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How mobility restrictions policy and atmospheric conditions impacted air quality in the State of São Paulo during the COVID-19 outbreak

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ABSTRACT

Mobility restrictions are among actions to prevent the spread of the COVID-19 pandemic and have been pointed as reasons for improving air quality, especially in large cities. However, it is crucial to assess the impact of atmospheric conditions on air quality and air pollutant dispersion in the face of the potential variability of all sources. In this study, the impact of mobility restrictions on the air quality was analyzed for the most populous Brazilian State, São Paulo, severely impacted by COVID-19. Ground-based air quality data (PM10, PM2.5, CO, SO2, NOx, NO2, NO, and O3) were used from 50 automatic air quality monitoring stations to evaluate the changes in concentrations before (January 01 - March 25) and during the partial quarantine (March 16 - June 30). Rainfall, fires, and daily cell phone mobility data were also used as supplementary information to the analyses. The Mann-Whitney U test was used to assess the heterogeneity of the air quality data during and before mobility restrictions. In general, the results demonstrated no substantial improvements in air quality for most of the pollutants when comparing before and during restrictions periods. Besides, when the analyzed period of 2020 is compared with the year 2019, there is no significant air quality improvement in the São Paulo State. However, special attention should be given to the Metropolitan Area of São Paulo (MASP), due to the vast population residing in this area and exposed to air pollution. The region reached an average decrease of 29% in CO, 28% in NOx, 40% in NO, 19% in SO2, 23% in PM2.5, 18% in PM10, and 16% in O3 concentrations when compared to the same period in 2019. On the other hand, Cubatão, a highly industrialized area, showed statistically significant increases above 20% for most monitored pollutants in both periods of 2020 compared to 2019. This study reinforces that the main driving force of pollutant concentration variability is the dynamics of the atmosphere at its various time scales. An abnormal rainy season, with above average rainfall before the restrictions and below average after it, generated a scenario in which the probable significant reductions in emissions did not substantially affect the concentration of pollutants.

| Key words: | Air quality | Coronavirus disease | Air pollutants | Mobility restriction |

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1. Introduction

Air pollution is responsible for more than seven million premature deaths annually worldwide (WHO, 2018). Exposure to air pollutants can lead to health problems, such as cardiovascular diseases (Mokona et al., 2019; Moolagavkar, 2000), respiratory diseases (Gautam et al., 2016; Guan et al., 2016; Xing et al., 2016), and also mental illnesses and disorders (Almendra et al., 2019; Silva et al., 2020; Song et al., 2018). In large urban centers, the major air pollution sources are vehicular emissions and industrial activities (Squizzato et al., 2017; Vilas Boas et al., 2018; Zhang and Batterman, 2013). With the Coronavirus Disease 2019 (COVID-19) outbreak, hundreds of articles have sought a nexus between pollution and the pandemic (e.g., Azuma et al., 2020; Casado-Aranda et al., 2020). However, both subjects, pollution and virus, are closely related to each other through the atmosphere (Martins et al., 2020).

In Brazil, São Paulo city and its metropolitan area are known for the pronounced concentrations of air pollutants, mainly due to their numerous vehicular fleets (Andrade et al., 2017; Kumar et al., 2016; Leirião and Miraglia, 2019). The Metropolitan Area of São Paulo (MASP) comprises 39 cities, including the city of São Paulo, the largest city in South America and its approximately 14 million vehicles have the highest vehicle traffic density of the country, which corresponds to 13% of the Brazilian fleet (DENATRAN, 2020). According to estimates published in the latest report by the Environmental Company of São Paulo State (in Portuguese Companhia Ambiental do Estado de São Paulo) (CETESB, 2019a), the mobile sources generated about 97% of carbon monoxide (CO), 84% of hydrocarbons (HC), 64% of nitrogen oxides (NOx), 26% of particulate material (PM) and 17% of sulfur oxides (SOx) of the total MASP emissions. As a region with such a marked difference between pollutants such as CO and SOx, it is an important open-air laboratory suitable for assessing how environmental policies impact concentration of pollutants.

Naturally, the emissions in this open-air laboratory, represented by MASP, cannot be controlled for the purpose of study. However, due to the pandemic of COVID-19, there was a sudden forced and marked reduction in productive activities followed by a sharp drop in the mobility of people, as reported in many other major cities in the world (Venter et al., 2020; Wang et al., 2020). Many recent studies carried out across the globe have suggested a significant reduction in air pollutants concentration (Bao and Zhang, 2020; Collivignarellici et al., 2020; Copat et al., 2020; Dutheil et al., 2020; Lokhandwala and Gautam, 2020; Marques et al., 2021; Sharma et al., 2020). In China, the first country affected by the pandemic, an evaluation carried out for 44 cities demonstrated reductions in sulfur dioxide (SO2) (−6.8%), PM2.5 (−5.9%), PM10 (−13.7%), NO2 (−24.7%), and CO (−4.6%) (Bao and Zhang, 2020). In India, the study conducted by Sharma et al. (2020) evaluated the concentration for six different pollutants (PM10, PM2.5, CO, NO2, O3, and SO2) in 22 cities, observing significant reductions for PM2.5 (−43%), PM10 (−31%), NO2 (−18%), and CO (−10%). Similar behavior in reducing pollutants due to the pandemic was observed in Europe and the United States, where reductions were observed in the NOx concentrations (Berman and Eibus, 2020; Blumberg, 2020; Collivignarellici et al., 2020; Filonchyk et al., 2020; Sicard et al., 2020). In Brazil, the partial quarantine, with reductions in road traffic and industrial activities, has also led to a decrease in the levels of pollutants in large cities, mainly for CO and NOx (Connerton et al., 2020; Dantas et al., 2020; Nakada and Urban, 2020; Siciliano et al., 2020b).

The time-scale variability in pollutant concentrations is linked to the emission sources and the weather conditions that affect the dispersion and the long-range transport from other regions (Anderson et al., 2007; He et al., 2017; Martins et al., 2018). Studies carried out during the pandemic in other regions demonstrate the impact of meteorological variables on air quality, showing that it is impossible to assess changes in pollutant concentrations in a dissociated manner (Hörmann et al., 2020; Ordóñez et al., 2020; Petetin et al., 2020). Furthermore, in Brazil, an important factor that cannot be neglected are the fires outbreaks, which affect different regions of the country, changing the level of pollutant concentrations, even in large centers (Lopes et al., 2012; Martins et al., 2018; Pereira et al., 2011; Targino et al., 2019). In MASP, favorable conditions for the dispersion of pollutants were found before (February 25 - March 23) and during the partial quarantine (March 24 - April 20), which indicates that the observed reductions in pollutants, during the first weeks of the COVID-19 outbreak, were not determined by changes in the atmospheric conditions (Nakada and Urban, 2020). The comparison between the period before and during the partial quarantine demonstrated a decrease in the air pollutant concentrations. In urban centers, substantial emission reductions were observed for NO (−40.4%), CO (−29.9%), NOX (−25.5%), and NO2 (−21.5%) (Nakada and Urban, 2020). An exception was observed in the industrial areas, where high air pollutant concentrations occurred even in the quarantine (Nakada and Urban, 2020).

Although there have been several studies on the impact of mobility restrictions on the concentration of air pollutants, including those of São Paulo, the analyses were carried out in the wake of the novelty of the pandemic. This means that the studies undergo a lack of a deeper and more detailed analysis that considers temporal and spatial distribution, as well as the atmospheric conditions for the period. Therefore, this work’s main objective is to fill this gap and offer an analysis that puts the period under the influence of the pandemic restrictions in a broader context (space and time) and that considers the natural atmospheric dynamics characteristics. To achieve this objective, it was used a dataset from January to June for both years, 2019 and 2020, as well as historical data were used.

2. Methodology

2.1. Study area

The study area is the São Paulo State, which is the highest per capita GDP and population density in Brazil (IBGE, 2018) (Fig. 1). São Paulo State has one of the largest urban agglomerations worldwide, the Metropolitan Area of São Paulo (MASP). MASP is home to more than 21 million inhabitants and covers about 8000 km2, 2000 km2 composed of urban areas, making this region the most densely populated in the country (EMPLASA, 2019; IBGE, 2020), shown in Fig. 1. These characteristics make the area one of the most interesting to assess the impact of social distance measures, especially considering that Brazil is one of the countries most affected by the COVID-19. According to the Köppen climate classification, the State of São Paulo has eight climatic zones, which are divided into two groups, the Humid subtropical zones (67%) and the Tropical zones (33%) (Alvares et al., 2013). The primary sources of air pollution in São Paulo State are related to its fleet, more than 30.3 million vehicles (DENATRAN, 2020), and industrial processes. São Paulo State concentrates 36% of Brazilian industrial production, with one of the leading industrial hubs located in Cubatão (composed of petrochemical/chemical industries, fertilizers, paper, cement, and non-metallic minerals - about 300 sources of pollution) (Nakazato et al., 2015; Vieira-Filho et al., 2015).

The vast amount of vehicles contributes to air quality problems in this region, making it a local of several studies (Andrade et al., 2015, 2017, 2017; Bravo et al., 2016; Brito et al., 2018; Castanho and Artuxo, 2001; Costa et al., 2017a; Martins et al., 2017; Vilas Boas et al., 2018). In the 1930’s, the Brazilian government, through a decree, made mandatory the blend of ethanol fuel with gasoline. Also, in the 1970s, the Brazilian government began promoting bioethanol as a fuel, mainly due to the oil crisis. Afterward, this program continued to evolve to use ethanol only in ‘flex-fuel’ vehicles, which resulted in a significant reduction of some air pollutants (Brito et al., 2018; Salvo et al., 2017). Programs like PROCONVE (Motor Vehicle Air Pollution Control Program - Programa de Controle da Poluição do Ar por Veículos Automotores) and PROMOT (Air Pollution Control Program by Motorcycles and...
Similar Vehicles - Programa de Controle da Poluiç̄ão do Ar por Motociclos e Veículos Similares) also encourage manufacturers developing cleaner technologies to reduce air pollutants emissions (CETESB, 2018). The creation of these programs with the regulation of stationary sources was essential to reduce some concentrations of pollutants. However, as vehicle fleet increase is a national trend (CETESB, 2019b), air pollution remains an important study object in São Paulo State.

2.2. Data set

The data used in this study are ground-based hourly concentrations of PM$_{10}$, PM$_{2.5}$, CO, SO$_2$, NO$_x$, NO$_2$, NO, and O$_3$ for the historical data series since 1998 (period of the first measurements for some stations) until 2018, for 2019 (year of reference without social distancing restrictions), and for the period from January to June of 2020 (period including days before and during the COVID-19 restrictions in Brazil).

The ground-based concentrations were obtained from the CETESB air quality monitoring network (https://qualar.cetesb.sp.gov.br). For this study, we considered only automatic air quality monitoring stations. Nowadays, CETESB has 62 automatic stations distributed throughout the São Paulo State, of which 51 contained available data for the analyzed period (Fig. 2); information about the selected stations is available in table S1 (Supplementary Material). As most stations do not have measures of all pollutants (or present low-quality data), 39 stations for PM$_{10}$, 19 for PM$_{2.5}$, 25 for NO$_x$, 32 for NO$_2$, 21 for NO, 33 for O$_3$, and 14 for CO were used. Daily values were calculated based on hourly data for stations with at least 16 hourly data, as recommended by CETESB (2020).

To assess mobility behavior during the period of transition to the pandemic, we used data from the Apple company webpage (https://covid19.apple.com/mobility) through a document called “Mobility Trends Reports”. The data is obtained from aggregated and information...
of anonymous smartphone users information during their travels with the navigation function enabled. The reports show the percentage change in visits to places in a geographical area. These places are grouped into three categories: private vehicles, public transport, and walking. The daily percentage changes are calculated based on January 13, 2020, a reference date considered before the mobility effects of the pandemic.

We also evaluated rain and fires in the region to see how much atmospheric conditions may have favored cleaning or accumulating air pollutants. Precipitation values were calculated based on the automatic stations of the National Institute of Meteorology–INMET (https://portal.inmet.gov.br/). Data of the total active fires detected by satellites each month were provided by the National Institute for Space Research (INPE). The information can be downloaded in the following online database: http://queimadas.dgi.inpe.br/queimadas/portal-static/estatisticas_estados/. The daily data are available since the year 1998.

2.3. Analysis method

The Shapiro-Wilk test was used to assess normality in the data. As air pollutants behave as non-parametric variables, as most environmental variables, the Mann-Whitney U test was used to determine whether there were differences between the measurements recorded in 2019 and 2020. Two periods were considered for 2019 and 2020: before (75 days from January 1 to March 15) and during (107 days from March 16 to June 30) the mobility restrictions imposed due to the COVID-19 outbreak. Most of the surface data used in this study are concentrated in urban and industrialized areas. The stations located in the countryside area, in general, more recent and do not have the measures of all pollutants. However, even if scarcer, this data’s presence was considered relevant for this study (see table S1 that provides information on the CETESB air quality monitoring stations). The expansion of the network of stations away from large urban centers is precisely a consequence of some field experiments suggesting the need to monitor pollutants far from the largest urban and industrial areas. Such experiments demonstrated that these regions are not free from urban pollution and can be impacted by the natural biomass burning and the thermoelectric plants of sugarcane bagasse, which are abundant in the countryside of the São Paulo State (Kawashima et al., 2020). These aspects are relevant to have a realistic assessment of how much the mobility restrictions imposed by the COVID-19 impacted the region’s air quality. Another aspect of great relevance is the long-range transport of pollutants from fires in central South America and the Amazon region (Martins et al., 2018; Targino et al., 2019). In this sense, the automatic air quality stations were grouped according to the economic vocation of the regions where they are located, as shown in Fig. 2. In addition to this grouping, the Hydrographic Units for Water Resources Management (HUWRMs) division was also maintained within each vocational unit. Somehow, HUWRMs are physically separated by their topography (Fig. 2), a physical barrier that should not be overlooked in air pollution studies.

3. Results and discussion

3.1. General behavior of ground-based data

13-day centralized moving averages were calculated to evaluate the annual pollutant cycle in all analyses due to the significant variability. In the graphs presented in the sequence of Figs. 3–10, the light gray area represents the interval between the minimum and maximum (considering the 13-day centralized moving average) values for the historical series. The dark gray line represents the average value for the historical series, while the blue and red lines represent the average for the year 2019 and the first six months of 2020, respectively. The vertical dashed black line indicates the 76th day of the year 2020 (03/16/2020), when the first social mobility restrictions began, particularly the suspension of classes at schools and universities (Siciliano et al., 2020a).

As expected, the highest values in the concentration of pollutants were observed in the region characterized by industrial vocation, where HUWRMs 2, 5, 6, and 7 are located. Discussions will focus on these four regions, which are best represented by the length of the data series and the number of the stations. The results for the other HUWRMs can be found in Table 1 and the figures S1 to S6 in the supplementary

![Fig. 3. ](PM10_concentration(μg/m^3_) for HUWRMs in the State of São Paulo. The light gray area represents the interval between the minimum and maximum. The dark gray line represents the average for the historical series; blue and red lines represent the average for the years 2019 and 2020, respectively. The vertical dashed black line indicates the 76th day of the year 2020 when the first restrictions were started. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
document. Although these regions have an industrial profile, the values vary both in intensity and in the behavior of the annual cycle.

The topography is an element that isolates these regions, which makes their characteristics the preponderant factor for the concentration of pollutants. The HUWRM 2 is characterized by the Paraíba River valley, which connects the two largest cities in Brazil, São Paulo, and Rio de Janeiro. The region is between two mountain ranges, Serra da Mantiqueira and Serra do Mar. In addition to high population density, it is an important industrial hub. The HUWRMs 5 and 7 are also industrialized, with the former located further inland, on the other side of the Serra da Mantiqueira concerning region 2, and the latter on the coast, between the Atlantic Ocean and Serra do Mar. While the HUWRMs 2 and 5 are more diversified, in HUWRM 7, the petrochemical, steel, chemical, and fertilizer sectors stand out, accounting for most of the national industry’s primary products. It is important to note that in the 1970s, means of communication came to consider the city of Cubatão, located in HUWRM 7, as the most polluted city in the world, calling it the “Valley of Death”, given the frightening environmental and health impact of resident populations in the area (Monteleone-Neto and Castillo, 1994). The town became a symbol of the negative consequences of the industrialization patterns in developing countries, which did not consider any pollution control measures (De Mello Lemos, 1998). In HUWRM 6, characterized by the MASP, most air quality stations capture vehicle traffic information, although it is highly industrialized in its

![Fig. 4. Same as in Fig. 3, but for PM$_{2.5}$ (μg·m$^{-3}$).](image1)

![Fig. 5. Same as in Fig. 3, but for CO (ppm).](image2)
surroundings. This region is also located between the Serra da Mantiqueira and Serra do Mar Mountains, but it is not part of the Paraíba Valley, being at a slightly higher altitude and with the somewhat lower adjacent mountain ranges. The individual behaviors of pollutants PM$_{10}$, PM$_{2.5}$, CO, SO$_2$, NO$_X$, NO$_2$, NO, and O$_3$ will be discussed below.

The information contained in Table 1 is strategic for understanding the impact of pandemic restrictions and assessing what is observed in Figs. 3–10. Table 1 presents the general behavior of the comparison between average pollutant concentrations for 2019 and 2020, considering the periods before and during the pandemic restrictions in 2020. It indicates (symbols) whether, in 2020, there was an increase or decrease compared to 2019 for the periods before (January 1 to March 15) and during (March 16 to June 30). The specific results of the Mann-Whitney U test can be seen in Table S2.

3.1.1. PM$_{10}$
PM$_{10}$ is the pollutant with the largest number of measurement stations in the State of São Paulo. Thus, it can provide a more complete spatialized view of the behavior of pollution in the study period, including information outside the industrialized region. The average annual concentrations of historical series for PM$_{10}$ in HUWRMs 2, 5, 6, and 7, were 25.7 [15.5–31.9], 34.8 [23.1–43.3], 38.8 [25.0–48.2] and 58.3 [36.6–74.1] µg·m$^{-3}$, respectively. The bracketed intervals represent the interquartile range. Notably, HUWRM 7 has a history of the

Fig. 6. Same as in Fig. 3, but for SO$_2$ (µg·m$^{-3}$).

Fig. 7. Same as in Fig. 3, but for NO$_X$ (ppb).
highest average concentration of this pollutant and does not show seasonality in concentrations (Fig. 3). It is precisely the region highly impacted by industry, especially petrochemicals, as described above. For the other regions, the annual cycle is very well defined, with the minimum values being recorded in the summer months (rainy season) and maximum values in the winter months (drier), as already observed in previous studies (e.g., Martins et al., 2017). The high recurrence of thermal inversion events in São Paulo city in the winter months plays an important role in episodes of high particulate matter concentration (Freitas et al., 2007). Besides, the resuspension of soil dust is responsible for most of the coarse particle mass (Andrade et al., 2017; Castanho and Artaxo, 2001). This characteristic is also observed for HUWRM 7, but in this case, the fertilizer factories and the soil resuspension represent about 70% of the coarse particle mass (Kerr et al., 2001).

Concerning the first six months of the year 2019 and 2020, it was observed that the PM$_{10}$ concentrations are significantly below the average values of the historical series. According to recent studies, all regions analyzed in this study have shown reduction trends for most pollutants in 2020, mainly due to the adoption of more strict policies to control emissions (Andrade et al., 2017; Carvalho et al., 2015). No significant differences (p-value > 0.05) were observed between the years 2019 and 2020 for the first period (Bef.) for most of the stations (Table 1). However, the year 2020 presents slightly lower concentrations (Fig. 3). Average concentrations in 2019 were 16.9, 21.2, 22.6, and...
37.0 μg m⁻³ for HUWRMs 2, 5, 6, and 7, respectively, and 15.1, 20.4, 20.1, and 33.8 μg m⁻³ for the same regions in 2020. In the period following the beginning of restrictions due to the pandemic (Dur.), there is no significant difference for most monitoring stations (Table 1). The average values in 2019 were 21.6, 32.9, 30.9, and 40.4 μg m⁻³ for HUWRMs 2, 5, 6, and 7, respectively, and 21.4, 32.0, 28.7, and 47.8 μg m⁻³ for the same regions in 2020. An exception to this behavior was HUWRM 7, where the difference was statistically significant with higher average concentrations in 2020 following the seasonality, the period before the average concentrations in 2020 (Dur. period), as already mentioned in HUWRM 7, where the difference was statistically significant with higher average concentrations. In 2019, average concentrations of PM₂.₅ were 12.0, 17.9, 18.1, and 16.5 μg m⁻³ for the HUWRMs 2, 5, 6, and 7, respectively, and 12.0, 13.9, 15.6, and 13.6 μg m⁻³ for the same regions in 2020. It is observed that this evident reduction in the concentration of PM₂.₅ for 2020, which was not observed for PM₁₀, is consistent with the observations of Sharma et al. (2020), which attributes this behavior to a more significant contribution of anthropogenic sources to the concentrations of PM₂.₅, mainly industrial and vehicular emissions (burning of fuels) (Alves et al., 2015; Pereira et al., 2017).

In this context, it is important to mention that until November of 2018, Brazil had no legislation establishing maximum limits for PM₂.₅ (currently legislated by CONAMA n° 491/2018) (CONAMA, 2018). Thus, there are few air quality stations in the country capable of carrying out PM₂.₅ measurements. Besides, when available, these stations bring only recent measures, which prevents an adequate assessment of the behavior of pollutant during the pandemic period concerning previous years.

Another relevant aspect for the context of this study is the use of in natura biomass as a fuel. According to some studies, the domestic use of wood for cooking or heating is usually reported as an important source of pollutants. Unlike other countries, especially in the northern hemisphere, the use of heating is almost non-existent in Brazil, mainly because there are only a few days in the year when the temperature gets closer to 0 °C (Alvares et al., 2013). On the other hand, the use of firewood and charcoal for pizzerias, restaurants, and steakhouses is...
9

years, there has been a reduction in this agricultural practice, mainly (El Chami et al., 2020; Tsao et al., 2012; Uriarte et al., 2009). Over the increasing concentrations of pollutants associated with fires (e.g., pre-harvest burning practiced has demonstrated a significant impact in (Rudke et al, 2019, 2021). Mostly in sugar cane plantations, the management of cultivated areas, especially in the interior of the S during (March 16 to June 30) the COVID-19 outbreak.

Table 1

Mann-Whitney U test results compare average daily concentrations between the years 2019 and 2020, considering the period before (January 1 to March 15) and during (March 16 to June 30) the COVID-19 outbreak.

| HuWRM   | Station name                        | PM$_{10}$ | PM$_{2.5}$ | NO$_x$ | NO$_2$ | NO | SO$_2$ | CO | O$_3$ |
|---------|-------------------------------------|-----------|------------|--------|--------|-----|--------|-----|-------|
| 2       | Guaratinguetá                        | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | NA     | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | NA     | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | NA     | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | NA     | ↓   | NA    |
| 5       | Campinas-Centro                     | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
| 6       | Capão Redondo                       | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
| 7       | Cubatao-Centro                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
| 10      | Sobeica                            | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
| 13      | Araquara                            | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
| 15      | Catanduva                          | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
| 19      | Araçatuba                          | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
| 21      | Marília                            | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |
|         |                      | ↓         | NA         | NA     | ↓      | ↓   | ↓      | ↓   | NA    |

Legend: Bef. Before the period of the pandemic restrictions; Dur. During the period of the pandemic restriction; ↓ Statistically different and lower concentration at a monitoring station in 2020 concerning 2019; ↑ Statistically different and higher concentration at a monitoring station in 2020 concerning 2019; = Monitoring station without statistically significant differences in the concentrations for 2019 and 2020; NA, not available data.

considerable in São Paulo (Kumar et al., 2016; Lima et al., 2020; Vieira-Filho et al., 2013). Vieira-Filho et al. (2013) indicate that approximately 7.5 ha of eucalyptus forest in the State of São Paulo are used as firewood per month by pizzarias and steakhouses. Besides, Kumar et al. (2016) suggest that 3% of atmospheric emissions at MASP are related to fuelwood burning by pizzarias. Another important factor is associated with land use and land cover in the region and the management of cultivated areas, especially in the interior of the São Paulo State (Rudke et al., 2019, 2021). Mostly in sugar cane plantations, the pre-harvest burning practiced has demonstrated a significant impact in increasing concentrations of pollutants associated with fires (e.g., smoke, inhalable particulate matter, and total suspended particulates) (El Chami et al., 2020; Tsao et al., 2012; Uriarte et al., 2009). Over the years, there has been a reduction in this agricultural practice, mainly due to sanctions from regional governments seeking to gradually encourage farmers to reduce fires (Tsao et al., 2012). Even so, more than half of the sugar cane cultivation areas continue to be burned in São Paulo State (Rudorff et al., 2010).

3.1.3. CO

CO is the most restrictive pollutant for a spatialized approach to behavior during the pandemic since from 14 stations that measure CO, most of them (12) is located in the MASP (HUWRM 6) and only two outside. The annual average and the interquartile range of CO concentrations in HUWRMs 2, 5 and 6 were 0.34 [0.22–1.3], 1.0 [0.7–5.6], and 1.2 [0.7–5.2] ppm, respectively. The highest concentrations are observed in HUWRM 6, in which mobile sources are responsible for 97% of their emission (CETESB, 2019a). According to CETESB, light vehicles
are the main source of carbon monoxide emissions (63%) in the region. For the other HUWRMs, there is also a greater contribution from mobile sources (for HUWRM 5 and 72% for HUWRM 2) (CETESB, 2019a).

Fig. 5 shows that the CO concentrations for the years 2019 and 2020 are below the average concentrations in the historical series, as observed for HUWRMs 5 and 6, which have long-time series. This behavior is directly related to reducing emissions from new light vehicles, in compliance with the PROCONVE and PROMOT phases (Andrade et al., 2017). However, this trend could not be seen in recent data as in HUWRM 2, where the measurements started in 2015. The efficiency of vehicular emissions control policies seems to have reached its maximum.

In all regions, statistically significant differences were observed between the average values for the period before 2019 and 2020 (p-value <0.05). 2019 observed average concentrations were 0.15, 0.65, and <0.05). 2019 observed average concentrations were 0.15, 0.65, and <0.05). For the other HUWRMs, there is also a greater contribution from mobile vehicles ( Andrade et al., 2017 ).

3.1.4. SO2

For NOX emissions, the concentrations are substantially below the historical average for HUWRM 6, a region with long data series. This reduction is related to the PROCONVE phases, which significantly restricted vehicles’ NOX emission limits ( Andrade et al., 2017 ). As for the first period of 2019 and 2020, concentrations were remarkably close for HUWRMs 2 and 7, higher values for 2020 in HUWRM 5, and lower values for 2020 in HUWRM 6. The significant increase for the first period of 2020 compared to the same period in 2019 was observed only for the Santa Gertrudes station at HUWRM 5, located in an industrial hub of the ceramic sector. It should be noted that the last months of 2019 were favorable for the ceramic industry since the civil construction sector reached the highest level of economic activity in comparison to previous years (CNI, 2019). In the first months of 2020, the civil construction sector performance maintained the high growth standards observed for the end of 2019.

During the restricted period, significant reductions in NOX concentrations were observed for most stations. On the other hand, increases in concentrations were observed, only in Santa Gertrude (HUWRM 5) and Cubatao-Vila Parisi (HUWRM 7). The concentrations were sufficiently high to change the average value trend in these regions. The 2019 average concentrations were 16.6, 21.1, 45.0, and 75.8 μg m⁻³ for HUWRMs 2, 5, 6, and 7, respectively (CETESB, 2019a, 2019b). The increase in NOX concentrations in these regions has been observed over the last few years in the CASP due to the limits adopted for vehicle emissions. However, the 2020 decrease may be related to the mobility restrictions imposed by COVID-19 since the reductions observed for the period are greater than those expected due to the implementation of a control policy. In this case, a decrease in the traffic was evident after the restrictions started due to the pandemic.

It should also be noted here that some international factors, but mainly a favorable condition for the appreciation of soy exports, may have stimulated the demand for fertilizers, whose sales peak in April and May (IEA, 2015). In this case, orders for the fertilizer industry will likely be placed sometime earlier, thus coinciding with the beginning of the restrictions due to the pandemic and directly impacting the NOX emissions in the Vila Parisi station, next to the petrochemical and fertilizer production. It is worth remembering that 100% of the ammonium nitrate consumed in Brazil is produced in this industrial hub.

For NO2 the annual average and the interquartile range of NO2 concentrations observed for HUWRMs 2, 5, 6, and 7 were 19.2 [13.4–23.9], 21.6 [14.4–29.1], 50.1 [36.3–61.4], and 33.4 [24.3–41.1] μg m⁻³, respectively. HUWRM 6 has the highest average concentrations recorded for the historic period. Like CO, NO2 is considered an important traffic marker (Costa et al., 2017b).

Except for HUWRM 7, in other HUWRMs, it is observed that the concentrations for 2019 and 2020 are below the average values of the historical series, demonstrating a reduction in NO2. There was a statistically significant difference for the first period of 2019 and 2020, especially in HUWRMs 2 and 6 (Fig. 8 and Table 1). In the period...
following the beginning of the restrictions, a significant difference was observed in almost all regions. In 2019, the averages found were 17.8, 22.9, 36.8, and 40.9 μg m⁻³ for HUWRM 2, 5, 6, and 7, respectively, and 14.0, 20.7, 29.1, and 44.0 μg m⁻³ for the same regions in 2020. An increase was observed for the Cubatão region, mainly due to high concentrations measured at the Cubatão V.Parisi station. Even during the period with mobility restrictions, the Cubatão station registered a daily average of 85.6 μg m⁻³ (March 19, with a maximum hourly average of 124 μg m⁻³), probably due to its intense industrial activity, as discussed previously for the NO₃ behavior.

For NO₂ the annual average and their interquartile range concentrations in HUWRMs 2, 5, 6, and 7 were 8.4 [1.9–9.5], 7.9 [2.3–10.3], 49.9 [19.2–63.6], and 96.7 [59.0–126.4] μg m⁻³, respectively. The highest concentrations in the historical series were observed for HUWRM7, specifically at Cubatão V.Parisi station, and for HUWRM 6, as observed for NOx and NO₃.

In the case of NO concentrations, most stations showed significant reductions in the first period of 2020 compared to the previous year (Fig. 9 and Table 1). On the other hand, significant increases in NO concentrations were observed at Cubatão V.Parisi, Sorocaba, and Santa Gertrudes stations. Average concentrations of 2.3, 5.3, 21.1, and 64.8 μg m⁻³ were observed in 2019 for HUWRM 2, 5, 6, and 7, respectively, and 1.9 23.8, 12.8, and 70.9 μg m⁻³ for the same regions in 2020. During the restricted period, a significant reduction was also observed in most stations. Significant increases were observed only for Cubatão V.Parisi and Santa Gertrudes stations, as already mentioned for NOₓ and NO₂ pollutants. The concentrations measured in 2019 for HUWRMs 2, 5, 6, and 7 were 7.2, 14.5, 31.0, and 96.4 μg m⁻³, respectively, and 5.3, 28.2, 20.9, and 138.7 μg m⁻³ in 2020. Therefore, when comparing the pandemic period with previous years, the concentrations suggest significant variations, increasing or decreasing, depending on the region of study and location of the stations.

3.1.6. O₃

The historical average and the interquartile range of O₃ concentrations in HUWRMs 2, 5, 6, and 7 were 34.2 [24.6–42.3], 42.8 [31.0–53.1], 34.4 [24.3–43.2], and 25.1 [17.3–31.8] μg m⁻³, respectively. The highest concentrations of O₃ were observed in HUWRM 5, where high concentrations are associated with emissions of ozone precursors from fixed and mobile sources and the chemical regime (VOCs-limited or NOₓ-limited). Modeling studies carried out in the metropolitan region of Campinas, the location with the highest average concentrations, indicate that the meteorological conditions in the region, associated with the topographic characteristic, are related to the low dispersion of ozone and precursors and favor transportation from the metropolitan region of São Paulo (Boia and Andrade, 2012). HUWRM 6 also has high concentrations, mainly related to vehicular emissions of NOₓ and VOCs, impacted by the type of fuel used (high ethanol content) and the age of their fleet (Alvim et al., 2018).

In contrast to the other pollutants, O₃ concentrations for 2019 and 2020 are above the average values of the historical series, showing a trend of increasing (Fig. 10). When comparing the first period of the years 2019 and 2020, lower average concentrations are observed for 2020, but with a non-significant difference (p-value > 0.05) for most stations. Average concentrations observed for the first period of 2019 were 40.8, 47.3, 42.1, and 29.3 μg m⁻³ for HUWRMs 2, 5, 6, and 7, respectively, and 36.1, 41.4, 37.3, and 25.8 μg m⁻³ for the same regions in 2020. In the restricted period, significant increases in O₃ concentrations were observed in most stations, especially those at MASP (HUWRM 6). HUWRMs 2, 5, 6, and 7 showed average concentrations during the restrictions period, respectively, of 33.5, 36.1, 32.1, and 19.8 μg m⁻³ in 2019, and 31.3, 36.5, 37.8, and 25.0 μg m⁻³ for the same period in 2020. The increases in O₃ concentrations in HUWRM 6 are strictly related to reductions in NOₓ concentrations (Nakada and Urban, 2020; Orlando et al., 2010) since in MASP, as in several other large urban areas in the world, the chemical regime is usually VOC-limited (Andrade et al., 2017; Martins and Andrade, 2008). This behavior has already been evaluated through simulations carried out for the region (Alvim et al., 2018; Orlando et al., 2010), as well as it was observed in other areas during the outbreak of COVID-19 (Collivignarelli et al., 2020; Sharma et al., 2020; Sicard et al., 2020; Siciliano et al., 2020b; Wang et al., 2020).

3.2. Mobility and social distancing

3.2.1. Introduction

Fig. 11 shows the evolution of the trend of displacement of cell phone users during the first half of 2020, whose movements were grouped into travel by private vehicles, public transport, and walking. The percentage shown in Fig. 11 is relative to the volume of displacement on January 13, 2020, when the effects of pandemic were non-existent in the State of São Paulo. Although they are a non-representative sample of society, since it considers users of a specific device, it is robust and capable of identifying trends in changing displacement patterns of people.

Fig. 11 shows an increasing trend in displacement as of February, which coincides with Brazil’s summer school holidays ends. From 14 to February 16, there is also a marked increase in the circulation of people on foot, which coincides with a date called “pre-carnival”, an occasion when crowds go to the streets to dance. The graph clearly shows that it is a weekend completely different from the others and that, instead of a normal decreasing, there is an increase in the number of people walking. The increase in the number of vehicles is also evident, just as the decrease in public transport is not so marked. On the weekend following the “pre-carnival”, which is a little longer, the traditional carnival party occurs from February 21 to 24. It is interesting to note the opposite behavior for the “pre-carnival” time, where there are no festive activities on the streets of the cities of the State of São Paulo, so different of what happens in coastal towns in northeastern Brazil, where many people go to streets during the carnival. In São Paulo, during this festival, the people prefer to stay at home or travel to other locations, including those with the street carnival. From March 16 to 22, there is a sharp drop in mobility of the people due to some restrictions to contain the pandemic, such as closing schools and universities and canceling public events (Siciliano et al., 2020a). During this period, there was a constant reduction in displacement, which reached an average decrease of more than 50% in relation to the reference date (January 13). From March 23 to April 03, a Partial lockdown occurred. Some other restrictions have been applied, such as closing shopping centers, restaurants, bars, beaches, and all the non-essential business and substantially reducing public transport. There was an average reduction of more than 60% during those days, reaching a decrease of more than 70% in driving and 80% in public transport displacements. The period from April 4 to June 30 is considered a “relaxed” partial lockdown; because, during those days, many of the closed shops have reopened, but with reduced opening hours. Even with relaxation in restrictions, the reduction in the displacements remained below those registered for the reference date, with an average decrease of 60% for driving and 76% for public transport.

3.3. Atmospheric conditions

The general conditions of atmospheric circulation play an important role in the concentration of pollutants (Martins et al., 2018; Petetin et al., 2020; Targino et al., 2019). For the study region, precipitation and long-distance transport conditions undergo considerable variations from one year to another. They can amplify or even completely cancel the effect of the pandemic restriction on air quality. This is especially true for precipitation, which has a high capacity for cleaning the atmosphere. The wet deposition is considered an important pathway for removing several air pollutants (Guo et al., 2014; Pan et al., 2017; Yoo et al., 2014). Yoo et al. (2014) indicate that scavenging of air pollutants is directly related to rain intensity. The authors also suggest that precipitation is especially associated with PM removal, followed by SO₂, NO₂, CO, and O₃.
By comparing the variation of the atmospheric pollutant concentrations (Figs. 3–10) and the precipitation data (Figure S7), the importance of the rain scavenging in the region is clear. The rainy season (October to March) is the period with the lowest concentrations of pollutants. In contrast, the dry season (April to September) is the period with the highest concentration of pollutants. For the first 45 days of 2020, the period with the most significant differences in the average concentrations for PM$_{2.5}$, the accumulated rainfall was significantly higher than the previous year (266.2 mm in 2019 and 415.5 mm in 2020) for the State of São Paulo. On the other hand, in March, coinciding with the beginning of the restrictions resulting from the pandemic, there was a significant decrease in precipitation, which lasted through April and May, potentially contributing significantly to the increase in the concentration of pollutants. A more detailed analysis can be found in the supplementary materials (Figures S7 and S8). For all stations with available data, it is confirmed that the absence of rain contributes significantly to the increase in the concentration of pollutants. A more detailed analysis can be found in the supplementary materials (Figures S7 and S8). For all stations with available data, it is confirmed that the absence of rain contributes significantly to the increase in the concentration of pollutants. A more detailed analysis can be found in the supplementary materials (Figures S7 and S8).

In addition, the absence of rain is directly related to the increase in the number of fire outbreaks. Although the maximum number of fires in the region occurs in the second half of each year, which is outside the study period, a few persistent fires are enough to disturb the pollutants concentration measured by an air quality monitoring network. There were more than 250 fire outbreaks in each month during the months of April and May in 2020, about three times the values observed for the same period in 2019 (Fig. 12), which are expected to have a measurable impact on the region.

Fires play an important role in changing the level of pollutant concentrations in the region (Lopes et al., 2012; Martins et al., 2018; Pereira et al., 2011; Targino et al., 2019). In 2020, this became evident by comparing the period before and during the pandemic, considering only days without rainfall events (Table S3). The results show that even in a period with reduced vehicle traffic (Fig. 11), there is a significant increase in pollutant concentrations, especially in the interior of the State (Table S3). Comparing the period during the pandemic and before for HUWRM 6, no significant changes are observed in most stations, especially for CO and NO$_2$ pollutants (pollutants related to vehicular transport), demonstrating a low impact of mobility restrictions when the entire period is analyzed.

The importance of fires in the air quality of the region is evident when we analyze the results in Fig. 12; there is a substantial increase in fires in the region, whose emissions could be transported to the areas where the monitoring stations are located (Figure S9). An example of such an assertion can be seen when analyzing particulate matter concentrations for the Itaim Paulista station, the station with the largest increases in PM$_{2.5}$ concentration during the pandemic. The highest concentrations of 2020 recorded in the station were observed from May 30 to June 2. In the same period, approximately 10% of the fire outbreaks of 2020 were registered in the São Paulo State, playing an important role in worsening the air quality of the region (Figure S9 shows the direction of the trajectories and the location of the fire outbreaks). This demonstrates the impact that pollutant transport has on the region, especially that related to the biomass burning emissions, which reached record levels in 2020 (Tomazela, 2020), even during the pandemic period.

Fig. 11. Evolution in the displacement of cell phone users during the first half of 2020. The vertical dashed line indicates the 76th day of the year 2020 when the first restrictions were started.

Fig. 12. Monthly number of fire outbreaks for 2019 (blue bars), 2020 (red bars), and historical average (2003–2018) (gray bars) for the State of São Paulo. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
4. Conclusions

This study evaluated the behavior of pollutant concentrations for the Metropolitan Area of São Paulo and its neighboring under the effects of the COVID-19 pandemic restrictions. In addition to historical averages, we compared the behavior of 2019 with the before and during mobility restrictions periods of 2020 for the main pollutants of interest for air quality studies. The region of the study was divided into sub-regions to facilitate the understanding of the behavior of pollutants. The area of interest can be understood as a nucleus influenced mainly by vehicular emissions but surrounded by predominantly industrial emissions and influenced by long-range transport. The main findings of this study are:

1) For most of the analyzed pollutants, there was no substantial reduction in the pollutant concentration for the period of COVID-19 restrictions compared to the before period months of 2020;
2) The few stations where significant reductions were observed are in the central core of the study region, which is the most impacted by vehicular emissions, with a decrease in primary pollutants CO and NOx and an increase in O3;
3) Compared to historical averages, 2019 and the months analyzed for 2020 showed significant reductions in pollutant concentration for most stations, mainly resulting from public policies to control emissions. However, this generalized reduction was not reflected in O3;
4) Some stations located in peripheral industrial areas showed an increase in the concentration of pollutants for 2020 compared to 2019, which may be associated with the specific industrial activities around those stations. The beginning of the pandemic may have coincided with the time of increase in some specific industrial activities; the pandemic may also have impacted the demand from some industrial sectors;
5) Despite being the rainy season, it was observed that precipitation was much above average in the period January to March 2020 and below average after the COVID-19 outbreak. During the dry season (fall and wintertime) the precipitation decreased, and as a tendency, the concentrations increased following the seasonality behavior. The rainfall above (below) the average before (after) the beginning of the pandemic restrictions promoted a reduction (increase) in the concentrations for the months before (after) the beginning of the pandemic in 2020 in comparison to the same period of 2019;
6) Above the average number of fire outbreaks in the months following the start of the pandemic restrictions may have impacted the study area and, together with abnormal rainfall distribution, prevent obvious evidence of improved air quality due to reduced human activities from the restrictions.

Finally, we suggest that any study focusing on analyzing the effects of the pandemic on air quality should consider the atmospheric conditions for the period. Neglecting such atmospheric contribution may produce misinterpretation of the results, especially when evaluating the effectiveness of emission control measures. Weeks with high volatile pollutant concentration alternated throughout the study period, suggesting that short analyses without considering seasonality can lead to misleading conclusions. The regionalization of the analysis is also fundamental for the adequate treatment of the different pollution sources, especially the vehicular and industrial, which are the dominant sources in the study region.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2021.111255.

Author statement

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