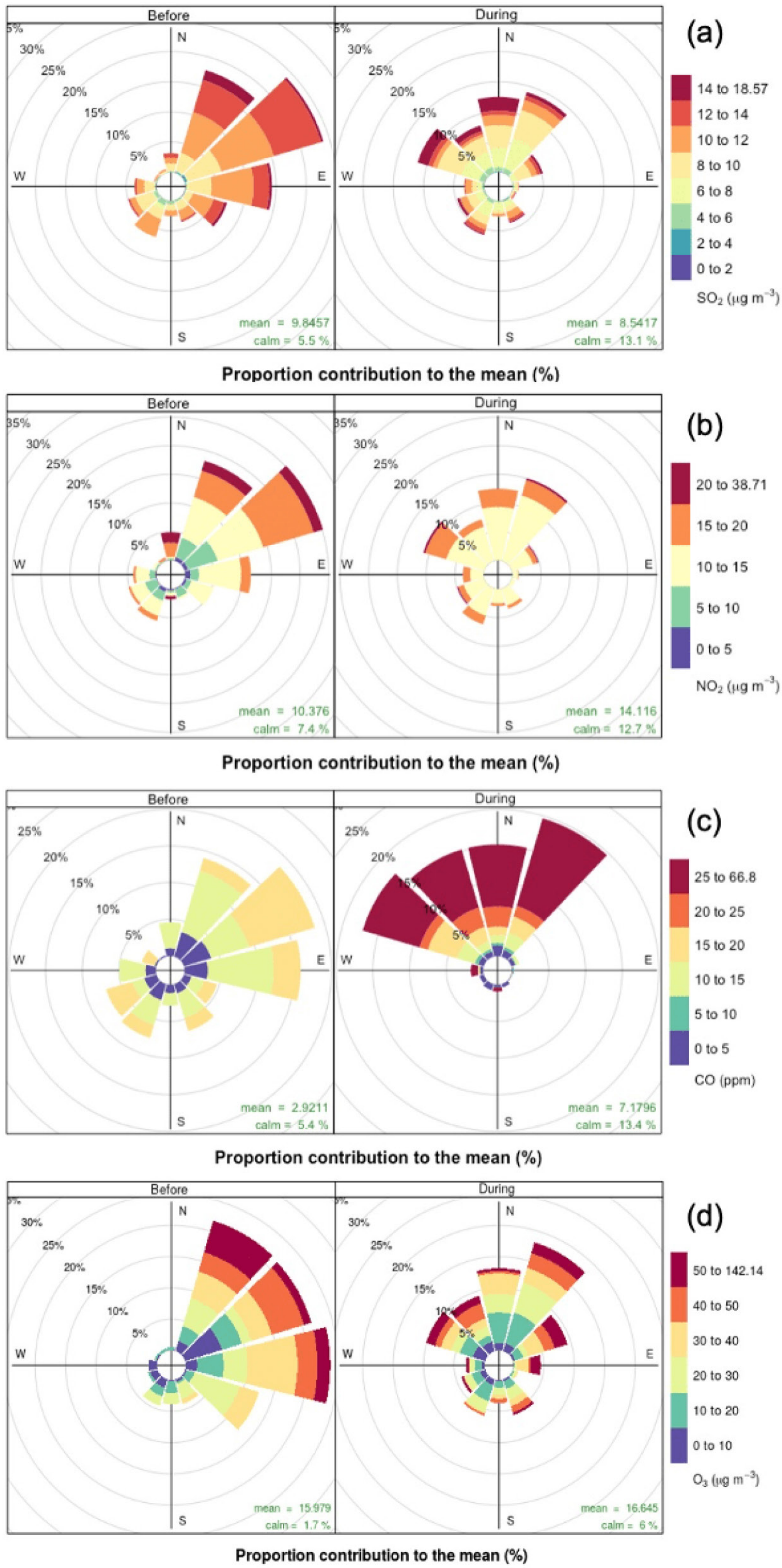

Figure 3. Pollution roses plot to show the relation between wind direction and pollutant concentrations at Manguinhos monitoring station: (a) SO_2, (b) NO_2, (c) CO and (d) O_3. Before: March 1st to 15th, 2020 and during: March 16th to April 12th, 2020.

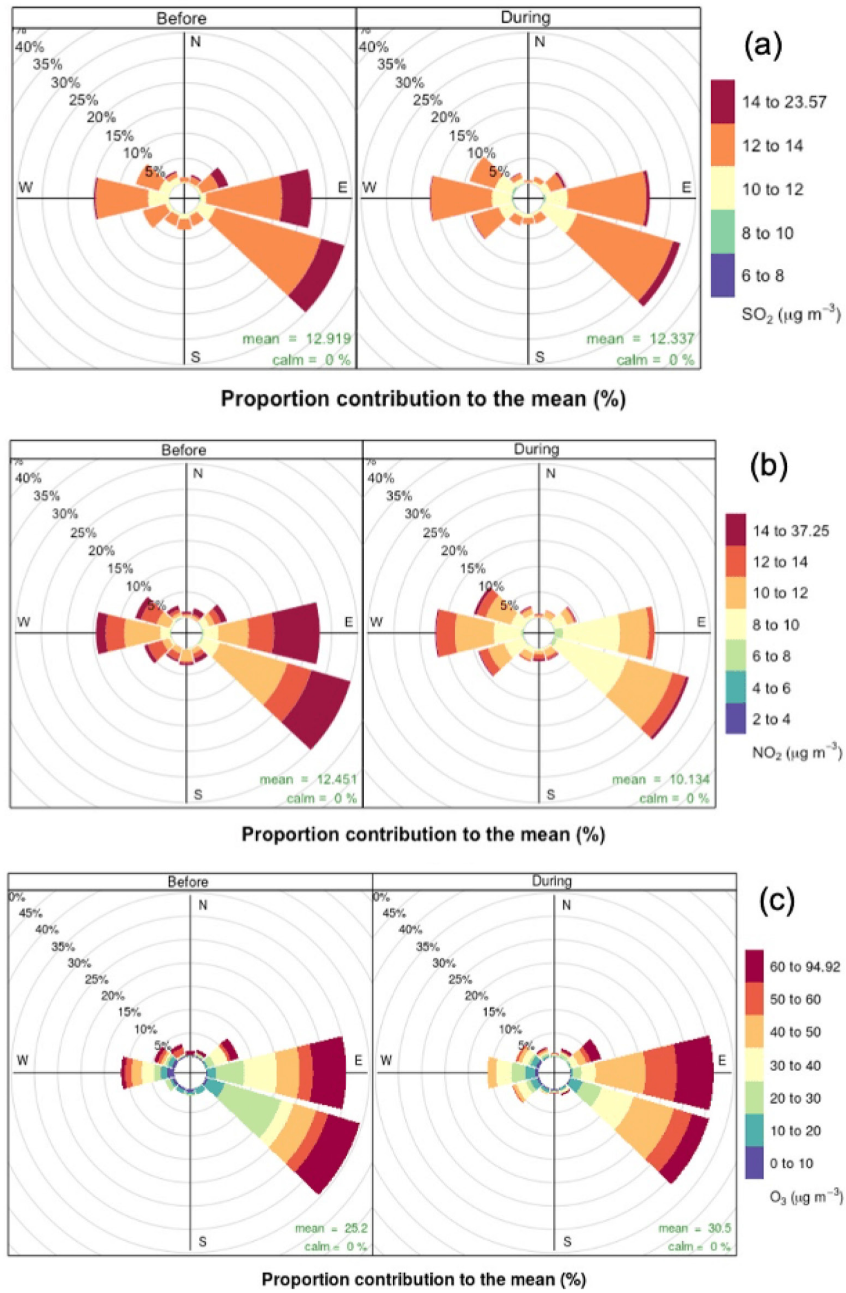

Figure 4. Pollution roses plot to show the relation between wind direction and pollutant concentrations at Monte Serrat monitoring station: (a) SO_2, (b) NO_2 and (c) O_3. Before: March 1st to 15th, 2020 and during: March 16th to April 12th, 2020.

and generated, probably, from Itaguaí City. The Federal Highway (2 km), the industrial complex of Santa Cruz (3 km), and Itaguaí port (7 km) surround this site.

São Luiz

Pollution roses for São Luiz are presented in Figure 5. Calm winds were observed in both periods, which indicates the influence of local pollution sources. In both periods O_3 is mainly coming from the east, while during the partial lockdown wind also comes from the northeast. The calm average wind was representative for both periods. Hence, it concluded that O_3 is source-specific and generated in Duque de Caxias City. The CO concentration came mainly from the east, both before and during the partial lockdown. Therefore, SO_2, NO_2 and O_3 decreasing during the partial lockdown may be related to the restriction of main industrial facilities and traffic intensity characteristic of the Duque de Caxias City. Highways, industrial facilities, and intense traffic activity surround this city. The CO decreasing during the partial lockdown may be related to the restriction of buses, vehicles, and subways movement around the city.

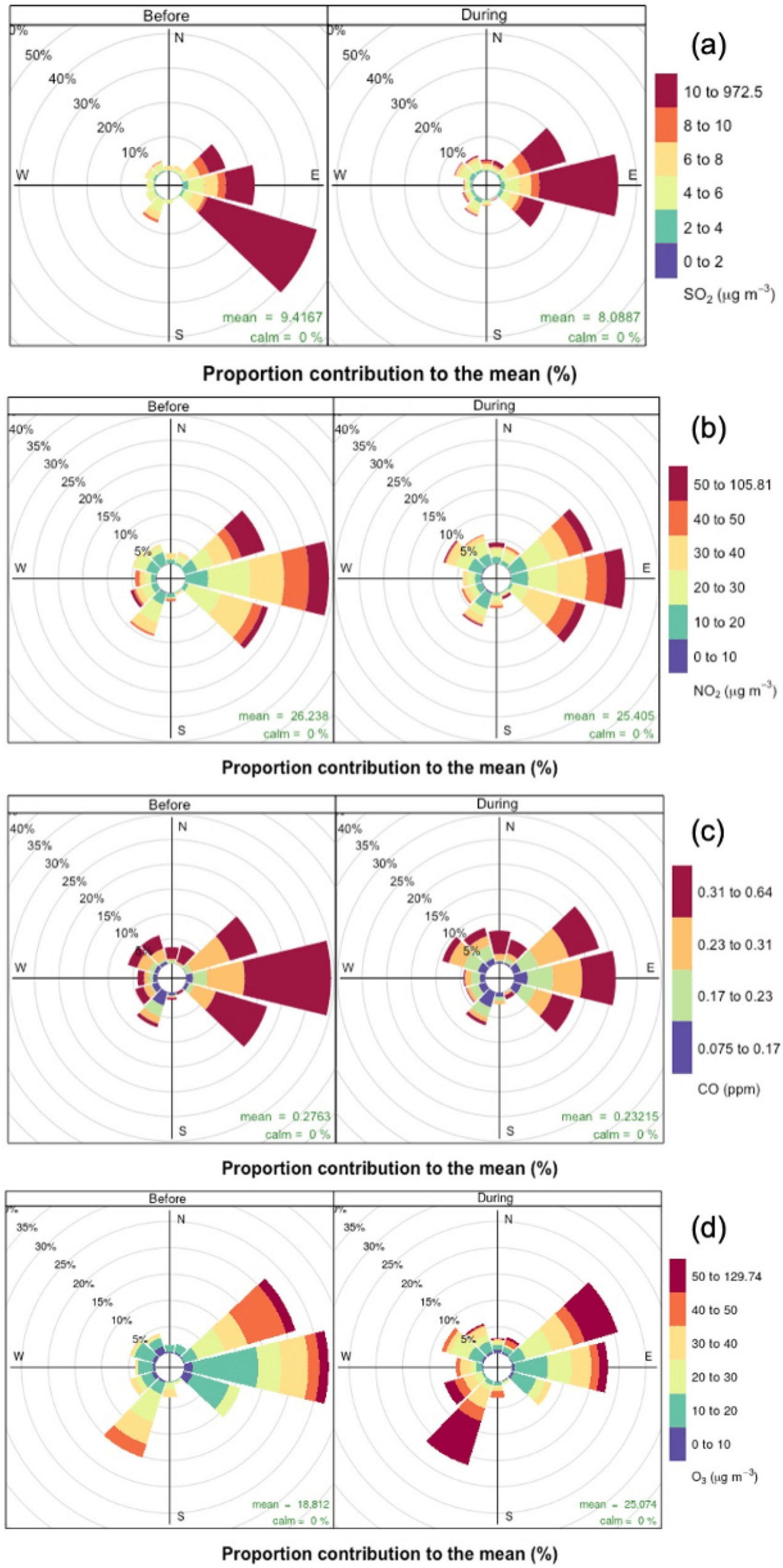

Figure 5. Pollution roses plot to show the relation between wind direction and pollutant concentrations at São Luiz monitoring station: (a) SO_2, (b) NO_2, (c) CO and (d) O_3. Before: March 1st to 15th, 2020 and during: March 16th to April 12th, 2020.

Conclusions

This study evaluated the influence of meteorological variables and partial lockdown on air quality in MRRJ from March to April 2019 and 2020. As in other cities around the world, the concentrations of some air pollutants decreased during lockdown measures. However, not only emission sources but also meteorological parameters play an important role on the variability of pollutant concentrations.

The Brazilian air quality standards for SO_2, NO_2 and O_3 were not exceeded in any of the monitoring stations in the evaluated periods. However, reductions in SO_2 concentrations ranged from 7 up to 89% during the partial lockdown, while NO_2 reduced from 1 to 65%. On the other hand, O_3 concentrations increased from 2 to 34%, which is related to the decrease in NO_2 concentration, that participates in O_3 depletion. CO was the only pollutant that exceed daily Brazilian air quality standard at Manguinhos in 2020, mainly during the partial lockdown, although industrial emission may be accountable for that increase, once diurnal cycle does not indicate peak concentration.

The classification of sites according to the AQI was expressed in relation to the worst result among the monitored pollutants. In 2020, Monte Serrat presented air quality classified as "good" 100% of the days while São Luiz presented only 7% of days with "moderate" to "poor". SO_2 was the pollutant responsible for the reduction of air quality on this monitoring station. In Manguinhos, 25% of the period evaluated in 2020 was ranked with "very poor" or "terrible" air quality due to high concentrations of CO. In Largo do Bodegão, the air quality was classified as "moderate" to "poor" in 47% of the period evaluated in 2020. SO_2 was the pollutant that contributed to the low air quality.

Few strong correlations between pollutants and meteorological variables were found during the evaluated period. The main correlations were verified between O_3 and T and WS, once ozone formation occurs throughout photochemical processes and pollutants from other regions participates in this process. Correlations between O_3 and NO_2 indicates that NO_2 participates in ozone formation, which may be corroborated by the decrease in NO_2 concentration and increase in O_3 concentration.

Although meteorological parameters may influence the pollutants concentration, the air pollution reduction during the partial lockdown was mainly a consequence of changes on emission sources. The comparison with the previous year indicated that between March 1st and April 12th Rio de Janeiro was under the same meteorological condition. Differences in weather conditions were observed between the weeks of 2020, which influenced the levels of some pollutants. Furthermore, pollution roses indicated that pollutants predominantly come from the east sector, which implies that sea breeze carries pollutants emitted by industries and vehicles on the main roads from the coastline to the continent.

Supplementary Information

Supplementary information is available free of charge at http://jbcs.sbq.org.br as PDF file.

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Author Contributions

Karmel Beringui was responsible for conceptualization, data curation, software, investigation, visualization, writing original draft and writing-review and editing; Elizanne P. S. Justo for investigation and writing-review and editing; Luciana M. Baptista Ventura for data curation, and writing-review and editing; Ruan G. de Souza Gomes for investigation, writing-review and editing; Vinícius Lionel-Mateus for software, writing-review and editing; Alex Huaman De La Cruz for investigation, software, writing-review and editing; Ana Carolina L. Bellot de Almeida for data curation and writing-review and editing; Michelle Branco Ramos for data curation and writing-review and editing; Julio Angeles Suazo for software; Pedro H. R. Valle for data curation; Adriana Gioda for conceptualization, formal analysis funding acquisition, writing-review and editing.

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