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Air Quality in Southeast Brazil during COVID-19 Lockdown: A Combined Satellite and Ground-Based Data Analysis

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Abstract: With the current COVID-19 pandemic being spread all over the world, lockdown measures are being implemented, making air pollution levels go down in several countries. In this context, the air quality changes in the highly populated and trafficked Brazilian states of São Paulo (SP) and Rio de Janeiro (RJ) were addressed using a combination of satellite and ground-based daily data analysis. We explored nitrogen dioxide (NO_2) and fine particulate matter ($PM_{2.5}$) daily levels for the month of May from 2015–2020. Daily measurements of NO_2 column concentrations from the Ozone Monitoring Instrument (OMI) aboard NASA's Aura satellite were analyzed and decreases of 42% and 49.6% were found for SP and RJ, respectively, during the year 2020 compared to the 2015–2019 average. Besides NO_2 column retrievals, ground-based data measured by the Brazilian States Environmental Institutions were analyzed and correlated with satellite retrievals. Correlation coefficients between year-to-year changes in satellite column and ground-based concentrations were 77% and 53% in SP and RJ, respectively. Ground-based data showed 13.3% and 18.8% decrease in NO_2 levels for SP and RJ, respectively, in 2020 compared to 2019. In SP, no significant change in $PM_{2.5}$ was observed in 2020 compared to 2019. To further isolate the effect of emissions reduction due to the lockdown, meteorological data and number of wildfire hotspots were analyzed. NO_2 concentrations showed negative and positive correlations with wind speed and temperature, respectively. $PM_{2.5}$ concentration distributions suggested an influence by the wildfires in the southeast region of the country. Synergistic analyses of satellite retrievals, surface level concentrations, and weather data provide a more complete picture of changes to pollutant levels.

Keywords: air quality; OMI; NO_2; $PM_{2.5}$; São Paulo; Rio de Janeiro

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1. Introduction

The new coronavirus (COVID-19) disease was declared as a global pandemic by the World Health Organization on 11 March 2020 [1]. Since then, several countries that had not yet adopted social isolation measures have been promulgating lockdown decrees to avoid the spread of the virus. In Brazil, small towns to bigger cities and entire states have implemented lockdown regulations in varying periods and social-economic activities, depending on local virus propagation, infrastructure and regional characteristics [2]. The southeastern states of Sao Paulo (SP) and Rio de Janeiro (RJ) were the first ones to implement lockdown measures in local areas due to their high numbers of COVID-19 cases. Considering that they are highly populated and industrialized regions, and hold the largest economic clusters in the nation, any imposed changes on their regular activities greatly affects the country's GDP (gross domestic product). Therefore, no lockdown rule was introduced for industries [3]. Public and private transportations, on the other hand, were considerably reduced (e.g., a limitation of travel based on the plate number).

A number of previous studies have investigated the impact of lockdown measures on the level of air pollution in several regions of the world, including Spain [4,5], India [6,7], East Asia [8–10], the United States [11,12], Morocco [13], Thailand [14], Iran [15], and Italy [16]. A typical observation, common to these studies, is that the COVID-19 lockdown across the countries of the world resulted in reductions of $PM_{2.5}$, PM_{10}, NO_2, CO, and volatile organic compounds (VOCs), a slight decrease or no change in SO_2, and an increase in O_3 (see, e.g., [17] for a review). In Brazil, Nakada and Urban [18] highlighted the air quality impacts of a partial lockdown in SP during 24 March to 20 April 2020. They found more than 50% lower concentrations of traffic-related pollutants (CO, NO_x) during this timeframe compared to a five-year mean value based on data from four near-road ground-based stations. A series of studies [3,19,20] was conducted in RJ during partial lockdown (2 March to 16 April 2020) that showed significant reductions in CO and NO_2, a slight reduction of PM_{10}, and an increased level of Ozone.

Although there is no shortage of studies relating the COVID-19 lockdown and level of air pollution, those that have based their analysis on collective information from satellite retrievals and ground-based pollutant measurements are rather rare, especially applied to Brazil. For example, the analysis of NO_2 levels in all the above-mentioned studies in Brazil were based on a limited number of ground-based measurements. The short chemical life-time of NO_2, however, provides a potential for surface emission observations to be well correlated with tropospheric NO_2 vertical column densities (VCDs), which are concentrations measured by satellite and converted from a slant plane to a perpendicular position in relation to the Earth's surface [21]. In fact, previous studies have shown the temporal correlation potential between NO_2 ground and satellite column concentrations [22–25]. Therefore, NO_2 VCDs may be used as a proxy of surface data especially when ground-based stations are sparse, as in some regions of Brazil. Although used in studies focusing on other regions of the world (see Table 1 for a summary), no previous studies have used NO_2 VCDs to quantify air pollution change due to COVID-19 in Brazil.

Table 1. Summary of recent studies using satellite data to investigate air pollution changes during the COVID-19 lockdown.

Study Area	Reference	Description
Global	[26]	TROPOMI NO_2 and CO, and MODIS AOD reductions were assessed during Feb/Mar 2020. Findings include a substantial reduction of NO_2, low reduction in CO, and a low-to-moderate reduction in AOD in major hotspots of COVID-19 outbreaks.
Global	[27]	TROPOMI and OMI NO_2 are evaluated during Jan-April 2020 compared to the same lockdown timeframe in 2019. The most significant drop was found in Chinese cities, with a cumulative −40% in 2020 compared to 2019. Decreases in western Europe and United States are also significant (−20% to −38%).
Multiple (34 countries)	[28]	TROPOMI NO_2 and O_3, as well as MAIAC AOD measurements, were evaluated during Feb/Mar 2020 compared to the same months in 2019. NO_2 decreases of 10.7% were found in remote areas, while the highest reductions (20%) were found in Europe and China. AOD increased slightly (+13.2%) overall, although local declines were evident in some parts of China.
Southeast Asia	[29]	AOD from the Himawari satellite and OMI NO_2 were observed during the local lockdown period, in addition to ground NO_2, SO_2, PM_{10}, $PM_{2.5}$, CO measurements. Larger tropospheric NO_2 reductions of 27–34 % were found over urban areas.
East Asia	[9]	TROPOMI NO_2, HCHO, SO_2 and CO concentrations, in addition to Himawari AOD were analyzed from imagery. NO_2 experienced the greatest reduction, with decreases of 54%, 83%, 33%, and 19% in BTH, Wuhan, Seoul, and Tokyo on February 2020 compared to the same month in 2019. Wuhan showed the greatest pollutant reduction overall, with 83%, 11%, 71%, and 4% decreases in NO_2, HCHO, SO_2, and CO, respectively.
Europe	[30]	Tropospheric NO_2 columns from TROPOMI are compared over the European region between similar periods of 2019 and 2020, according to lockdown timeframes. A decrease of up to 85% in 2020 in some of the big cities was observed. Cross-correlation were performed between the NO_2 column and ground values, and a R^2 ranging between 0.5 and 0.75 was found in different locations. The Industrial Production Index and air traffic volumes are included, confirming the reason behind the study findings.

Table 1. *Cont.*

Study Area	Reference	Description
Thailand	[14]	Assessment of lockdown on the air quality of a medium-sized urban area. TROPOMI NO_2 and ground NO_2, SO_2, PM_{10}, $PM_{2.5}$, CO and O_3 were studied. Tropospheric NO_2 is in agreement with ground observations.
California, USA	[12]	Ground and tropospheric OMI NO_2 is evaluated during the 2020 lockdown weeks compared to previous 2015–2019 historical data. Spatial patterns of OMI NO_2 showed a decreasing trend over powerplant locations and an increasing trend over residential areas near national highways.

In addition, conclusions of several studies investigating the relations between COVID-19 lockdown and regional air quality have been limited due to not investigating meteorological fields and/or natural emissions that might influence pollutant concentration variations [12,17,19,29].

In this paper, we investigated pollutant concentration changes before and during COVID-19 lockdown in two Brazilian states of SP and RJ using a combined analysis of satellite and surface data. In addition, the effect of meteorological variables and natural wildfire emissions on the findings was evaluated.

We focused on nitrogen dioxide (NO_2) and fine particulate matter ($PM_{2.5}$) as the two major pollutants emitted by motor vehicles [31]. It is estimated that road traffic accounts for 82% of the NO_x in the metropolitan region of SP [32]. Additionally, de Fatima Andrade et al. [33] found that vehicle emissions contribute to at least 40% of the $PM_{2.5}$ mass in six metropolitan cities including Sao Paulo and Rio de Janeiro. Short-term NO_2 exposure can increase the risk of total, cardiovascular, and respiratory death, while there is evidence of a long-term effect of NO_2 on mortality [34,35]. A range of health issues can happen if particulate matters are inhaled [36]. Fine particulate matters ($PM_{2.5}$) are especially of interest as they may penetrate deep into the respiratory tract. Islam et al. [37] investigated diesel-exhaust particulate transport and deposition in the upper airways and found differences in deposition associated with particle size.

By evaluating NO_2 data from satellite and ground-based monitoring systems, we aim to highlight the importance of a synergistic analysis of both datasets, especially in a location that lacks ground measurements to provide accurate NO_2 trends. Since the COVID-19 pandemic has begun in Brazil, no previous scientific literature has adopted satellite data for air quality evaluations, and in fact quantitative analyses of satellite retrievals (as opposed to the common usage of composite satellite imagery) are rather rare in studies focusing on other regions of the world. Furthermore, meteorological measurements are not always included in air pollution analysis. For instance, in Brazilian studies mentioned above [3,19,20], no actual weather data were provided besides dispersion information on air quality results during the pandemic. By studying the cross-correlation between meteorological and air quality variables, this study aims to provide a broader and more quantitative understanding of the regional air quality effects due to COVID-19 lockdown. Finally, it is important to explore relationships between NO_2 and $PM_{2.5}$ concentrations with natural emissions trends.

2. Materials and Methods

2.1. The Study Area and Time Frame

The areas of interest adopted for the present study were the Brazilian states of SP and RJ, with their hydrographic regions shown in Figure 1. We focused on two metropolitan areas, namely Alto Tiete in SP and Baia de Guanabara in RJ (Figure 1C,E), where air pollution due to transportation is expected to be high.

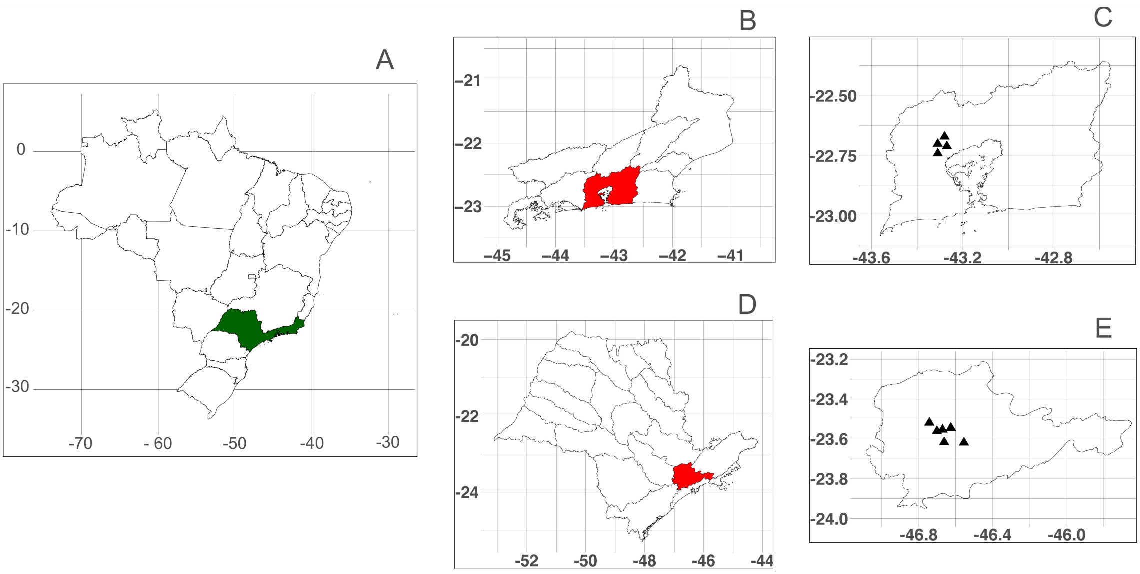

Figure 1. The map of Brazil (**A**) highlighting the states of Rio de Janeiro (**B**) and São Paulo (**D**). Four ground stations in RJ's Baia de Guanabara hydrographic region (**C**) and six ground stations in SP's Alto Tiete hydrographic region (**E**) were selected for analysis in this study.

Monthly-averaged NO_2 and $PM_{2.5}$ concentrations during May 2020 were compared to those of May 2015–2029. This timespan was selected after carefully reviewing the timeframe of local lockdown decrees. Earlier studies in southeast Brazil [3,18–20] have focused on early months of partial lockdown (March and April). However, recently, Noda et al. [38] used a social isolation index and noticed two distinct time-periods of lockdown in SP: before and after 1 May 2020. The first period was associated with greater reductions in the emissions, while the second period was characterized by greater fluctuations in pollutant concentrations. Emphasizing that the pollutant levels were not similar throughout the lockdown, Noda et al. [38] called for more studies focusing on the second interval.

2.2. Satellite Retrievals of Tropospheric NO_2

The Ozone Monitoring Instrument (OMI)—a nadir-viewing near-UV/Visible spectrometer (264–504 nm spectrum) aboard NASA's Aura satellite—was adopted for NO_2 VCD retrievals in this study. OMI was launched on 15 July 2004 and provides daily measurements of key air quality components including NO_2 over the whole globe. It orbits the Earth in accordance with Aura's polar Sun-synchronous pattern. Its field of view (FOV) is approximately 13 km $\times$ 24 km near nadir and its local equator crossing time (LECT) is 13:45 $\pm$ 0:15. For our study area in Brazil, the overpassing time was approximated to be 30 min after LECT, or 14:15 $\pm$ 0:15, in accordance with the $OMNO_2$ product description [39]. We used cloud-screened tropospheric column Level-3 daily global gridded (spatial resolution of 0.25° $\times$ 0.25°) OMI NO_2 V3 ($OMNO_2$d) [40]. By choosing tropospheric instead of total column, stratospheric values are removed, which is expected to result in a better correlation between column and surface concentrations. The $OMNO_2$d daily values were then averaged for the May months of 2015–2019 as well as for May 2020. Additionally, NO_2 mean column values were calculated for grid cells covering SP and RJ to be used for quantitative comparisons and correlation analyses with ground-based data.

2.3. Ground Measurements

The NO_2 surface-level concentrations were obtained from the State's Environmental Agencies Air Quality Information Systems, CETESB (Companhia Ambiental do Estado de São Paulo) in SP and INEA (Instituto Estadual do Ambiente) in RJ [41,42]. The NO_2 measurement technique is consistent between the two datasets both using a chemiluminescence method. The $PM_{2.5}$ ground measurements were only available from the CETESB Agency in SP. The temporal resolution of NO_2 and $PM_{2.5}$ data was hourly and daily, respectively.

The ground stations of interest were located within the metropolitan areas in each state (see Figure 1C,E). All SP stations are within the Water Resources Management Unit n° 6 (WRMU 6) which encompasses the Alto Tiete hydrographic region, and all RJ stations are within the West Side of the Baia de Guanabara Hydrographic Region. Stations of interest were chosen objectively and according to a defined set of criteria. Six stations in SP and four stations in RJ were selected. All of these stations recorded NO_2 mass concentrations higher than 60 μg/m^3 at least once for each year. The stations in SP had $PM_{2.5}$ measurements available for at least 15 days of the month. All stations in SP and RJ were situated strategically close to busy highways. Therefore, it can be assumed that NO_2 emissions were due to vehicles. The only exception was the RJ station Campos Eliseos, which is located close to a petrochemical pole that is a potential NO_2 emitter. Table 2 summarizes the selected stations in each state.

Additionally, daily ground weather data (temperature, humidity, wind speed) was collected for the main airports in the cities of SP and RJ.

Table 2. The selected ground stations in SP and RJ.

SP		
Station	Location (Lat, Lon)	Description
D Pedro II Park	(−23.5440, −46.6270)	Cut by five viaducts and state avenues. D Pedro II Bus Terminal (the busiest in the city), D Pedro II Metro Station and State School of Sao Paulo are within the park area.
Congonhas	(−23.6160, −46.6630)	Close to Congonhas Airport. Located about six meters from two boulevards, one with heavy traffic including heavy and light duty vehicles.
Sao Caetano do Sul	(−23.6180, −46.5560)	Located within a residential and industrial region. Two busy boulevards (heavy and light duty vehicles) are nearby.
Cerqueira Cesar	(−23.5530, −46.6720)	Located within a public school and about seven meters from a heavily trafficked boulevard (heavy and light duty vehicles).
Pinheiros	(−23.5610, −46.7020)	Very close to highly trafficked Marginal Pinheiro highway. Heavy and light duty vehicles.
Marginal Tiete	(−23.5180, −46.7430)	Located close to main express highway of the city of Sao Paulo. Very busy.
RJ		
Station	Location (Lat, Lon)	Description
Campos Eliseos	(−22.7065, −43.2703)	Petrochemical pole and heavy diesel vehicle traffic nearby. Located within a small state school.
Jardim Primavera	(−22.6746, −43.2851)	Very urbanized and also close to heavy diesel vehicle traffic. Located within the Federal Highway Police area.
Pilar	(−22.7058, −43.3118)	Close to municipal school and BR−101, a federal busy highway, connecting the entire Eastern Brazil, hence being highly trafficked.
Sao Bento	(−22.7398, −43.3133)	Positioned within Municipal Environmental Secretariat, and also close to BR−101.

2.4. Data Processing and Analysis

Figure 2 shows a schematic of the workflow to process and analyze data in this study. To obtain local NO_2 mean columns and averaged ground NO_2 and $PM_{2.5}$ concentrations, different approaches were adopted. For NO_2 satellite data, the overall daily values within the geographic coordinates were averaged for the May months of each year (2015–2020). Then, the averaged data frame was retrieved for each state with its limits defined using shapefiles for each local hydrographic region. In addition, the arithmetic mean of ground-level concentrations were averaged using the hourly maximum value of NO_2 for each day, and $PM_{2.5}$ daily values, respectively, for each chosen ground station. Finally, the averaged values for all SP and RJ stations were calculated.

The Pearson correlation coefficient (r_s) was considered for this study. This choice was made based on its wide use and efficacy in measuring linear relations between satellite and ground-based data, as well as previous studies investigating air quality during the COVID-19 lockdown [30,43–45]. Accounting for sample covariance and standard deviation, r_s values give information about magnitudes and directions of correlation. Its range goes from −1 to 1, resulting from the following equation:

$$r_s = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_i - \bar{y})^2}}, \quad (1)$$

where, x_i = yearly May OMNO2 mean satellite columns; $\bar{x}$ = average of yearly May OMNO2 mean satellite columns; y_i = yearly May ground NO_2 mean for all local stations from 14:00–15:00; and $\bar{y}$ = Average of yearly May ground NO_2 means from 14:00–15:00. Note that OMI's overpassing time in Brazil is around 14:30 local time.

To add on the weather data analysis and check on relationships amongst weather variables and ground NO_2 and $PM_{2.5}$ concentrations, pairwise correlation using the same Pearson coefficient was performed for the SP region.

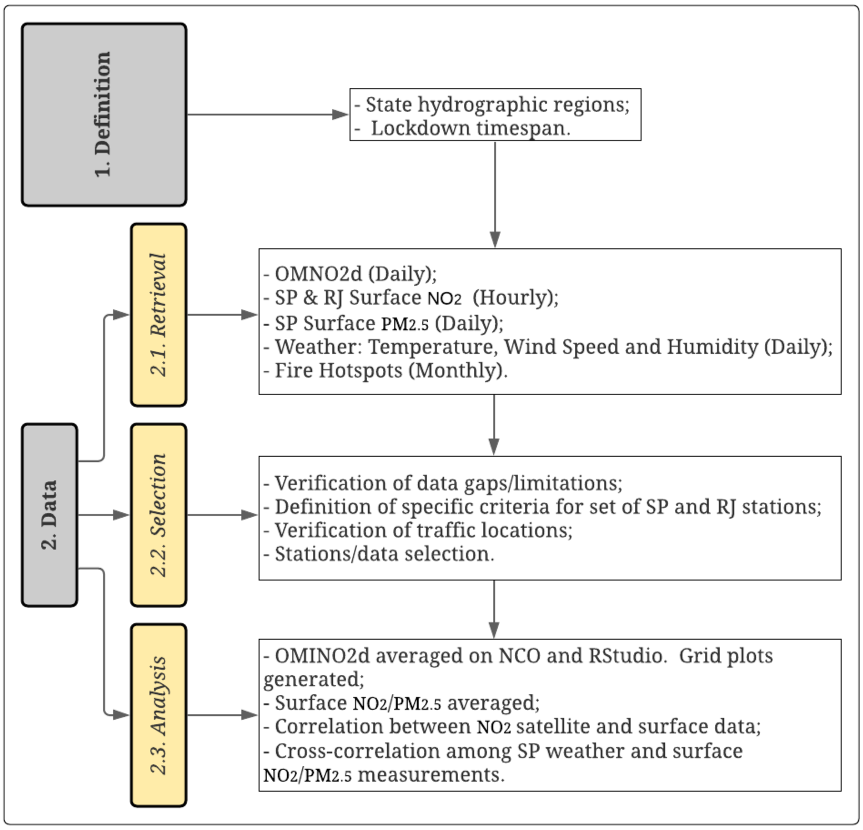

Figure 2. The workflow diagram for data analysis in this study.

2.5. Data Limitations

Retrieval errors are present when the OMNO$_2$d product is conceived [39]. These include a fitting error in the slant column, estimated to be $0.3 - 1 \times 10^{15}$ no. molecules/cm^2 for all data product levels. In addition, there are missing values in the daily dataset, but since the data was averaged for the whole month of each year, the gaps do not represent a significant error within the product datasets. Ground data limitations include gaps in daily and hourly concentrations. If gaps were present in 15 days or more in a month, the corresponding station would be discarded from the analysis. In addition, some hours did not have data available, but if there were data available for at least half of a day, the station would be included in the daily averaging.

3. Results and Discussion

Figure 3 shows the satellite-retrieved NO_2 column values for SP and RJ. It is seen that the metropolitan area of the city of São Paulo represents the most polluted region in SP, while in RJ, areas surrounding the Guanabara Bay show the highest NO_2 value. The NO_2 column values showed a clear visual distinction in molecule density between the two periods of May 2020 and May 2015–2019. For both Brazilian states, NO_2 column concentrations considerably decreased during May 2020 when compared to the average value from the previous five years. The averaged NO_2 VCDs in SP were 9.10×10^{15} and 5.28×10^{15} molecules/cm^2 in 2015–2019 and 2020, respectively, showing a decrease of 42% (3.82×10^{15} molecules/cm^2 or 63.45 mol/km^2) when a time span before COVID-19 is compared to the partial lockdown period. For RJ, averaged NO_2 VCDs showed values of 5.28×10^{15} and 2.66×10^{15} molecules/cm^2 for 2015–2019 and 2020, respectively, suggesting a decrease of 49.6% (2.62×10^{15} molecules/cm^2 or 43.52 mol/km^2). In SP, the range of NO_2 column density values within the hydrographic region was 4.75×10^{15} molecules/cm^2 (78.83 mol/km^2) during both timeframes (May 2020 and May 2015–2019). This range for RJ was 5.28×10^{15} molecules/cm^2 (87.7 mol/km^2) during 2015–2019, and 1.75×10^{15} molecules/cm^2 (29 mol/km^2) for 2020. These observations suggest that the partial lockdown had a more pronounced impact on the reduction of NO_2 in RJ when compared to SP.

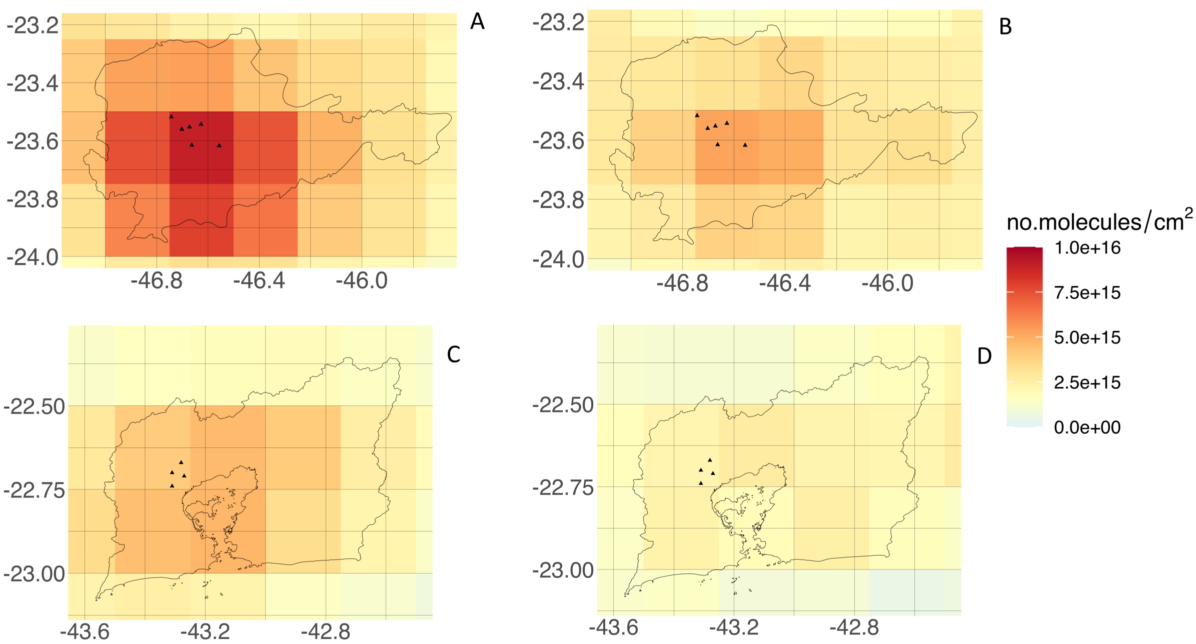

Figure 3. The NO_2 column values during the May months of 2015–2019 in SP (**A**) and RJ (**C**), and during May 2020 in SP (**B**) and RJ (**D**).

The May-month-average ground-based observations for each year were transcribed into a boxplot for the six SP and four RJ ground stations and are shown in Figures 4 and 5 for NO_2 and $PM_{2.5}$, respectively. The cross in each box represents the average value for the month of May based on daily data from all stations, and the data within the boxes are within the 25% and 75% percentiles.

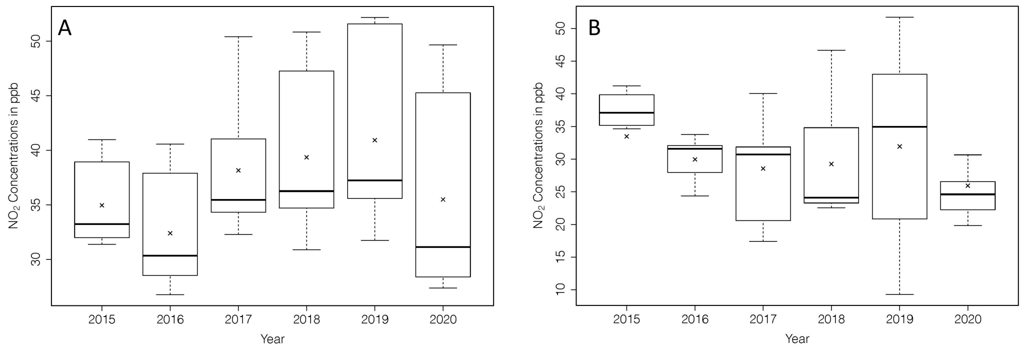

Figure 4. The NO_2 daily ground-level concentrations during May 2015–2020 measured by the selected SP (**A**) and RJ (**B**) stations.

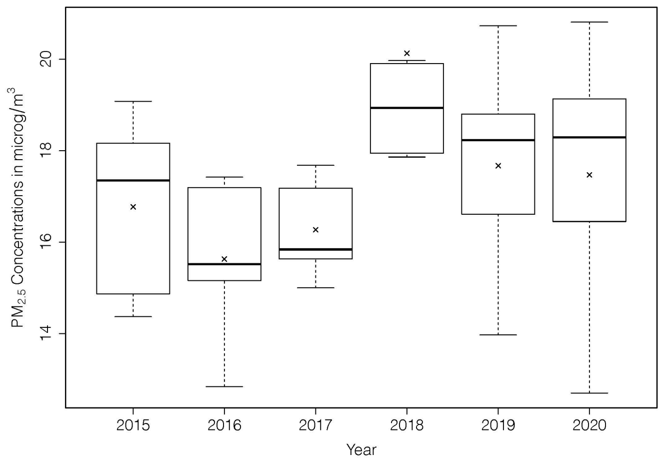

Figure 5. The $PM_{2.5}$ daily ground-level concentrations during May 2015–2020 measured by the selected SP stations.

In SP, there was a slight variation in the NO_2 mean concentration throughout the years, with the highest relative difference observed between 2016 and 2017 (5.76 ppb or 15%) and the second highest between 2019 and 2020 (5.44 ppb or 13.3%). The former disparity was attributed to an unusual favorability in air pollutant dispersion during the winter months (May–September) of 2016 over the state of SP, as described in the CETEB's 2016 Annual Air Quality Report [46]. The latter difference might be attributed to reduction in traffic due to the local COVID-related lockdown decree. A decrease of 18.8% (6.01 ppb) was observed in NO_2 mean concentrations between years 2019 and 2020 in RJ as shown in Figure 4B. A student's *t*-Test was performed between the data in years 2020 and 2019 and a difference within monthly means was found to be statistically significant for both states assuming a 90% confidence interval with *p*-values of 0.099 and 0.077 for SP and RJ, respectively. Data normality was tested for each yearly dataset before the statistical test was conducted.

The ground-level $PM_{2.5}$ mass concentrations were investigated for SP only because, for RJ, there were no consistent data for all stations throughout the years passing the criteria described in Section 2. As shown in Figure 5, there was not a remarkable drop in $PM_{2.5}$ concentrations between 2019 and 2020 (only 0.2 $\mu g/m^3$ or 0.01%). Similar to the NO_2 trend, however, the $PM_{2.5}$ mean concentrations showed a clear decrease in 2016—in fact, 2016 represents the lowest May-month-average across the six years.

To further investigate multi-year trends in satellite data, the mean values of NO_2 VCDs were retrieved for the grid cells covering the selected ground stations, and the results are illustrated in Figure 6. By averaging the 2015–2019 NO_2 values above and comparing the result to the 2020 mean, we found a relative decrease of ∼42% (or 151 mol/km^2). A Pearson correlation between year-to-year changes in satellite column NO_2 and surface data from six SP stations collected between 14:00 and 15:00 (associated with OMI's local overpassing time) was calculated and a value of 0.77 was obtained. For RJ, the 2020 mean value was 2.21×10^{15} no. molecules/cm^2 (∼36.71 mol/km^2), and constitutes a decrease of 48.1% from the 2015–2019 mean. A Pearson correlation coefficient of 0.53 was found between year-to-year trends of RJ stations and the corresponding satellite column values.

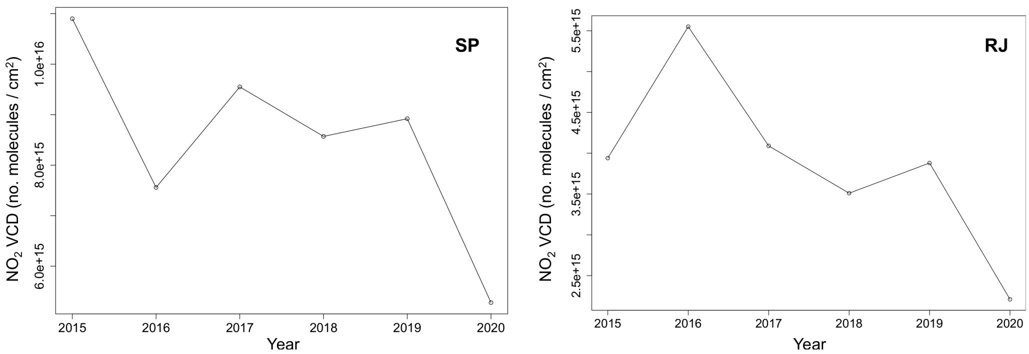

Figure 6. Yearly time-series of mean NO_2 VCDs for the satellite grid cells covering the selected SP and RJ ground stations.

Wind speed and temperature data measured at the Congonhas and Galeao airports for SP and RJ, respectively, were also studied. To assess the role of atmospheric dispersion in pollutant concentrations, we adopted the criteria suggested by the CETESB in objectively defining favorable/unfavorable conditions for dispersion. Unfavorable conditions for air pollutant dispersion were considered [41] as (1) no rainfall, and (2) wind speed less than 1 m/s. All daily rainfall data for SP and RJ averaged for the May months of 2015–2020 showed less than one inch of rainfall, so the effect of rain was considered to be negligible. Daily wind speeds averaged during the month of May were higher than 1 m/s for all years in both SP and RJ with no significant difference seen between years (see Figure 7). Therefore, no considerable unfavorable conditions for pollutant dispersion were detected for May 2015–2020 with a potential to impact concentration levels observed in this study. Temperature variations, however, showed a noticeable decrease in May 2020 in both SP and RJ compared to May 2015–2019. For both states, this decrease was ∼3 °C when compared to 2019, and it was 1.3 °C and 1.4 °C in SP and RJ, respectively, when compared to the average of 2015–2019. It should be noted that the standard deviation of temperature variations over 2015–2020 was 1.16 °C and 1.07 °C for SP and RJ, respectively. Further analysis to understand implications of this lower temperature in 2020 on pollutant levels should be conducted in future studies.

We further analyzed cross-correlations amongst various variables in SP throughout May 2015–2020, with results summarized in Table 3. We observed a high negative correlation (−0.76) between wind speed and NO_2. On the contrary, the temperature showed a positive correlation with NO_2 and a negative relationship with wind speed. This result reflects the influence of wind speed and temperature on the dispersion, and the retention of downwind NO_2 concentrations. Several studies have shown this relationship by using a noise barrier as an inducer and high-resolution modeling [47–49]. Atmospheric stability is also mentioned on these studies, as it is directly related to environmental air temperature, humidity and pressure, and can have an influence on atmospheric pollutant concentrations. As shown in Table 3, $PM_{2.5}$ showed a small positive correlation with NO_2 which could be associated with secondary PM, originated in NO_x chemical reactions. There is also a relatively high negative correlation of $PM_{2.5}$ with ambient humidity, and small positive correlations with temperature and wind speed. The latter could be increasing $PM_{2.5}$ by long-range transport from fire hotspots. This is evident by the correlation between $PM_{2.5}$ and number of fire hotspots (0.59), in addition to $PM_{2.5}$ and wind speed.

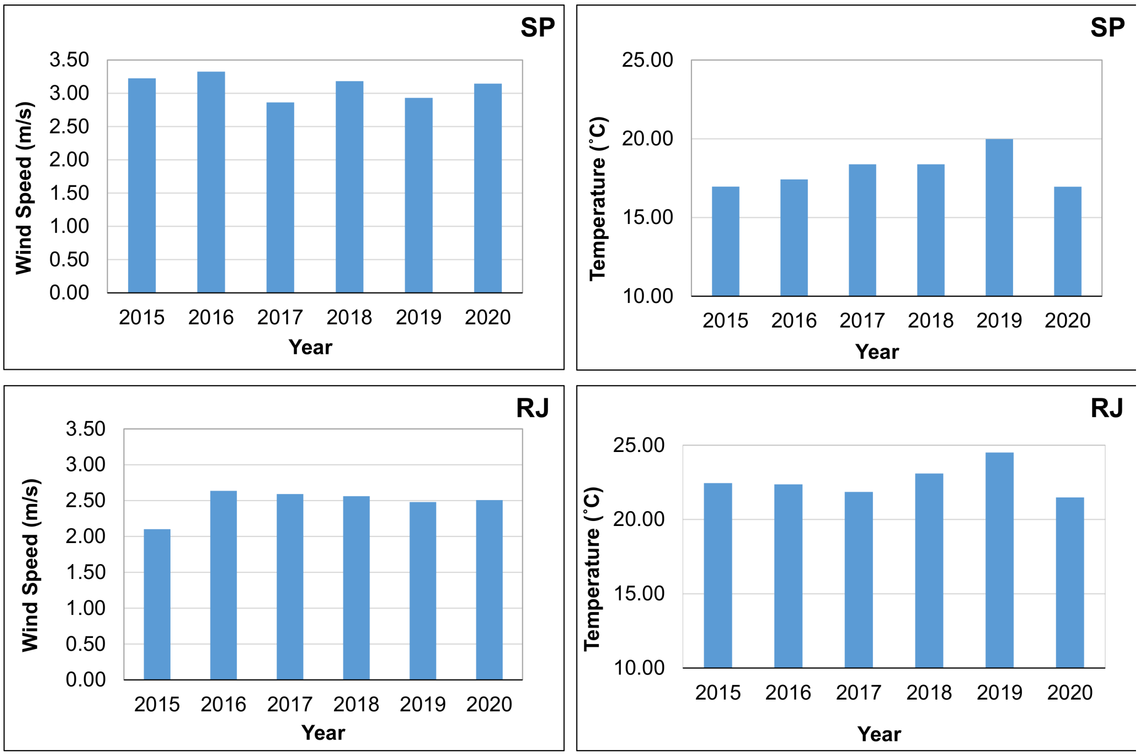

Figure 7. Daily wind speed and temperature values averaged during the month of May for 2015–2020 in SP (Congonhas airport) and RJ (Galeao airport).

Table 3. Cross-correlation amongst various variables in SP (the number of fires are for the entire southeast Brazil).

	Temperature	Humidity	Wind Speed	NO_2	$PM_{2.5}$	Fire Hotspots
Temperature	1.00	0.26	−0.68	0.63	0.13	−0.24
Humidity	0.26	1.00	−0.21	−0.39	−0.67	−0.68
Wind Speed	−0.68	−0.21	1.00	−0.76	0.24	0.51
NO_2	0.63	−0.39	−0.76	1.00	0.38	0.10
$PM_{2.5}$	0.13	−0.67	0.24	0.38	1.00	0.59
Fire Hotspots	−0.24	−0.68	0.51	0.10	0.59	1.00

In addition to meteorological parameters, the number of fire hotspots reported by the National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais) [50] were also investigated for southeast Brazil, including both states of SP and RJ. The emissions from wildfires are known to contribute to particulate matter and NO_x levels [51], hence it is important to assess whether there is a potential interference of fire burnings in our yearly data of $PM_{2.5}$ and NO_2.

As shown in Figure 8, a clear increase (46%) in number of fires during May 2020 was observed in comparison to the same month in 2019. Compared to the average counts for 2015–2019, this increase in 2020 was 35%. These results indicate that ground $PM_{2.5}$ and NO_2 levels in May 2020 would potentially be higher than in previous years if only wildfires were considered to impact pollutants' concentrations. This seems to be more pronounced for $PM_{2.5}$, as we did not see any significant decrease in 2020 values during the COVID-19 lockdown period. Furthermore, the distribution of $PM_{2.5}$ values shown in Figure 5 seems to follow the same yearly pattern of the fire counts in the southeast region, suggesting that the long-range transport of pollutants emitted from fires within southeastern states could have impacted $PM_{2.5}$ values in SP. The relatively high positive correlation between $PM_{2.5}$ and number of hotspots (Table 3), as well as the dominant northwesterly wind direction (i.e., from the fire hotspots towards the Sao Paulo metropolitan area) measured at the Congonhas Airport station during May 2020 further supports this argument.

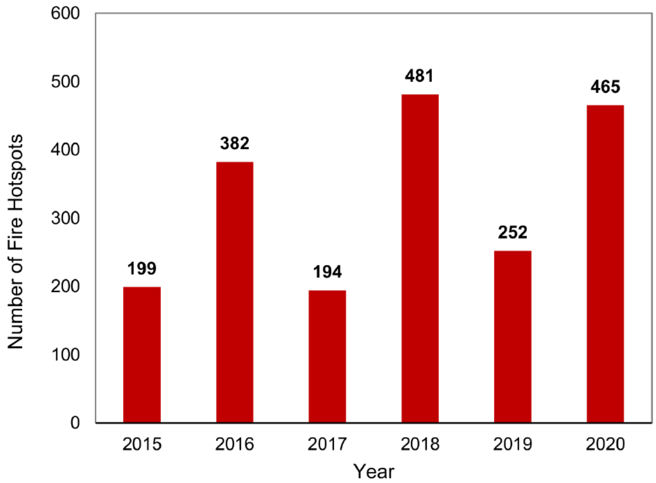

Figure 8. Number of fire hotspots in southeast Brazil during May of 2015–2020.

4. Conclusions

Qualitative and quantitative differences in NO_2 and $PM_{2.5}$ concentrations were investigated for timeframes before and during the COVID-19 lockdown determined by the Brazilian government. To analyze if there were any significant differences in NO_2 and $PM_{2.5}$ concentrations in 2020 during lockdown compared to previous years, satellite and ground-based measurements were synergistically analyzed. After finding a clear visual difference in gridded NO_2 column densities for the month of May in 2015–2019 and 2020 within the hydrographic regions of interest (where the selected ground stations were located), a quantitative analysis was executed. From OMI satellite retrievals, we found a decrease of 42% in 2020 compared to the 2015–2019 period in SP's Alto Tiete. An even higher decline of 49.6% was found in RJ's Baia de Guanabara for the same time interval.

Aside from satellite NO_2 columns, ground concentrations also presented differences within years. However, the difference seemed to be smaller than that for satellite retrievals. In May 2020, NO_2 levels were 13.3% lower (p-value = 0.099 with a 90% confidence interval) than for the same month in 2019 for SP, while in RJ this drop was equal to 18.8% (p-value = 0.077 with a 90% confidence interval) in 2020. $PM_{2.5}$ mass concentrations, however, did not show a significant contrast between 2020 and the previous years. The correlation coefficients between year-to-year trends of satellite column NO_2 and ground-based measurements for multiple selected stations were $\sim$0.77 for SP and $\sim$0.53 for RJ.

To examine if there was any weather interference on the statistical comparison performed on this study, the dispersion conditions and mean air temperature for selected stations were studied for SP and RJ. Both SP and RJ stations showed mostly favorable dispersion days for all days during the month of May in all years, so this factor was not considered to be affecting the NO_2 decrease found for 2020. In addition, a high negative correlation between wind speed and NO_2 (-0.76) further supports this statement. Nevertheless, the average temperature during May 2020 was lower than that for the same period during 2015–2019, while we observed a positive correlation between temperature and $NO_2/PM_{2.5}$. Together, these suggest that temperature might have a role in reducing concentrations observed during May 2020 in southeast Brazil, warranting additional studies. Finally, natural emissions by wildfire were examined using the number of hotspots within the southeast region, and it was concluded that $PM_{2.5}$ concentrations were potentially affected by those fires.

The results of this work can serve as a reference for local air quality compliance, in particular at locations that lack ground monitoring stations. Moreover, the combined results with meteorology observations can give a more precise overlook of NO_2 and $PM_{2.5}$ scenarios during the COVID-19 lockdown, also serving as a base of analysis for future extreme air pollution events. Suggestions for future work include extending these analyses to other pollutants, as well as other Brazilian regions. This is important because ground-based stations are temporally and spatially sparse in Brazil.

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