



# COVID-19: Has social isolation reduced the emission of pollutants in the megacity of São Paulo—Brazil?

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## Abstract

The first case of COVID-19 in Brazil was registered in the city of São Paulo on February 26, 2020; however, restrictive measures and social distancing were only determined in the city on March 17, 2020. A partial lockdown aimed to mitigate the advance of the virus by raising the social isolation rates, by limiting the operation of several services and the mobility of the population. Thus, this study aims to analyze the relationship between the social isolation index in the city of São Paulo and the emission levels of the main air pollutants (PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>x</sub>, NO, NO<sub>2</sub>, SO<sub>2</sub> and CO), as well as air temperature. We analyzed the data collected from three urban air quality monitoring stations located in the city center of São Paulo from March 16, 2020 to July 20, 2020. The data for 2020 were compared with those of the previous period in 2020 and the same period in the previous 5 years (2015–2019), and also to the city's official indices of social isolation. The relationships between pollutant concentrations and the social isolation index showed that the decrease in mobility influenced the reduction in air pollution. Pollutants NO<sub>2</sub>, NO<sub>x</sub>, NO and CO had the strongest negative associations (Pearson's correlation = −0.582; 0.481; −0.433 and −0.367, respectively). Our results showed that the partial lockdown (from March 17, 2020, to July 20, 2020) had a positive impact on air quality, with a reduction in the emission of pollutants NO (31.75%), NO<sub>2</sub> (20.60%), NO<sub>x</sub> (27.21%) and CO (29.95%). The greatest reductions in the emission of pollutants were observed when the social isolation index reached an average of 52.20%. Small negative fluctuations in the social isolation index broke the most significant reductions observed at the beginning of social isolation.

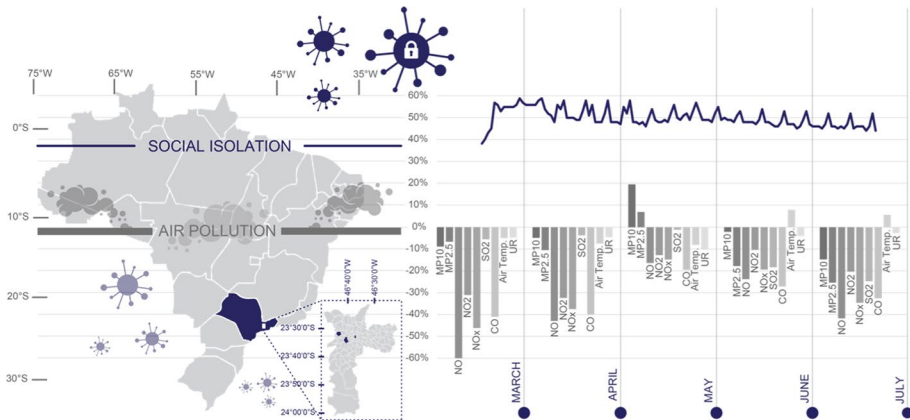
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## Graphic abstract



**Keywords** Air quality · Atmospheric pollution · Quarantine · Partial lockdown · Urban mobility

## 1 Introduction

In December 2019, the world found itself living with an unknown type of highly contagious biological agent that caused severe respiratory symptoms. The first case of the disease caused by SARS-CoV-2 was reported in the Chinese province of Wuhan and quickly spread across the globe to reach the status of pandemic (Layne et al. 2020; Yang et al. 2020; Shehzad et al. 2020). COVID-19 spread so quickly in 2020 that it required worldwide emergency measures of social distancing and quarantine in almost all major cities around the world as a way to reduce contagion (Rodríguez-Urrego and Rodríguez-Urrego 2020; Bera et al. 2020). Closing schools and restaurants, urging people to stay at home and reduce physical contact and interactions still are the most effective form of prevention (Guo et al. 2020; Tian et al. 2020; Wilder-Smith and Freedman 2020). In Wuhan, the first isolation measures adopted were to ban travel, limit traffic, suspend transport and close factories, which had a substantial effect and reduced the spread of the virus (Bao and Zhang 2020).

The pandemic, a challenge in terms of global health, has shed light, in quantitative terms, on the impact of the emission of pollutants generated by human activity in the cities, in a context of reduced urban mobility never before seen in the twenty-first century. Muhammad et al. (2020) state that transport is the sector affected the most by the lockdown; based on Google's Mobility Index Report, those researchers identified reductions in the transport sector between February 23rd and April 5th, 2020, in Spain (89%), Italy (86%), France (82%), England (70%), Germany (47%) and the USA (54%), and there is a consensus that anthropogenic emission reductions, mainly in transportation and the industry, contributed to a decrease in air pollutant concentrations (Wang et al. 2020). In this context, several studies identified various levels of pollutant reduction in the main cities that have adopted urban mobility constraints as a strategy to mitigate COVID-19 contamination.

Initially, by combining satellite observations with detailed computer models of the atmosphere, studies released at the beginning of the pandemic indicated a reduction of about 20–30% in particulate matter (PM) on the surface of much of China. Part of the reduction in the concentration of nitrogen dioxide (NO<sub>2</sub>) in the troposphere was attributed to the impact of the Coronavirus, with a reduction of about 40% in Chinese cities (EESA 2020a). Satellite images also demonstrate a significant reduction in average NO<sub>2</sub> concentrations in major cities in India, with a pollutant decrease of about 40–50% in Mumbai and Delhi (India) compared with the same period in 2019 (EESA 2020b). In Italy and France, NO<sub>2</sub> levels decreased between 45 and 50% compared with the same period in 2019. Madrid (Spain), Milan and Rome (Italy) had drops of around 45% while Paris (France) had a dramatic reduction of about 54%, coinciding with the strict quarantine measures implemented across Europe (EESA 2020c).

Confirming findings from satellite images, local studies assessed the impacts of lockdown on air quality and pollutant emissions of anthropogenic origin using data from local monitoring stations. The first city to adopt the lockdown, Wuhan (China) had strong reductions in PM concentration (~42%), in nitrogen oxides (NO<sub>x</sub>) rates (~56%), and average NO<sub>2</sub> concentrations (~57%), when comparing the isolation period with the same period in the years 2017–2019 (Sicard et al. 2020). Data from urban stations in Delhi (India), one of the cities with the highest pollution indices in the world, showed that during the lockdown there was a significant improvement in air quality, especially when comparing the concentrations of particulate matter with an aerodynamic diameter under 2.5 μm (PM<sub>2.5</sub>) and 10 μm (PM<sub>10</sub>), whose maximum reduction reached 50% when compared with a period prior to the lockdown. NO<sub>2</sub> concentrations and carbon monoxide (CO) emissions also decreased by 52.68% and 30.35%, respectively (Mahato et al. 2020). Kolkata (India) had a reduction in the PM<sub>10</sub> and PM<sub>2.5</sub> concentration around 17.5%, while the pollutants CO, NO<sub>2</sub> and sulfur dioxide (SO<sub>2</sub>) significantly decreased due to the closedown of all industrial and transport activities during lockdown when compared with previous years (Bera et al. 2020). There was also a prominent reduction of surface temperature by 0.23–3.2 °C within the lockdown ambience in Kolkata.

In Milan (Italy), urban station results demonstrate there was a significant reduction in the levels of PM<sub>10</sub>, PM<sub>2.5</sub>, black carbon (BC), benzene, CO and nitrogen oxides (NO<sub>x</sub>) during the lockdown. SO<sub>2</sub> levels remained unchanged in most peripheral areas, and despite the decrease in NO<sub>2</sub> levels, there was an increase in ozone (O<sub>3</sub>) levels, probably due to lower nitrogen monoxide (NO) concentrations (Collivignarelli et al. 2020). In European cities Nice (France), Rome and Turin (Italy), and Valencia (Spain), NO<sub>2</sub> concentrations decreased by ~53% in urban stations and ~65% in traffic zone stations while nitrogen monoxide concentrations (NO) decreased further, by ~63% at urban stations and ~78% at traffic stations, when the isolation period is compared with the same period in the years 2017–2019 (Sicard et al. 2020). The concentration of PM<sub>2.5</sub> reduced by 20–60% in other world cities, such as Bogota (Colombia), Kubait City (Bahrain), Tehran (Iran), Taskhent (Uzbekistan), Ulaanbaatar (Mongolia), Kabul (Afghanistan), Colombo (Sri Lanka), Almaty (Kazakhstan) and Turkey compared with a period prior to the lockdown or compared with the average figures for the same days in 2018–2019 (Rodríguez-Urrego and Rodríguez-Urrego 2020; Kerimray et al. 2020; Aydin et al. 2020). Salé (Morocco) showed reductions by 75% for PM<sub>10</sub>, 49% for SO<sub>2</sub>, and 96% for NO<sub>2</sub> levels during the lockdown when compared with the previous period (Otmami et al. 2020).

In the state of São Paulo (Brazil), during the initial period of partial lockdown (until April 20th, 2020) drastic reductions were observed in the emissions of NO (up to 77.3%) and NO<sub>2</sub> (up to 54.3%), as well as a reduction in CO concentrations (up to

64.8%) compared with the monthly average of previous years. However, an increase of about 30% was observed in O<sub>3</sub> concentrations in urban areas, probably due to reduced car traffic and decreased NO emissions (Nakada and Urban 2020). Krecl et al. (2020) compared the NO<sub>x</sub> reductions (40–70%) of this unprecedented event with reductions brought about by the strike organized by truck drives which brought several sectors of Brazil to a halt for 10 days in 2018. In Rio de Janeiro, the second-most populous city in Brazil, measurements of the city's air quality showed significant reductions in CO levels (between 37.0% and 43.6%) and NO<sub>2</sub> (between 24.1 and 32.9%) during the first lockdown month compared with the same period of 2019. Levels of PM<sub>10</sub> were only reduced in the first lockdown week (Dantas et al. 2020). In Brazil, there was no consensus about the importance and the need for social distancing, reflected in an increase in urban mobility, even during the pandemic (Dantas et al. 2020).

While the positive impact on air quality may be temporary, this type of reduction can assist governments and individuals to learn how to reduce pollution in the long term, and to foresee alternatives to decrease the use of fossil fuels in the future (Muhammad et al. 2020; Rodríguez-Urrego and Rodríguez-Urrego 2020). Pandemics and calamities have occurred several times throughout human history, leading to—besides numerous deaths—changes in society's habits and urban planning. According to Gouveia and Kanai (2020), the pandemic caused by SARS-CoV-2 once again reveals the relationship between health and the urban environment. Anthropogenic action modifies or destroys biodiversity; this fact, allied to climate change, is possibly directly related to the emergence of new viruses, as is the case of the virus that causes COVID-19 (Lorentzen et al. 2020). Moreover, urban design, climatic and environmental variables, housing configurations, population density, and sanitary and transport infrastructure, may or may not favor the control of a pandemic.

Most recent studies related to the emission of pollutants during the COVID-19 pandemic have evaluated changes in air quality compared with a period prior to the lockdown (Aydin et al. 2020; Bashir et al. 2020; Collivignarelli et al. 2020; Dantas et al. 2020; Mahato et al. 2020; Muhammad et al. 2020; Nakada and Urban 2020; Otmani et al. 2020; Rodríguez-Urrego and Rodríguez-Urrego 2020; Sarkar et al. 2020; Sicard et al. 2020). Some authors sought to correlate other aspects, such as climatic variables and the spread or lethality of COVID-19 (Conticini et al. 2020; Fattorini and Regoli 2020; Guo et al. 2020; Hendryx and Luo 2020; Jahangiri et al. 2020; Kerimray et al. 2020; Ogen 2020; Prata et al. 2020; Rehman et al. 2020; Singh et al. 2020; Qi et al. 2020). The effect of mobility habits in the spread of the Coronavirus in Italy was analyzed by Cartenì et al. (2020) in Italy, while Bao and Zhang (2020) related mobility indices to air quality in the lockdown period in Chinese cities.

This article is distinctive and relevant because it identifies the relationship between the pollutant concentrations during the prolonged lockdown at the time of the COVID-19 pandemic and the reduced movement of people in the city of São Paulo; São Paulo is the largest city in Latin America, moreover, no studies in South America have addressed this type of analysis so far. Furthermore, the main question raised in this study is: “*What is the impact on air pollutant emissions in the context of social isolation in a longer term?*” With this question in mind, this study aims to detect the relationship between the social isolation index in the megacity of São Paulo and the fluctuation in the levels of the main air pollutants (PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>x</sub>, NO, NO<sub>2</sub>, SO<sub>2</sub> and CO) and air temperature. This study analyzed the period between March 16th, 2020, and July 20th, 2020, and compared it with the previous period in 2020 and the previous 5 years (2015–2019), based on data from three urban air quality monitoring stations located in the city center of São Paulo.

## 2 Description of the studied area

São Paulo is the largest urban agglomeration in the Southern Hemisphere, with an area of 7,946 km<sup>2</sup>, connecting 39 municipalities and a population of 20 million, and it is one of the most populous cities in the world (Krecl et al. 2020; SEADE 2020). São Paulo also has one of the largest vehicle fleets in the country, and a high concentration of industries that have a direct impact on urban air quality in the area. Due to this fact, São Paulo has the worst air pollution indices in the country, with emissions of 132 thousand t/Year of carbon monoxide (CO), 42 thousand t/Year of hydrocarbons (HC), 77 thousand t/Year of nitrogen oxides (NO<sub>x</sub>), 4.5 thousand t/Year of particulate matter (PM) and 11 thousand t/Year of sulfur oxides (SO<sub>x</sub>); vehicles are responsible for 97% of CO emissions, 81% HC, 80% NO<sub>x</sub>, 48% SO<sub>x</sub> and 40% PM (Gouveia et al. 2017).

The disordered urbanization and increase in the number of sources of air pollution over the years, mainly due to the high concentration of cars and factories, has led to a critical situation with regard to air quality in São Paulo (Andrade et al. 2017). Occupying cities more densely is very effective in terms of economy and the footprint left by carbon dioxide (CO<sub>2</sub>) emissions; however, when high density is the result of a disordered urbanization process, it leads to problems associated with the population's quality of life, especially the poorest *strata*, which makes urban live unsustainable (Jacobi 2013). Thus, it is noteworthy that in addition to population density, the transmission of COVID-19 can be affected by different factors such as climatic conditions (temperature and humidity) and the quality of the health system (Wang et al. 2020; Jahangiri et al. 2020). Moreover, the high concentration of pollutants in the air may be directly associated with a higher probability of contamination in this pandemic (Zhu et al. 2020; Fattorini and Regoli 2020; Hendryx and Lou 2020; Conticini et al. 2020), while the long-term exposure to nitrogen dioxide (NO<sub>2</sub>) can be one of the factors that most contribute to mortality caused by the Coronavirus (Ogen 2020). On the other hand, paradoxically, the COVID-19 pandemic may have decreased the total number of deaths from air pollution during the lockdown periods (Dutheil et al. 2020).

The first case of COVID-19 in Brazil was confirmed on February 26, 2020. On July 20, 2020, the country counted 2,121,645 cases and 80,251 deaths (Brazil 2020). The city of São Paulo continued to lead the numbers of cases and deaths, which caused the prolongation of the social isolation rules. A municipal decree issued on March 17, 2020, marked the beginning of restrictions while the first actions to ease the partial lockdown were put in practice on June 10, 2020, when some businesses were reopened. July 20, 2020, is the 125th day of social isolation and reductions in urban mobility, albeit with different restriction levels.

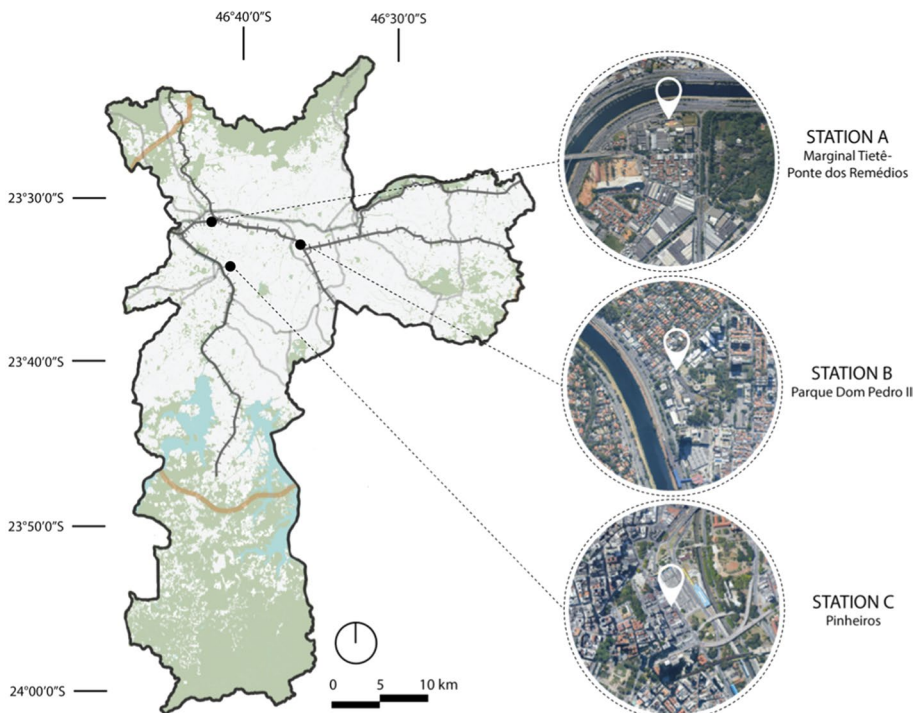
## 3 Methods

### 3.1 Environmental variables and pollutants data

The primary data of the pollutant concentrations PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>x</sub>, NO, NO<sub>2</sub>, SO<sub>2</sub>, CO and the environmental variables (air temperature and relative humidity) were obtained from the regional agency in charge of the air quality monitoring stations in the state *Companhia Ambiental do Estado de São Paulo*, CETESB (2020). In addition to pollutants related to air quality, we chose to verify air temperature since internal combustion

engine vehicles are responsible for considerable emissions of anthropogenic heat in urban centers. For this study, three air quality monitoring stations were selected in the Central Region of São Paulo, an urban area characterized by heavy automobile traffic. We prioritized air quality monitoring stations registering the same variables, with 84.4% of the primary data validated: *Marginal Tietê* (Station A); *Dom Pedro II* Bus Terminal (Station B) and *Marginal Pinheiros* (Station C) (Fig. 1). Station B is setup at a bus terminal, while stations A and C are next to heavy traffic expressways.

We collected the primary data of the three stations in the form of hourly averages, and then we calculated daily averages (arithmetic mean of 24-h monitoring values) for each pollutant and environmental variable, from January 1 to July 20, 2020. Adopting daily values for the variables allowed us to compare them with the social isolation indices, as explained in item 2.3, to detect changes in the time series and quantify the effect of social isolation on the emission levels of pollutants, and environmental variables. In the weeks preceding the decree that started social isolation, there was a national holiday, which traditionally implies a reduction in the operation of businesses and, consequently, in mobility in urban centers. For this reason, this study prioritized analyzing the variations of the daily average concentrations compared with the same period of the previous 5 years, from 2015 to 2019. In an initial analysis, a similar behavior was observed in the daily variations at each monitoring station, so the average value of the three monitoring stations was used as a reference in this study.



**Fig. 1** Location of air quality monitoring stations in the city of São Paulo



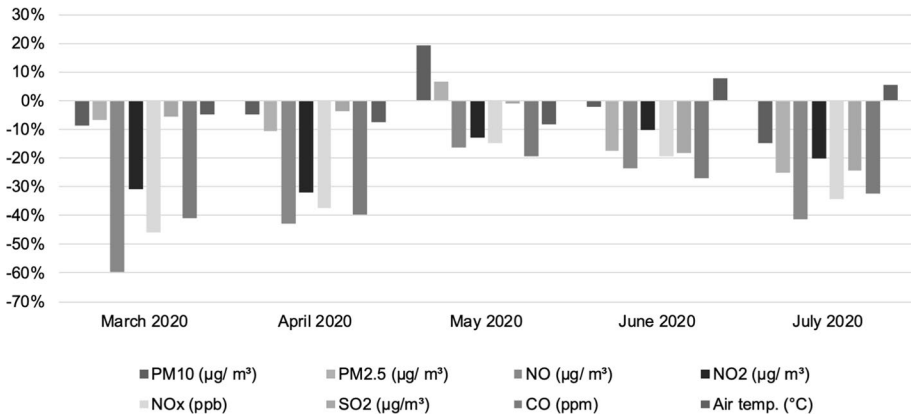
### 3.2 Social isolation index

The decree that reduced urban mobility in São Paulo did not lead to a total stop (lockdown), rather, it was considered partial (partial lockdown) compared with the level of restrictions observed in other cities around the globe. The reduction in population movement was quantified by the “*social isolation index*” created by the São Paulo State Government, as a yardstick for adopting official measures to fight COVID-19 (São Paulo 2020). Bao and Zhang (2020) indicated human mobility as one potential mechanism to estimate the effects of the implementation of travel restrictions on air pollution. To establish the link between lockdown and air pollution reductions, the authors used a human mobility index measured on mobility records from a Chinese online search engine with a desktop and mobile mapping application. Carteni et al. (2020) used an average daily mobility rate estimated by an institute for research about mobility and logistics in Italy plus data collected by car traffic count automatic sensors from the “COVID-19 mobility observatory” of the Italian Transport Ministry to quantify the effect of mobility habits in the spread of the Coronavirus in Italy. The two aforementioned studies used different types of local data sources regarding the mobility and movement of people in cities.

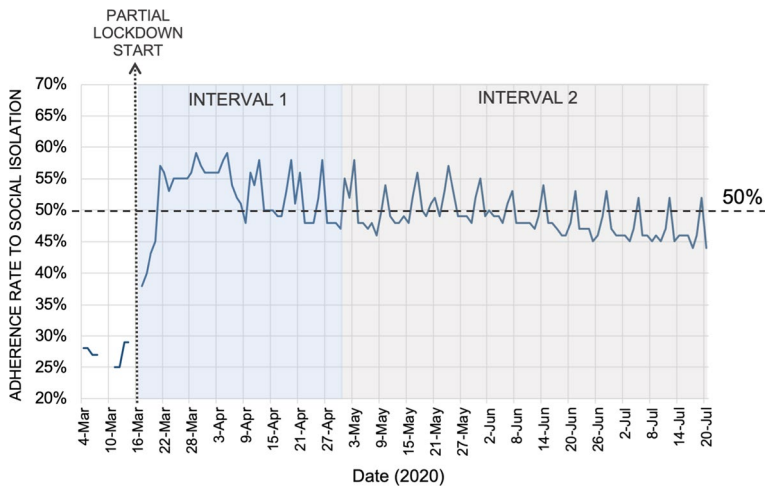
To establish the link between urban mobility and air pollution reductions in the period of partial lockdown, we used the official daily numbers of the social isolation index for the city of São Paulo (São Paulo 2020). The monitoring system in São Paulo, where the technical team of the Institute of Technological Research (*Instituto de Pesquisas Tecnológicas*—IPT) operates, updated the daily index of adherence to social isolation upon analyzing mobile phone data to indicate mobility trends and assess the effectiveness of social isolation measures. The index is based on the location obtained by cell phone antennas (Base Radio Stations), which identify a reference for the place where the cell phone “slept” between 10 p.m. and 2 a.m. During the day, a mobile phone that has moved about 200 m away from this reference point is accounted for as a device not in isolation. The data are made available by telecommunication service providers present in the state of São Paulo and managed by the Brazilian Association of Telecommunication Resources (*Associação Brasileira de Recursos em Telecomunicações*) through a Big Data platform (IPT 2020). Because the system locates the telephones in use through their antennas—and not the GPS—their location cannot be hidden.

### 3.3 Data analysis

The collected data were tabulated and analyzed on a Microsoft Excel spreadsheet. Descriptive analysis was performed for all the data, and linear regression analysis and Pearson’s correlation were conducted to verify the relationship between social isolation and the emission of pollutants. For statistical analyses, the initial procedure consisted of verifying the normality of all data, by using as criteria the Asymmetry values ranging from +3 to −3, and Kurtosis values between +8 and −8, as proposed by Kline (2011) to accept data as normal. Correlation analyses were used in other studies related to the COVID-19 pandemic to identify, for example, the relationship of the number of cases and deaths with environmental variables (Singh et al. 2020; Bashir et al. 2020), and the association among the different pollutants (Sarkar et al. 2020). Linear regression was used by Prata et al. (2020) to identify the relationship of the number of cases with air temperature and population density.



**Fig. 2** Pollutant monthly variation (March 17, 2020, to July 20, 2020)



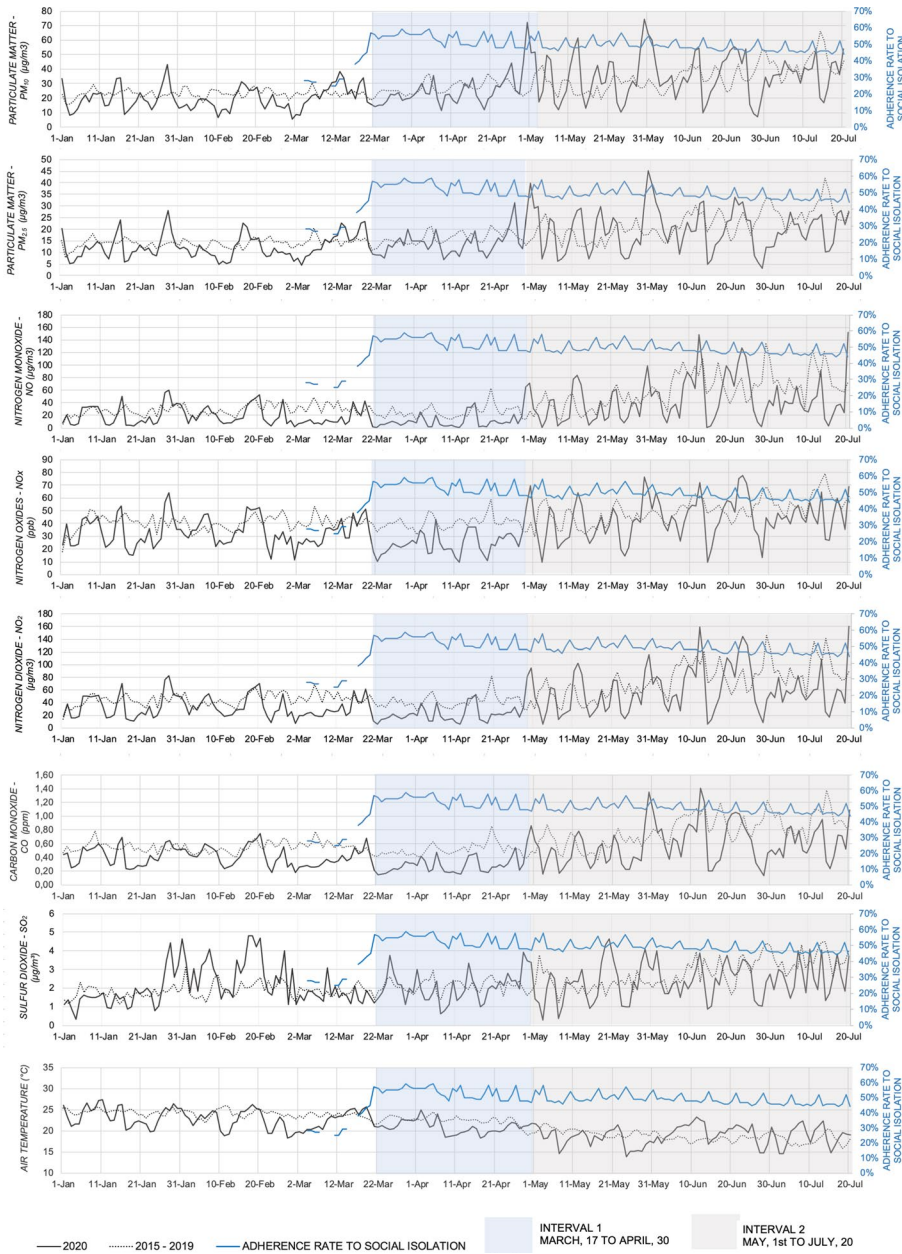
**Fig. 3** Social isolation adherence index identified by the São Paulo State Government. Two distinct ranges are identified: interval 1 (from March 17, 2020, to April 30, 2020) and interval 2 (from May 1, 2020)

## 4 Results

The pollutants' daily average values, calculated on the three monitoring stations located in the Central Region of São Paulo, demonstrate a reduction in concentrations in 2020 compared with the average for the same period of the previous 5 years (2015–2019). However, such reduction was more pronounced in the period of social isolation due to the COVID-19 pandemic, especially in the first months after the decree that reduced mobility in the city, for the pollutants NO, NO<sub>2</sub> and CO, as reported by Nakada and Urban (2020), and also NO<sub>x</sub> (Fig. 2).

By superimposing the daily average data for 2020, the daily average data for the preceding 5 years (2015–2019), and the social isolation index (Figs. 3, 4), we notice a similar behavior in the emissions of all the pollutants during two distinct time periods of the pandemic: the first 45 days (interval 1—March 17, 2020, to April 30, 2020), when isolation





**Fig. 4** Average values of pollutants and environmental variables in 2020, 2015–2019 average, and social isolation index

rates were mostly over 50% (yet below 70% recommended by the World Health Organization—WHO); and the next few months (interval 2—May 1, 2020, to July 20, 2020), with bigger fluctuations, and averages predominantly below 50% (Fig. 3). The national holiday on May 1st marks the beginning of interval 2. While the first period of partial lockdown is

marked by greater reductions in the emission of pollutants, the second period is characterized by greater fluctuations of nearly all pollutants analyzed in this study. In this period, the maximum averages stand out because they reached higher values than those for both the period prior to the partial lockdown and the average of the previous 5 years (Fig. 4). Table 1 and Fig. 5 show the average values for the months of January to July 20, 2020, and for the same period of the previous 5 years and demonstrate significant reductions in the months of March and April 2020 for pollutants NO (59.62% Mar and 42.65% Apr); NO<sub>2</sub> (30.86% Mar and 32.21% Apr); NO<sub>x</sub> (45.84% Mar and 37.27% Apr) and CO (40.81% Mar and 39.68% Apr). In May, however, the reduction trend did not stand, and the emission of pollutants NO, NO<sub>2</sub>, NO<sub>x</sub> and CO reached higher averages than in the immediate period preceding the pandemic (February) and very close averages to those in the same period in the previous 5 years. About the inhalable particulate matter PM<sub>10</sub> and fine inhalable particulate matter PM<sub>2.5</sub>, their reductions in the months of March and April 2020 were lower than in the period preceding the pandemic; in addition, in May they presented higher average levels than in the previous 5 years: PM<sub>10</sub> = +19.39% and PM<sub>2.5</sub> = +6.79%. In July, reductions reached 14.62% and 25.24%, respectively (Table 1).

In a semi-monthly analysis since the beginning of the pandemic (Table 2 and Fig. 6), the influence of social isolation indices on the fluctuation of pollutants becomes more evident, with the most relevant negative variations in the 2nd half of March/2020 and in the 1st half of April 2020: NO (48.86% Mar and 50.13% Apr); NO<sub>2</sub> (33.37% Mar and 37.58% Apr); NO<sub>x</sub> (40.86% Mar and 43.29% Apr) and CO (34.06% Mar and 44.32% Apr). The reductions in these pollutants tend to decrease from the 2nd half of April/2020 on. Inhalable particulate matter PM<sub>10</sub>, and fine inhalable particulate matter PM<sub>2.5</sub> reduced slightly in the first 30 days of partial lockdown while they increased as of the 2nd half of April. Reduced concentrations of PM<sub>2.5</sub> are observed from the first week of June while reduced concentrations of PM<sub>10</sub> are observed from the second week of June (Table 2).

By analyzing the associations between the social isolation index and the concentration of the seven pollutants (Fig. 6 and Table 3), we see negative correlations between the variables, which demonstrates that the restriction measures and the lesser circulation of people influenced the reduction of air pollution. As to the results, the pollutants NO, NO<sub>2</sub>, NO<sub>x</sub> and CO presented the strongest correlations, which allow us to affirm that social isolation explained 18.81%; 33.9%; 23.24%, and 13.45%, respectively, of the concentrations of these pollutants in the period. These results agree with Bao and Zhang (2020), who found that travel restriction measures taken in 44 cities in China significantly reduced air pollution emissions of SO<sub>2</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, and CO (a decrease by 6.76%, 5.93%, 13.66%, 24.67%, and 4.58%, respectively).

Human activity in cities is responsible for generating anthropogenic heat, which comes from various sources such as buildings and cars (Gartland 2010). Vehicle traffic decreased considerably during the partial lockdown and positively affected air quality (Nakada and Urban 2020; Krecl et al. 2020). Besides affecting air quality, automotive vehicles are assumed to influence air temperature records, especially in the areas where the monitoring stations of this study are located, that is, next to intense traffic roads. About the temperature, even if there is a natural decrease due to the season (autumn), in the months of April and May reduction scores are 7.45% and 8.11% compared with the five previous years. In June and July, the mean air temperature is higher than in previous years: +7.83% in June and +5.50% in July (Table 1). On the other hand, the result of the linear regression between air temperature and social isolation (Fig. 7), and Pearson's correlation (Table 3) demonstrate no relevant association between these variables, and it is not possible to assert that social isolation contributed to the oscillation of air temperature in the period.

**Table 1** Monthly averages in 2020, 5-year series (2015–2019) of pollutants PM10, PM2.5, NO, NO2, NOx, SO2, CO, and environmental variables, namely, air temperature, calculated on data from 3 air quality stations in São Paulo–SP

	PM <sub>10</sub> <sup>a</sup> (µg/m <sup>3</sup> )	PM <sub>2.5</sub> <sup>b</sup> (µg/m <sup>3</sup> )	NO (µg/m <sup>3</sup> )	NO <sub>2</sub> (µg/m <sup>3</sup> )	NO <sub>x</sub> (ppb)	SO <sub>2</sub> <sup>c</sup> (µg/m <sup>3</sup> )	CO (ppm)	Air temp. <sup>d</sup> (°C)
2020								
Jan.	20.07	12.54	21.09	33.31	34.76	1.75	0.43	23.69
Feb.	17.67	11.14	20.49	33.98	34.65	2.87	0.44	22.47
Mar.	21.31	13.58	11.72	28.17	24.47	1.78	0.31	22.18
Apr.	26.97	15.17	15.03	27.89	27.03	2.07	0.32	20.68
May	34.75	19.28	33.09	38.58	47.37	2.21	0.49	18.10
June	34.48	19.17	55.88	46.52	70.18	2.42	0.66	19.70
July****	37.38	20.43	44.01	46.28	60.30	2.62	0.63	18.77
2015–2019								
Jan.	22.69	13.66	25.83	40.21	42.27	1.71	0.54	24.54
Feb.	23.63	13.85	29.82	39.94	45.36	2.02	0.54	24.15
Mar.	23.37	14.54	29.03	40.75	45.18	1.88	0.53	23.34
Apr.	28.34	16.94	26.21	41.15	43.10	2.15	0.53	22.34
May	29.10	18.06	39.52	44.20	55.52	2.24	0.61	19.69
June	35.23	23.28	73.14	51.88	86.97	2.96	0.90	18.27
July****	43.78	27.32	75.18	58.01	91.90	3.47	0.93	17.79
Variation (2020–5-year series)								
Jan.	-11.58%	-8.16%	-18.37%	-17.15%	-17.78%	2.22%	-21.64%	-3.46%
Feb.	-25.22%	-19.59%	-31.31%	-14.92%	-23.60%	41.77%	-18.12%	-6.94%
Mar.	-8.82%	-6.63%	-59.62%	-30.86%	-45.84%	-5.44%	-40.81%	-4.97%
Apr.	-4.83%	-10.43%	-42.65%	-32.21%	-37.27%	-3.75%	-39.68%	-7.45%
May	19.39%	6.79%	-16.26%	-12.71%	-14.68%	-1.17%	-19.44%	-8.11%
June	-2.12%	-17.66%	-23.60%	-10.31%	-19.31%	-18.24%	-26.95%	7.83%
July****	-14.62%	-25.24%	-41.45%	-20.21%	-34.38%	-24.57%	-32.32%	5.50%

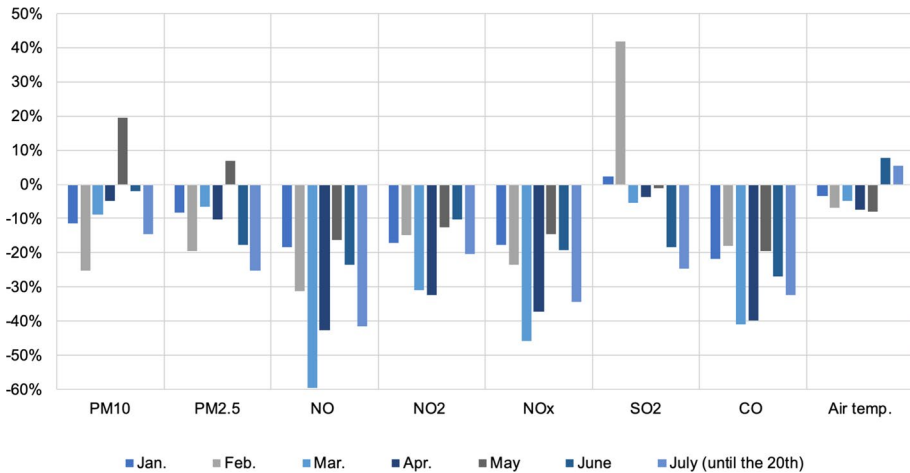
All averages calculated on data from three monitoring stations, except

\*2015 and 2016 data from two stations

\*\*2016 data from one station

\*\*\*Data from 2015 to 2020 from one station

\*\*\*\*Up to July 20



**Fig. 5** Pollutant variation (%) in 2020 compared to the 5-year series (2015–2020), from January to July

## 5 Conclusions

This study concluded that the decrease in urban mobility due to the social isolation imposed by the COVID-19 pandemic had a positive impact on air quality, with a reduction in the emission of pollutants NO (31.75%), NO<sub>2</sub> (20.60%), NO<sub>x</sub> (27.21%) and CO (29.95%) considering the partial lockdown period from March 16, 2020, to July 20, 2020. A more notable fall was observed in the initial period of the lockdown, however, when analyzing a longer period (since the lockdown in São Paulo was successively prolonged), from the third month on we noticed a decline in such reductions compared to the beginning of the pandemic. Subtle falls in social isolation rates in the city of São Paulo were reflected in the emission of pollutants in the period.

About the inhalable PM<sub>10</sub> and fine inhalable PM<sub>2.5</sub> particles, their reductions in the first months of social isolation were lower than in the period immediately before the pandemic; moreover, in May they presented higher average levels than in the previous 5 years: +19.39% and +6.79%, respectively. More relevant reductions were only identified in July (14.62% and 25.24%), which may have been influenced by other aspects not addressed in this study.

From the analyses conducted in this study, we highlight:

- Higher drops in the emission of pollutants NO, NO<sub>2</sub>, NO<sub>x</sub> and CO were observed when the social isolation index reached an average of 52.20%;
- Small negative fluctuations in the social isolation index broke the reductions observed at the beginning of the lockdown;
- We notice two distinct periods of the partial lockdown in São Paulo-SP, with the predominance of indices above 50% in the first 45 days (interval 1) and predominance of indices below 50% in the following period (interval 2).
- The relationships between pollutant concentrations and the social isolation index showed that the decrease in mobility influenced the reduction of air pollution. Pollutants NO<sub>2</sub>, NO<sub>x</sub>, NO and CO had the strongest negative associations (Pearson's correlation ( $\rho$ ) = -0.582; 0.481; -0.433 and -0.367, respectively).

**Table 2** Biweekly averages during the partial lockdown period started on March 17, 2020, 5-year series (2015–2019), and variation across reference periods of pollutants PM10, PM2.5, NO, NO2, NOx, SO2, CO and environmental variables, namely air temperature calculated on data from three air quality stations in São Paulo—SP

	PM <sub>10</sub> * (µg/m <sup>3</sup> )	PM <sub>2.5</sub> ** (µg/m <sup>3</sup> )	NO (µg/m <sup>3</sup> )	NO <sub>2</sub> (µg/m <sup>3</sup> )	NO <sub>x</sub> (ppb)	SO <sub>2</sub> ** (µg/m <sup>3</sup> )	CO (ppm)	Air temp.* (°C)	Social isolation (%)
<b>2020</b>									
2nd half Mar	20.44	14.33	12.31	26.21	23.91	1.88	0.31	22.31	52.00
1st half Apr	23.23	12.68	11.04	25.04	22.27	1.81	0.28	20.90	53.87
2nd half Apr	30.72	17.67	19.03	30.74	31.80	2.34	0.36	20.45	50.69
1st half May	33.80	17.75	30.47	35.95	43.88	1.76	0.44	18.61	49.87
2nd half May	35.63	20.73	35.55	41.06	50.65	2.63	0.54	17.61	51.50
1st half June	33.95	19.76	51.74	44.07	65.56	2.25	0.70	20.19	49.27
2nd half June	35.02	18.57	60.02	48.98	74.80	2.59	0.62	19.21	47.67
1st half July	36.07	19.34	40.61	44.33	56.48	2.52	0.61	18.84	46.67
<b>2015–2019</b>									
2nd half Mar	23.28	14.34	24.07	39.34	40.43	1.99	0.46	22.88	
1st half Apr	28.06	16.74	22.14	40.12	39.26	2.18	0.51	22.92	
2nd half Apr	28.62	17.14	30.29	42.17	46.94	2.13	0.56	21.76	
1st half May	29.29	17.74	32.64	42.71	49.16	2.23	0.59	20.30	
2nd half May	28.93	18.36	45.96	45.60	61.49	2.24	0.63	19.13	
1st half Jun	33.00	21.89	73.88	51.36	87.27	2.69	0.89	18.07	
2nd half June	37.46	24.67	72.40	52.39	86.67	3.23	0.91	18.47	
1st half July	44.83	27.97	78.91	58.15	95.02	3.52	0.94	17.95	
<b>Variation (2020—5-year series)</b>									
2nd half Mar	-12.18%	-0.07%	-48.86%	-33.37%	-40.86%	-5.30%	-34.06%	-2.47%	
1st half Apr	-17.21%	-24.28%	-50.13%	-37.58%	-43.29%	-16.90%	-44.32%	-8.82%	
2nd half Apr	7.31%	3.09%	-37.18%	-27.11%	-32.24%	9.72%	-35.45%	-6.01%	
MEAN, INTERVAL 1	-7.36%	-7.08%	-45.39%	-32.69%	-38.80%	-4.16%	-37.94%	-5.76%	52.20

**Table 2** (continued)

	PM <sub>10</sub> * (µg/m <sup>3</sup> )	PM <sub>2.5</sub> ** (µg/m <sup>3</sup> )	NO (µg/m <sup>3</sup> )	NO <sub>2</sub> (µg/m <sup>3</sup> )	NO <sub>x</sub> (ppb)	SO <sub>2</sub> *** (µg/m <sup>3</sup> )	CO (ppm)	Air temp.* (°C)	Social isolation (%)
1st half May	15.41%	0.05%	-6.65%	-15.84%	-10.75%	-20.84%	-25.29%	-8.32%	
2nd half May	23.17%	12.89%	-22.65%	-9.96%	-1.762%	17.16%	-14.34%	-7.90%	
1st half Jun	2.86%	-9.71%	-29.97%	-14.20%	-24.88%	-16.26%	-21.78%	11.75%	
2nd half June	-6.52%	-24.71%	-17.10%	-6.50%	-13.69%	-19.90%	-32.03%	3.99%	
1st half July	-19.55%	-30.83%	-48.54%	-23.76%	-40.56%	-28.41%	-35.31%	4.95%	
MEAN, INTERVAL 2	3.08%	-10.46%	-24.98%	-14.05%	-21.50%	-13.65%	-25.79%	0.89%	48.86
Variation (%)									
2nd half Mar 2020 to July 20, 2020	-0.22%	-8.50%	-31.75%	-20.60%	-27.21%	-9.61%	-29.95%	-1.53%	

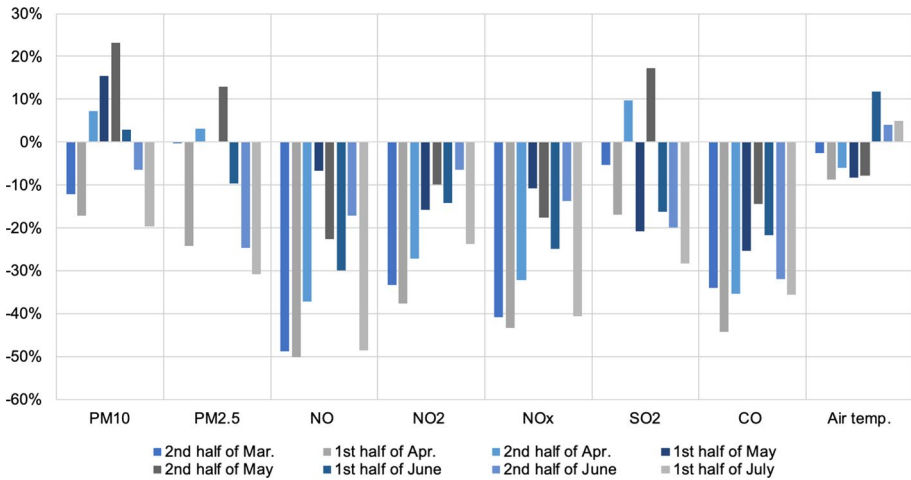
All averages calculated on data from three monitoring stations, except

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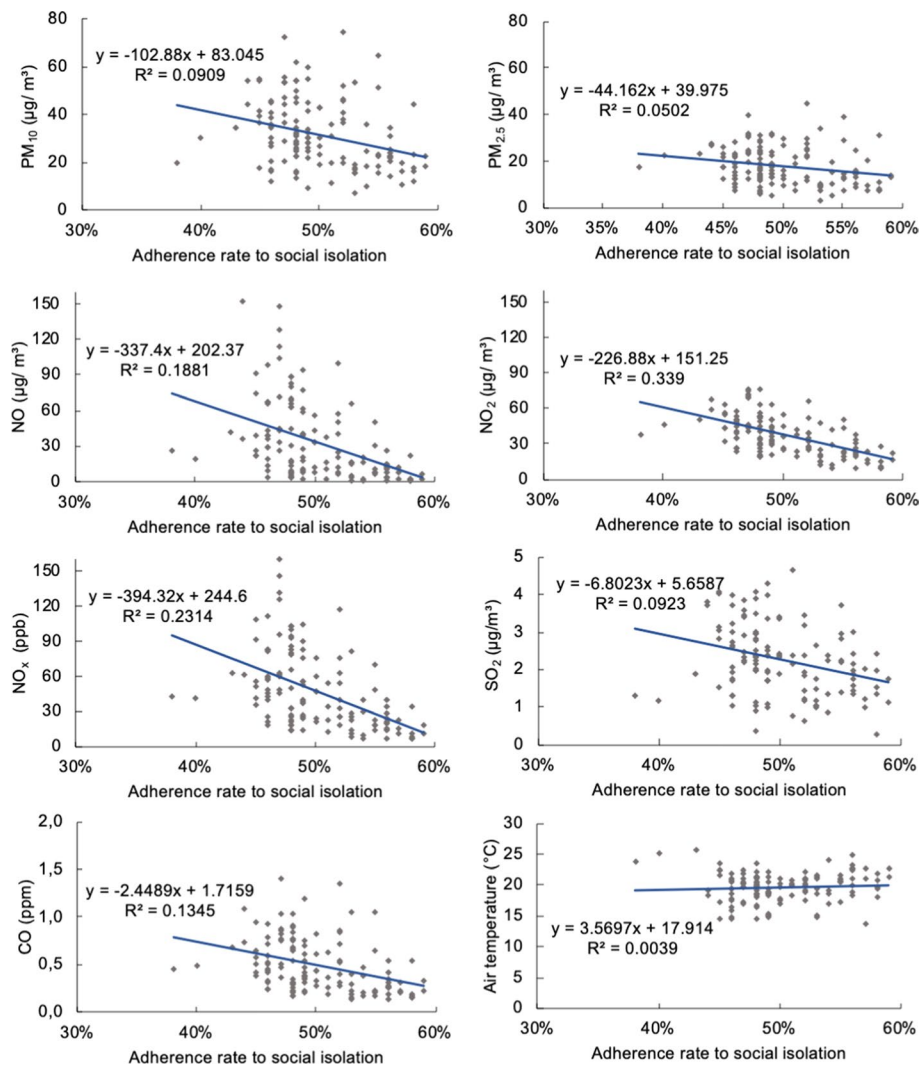
**Fig. 6** Pollutant biweekly variation (%) in 2020 compared to the 5-year series (2015–2020) during the partial lockdown period

**Table 3** Pearson’s correlation ( $\rho$ ) and linear regression ( $R^2$ ) between adherence rate to social isolation with different pollutants and air temperature from March 17 to July 20, 2020, in São Paulo, Brazil

Variables	Pearson ( $\rho$ )	$R^2$
PM <sub>10</sub> ( $\mu\text{g}/\text{m}^3$ )	-0.301	0.0909
PM <sub>2.5</sub> ( $\mu\text{g}/\text{m}^3$ )	-0.223	0.0502
NO ( $\mu\text{g}/\text{m}^3$ )	-0.433	0.1881
NO <sub>2</sub> ( $\mu\text{g}/\text{m}^3$ )	-0.582	0.339
NO <sub>x</sub> (ppb)	-0.481	0.2314
SO <sub>2</sub> ( $\mu\text{g}/\text{m}^3$ )	-0.304	0.0923
CO (ppm)	-0.367	0.1345
Air temperature ( $^{\circ}\text{C}$ )	0.062	0.0039

- Other contextual factors may have influenced the fluctuations that occurred for all pollutants in the second period of the partial lockdown, in which maximum values observed are above the last 5 years’ average.

This study identified that the reductions of the pollutant levels were not regular in the analyzed period; great oscillations were observed in May and June 2020, which may be the object of further, more in-depth studies. The results herein presented, analyzed on a local scale, demonstrate the potential of a megacity such as São Paulo to reduce the concentrations of air pollutants generated by anthropogenic activities related to urban mobility, even if due to temporary circumstances. As a conclusion, we highlight the importance of understanding the short-term causes, changes and benefits as a path to permanent transformations.



**Fig. 7** Relationship of adherence rate to social isolation with different pollutants and air temperature from March 17 to July 20, 2020, in São Paulo, Brazil

## 6 Limitations

- The air quality monitoring system in São Paulo has a wide network of stations, however, they do not record the same variables. For this reason, only three stations that recorded the same variables were chosen for this study, thus allowing the comparison over time.
- There are data gaps, especially PM<sub>10</sub> and PM<sub>2.5</sub> in 2015 and 2016, and SO<sub>2</sub> from 2015 to 2020.

## 7 Future research directions

- Since the COVID-19 pandemic is not over; the population has not yet been vaccinated and immunized; and, there are forecasts of new contamination peaks, a longitudinal study is recommended to identify the long-term impact of the reduction of urban anthropogenic activities due to the pandemic.
- Other contextual factors can be investigated to identify the oscillations and peaks in the emission of pollutants in the second partial lockdown period (from May to June 2020).
- Other sources of data on mobility during the pandemic, such as the Google Community Mobility Report, may contribute to better understand the impact of a partial lockdown on urban activities.

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## Compliance with ethical standards

**Conflicts of interest** The authors declare that they have no conflict of interest.

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