



São Paulo's atmospheric pollution reduction and its social isolation effect, Brazil

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Abstract

Since January 2020, studies report reductions in air pollution among several countries due to social isolation measures, which have been adopted in order to contain the coronavirus outbreak progress (COVID-19). This study aims to evaluate the change in the atmospheric pollution levels by NO and NO₂ in São Paulo City for the social isolation period. The NO and NO₂ hourly concentrations were obtained through air quality monitoring stations from CETESB, from January 14, 2020 to April 12, 2020. Mann-Kendall and the Pettitt tests were performed in the air pollutant time series. We observed an overall negative trend in all stations, indicating a decreasing temporal pattern in concentrations. Regarding NO, the highest absolute decrease rates were observed in the Congonhas ($-6.39 \mu\text{g m}^{-3} \text{ month}^{-1}$) and Marginal Tietê ($-6.19 \mu\text{g m}^{-3} \text{ month}^{-1}$) stations; regarding NO₂, the highest rates were observed in the Marginal Tietê ($-4.45 \mu\text{g m}^{-3} \text{ month}^{-1}$) and Cerqueira César ($-4.34 \mu\text{g m}^{-3} \text{ month}^{-1}$) stations. In addition, we identified a turning point in the NO and NO₂ series trends that occurred close to the start date of the social isolation period (March 20, 2020). Moreover, from statistical analysis, it was found that NO₂ is a suitable surrogate for monitoring economic activities during social isolation periods. Thus, we concluded that social isolation measures implemented on March 20, 2020 caused significant changes in the air pollutant concentrations in the city of São Paulo (as high as -200% in NO₂ levels).

Keywords Air pollution · NO₂ · Coronavirus outbreak · COVID-19 · São Paulo

Introduction

The population increase in urban centers causes serious environmental problems, among which the degradation of air quality stands out due to the emission of air pollutants by internal combustion engines (Aleixo and Neto 2009; Cetin et al. 2019). Such air pollutants may come from either mobile or stationary sources. It is noteworthy that in highly urbanized regions, such as the São Paulo Metropolitan Area (SPMA), the main source of air pollutant emissions is the vehicle fleet. According to the official emission inventory, SPMA mobile sources in 2017 were responsible for 97% of carbon monoxide (CO) emissions, 75% of hydrocarbons (HC), 64% of nitrogen

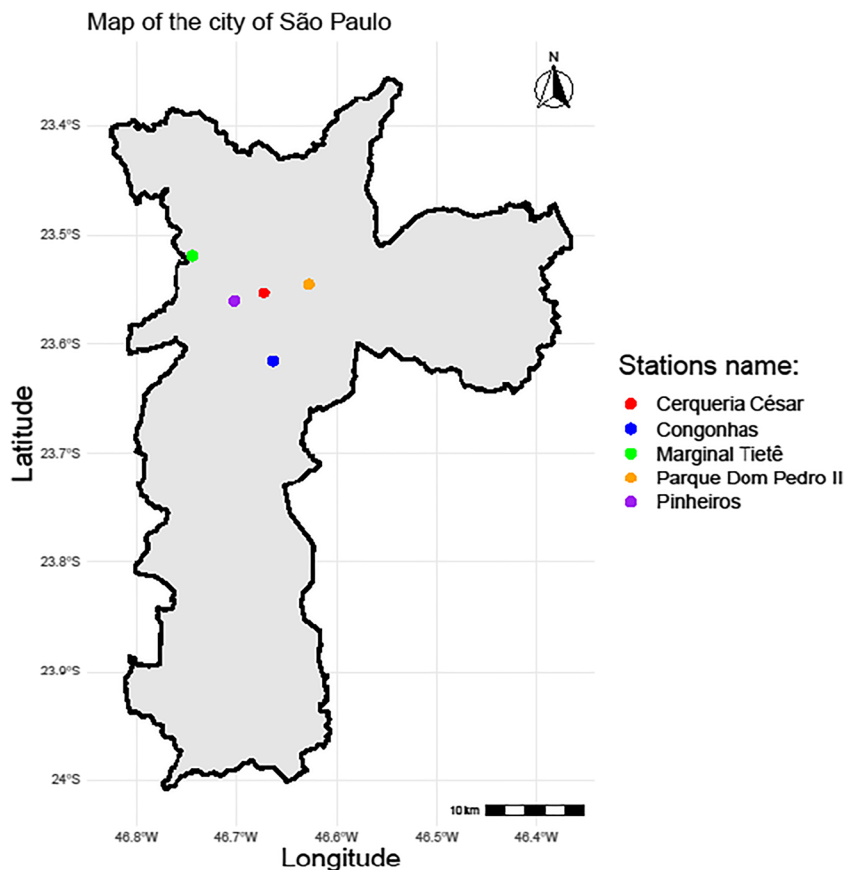
oxides (NO_x), 17% of sulfur oxides (SO_x), and 40% of particulate material (PM₁₀) to the atmosphere (CETESB 2020).

According to data from the World Health Organization (WHO), 91% of the world's population breathes polluted air (WHO 2016) causing thousands of deaths each year from illnesses including heart disease, lung cancer, stroke, and both acute and chronic respiratory diseases. The most affected polluted area in Brazil is São Paulo State which stems from its demographic features that possess almost 46 million inhabitants (IBGE 2019). From this total, almost 25% reside in São Paulo City, 1521 km² in area, correlated with the largest vehicle fleet in the country, exceeding 8 million vehicles (~90% light vehicles) (Dapper et al. 2016; Silva et al. 2017; Koga et al. 2020; Ministério da infraestrutura 2020). Given this perspective, the emission of NO (nitrogen monoxide) and NO₂ (nitrogen dioxide), which are pollutants derived directly from the burning of fossil fuels, stands out as major air pollutants in urbanized areas (Ribas et al. 2016). Regarding NO_x levels, NO₂ can also be formed in the atmosphere from chemical reactions of NO with oxidizing compounds, which implies higher concentrations of nitrogen dioxide in urban zones

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Fig. 1 Geographic delimitation of the study area (São Paulo municipality) and location of the stations used in the study



(Casqueiro-Vera et al. 2019; Yao et al. 2019; Zhang et al. 2020).

In early 2020, several nations adopted social isolation measures in order to contain the advance of the COVID-19 outbreak (cause by a novel coronavirus, SARS-CoV-2) (Andersen et al. 2020; Pelicioni and Lord 2019) containing high rates of transmission and contagion. Similar measures adopted in the city of São Paulo from the first half of March (Sanar Saúde 2020) lead to closures of universities, institutions, and a commerce lockdown in order to reduce contagion (São Paulo 2020). However, we should note that adherence to

isolation was not widespread and varied from one location to another in São Paulo City (Revista Veja 2020).

Social isolation caused a decrease in vehicular traffic and industrial activities, consequently changing the pattern in atmospheric pollutant emissions (Agarwal et al. 2020; Karuppasamy et al. 2020; Sharma et al. 2020). Recent studies found that carbon and NO₂ emissions in China reduced upon social isolation measures commencing (He et al. 2020). From this perspective, this study has the objective to evaluate the changes caused by the period of social isolation in relation to NO and NO₂ emissions in the city of São Paulo, in order to determine whether such measures were representative and mathematically significant.

Table 1 Geographic location of air quality monitoring stations and number and percentage of data available

Station	Longitude	Latitude	Code	<i>n</i>	%
Cerqueira César	−46.67	−23.55	91	86	95
Congonhas	−46.66	−23.61	73	90	100
Marginal Tietê	−46.74	−23.51	270	90	100
Parque Dom Pedro II	−46.62	−23.54	72	90	100
Pinheiros	−46.70	−23.56	99	89	98

n number of observations; “%” percentage of data available for the analyzed period

Data and methodology

Study region characterization

The municipality of São Paulo is located in the south-east portion (23.5477° S; 46.6336° W) of the state of São Paulo and has a territorial area equal to 1521 km² (Fig. 1). The population estimation in July 2019 for São Paulo classifies the municipality as the most populated in Brazil, with 12.25 million inhabitants (IBGE 2019;

Table 2 Results of statistical analyses (value of Sen and Pettitt) related to NO

Station	<i>n</i>	Value of Sen $\mu\text{g m}^{-3} \text{ month}^{-1}$	P1 (01/14–04/12)	P2 (03/01–04/12)
Cerqueira César	86	–2.60	02/26	03/21
Congonhas	90	–6.39	03/06	03/22
Marginal Tietê	90	–6.19	02/26	04/04
Parque Dom Pedro II	90	–1.59	02/29	03/21
Pinheiros	89	–3.19	03/20	-

All stations showed statistically valid trends after applying the MK test ($p < 5\%$)

n number of daily data for the period from January 12th to April 14th, 2020; P1 and P2 points of intervention found

Zeri et al. 2016). Economically, it presents a large industrial district, dominated mainly by food, chemical, and oil industries. Its vehicle fleets, in March 2020, were composed of 8.631 million vehicles, of which 5,902,755 (88%) were automobiles and 1,022,157 (12%) were motorcycles (Ministério da Infraestrutura 2020). It is important to highlight that a large part of the flow of vehicles in São Paulo segways neighboring cities in the so-called São Paulo Metropolitan Area (SPMA), increasing the number of vehicles and traffic jams. The SPMA vehicle fleets comprised 13,908,845 vehicles, of which 9,394,570 (68%) were automobiles and 4,514,275 (32%) were motorcycles, for the same period (INVESTSP 2020; Ministério da Infraestrutura 2020).

It is also worth mentioning that the region is surrounded by Serra da Cantareira and Serra do Mar, which reaches 700–1000 m elevation. In the summer, the South Atlantic Convergence Zone (SACZ) and the Mesoscale Convective Systems (MCS) are the driving force of precipitation and greater atmospheric instability. Due to a reduction of precipitation and the occurrence of thermal inversions, the atmosphere tends to acquire a greater stability in the winter, which causes the stagnation of atmospheric pollutants from industrial activities as well as the burning of fuels in the lower atmospheric layers and near the surface (Vieira-Filho et al. 2015; Segalin et al. 2016; Zeri et al. 2016).

Atmospheric pollutants (NO_x)

Data was retrieved from that of nitrogen monoxide (NO) and nitrogen dioxide (NO₂) from air quality monitoring stations operated by São Paulo environmental agency (CETESB, 2020) in hourly resolutions. For this study, we considered the period between January 14 and April 12 (2020), with a maximum number of 90 daily observations. We chose this 90-day period due to its proximity to a greater political uniformity in relation to political measures of social isolation. We selected the following air quality monitoring stations: Cerqueira César, Pinheiros, Congonhas, Parque Dom Pedro II, and Marginal Tietê as a result of the availability of measures. Information regarding each station is represented in Table 1.

Statistical analysis

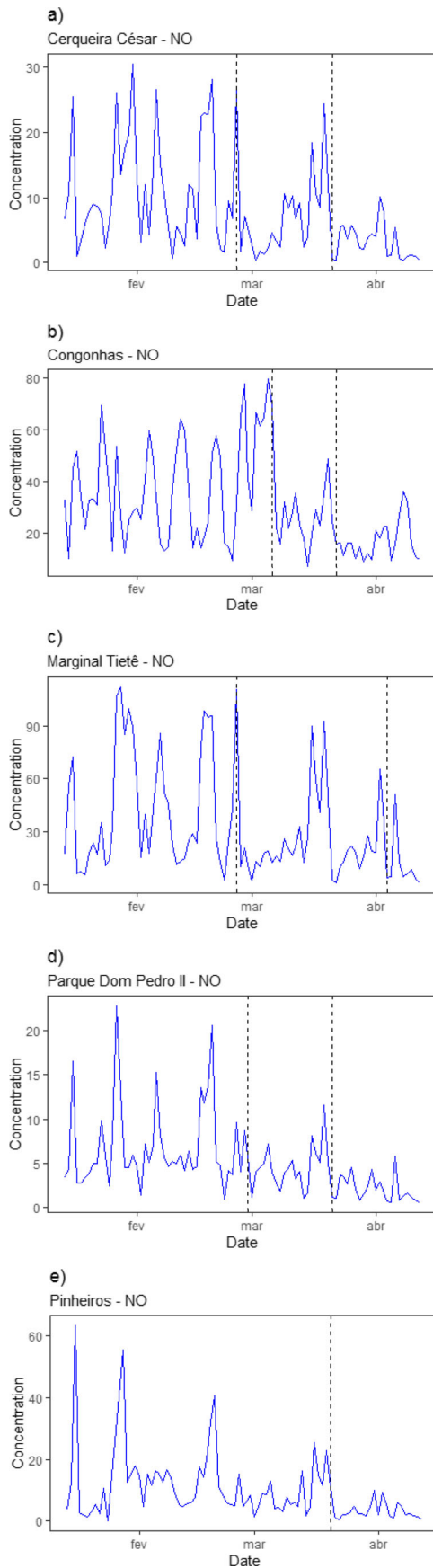
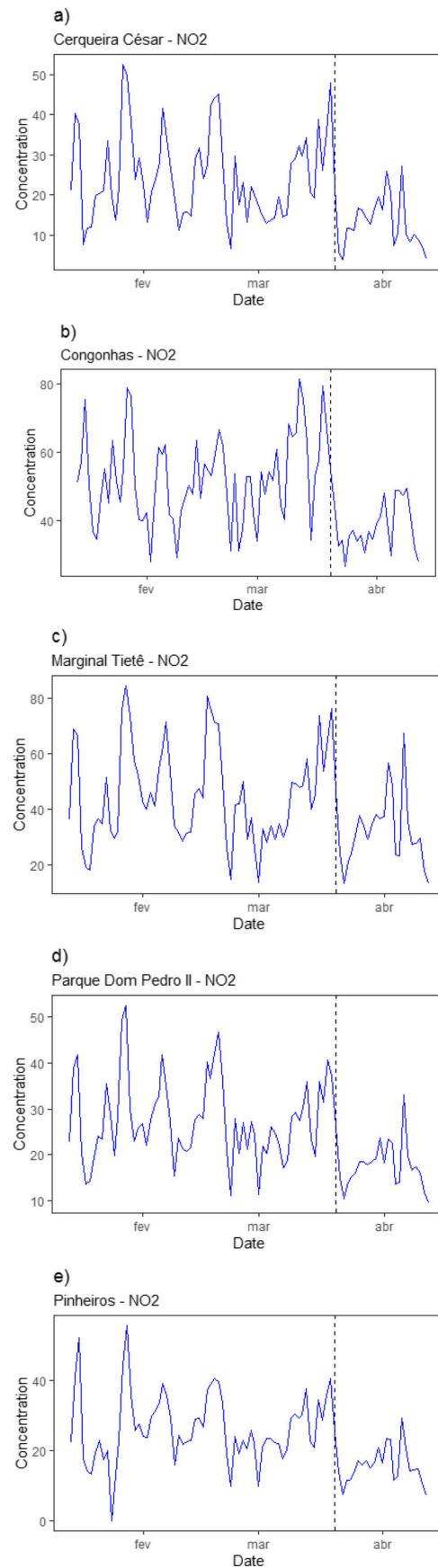
We performed the statistical treatment of the data with the use of programming in R language, through the RStudio interface, using the packages *openair* (Carslaw and Ropkins 2012), to manipulate the atmospheric data series; *lubridate* (Grolemund and Wickham 2011), to manipulate hourly and daily data; *trend* (Pohlert 2015), to perform the Pettitt's test; and *ggplot2* (Wickham 2016), to generate the graphics. From the data collected, we performed the following tests: Mann-Kendall, Slope, and Pettitt.

Table 3 Results of statistical analysis (value of Sen and Pettitt) related to NO₂

Station	<i>n</i>	Value of Sen $\mu\text{g m}^{-3} \text{ month}^{-1}$	P1 (01/14–04/12)	P2 (03/01–04/12)
Cerqueira César	86	–4.34	03/20	-
Congonhas	90	–3.78	03/20	-
Marginal Tietê	90	–4.45	03/20	-
Parque Dom Pedro II	90	–3.68	03/20	-
Pinheiros	89	–4.11	03/20	-

All stations showed statistically valid trends after applying the MK test ($p < 5\%$)

n number of daily data for the period from January 12th to April 14th, 2020; P1 and P2 points of intervention found

NO – Nitrogen monoxide (2020)**NO₂ – Nitrogen dioxide (2020)**

◀ **Fig. 2** Time series of daily mean NO (left) and NO₂ (right) concentration, in units of μg m⁻³, in the period between January 14th and April 12th, 2020. Note: the dashed vertical lines indicate the intervention points determined via Pettitt’s test

Mann-Kendall test

The Mann-Kendall (MK) test aims to identify trends in time series (Alashan 2020) and the test statistic is calculated according to:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \tag{1}$$

Here, $\text{sgn}(x_j - x_k)$ is equal to -1 for $x < 0$, $+1$ for $x > 0$, and 0 when $x = 0$ and the variance is calculated by Eq. 2:

$$\sigma^2 = \left\{ n(n-1)(2n+5) - \sum_{j=1}^p t_j(t_j-1)(2t_j+5) \right\} / 18 \tag{2}$$

Here, p is the number of the tied groups in the date set and t_j is the number of data points in the j th tied group. Following the Z-transformation in Eq. 3:

$$Z = \text{sgn} \left(\frac{S-1}{\sigma} \right) \tag{3}$$

Here the S is closely related to Kendall’s τ by Eq. 5:

$$\tau = S/D \tag{4}$$

where:

$$D = \left[\frac{1}{2}n(n-1) - \frac{1}{2} \sum_{j=1}^p t_j(t_j-1) \right]^{1/2} \left[\frac{1}{2}n(n-1) \right]^{1/2} \tag{5}$$

The null hypothesis, H_0 , in the MK test is that the data come from a population with independent realizations and are identically distributed. The alternative hypothesis, H_A , is that the data follow a monotonic trend.

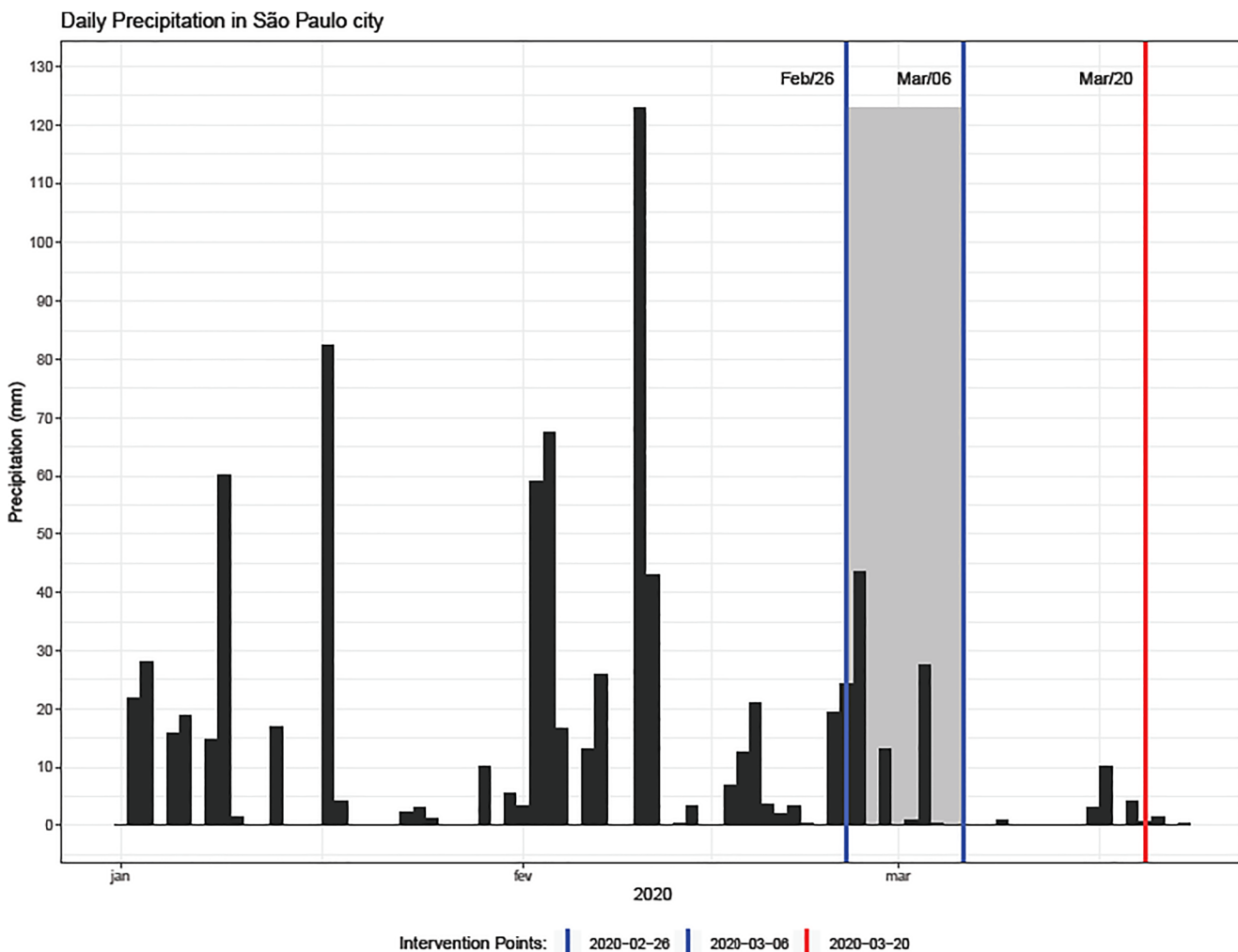
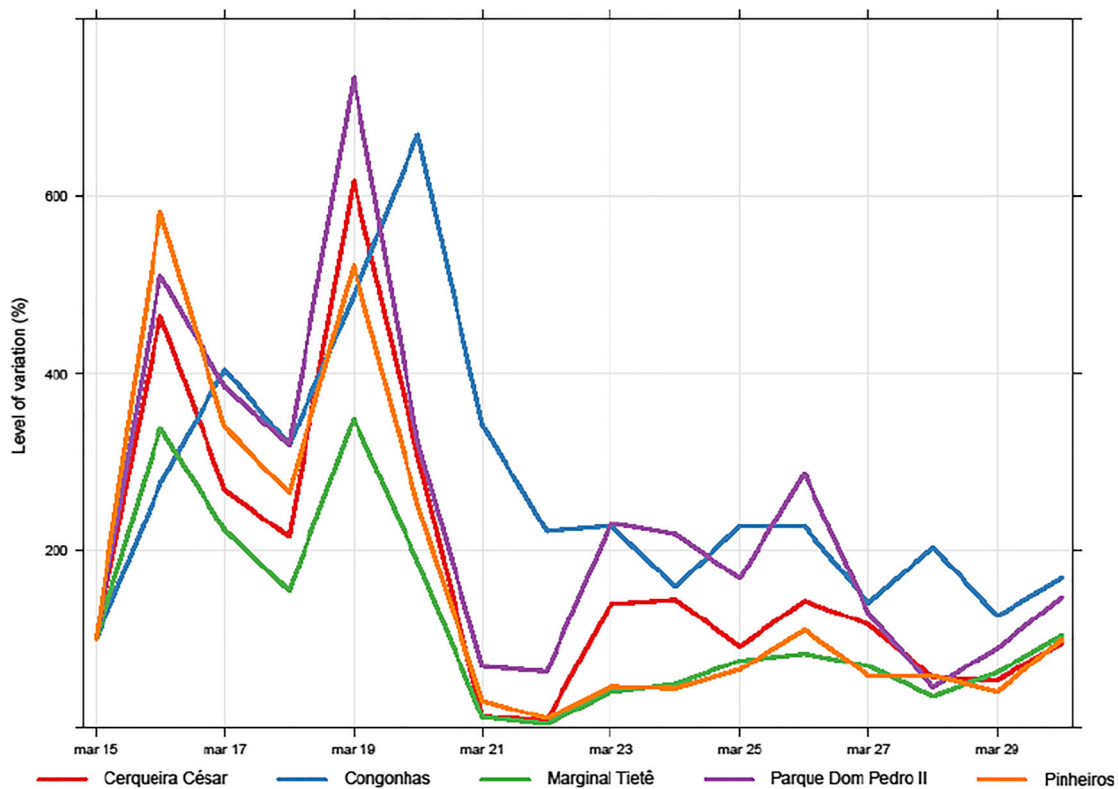
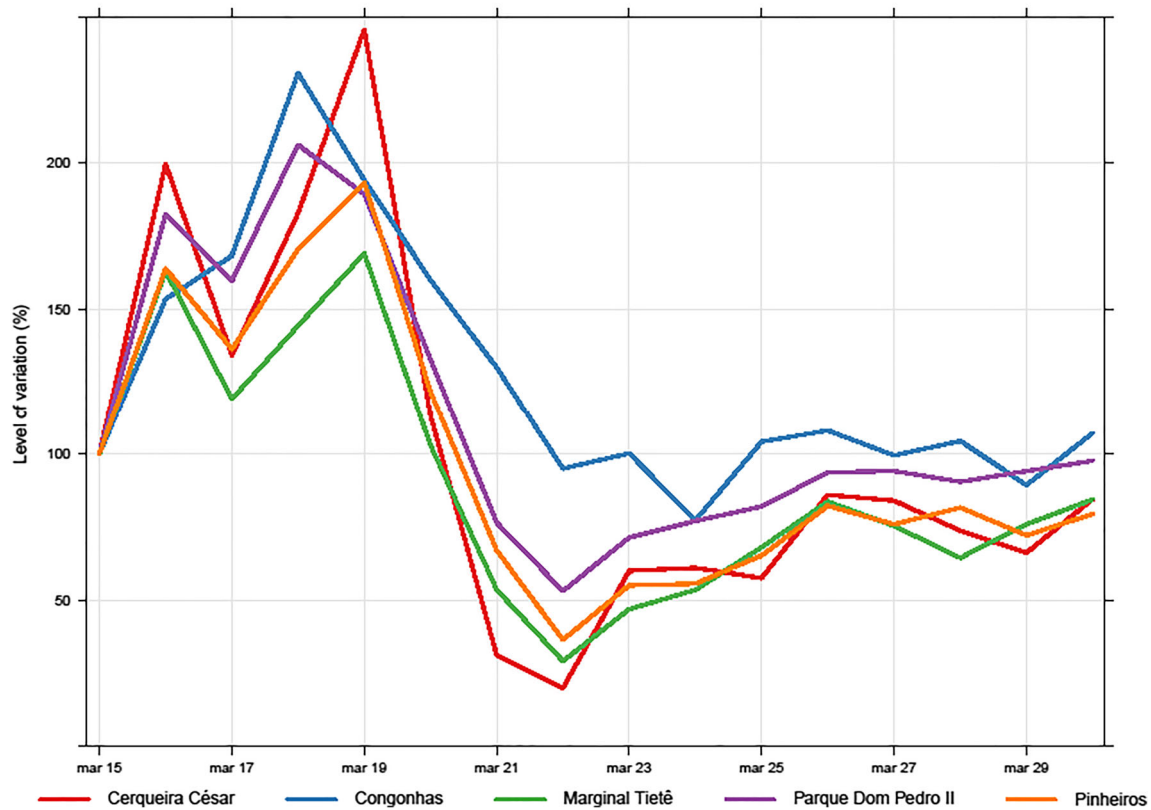


Fig. 3 Daily precipitation series in millimeters. The highlighted gray area is the range of intervention points observed at the stations analyzed for NO.

a) Percentage variation per station – NO

b) Percentage variation per station – NO₂

◀ **Fig. 4** Daily concentration percentage variation of NO (top) and NO₂ (bottom) in the period from March 15th to March 30th in 2020 at the stations Cerqueira César, Congonhas, Marginal Tietê, Parque Dom Pedro II, and Pinheiros

Sen's slope

Following the Mann-Kendall test, we determine the value of the slope (Eq. 5) with the Sen's slope (Pohlert 2015; Sen 1968; Salarijazi et al. 2012) equation:

$$d_k = \left(\frac{X_j - X_i}{j - i} \right) \quad \text{for } 1 \leq i < j \leq n \quad (6)$$

Here, X_i and X_j represent the values of the variable under study in positions i and j . And d_k is the slope and n is the number of observations.

Pettitt test

In order to identify discontinuity points in the data series, we have applied the Pettitt test (Diego and Neumann 2011, Pohlert 2015; Verstraeten et al. 2006):

$$U_k = 2 \sum_{i=1}^k r_i - k(n+1), \quad k = 1, \dots, n \quad (7)$$

The ranks r_i of the X_n are used to calculate the Pettitt statistic over a period of time. The test statistic is the maximum of the absolute vector value:

$$\hat{U} = \max |U_k| \quad (8)$$

The p value was calculated through the following equation:

$$p = 2 \exp^{-6K^2/(T^3)+T^2} \quad (9)$$

Here, K is the probable change point when Eq. 9 is fulfilled. The probable change point K is located where \hat{U} has its maximum (Eq. 9).

The null hypothesis was tested as of no sudden change in the series. In this study, we applied the Pettitt test in two periods: P1—complete time series (Jan 14th–April 12th) and P2—partial time series (March 1st–April 12th), in order to verify the point of sudden change. The purpose of this methodology was to verify if a significant intervention point is closer to the social isolation measures. If it was not, the Pettitt test is repeated for a more restricted period (P2).

Results and discussion

In order to verify trends in the nitrogen monoxide (NO) and nitrogen dioxide (NO₂) series, we applied the Mann-Kendall

and Pettitt tests to the five air quality monitoring stations. The results are presented in Tables 2 and 3.

From the data, we verified statistically significant trends in NO and NO₂ levels in all the analyzed stations, since they presented a p value of less than 5% in the MK test (Ahmad et al. 2015; Cukurluoglu and Bacanliu 2018; Folhes and Fisch 2006). Also, we calculated the value of Sen in order to verify the magnitude (growth/decrease) of the trend of the series (Chaudhuri and Dutta 2014) and we observed that the values of Sen, without exception, were all negative, which indicates decreased patterns from January to April 2020. These results suggest that the concentrations, in $\mu\text{g m}^{-3}$, of NO and NO₂ decreased during the period of Jan 14th–April 12th at the monthly rate presented by the third columns of Tables 2 and 3.

Moreover, columns “P1” and “P2” (Tables 2 and 3) show the intervention points determined by the Pettitt test (Salarijazi et al. 2012; Ferreira et al. 2015; Jaiswal et al. 2015; Ahmad et al. 2018; Penreiro and Meschiatti 2018; Gaponov et al. 2019) for each period. In order to visualize the decreasing trends (negative values of Sen) and the intervention points, we have constructed Fig. 2.

Regarding the intervention points for NO (Table 2), Pinheiros, Parque Dom Pedro II, Cerqueira César, and Congonhas stations presented changes in their trends near the quarantine start date (March 20th). Assuming that social isolation would cause a sharp decrease in vehicular flow in the municipality of São Paulo, it would be expected that intervention points were more significant in the second half of March, which is also verified by P1 dates from NO₂ (Table 3). NO₂ shows an even sharper change (Fig. 2) in comparison to NO. Although emitted together with NO₂, NO has a shorter residence time; however, both are major species in photochemical smog that culminates in NO₂ and O₃ species (Han et al. 2011; Salonen et al. 2019).

Although most intervention points were identified on dates closer to the quarantine start date, an opposite behavior was observed in the NO concentrations observed in Cerqueira César (February 26th) and Congonhas (March 6th) stations (Table 2). Several meteorological factors may/may not have been influenced by the earlier intervention points by the Pettitt test (before quarantine). Among them, we emphasize the high rainfall volume in the São Paulo City in February 2020 (496.7 mm), which is a 248% increase from the climatological value (200 mm, period 1981–2010) and also higher than the last 4 years (INMET 2020).

Among the implications of a high total rainfall is the increase of scavenging air pollutants by wet deposition (Shukla et al. 2008; Freitas and Solci 2009; Vieira-Filho et al. 2013; Yoo et al. 2014; Santos et al. 2019). Thus, given the high precipitation at the end of February, the NO concentrations were altered and, therefore, the identified intervention points were off in comparison to the social isolation period. In Fig. 3, we depicted the daily precipitation series for the studied

period, and we verified that the greatest precipitation period precedes the intervention points found for NO, which does not occur in the intervention points at the beginning of the period of social isolation (~ March 20th). Such behavior was due to meteorological influence, specifically the total rainfall in February.

A plot of the daily percentage variation of NO (Fig. 4a) and NO₂ (Fig. 4b) (Agustine et al. 2017; Silver et al. 2018) is depicted covering only from the period of March 15th to March 30th, highlighting the social isolation period (Koga et al. 2020).

From Fig. 4, sharp decreases were observed in NO₂ and NO levels in Cerqueira César and Marginal Tietê stations on March 19th and 20th. In this perspective, Cerqueira César station shows a reduction of –80% in NO₂ levels (Fig. 4b) and –92% in NO levels (Fig. 4a), compared to its average concentration on March 15th. Regarding Marginal Tietê station, we notice reductions of –70% and –96% in NO₂ (Fig. 4b) and NO (Fig. 4a) levels, respectively, for the same period. It is noteworthy that both stations (Cerqueira César and Marginal Tietê) are located in urban agglomeration points (urban terminals and bus lanes); moreover, Marginal Tietê station is located in the vicinity of main interstate roadway where heavy vehicles commute. Furthermore, Cerqueira César station is located in a high population zone with commercial centers, museums, theaters, and cultural institutions.

Preliminary Brazilian media (IPEN, 2020) studies showed an emphasis in the reduction of primary pollutant concentration levels during the social isolation period using satellite measurements for the SPMA area. Such studies reported reduction decrease by as much as –50%; however, analyzing the air quality data stations, we observe reductions in NO_x levels as much as –200% from March 19th to March 21th in Cerqueira Cesar. Figure 4 also highlights the sharp decrease in NO and NO₂ concentrations on March 20th, which is reasonable with Sen slope's values and also the intervention points (Tables 2 and 3). The difference between the reduction values determined by the satellite and those we calculate can be explained by shortcomings from satellite measurements, such as the level of resolution and specific information. Pettitt test, associated to Mann-Kendall test, indicated a downward trend as well as an anomalous behavior of the data daily series since the quarantine started.

Conclusion

São Paulo's air pollutant time series concentrations from the air quality stations showed sudden pattern changes, as a result of social isolation measures and greater political uniformity in the 90-day period from January until April 2020. Analyzing the NO and NO₂ levels from this period, we observed statistically significant negative trends within São Paulo, and the

highest absolute rates were observed in the Congonhas (–6.39 μg m³ month^{–1}) and Marginal Tietê (–6.19 μg m³ month^{–1}) stations for NO; and the Marginal Tietê (–4.45 μg m³ month^{–1}) and Cerqueira César (–4.34 μg m³ month^{–1}) stations for NO₂. Assuming NO₂ decrease rates of Marginal Tietê and Cerqueira César stations remain at a standstill until the end of 2020, the total pollution reduction will be above 9500 tons in the SPMA area. In addition, it should be noted that the stations with the most significant reductions since March 15th were Cerqueira César and Marginal Tietê. Moreover, we conclude that NO₂ is a more suitable surrogate for vehicle and economic activities than NO, as per the Pettitt statistical test. We concluded that the social isolation measures as of March 20th were sufficient enough to change the dynamics of atmospheric pollutant concentrations such as NO and NO₂ originating from the burning of automobile fuels and from chemical reactions in the atmosphere of São Paulo.

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