Atmospheric Pollution Reduction in São Paulo City and the Social Isolation Effect

Vinicius Possato Rosse
UFLA https://orcid.org/0000-0002-1211-7746
Jaqueline Natiele Pereira
UFLA https://orcid.org/0000-0003-4374-2285
Arthur Boari
UFLA https://orcid.org/0000-0001-9228-3615
Gabriel Vinicius Costa
UFLA https://orcid.org/0000-0001-8702-1397
João Pedro Colombo Ribeiro
UFLA https://orcid.org/0000-0003-1743-2371
Marcelo Vieira-Filho (marcelo.filho@ufla.br)
UFLA https://orcid.org/0000-0003-4290-7180

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ATMOSPHERIC POLLUTION REDUCTION IN SÃO PAULO CITY AND THE SOCIAL ISOLATION EFFECT

Vinicius Possato Rosse[a] , Jaqueline Natiele Pereira[a], Athur Boari[a], Gabriel Vinicius Costa[a], João Pedro Colombo Ribeiro[a], Marcelo Vieira-Filho*[a]

[a] Departamento de Recursos Hídricos e Saneamento, Universidade Federal de Lavras, Campus da UFLA, 37200-000, Lavras, Minas Gerais, Brazil

ABSTRACT:

Since January 2020, some studies have been reporting a reduction in air pollution in 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 NO_2 in São Paulo city in the social isolation period. The NO and NO_2 hourly concentrations were obtained through air quality monitoring stations from CETESB, from January 14 to April 12, 2020. Mann-Kendall and the Pettitt tests were performed in the air pollutants time series. We observed an overall negative trend in all stations, indicating a decreasing temporal pattern in concentrations. Regarding NO, the highest decrease rates were observed in Congonhas (-6.39 $\mu g.m^{-3} month^{-1}$) and Marginal Tietê (-6.19 $\mu g.m^{-3} month^{-1}$) stations; Regarding NO_2, the highest rates were observed in Marginal Tietê (-4.45 $\mu g.m^{-3} month^{-1}$) and Cerqueira César (-4.34 $\mu g.m^{-3} month^{-1}$) stations. In addition, we identified a turning point in the NO and NO_2 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 NO_2 is a suitable surrogate for monitoring economic activities during social isolation period. Thus, we concluded that social isolation measures implemented in March 20, 2020 caused significant changes in the air pollutants concentrations in São Paulo city (as high as -200% in NO_2 levels).

Keywords: Air pollution, NO_2, Coronavirus outbreak, COVID19, São Paulo.

1. 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 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 emissions 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 (MP_{10}) to the atmosphere (Cetesb 2020).

According to World Health Organization (WHO) data, 91% of the world's population breathes polluted air (WHO 2016) which causes thousands of deaths each year from heart disease, lung cancer, stroke and acute and chronic respiratory diseases. The Southern region of Brazil is the most affected area regarding air pollution, especially São Paulo State due to its demographic features, since it has almost 46 million inhabitants. From this total, almost 25% resides in São Paulo city in an area of 1,521 km^2, associated with the largest vehicle fleet in the country, exceeding 8 million vehicles (~ 90% light vehicles) according to 2019 IBGE´s data (Dapper et al. 2016; Silva et al. 2017; Koga et

***Correspondence author:** Marcelo Vieira da Silva Filho (marcelo.filho@ufla.br) **,** phone: (+55)11-9 8598 6567

al. 2020; Ministério da infraestrutura 2020). Given this perspective, the emission of NO (nitrogen monoxide) and NO_2 (nitrogen dioxide), which are pollutants derived directly from the burning of fossil fuels, stands out (Ribas et al., 2016). Regarding NO_X levels, NO_2 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 (Casquero-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 Coronavirus outbreak (Covid-19), categorized in China as Sars-CoV-2 (Andersen et al. 2020; Chean and Lanjuan 2020) and which has a high rate of transmission and contagion. The same measure was adopted in the city of São Paulo from the first half of March (Sanar Saúde 2020), leading to the closure of universities, institutions and 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).

The social isolation caused a decrease in vehicular traffic and industrial activities, which consequently changed the pattern of emissions of atmospheric pollutants. In a recent study, it was found that carbon and NO_2 emissions in China were reduced by 30 and 25%, respectively, after the beginning of isolation measures (Isaifan 2019). Based on this perspective, this study has the objective to evaluate the changes caused by the period of social isolation in relation to NO and NO_2 emissions in the city of São Paulo, in order to determine whether such measures were representative and mathematically significant.

2. MATERIALS AND METHODS

2.1. Characterization of the Study Region

The municipality of São Paulo is located in the southeast portion (23.5477ºS; 46.6336º W) of the state of São Paulo and has a territorial area equal to 1,521 km^2 (Figure 1). In population estimative for July 2019, São Paulo is classified as the most populated municipality in Brazil, with 12.25 million inhabitants (IBGE, 2019; ZERI et al., 2016). Economically, it presents a large industrial district, dominated mainly by food, chemical and oil industries. Its vehicle fleet, 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. It is important to highlight that a large part of the flow of vehicles in São Paulo is due to neighboring cities in the so-called São Paulo Metropolitan Area (SPMA), increasing the number of vehicles and traffic jam. The SPMA vehicle fleet were about 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 – 1000m elevation. In the summer, the South Atlantic Convergence Zone (SACZ) and the Mesoscale Convective Systems (SCM) are main drivers for precipitation and greater atmospheric instability. In winter, due to the reduction of precipitation and the occurrence of thermal inversions, the atmosphere tends to acquire a greater stability, which causes the stagnation of atmospheric pollutants from industrial activities and from 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).

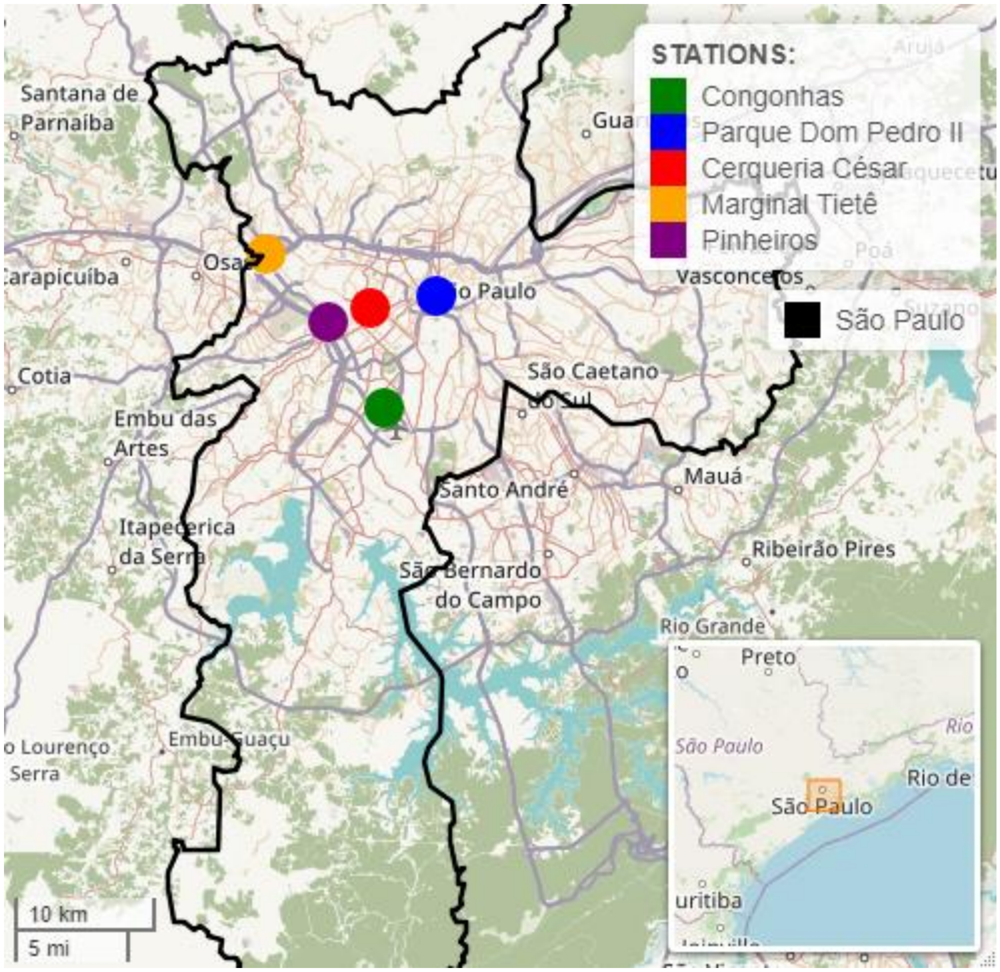


Figure 1 – Geographic delimitation of the study area (São Paulo municipality) and location of the stations used in the study.

2.2. Atmospheric pollutants (NO_X)

Data of nitrogen monoxide (NO) and nitrogen dioxide (NO_2) were retrieved from air quality monitoring stations, operated by São Paulo environmental agency (CETESB, 2020) in hourly resolution. For this study, we considered the period between January 14 and April 12 (2020), with a maximum number of 90 daily observations. We selected the following air quality monitoring stations: Cerqueira César, Pinheiros, Congonhas, Parque Dom Pedro II and Marginal Tietê due to the availability of validated measures. Information regarding each station are represented in Table 1.

Table 1 – Geographic location of air quality monitoring stations, number of data available and data series representativity.

STATION	LONGITUDE	LATITUDE	CODE	n	%
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; "%" – the percentage of data series representativity

2.3. 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), *lubridate* (Grolemund and Wickham 2011), *trend* (Pohlert 2020) and *ggplot2* (Wickham et al. 2020).

From the data collected, we performed the following tests: Mann-Kendall, Slope and Pettitt.

Mann-Kendall Test

The Mann-Kendall (MK) test aims to identify trends in time series (Wilks 2005). The equations we use are the following:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sinal}\,(X_j - X_i) \tag{1}$$

"X" represents the values of the series; "i" and "j" are the time indices and "n" is the number of elements of the series.

$$sinal\,(X_j - X_i) = \begin{cases} +1\ se\ \ (X_j - X_i) > 0 \\ 0\ se\ \ (X_j - X_i) = 0 \\ -1\ se\ \ (X_j - X_i) < 0 \end{cases} \tag{2}$$

We also calculate the mean and variances (Equations 3 and 4):

$$E(S) = \frac{n(n-1)}{4} \qquad (3)$$

$$VAR(S) = \frac{n(n-1)(2n+5)}{72} \qquad (4)$$

The significance of the MK test was performed through a bilateral test, with standardized statistics Z (Equation 5).

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{se } S > 0 \\ 0 & \text{se } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & \text{se } S < 0 \end{cases} \qquad (5)$$

We emphasize that the statistical significance was valided through the value of p. The null hypothesis tested predicts no trend in the timeseries.

Sen’s slope analysis

Following the Mann-Kendall test, we determine the value of the slope (Equation 6), from which we determine the magnitude of temporal trends is given (Sen 1968; Salarijazi et al. 2012).

$$\beta = \text{Median}\left(\frac{X_j - X_i}{j-1}\right) \quad com\ i < j \qquad (6)$$

"X_i" and "X_j" represent the values of the variable under study in positions "i" and "j". Positive or negative values for β indicate increasing or decreasing trends.

Pettitt Test

In the following, we applied the Pettitt test (Equations 7, 8 and 9) in order to identify discontinuity points in the data series (Pettitt 1979).

$$U_{t,T} = U_{t,T} + \sum_{j=1}^{T} sinal(Y_i - Y_j) \qquad (7)$$

Where:

$$\text{Sinal } (Y_i - Y_j) = \begin{cases} +1, \text{se } (Y_i - Y_j) > 0 \\ 0, \text{se } (Y_i - Y_j) = 0 \\ -1, \text{se } (Y_i - Y_j) < 0 \end{cases} \qquad (8)$$

This statistic makes it possible to locate the point where there was a sudden change in the series pattern (Kcrit.), at "t" position.

$$\mathbf{Kcrit} = \pm\sqrt{\frac{-\ln\left(\mathbf{p}/_{2}\right)(\mathbf{T}^3+\mathbf{T}^2)}{6}} \quad , com\ \mathbf{p} = 2\mathbf{e}^{\frac{-6\mathbf{K}^2(\mathbf{t})}{(\mathbf{T}^3+\mathbf{T}^2)}} \tag{9}$$

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

3. RESULTS AND DISCUSSION

In order to verify trends in the nitrogen monoxide (NO) and nitrogen dioxide (NO_2) series, we applied the Mann-Kendall and Pettitt tests for the five air quality monitoring stations. The results are presented in tables 2 and 3.

Table 2 - Results of statistical analyses (MK, value of Sen and Pettitt) related to NO.

STATION	**n**	**Value of Sen** $\mu g.m^{-3}month^{-1}$	**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	-

"$_n$": number of daily data for the period from January 12th to April 14th, 2020; "$_{P1}$ and $_{P2}$": points of intervention found.

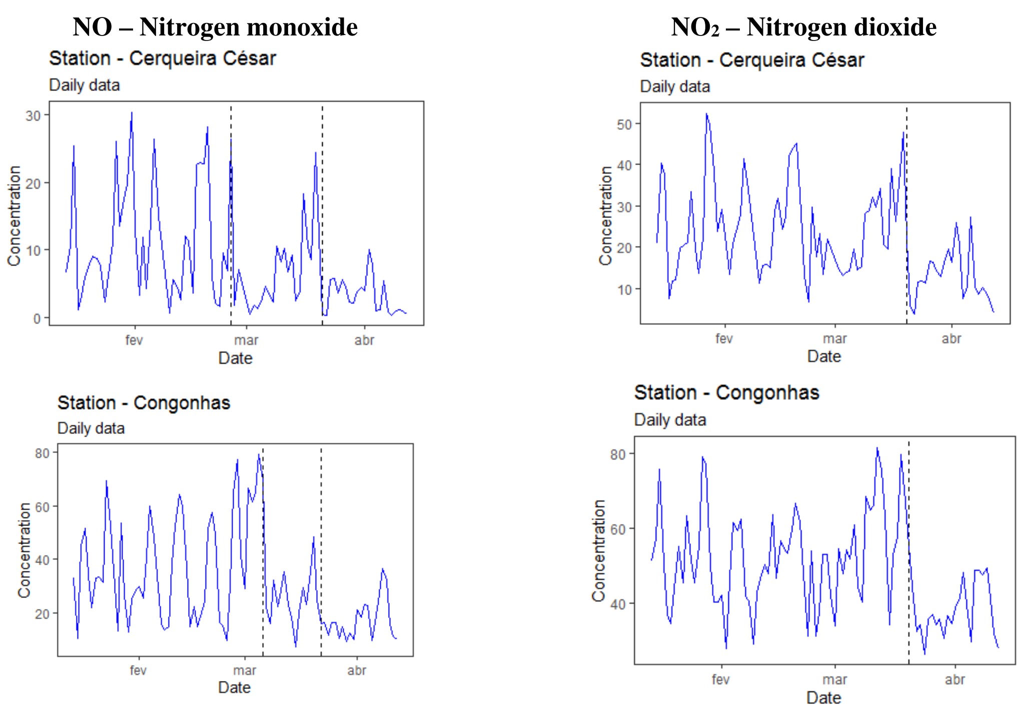
From the data, we verified statistically significant trends in NO and NO_2 levels in all the analyzed stations, since they presented a p value of less than 5% in the MK test (Folhes and Fisch 2006; Cukurluoglu and Bacanli 2018). Also, we calculated the value of Sen in order to verify the magnitude (growth/decrease) 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 decrease patterns from January to April 2020. These results suggest that the concentrations, in $\mu g.m^{-3}$, of NO and NO_2 decreased in the period of Jan, 14th - April, 12th at the monthly rate presented by third columns of tables 2 and 3.

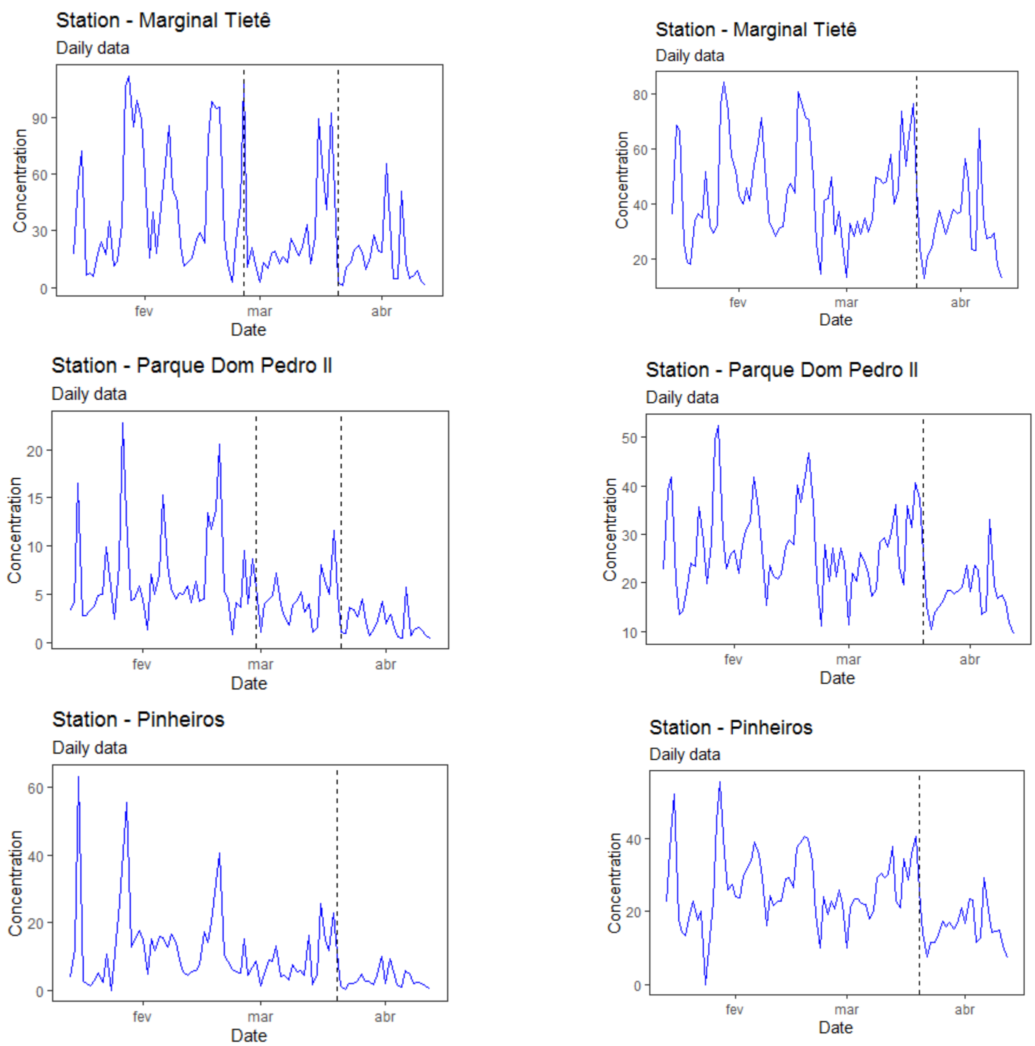
Table 3 - Results of statistical analysis (MK, value of Sen and Pettitt) related to NO2.

STATION	n	Value of Sen $\mu g.m^{-3}month^{-1}$	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	-

"$_n$": number of daily data for the period from January 12th to April 14th, 2020; "$_{P1}$ and $_{P2}$": points of intervention found.

Moreover, columns "P1" and "P2" show the intervention points determined by the Pettitt test (Salarizaji et al. 2012; Ferreira et al. 2015; Jaiswal et al. 2015; Ahmad et al. 2018; Penereiro and Meschiatti 2018; Gaponov et al. 2019) for each period. In order to visualize the decreasing trends and the intervention points, we have elaborated the Figure 2.





Note: the dashed vertical lines indicate the intervention points determined via Pettitt's test.

Figure 2 - Time series of daily mean NO and NO_2 concentration, in units of $\mu g.m^{-3}$, in the period between January 14th and April 12th, 2020.

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 close to the second half of March, which is also verified by P1 dates from NO_2 (Table 3). NO_2 shows an even more sharp change (Figure 2) in comparison with NO. Although emitted together with NO_2, NO, has a short residence time, and a major species in photochemical smog that culminates in NO_2 and O_3 species (Han et al. 2011; Salonen et al. 2019)

Although most intervention points were identified on dates closer to quarantine start date, an opposite behavior was observed in NO concentrations observed in Cerqueira César (February, 26th) and Ibirapuera

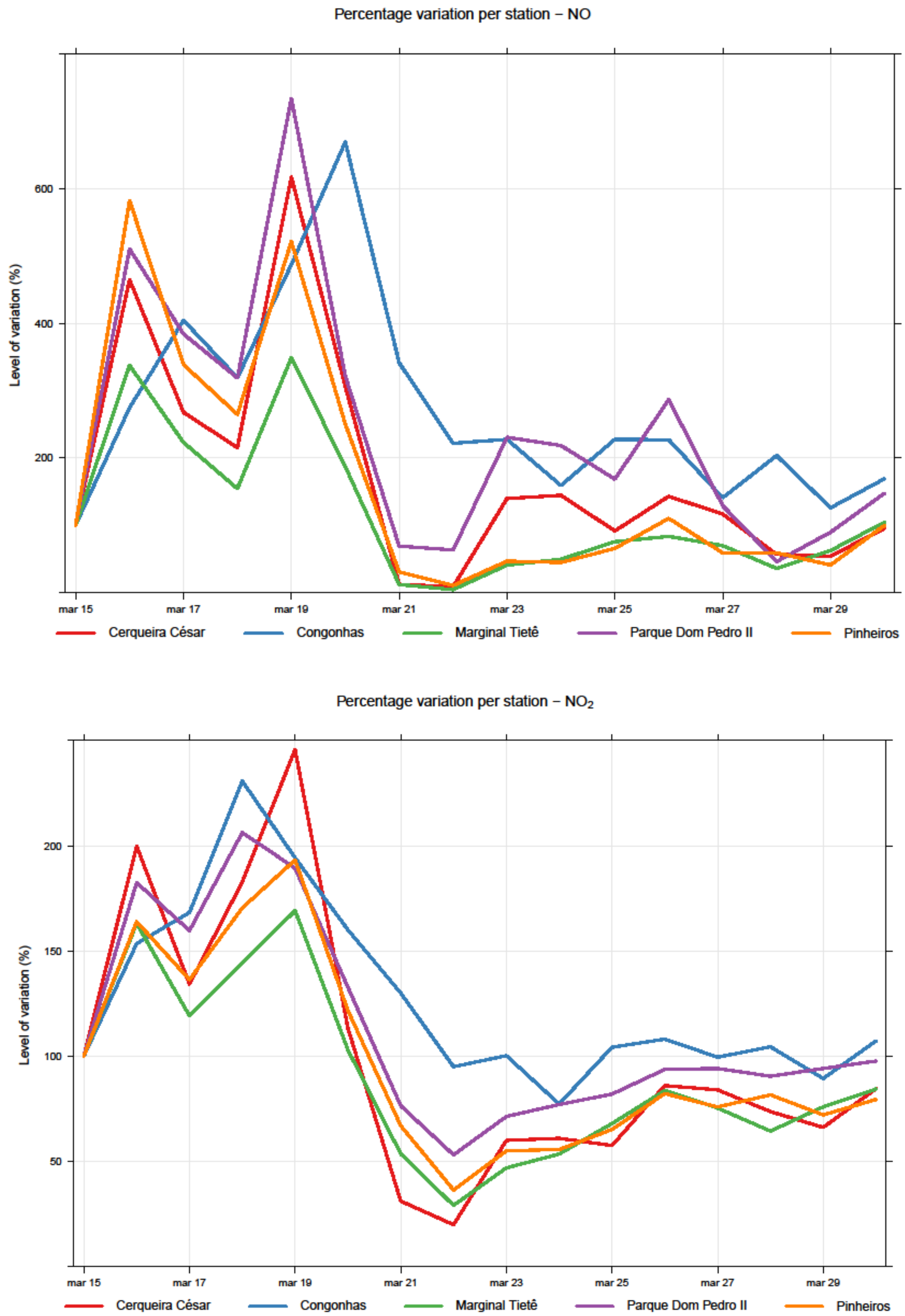


Figure 3 - Daily concentration percentage variation of NO (top) and NO_2 (bottom)in the period from March, 15th to March, 20th in 2020.

(March, 6th) stations (Table 2). Several meteorological factors may influence 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 (496.7mm), 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 rainfall index, is the increase of scavenging air pollutants by wet deposition (Torres and MARTINS 2005; 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 not close to the social isolation period.

A plot of the daily percentage variation of NO (Figure 3a) and NO_2 (Figure 3b) (Agustine et al. 2017; Silver et al. 2018) is depicted covering only the period from March, 15th to March, 30th, highlighting social isolation period (Koga et al. 2020).

Sharp decreases were observed in NO_2 and NO levels in Cerqueira César and Marginal Tietê stations from March, 19th and 20th. Cerqueira César station shows a reduction of -60% compared to average concentration on March, 15th in NO_2 levels. Furthermore, 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.

Some preliminary studies showed in Brazilian media such as IPEN (2020), emphasized the reductions of primary pollutants concentration levels in the social isolation period using satellite measurements for SPMA area. The reduction reported in these studies were up to 50%, however analyzing the air quality data stations we could observe that reductions in NOx levels as high as -200% from March, 19th to March, 21th in Cerqueira Cesar. Figure 3 also highlights the sharp decrease in NO and NO_2 concentrations on March, 20th , which is reasonable with the values of Sen Slope and also the interventions points (Tables 2 and 3). Pettitt test, associated to Mann-Kendall test, indicated a downward trend and anomalous behavior of the data daily series since quarantine started.

4. CONCLUSION

Analyzing the NO and NO_2 levels from January to April 2020, we could observe statistically significant negative trends in São Paulo city, and the highest absolute rates were observed in Congonhas (-6.39 $\mu g.m^{-3}month^{-1}$) and Marginal Tietê (-6.19 $\mu g.m^{-3}month^{-1}$) stations for NO; and Marginal Tietê (-4.45 $\mu g.m^{-3}month^{-1}$) and Cerqueira César (-4.34 $\mu g.m^{-3}month^{-1}$) stations for NO_2. Assuming NO_2 decrease rates of Marginal Tietê and Cerqueira César stations at a standstill until the end of 2020, the total pollution reduction would be above 9,500 tons in SPMA area.

In addition, it should be noted that the stations with the highest percentage reductions since March 15th were Cerqueira César and Marginal Tietê. Moreover, we conclude that NO_2 is more suitable surrogate for vehicle and economic activities than NO, due to Pettit statistical test.

We concluded that the social isolation measures as of March, 20th were sufficient to change the dynamics of concentrations of atmospheric pollutants such as NO and NO_2 originating from the burning of automobile fuels and from chemical reactions in the atmosphere.

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Declarations: all the authors have no competing interests to declare.

Figures

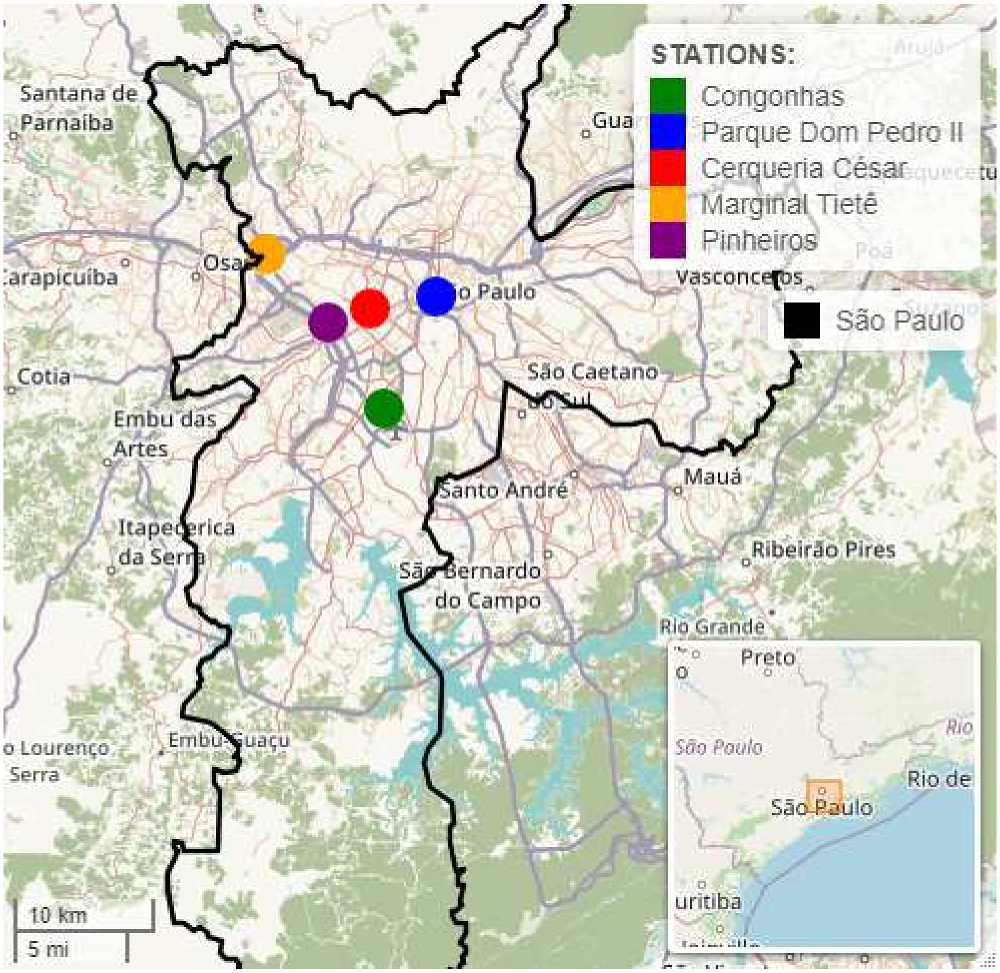
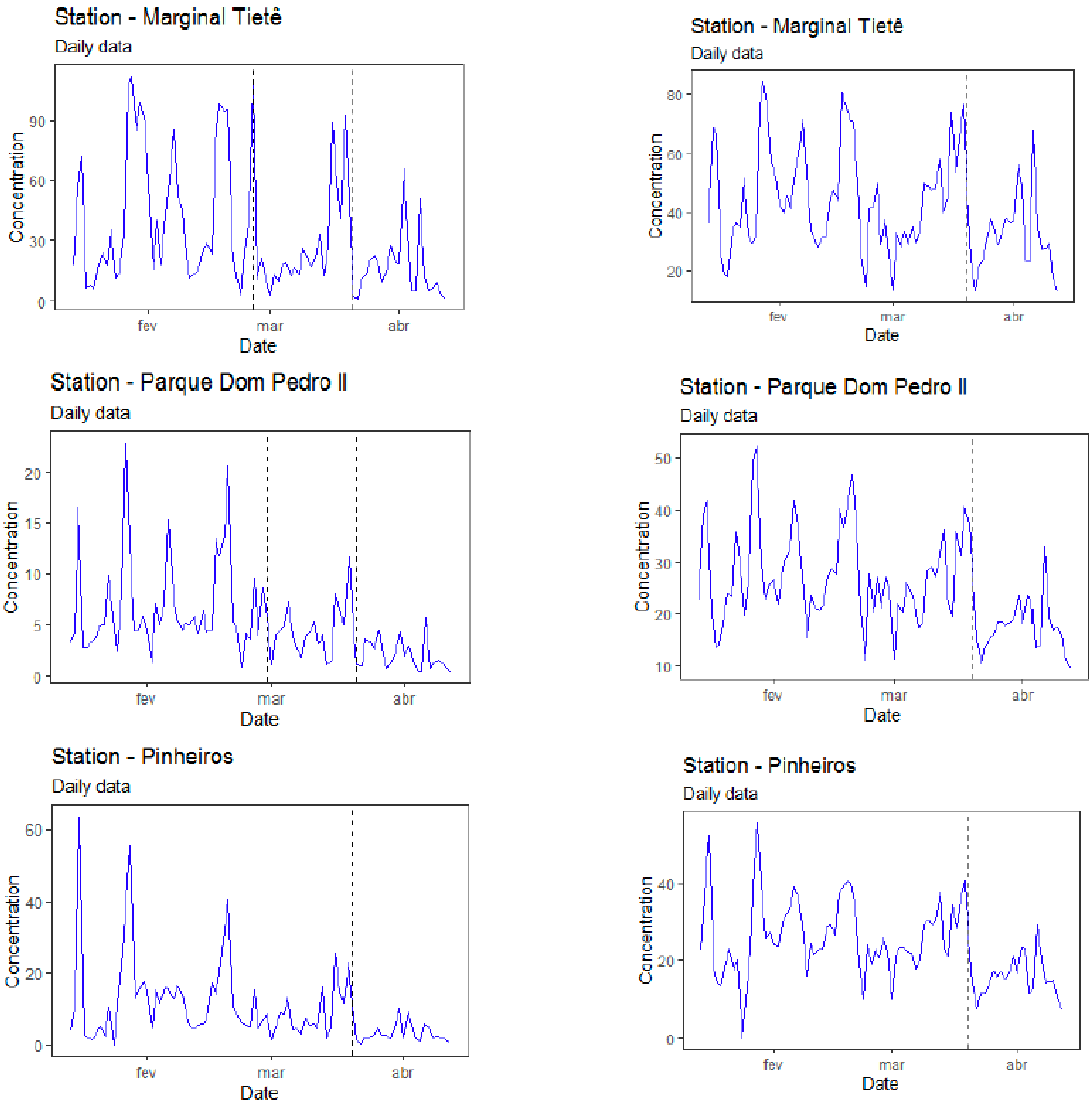


Figure 1

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



Note: the dashed vertical lines indicate the intervention points determined via Pettitt's test.

Figure 2

Time series of daily mean NO and NO2 concentration, in units of μg.m-3, in the period between January 14th and April 12th, 2020.

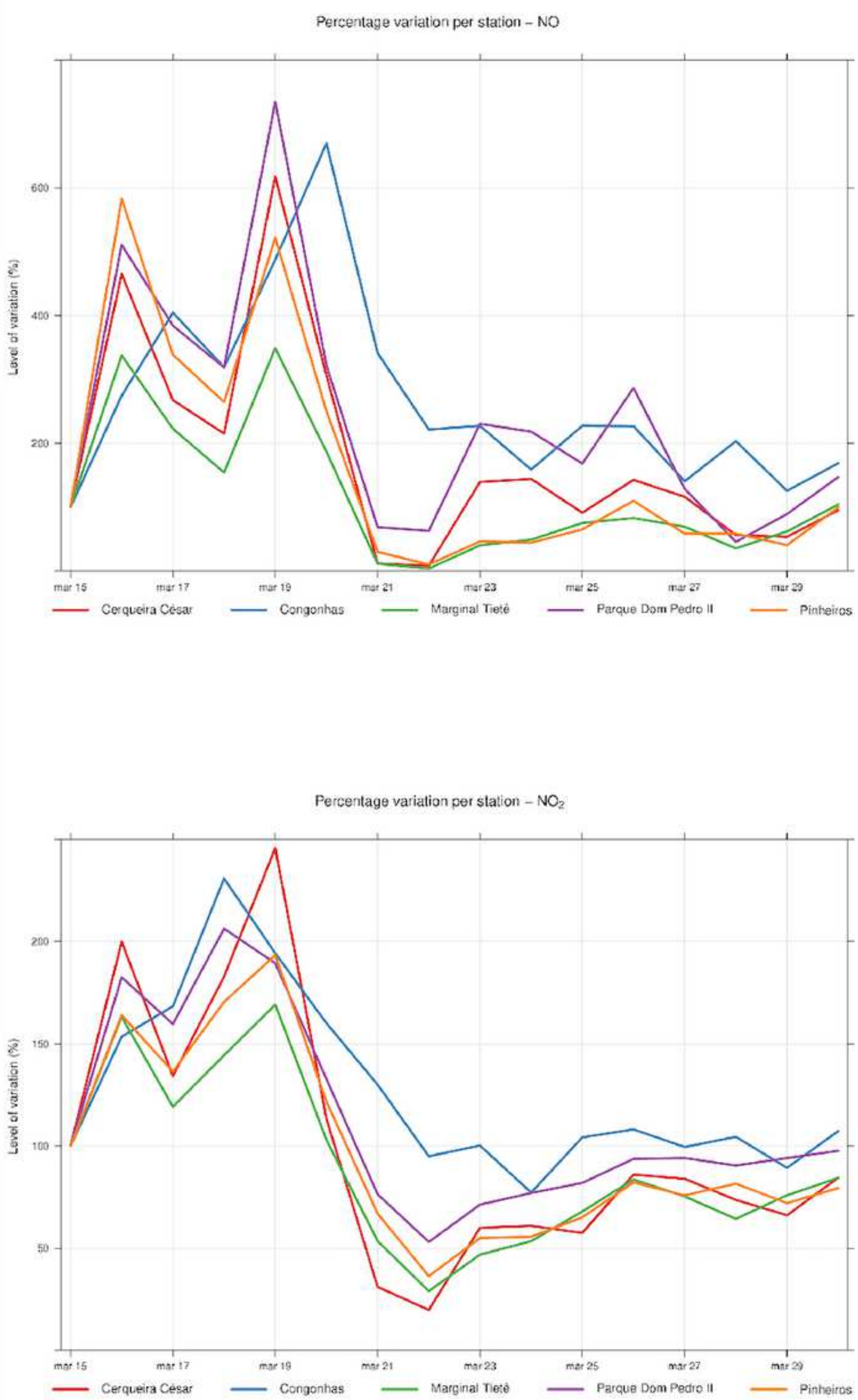


Figure 3

Daily concentration percentage variation of NO (top) and NO2 (bottom)in the period from March, 15th to March, 20th in 2020.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- NO.xlsx
- NO2.xlsx