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Heterogeneous impacts of mobility restrictions on air quality in the State of Sao Paulo during the COVID-19 pandemic.

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Abstract

Air quality in the state of Sao Paulo was evaluated during the first general State plan of mobility restrictions due to the COVID-19 pandemic (24th March to 31st May 2020). Nitrogen dioxide (NO_2), ozone (O_3), particulate matter PM_{10} and $PM_{2.5}$ and sulphur dioxide (SO_2) concentrations were assessed in cities of the Sao Paulo state with a monitoring station and compared to historical data. Linear regression models were built to assess the relationship between the isolation of the population – determined using mobile phone monitoring data - and the concentration of each pollutant during the studied period. Although the reduction of pollutants such as NO_2, SO_2 and $PM_{2.5}$ is very clear, economic and climatic characteristics of each region were decisive in the general behaviour of O_3 and PM_{10}. It was not possible to establish a correlation between the pollutants and the social isolation index, partly due to the lack of data, partly due to the compliance of the population to those measurements, which was variable over time. Another important limitation factor was the absence of data related to the pollutants of interest in many of the stations.

Even so, the isolation measures carried out in the state opened the opportunity to individually assess the air quality measurements in each of the stations, allowing, in the future, that air quality policies be designed together with local sanitary policies.

Keywords: air quality, mobility restrictions, COVID-19, air pollution, social isolation

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Declaration of competing financial interests

The authors declare they have no actual or potential competing financial interests.

Author contributions

SSRC: Investigation, Data curation, Writing - original draft. **PFR:** Conceptualization, Investigation, Writing - original draft, Writing - review & editing. **PB:** Software, Validation, Formal analysis, Writing - original draft. **EV:** Conceptualization, Investigation, Data curation. **RN:** Software, Formal analysis. **AVBA:** Investigation, Data curation. **MV:** Conceptualization, Resources. **SS:** Conceptualization, Resources, Supervision. **PHNS:** Conceptualization, Resources, Supervision.

1. Introduction

The world is experiencing a global epidemic of COVID-19, a disease caused by the SARS-CoV-2 virus. Declared by the World Health Organization (WHO) on March 11th, 2020, this disease can cause symptoms such as fever, cough, fatigue, headache and diarrhoea, and can lead to hospitalisation, Intensive Care Unit admission and death (Rothan and Byrareddy 2020; Zhou et al. 2020; Huang et al. 2020). Worldwide, until the end of December 2021, the pandemic has caused more than 5.4 million deaths in more than 281 million reported cases. By the end of December 2021, Brazil had the third-highest number of cases (more than 22.3 million) and the second-highest number of deaths in the world (more than 619,000) (Johns Hopkins University 2021). Sao Paulo, the country's most populous state, reported, until the end of December 2021, more than 4.4 million cases and almost 155,000 deaths (Sao Paulo State Government 2021b).

To reduce the transmission, countries worldwide have been applying measures like the use of masks, social distancing, and lockdown periods, each measure having its own economic, logistic and scientific challenges (Ibarra-Vega 2020; Gros 2020; Haug et al. 2020). In Brazil, the states and municipalities of the federation are independent to take action in issues related to public health (article 23, item II, 198, item I, and 200, item II of the Federal Constitution (Federative Republic of Brazil 1988)) and were able to make autonomous decisions, according to the public health situation due to COVID in each region (Brazilian Federal Supreme Court 2020). In particular, in the state of Sao Paulo, the restrictions to mobility started in mid-March (gradual closure of schools) and were fully recommended to all non-essential activities from 24th March to 31st May 2020, in all the 645 municipalities of the state (Sao Paulo State Government 2020b). Although there was no mandatory lockdown, non-essential activities, like shopping centers, stores, beauty centers, restaurants, churches and temples, schools and Universities were closed (Barbosa and Ribeiro 2020; Sao Paulo State Government 2021b). This caused a consequent reduction of urban displacement, and government advertisements were run on the internet, radio and television to encourage people to stay at home whenever possible. Industrial activity was not interrupted (Sao Paulo State Government 2021a), although some industries suffered a decrease in demand (Nakada and Urban 2020). At the same time, a monitoring system was developed by the government of the state, based on anonymous mobile phone data was established to estimate the compliance of the population with social distance measures. The monitoring system was available for each municipality and calculated the so-called "isolation index", understood as the percentage of the population that stayed at home (Sao Paulo State Government 2020a; Torres et al. 2021).

Lockdowns and social distance measures have effectively reduced the spread of COVID-19 (Iezadi et al. 2021; Bo et al. 2021; Brauner et al. 2021; Thu et al. 2020) and many cities and countries reported notable changes in air quality because of reductions in mobility and industrial activity during the adoption of those measures. But as the concentration of air pollutants is directly affected by factors such as emission sources, atmospheric conditions, chemical interactions and dispersion time, the reported results strongly depended on local particularities (Wang et al. 2021; Briz-Redón, Belenguer-Sapiña, and Serrano-Aroca 2021).

Assessing effects of mobility restrictions on air pollution is important for the design of air quality regulation policies (Carvalho et al. 2015; Dholakia et al. 2013). The importance of this assessment during the COVID outbreak becomes is even more important as there are increasing evidences that more polluted areas can bring higher risks for the spread of the disease, especially because of the previous health impacts caused by the pollutants (Bourdrel et al. 2021; Gupta et al. 2021; Wu et al. 2020; Liang et al. 2020; Konstantinoudis et al. 2021; Pozzer et al. 2020). In this sense, small-scale variations in air pollution and socio-demographic factors can cause a difference in public health management, as recently demonstrated by Saldiva et al., (2018) for premature births and by (Lorenz et al. 2021; Bermudi et al. 2021) for COVID cases in the city of Sao Paulo. As in the Sao Paulo metropolitan region (SPMR) the poorest and most vulnerable areas are also the ones exposed to the higher levels of air pollutants, due to land use, time of permanence in public transport and poor quality of house constructions, among others (Martins et al. 2004), these small scale differences in pollutants measurements detected by the monitoring stations spread in the SPMR are important to be assessed individually.

Lal et al. (2020) used satellite and climate data to report a substantial reduction in nitrogen dioxide (NO_2) and a low-to-moderate reduction of aerosol optical depth (AOD) in the major hotspots of COVID-19 during February and March of 2020, places that were facing more or less severe lockdowns. The reduction of NO_2 and NOx was also reported by many other studies using ground-based monitoring stations, e.g. Adams (2020) for Ontario, Canada, Baldasano (2020) and Briz-Redón, Belenguer-Sapiña, and Serrano-Aroca (2021) for major cities in Spain, Bao and Zhang (2020), Lian et al. (2020) and Pei et al. (2020) for China, Berman and Ebisu (2020) for continental USA, Collivignarelli et al. (2020) for Milan, Italy, Gama et al. (2021) for Portugal, Kanniah et al. (2020) in Malaysia (in areas not affected by seasonal biomass burn), Nakada and Urban (2020), Krecl et al. (2020), Dantas et al. (2020), Siciliano et al. (2020), Rudke et al. (2021) and Rosse et al. (2021) for Brazil (São Paulo and Rio de Janeiro), and Selvam et al. (2020), Sharma et al. (2020), Sathe et al. (2021) for India, among others. Only Briz-Redón, Belenguer-Sapiña, and Serrano-Aroca (2021) found an increase in Spain for the city of Santander.

The studies also reported reductions in black carbon (BC), sulphur dioxide (SO_2) and carbon monoxide (CO). For $PM_{2.5}$, all studies showed a low-to-moderate reduction in atmospheric concentration, especially in the early periods of the lockdowns, except for Adams (2020), that reported no changes in $PM_{2.5}$ concentrations. For ozone (O_3), results of the majority of the studies showed an increase in this pollutant (Briz-Redón, Belenguer-Sapiña, and Serrano-Aroca 2021, Collivignarelli et al. 2020; Dantas et al. 2020; Kerimray et al. 2020; Lian et al. 2020; Nakada and Urban 2020; Pei et al. 2020; Selvam et al. 2020; Sharma et al. 2020; Sicard et al. 2020; Siciliano et al. 2020), with Adams (2020) showing variable results for the city of Ontario, depending on the location of the station and Menut et al. (2020) showing a mitigated effect for western Europe using modelling.

Among the six studies published for Brazil, Krecl et al. (2020) and Rosse et al. (2021) looked at the scenario for the city of Sao Paulo, showing the reduction of daily mean NOx concentrations at monitoring stations in the Sao Paulo metropolitan region (SPRM) during the first week of the adoption of mobility restriction measures by the state government. Furthermore, Nakada and Urban (2020) addressed two stations in the Sao Paulo Metropolitan Region (SPMR) and one in the city of Cubatão, which belongs to the near coast area (Baixada Santista) and is one of the major industrial sites in the country. Although they verified a general decrease in NO, NO_2 and CO, they reported an important increase in NO_2 for the industrial area of Cubatão, pointing already at a dependence of the major characteristics of emissions and sanitary measures of the monitoring site on the results. Rudke et al. (2021) carried a study taking into consideration 6 pollutants in 50 monitoring stations of the state and investigated the relationship of the observed changes with social isolation measures, although presenting their results in terms of geographic mesoregions in the state, emphasizing the SPMR, and using a mobility indicator that has strong limitations for representativeness of the Brazilian population.

The state of São Paulo has the largest monitoring network in Brazil, with a coverage of 65 stations in 35 different municipalities (CETESB 2020), which makes the state a territory of interest for studying the effects of mobility restriction measures in air quality at city scale with implications for public health. Associated to the fact that all the municipalities in Brazil were independent to take action during the mobility restrictions, this understanding is important to establish customized pollution control targets for different cities in the same region and for different areas inside big cities..

This article seeks to make an individual analysis of air quality changes for the municipalities of Sao Paulo having a monitoring station, addressing changes in NO_2, O_3, PM_{10}, $PM_{2.5}$ and SO_2 concentrations during the first period of mobility restrictions in the state, imposed from 24th March to 31st May 2020. Data were compared to historical data from 2018 to 2019 and correlated with restrictions in mobility imposed by the management of COVID-19 outbreak. Results are expected to provide knowledge for better application of detailed control policies for each municipality and also serve as a basis for future studies that intend to identify impacts of air pollution on health at the city or sub-city scale.

2. Materials and methods

2.1 Characterization of Sao Paulo State – Economic Hubs, Mesoregions and Meteorology

The state of Sao Paulo has the largest population in the country - about 44 million inhabitants. It comprises 645 cities and covers 248,219 km², corresponding to 2.9% of the national territory (Sao Paulo State Government 2020a). Robust and diversified, the state of Sao Paulo economy has the most significant industrial park in the country. The agricultural sector is also expressive and exhibits high levels of productivity. The state has the largest economy in the country, with a Gross Domestic Product (GDP) of R$ 2.38 trillion, corresponding to 32% of the Brazilian GDP (Sao Paulo State Government 2020a). The vehicle fleet registered in the state is represented by 29 million unities (CETESB 2020).

Geographically and for environmental management purposes, the state is divided in 15 mesoregions called Hydrographic Units for Water Resources Management (HUWRMs). Each mesoregion has a vocational unit - Industrial, In Industrialization and Farming – pointing to the predominance of the economic activities in each specific HUWRM (CETESB 2019). A map in the Supplementary material (Figure S1) shows the geographic representation of all the 15 mesoregions, as well as the location of the monitoring station in the state.

It is important to highlight four important industrial regions in the state, namely the Paraiba (river) Valley, HUWRM 2, which contains an aerospace and automotive production hub, where the presence of companies such as Embraer stands out. The valley is in between Serra do Mar and Serra da Mantiqueira and the two mountain ranges make it difficult to disperse pollutants (Veiga, Velho, and Freitas 2009). Also noteworthy is the area known as Baixada Santista, where the city of Cubatão (one of the largest industrial hub in Latin America) and the port of Santos, also one of the largest in Latin America, are located (HUWRM 7). Cubatão was considered the most polluted city in the world in the ´80s, both because of its emission and because of its geography, next to the cost but enclosured by the Serra do Mar mountain range (Vieira-Filho, Lehmann, and Fornaro 2015). Additionally, in the region known as ABCD Paulista, or greater ABC, part of the metropolitan region of Sao Paulo (MRSP), the intense automotive industry stands out. It is formed by the cities of Santo Andre, Sao Bernardo, Sao Caetano, Diadema, Maua, Ribeirao Pires e Rio Grande da Serra (HUWRM 6). Other cities in the SPMR, like Osasco, are also important because of heavy metallurgy industries. Of particular demographic prominence, the SPMR has 21 million inhabitants (48% of the population of the state) and is formed by 39 cities, including the capital - Sao Paulo city - with 11.9 million inhabitants (IBGE 2021). One-third of the vehicle fleet of the state it registered in the city of Sao Paulo (CETESB 2020). Finally, the Santa Gertrudes Ceramic Pole stands out for the concentration of ceramic flooring activity from clay, being responsible for a considerable portion of the national production of ceramic flooring. This hub encompasses the municipalities of Santa Gertrudes, Cordeirópolis, Rio Claro, Ipeúna, Limeira and Piracicaba. At this pole, the activities of extraction and handling of raw materials constitute the main sources of emission of particulate material (PM), notably by fugitive emissions, and the concentration of these activities in the municipalities makes the impacts on air quality to be significant (CETESB 2019)

Meteorological conditions that might have influenced the concentration of pollutants in the state for 2020 were reported by the Environmental Company of the State of São Paulo - CETESB (Companhia Ambiental do Estado de Sao Paulo) (CETESB 2020). March 2020 was the driest month in the state in 36 years in general, and with the exception of Santos, rainfall was below the climatological averages in all regions of the state. In April and May, the rainfall in the state continued below the climatological averages, except for Presidente Prudente.

In March, temperature averages were higher than the respective climatological averages in almost all regions, with an important exception for Paraiba Valley and the SPMR. In April and May, the monthly averages were below or close to the respective climatological averages in the RMSP, Vale do Paraíba and the North (May), South, Southwest (May) regions.

2.2 Air quality data collection

Daily mean concentrations of NO_2, O_3, PM_{10}, $PM_{2.5}$ and SO_2 were obtained from Sao Paulo state official Air Quality Monitoring Network, managed by CETESB. The network monitors air pollutants concentrations in 65 stations: **i)** 31 in the metropolitan region (MRSP), 18 of which are in the capital; **ii)** 29 in the inner part of the state; and **iii)** 5 in the coast, the region known as "Baixada Santista".

The data used in this study refer to the period of the first general state plan of mobility restrictions, i.e., from 24th March to 31st May 2020. Historical data was used for comparisons, i.e., the daily concentration data for the pollutants in the same period for the year of 2018 and 2019. Information from previous years was also retrieved. But due to the large unavailability of data in this expanded database when more years prior to 2018 were included, the number of stations became so small that it precluded any comparison with statistical significance. Therefore, only these two years were considered for historical analysis. Stations with incomplete data (less than 85% of data in the studied period in each year considered) were excluded. Considering that not all the stations monitor the pollutants of interest for this study, 49 stations in total (in 31 Sao Paulo state municipalities) were included: 27 stations for NO_2, 39 for O_3, 29 for PM_{10}, 13 for $PM_{2.5}$, and 6 for SO_2.

All the stations were identified by their official code and grouped by geographic location and HUWRMs, for the sake of interpretation of results. Stations located at the same HUWRM have the same economic vocation and similar climate conditions, allowing the implementation of customized solutions for air pollutions monitoring and control (CETESB 2020).

Stations were also identified by their spatial representation, considering the following categories (scales): **(i)** micro, related to the spatial representation of areas with dimensions from a few meters to 100 meters; **(ii)** meso, related to the spatial representation of blocks of urban areas (few blocks with similar characteristics) with dimensions between 101 and 500 meters; **(iii)** neighbourhood, related to the spatial representation of urban neighbourhood areas with uniform activity and dimensions between 501 and 4,000 meters; **(iii)** urban, related to the spatial representation of cities or metropolitan regions, in the order of 4 to 50 km (CETESB 2016). Only stations with spatial representation in microscale were considered to suffer direct and immediate impact from traffic (CETESB 2013).

Table S1 (Supplementary Material) shows the code used the state monitoring stations, station name and location, as well as their economic vocation, main economic activities and pollutants in each studied station. This table also shows which pollutants were not available for the periods of interest for this study, even when the station had the instrumental capacity to measure it.

2.3 Social isolation index data collection

Social isolation index data were obtained from the Sao Paulo Intelligent Monitoring and Information System (SIMI-SP) website at http://saopaulo.sp.gov.br/coronavirus/isolamento. The SIMI-SP was implemented through an agreement with mobile telephone operators through the ABR (Brazilian Association of Telecommunications Resources) and the IPT (Institute for Technological Research) so that the State could consult aggregated and anonymous information about displacement in the mapped São Paulo municipalities. According to the telecommunication service providers, the isolation index was based on the location of cellphones, establishing a reference to the place where the cell phone was between 10:00 pm and 2:00 am ("home Cell Site"). During the day, a cellphone that has moved away from this reference more than a certain distance (which was variable but approximately 200 meters in the city of São Paulo), was considered out of isolation. The ratio between the number of mobile phones that have moved and the total number of monitored phones, in percentage, is the so-called social isolation index. The percentage represents the population that remained inside their houses. The index was updated daily, always showing the values referring to the previous day. This time span was due to the work of the operators to aggregate and anonymize the data, before generating the indices that are passed on to SIMI-SP, respecting the privacy of each user (Sao Paulo State Government 2020a; Torres et al. 2021).

This study considered the isolation index data from the municipality where that station was placed for each air quality monitoring station. There was no isolation index data available in one case, namely one station measuring NO_2 and $PM_{10,}$ located in Santa Gertrudes, code SP_12, in the inner country.

2.4 Data analysis

Descriptive statistics were used to express the concentrations of each air pollutant in each station and the characteristics of the isolation index in the corresponding municipality where the air quality monitoring station was placed. Spearman's correlation coefficient was used to evaluate correlations between the concentrations of each air pollutant in different monitoring stations. Normality was assessed through the Shapiro-Wilk normality test. As the air pollutants' concentrations, distributions often did not follow a normal distribution, the non-parametric Wilcoxon Rank Sum Test (also called Mann-Whitney *U* test) was used to test the significance of the differences between the daily 2020 and the historical daily concentrations.

Aiming to deepen the analysis by understanding whether the levels are of concern or not, daily mean concentrations were compared with reference values to calculate exceedances, namely with WHO (2006) guidelines for 24-hour means of PM_{10} (50 µg m^{-3}), $PM_{2.5}$ (25 µg m^{-3}) and SO_2 (20 µg m^{-3}). The available original data did not allow comparisons with WHO guidelines for the other studied pollutants, NO_2 and O_3.

Statistical computations were performed with R studio, version 1.1.463, using the openair package version 2.7-2 (Carslaw and Ropkins 2012) to perform some of the analyses. The level of statistical significance was set at 0.05, except when stated otherwise. All the maps were created using the QGIS open-source software, version 3.4.4-Madeira (QGIS 2021).

3. Results

3.1 Air quality characterisation during mobility restrictions

3.1.1 Nitrogen dioxide (NO_2)

Of the 65 stations available in the state, only 42 monitor this pollutant. 27 stations had enough data to analyse NO_2, with the majority located in HUWRMs 2 and 6 (industrial vocation). Results were statistically significant in 19 (70%), with 18 showing a reduction and only one showing an increase. The biggest reductions were observed in stations within the HUWRM 2, 5 and 6, in which are located the biggest cities, including the SPMR. But stations located in farming vocation areas, namely Cataduva (SP_52), Marília (SP_54), Presidente Prudente (SP_55) also presented an important reduction in this pollutant. An important increase was seen for the city of Cubatão (SP_41) in the Baixada Satista area, characterized by its heavy industrial pole (petrochemical, chemical, steel, fertilizers, and energy).

The absolute differences between NO_2 2020 concentrations and historical data (2019 and 2018) can be seen in Table S2 (Supplementary Material) for all the stations considered for analysis. Figure S2 (Supplementary Material) shows the concentrations for this pollutant for the year 2018, 2019 and 2020.

3.1.2. Ozone (O_3)

Results for O_3 are not as homogeneous as those observed for NO_2. 54 stations monitor Ozone, although only 39 stations were included in the analysis, 18 presenting significant changes when compared to historical data, mainly located in HUWRMs 2, 5 and 6 (industrial vocation). 10 stations showed a significant increase in ozone, the majority of them being located at the Capital and at the SPMR (HUWRM 6).

Particularly, 8 stations (45% of the ones with significant results) showed a decrease of this pollutant, contrary to what is described in the literature. The decrease was homogeneously noticed for HUWRMs 2 and 5, and those stations also showed a homogeneous decrease for NO_2. Both are characterized by heavy industrial activity. Presidente Prudente (SP_55), a farming vocational station, also presented a small reduction in this pollutant.

The absolute differences between O_3 2020 concentrations and historical data can be seen in Table S2 (Supplementary Material) for all the stations considered for analysis. Figure S3 (Supplementary Material) shows the concentrations of ozone for the years 2018, 2019 and 2020.

3.1.3. Particulate matter (PM_{10} and $PM_{2.5}$)

For Particulate matter, 29 stations were included for PM_{10} (from the 54 monitoring this pollutant), 10 presenting significant changes, and for $PM_{2.5}$ 13 were included (from 31), 6 presenting significant changes. PM_{10} concentrations increases in all stations in HUWMR 7 (Baixada Santista), with Santos – Ponta da Praia (SP_45), the port area, showing an increase of 62%. Conversely, there is a reduction for $PM_{2.5}$ of 15% for this same station, as reduction of $PM_{2.5}$ was homogeneous for all the stations with significant changes of this pollutant.

It is important to highlight the city of Piracicaba (SP_10), HUWMR 5, which presented an increase of 75% in PM_{10}.

Figures S4 and S5 (Supplementary material) show the PM_{10} and $PM_{2.5}$ concentrations for the 3 years (2018, 2019 and 2020) in each analyzed station, respectively. The differences between PM_{10} and $PM_{2.5}$ 2020 concentrations and historical data (2019 and 2018) can be seen in Table S4 and S5 (Supplementary Material), respectively.

3.1.4. Sulfur dioxide (SO_2)

Figure S6 shows the SO_2 concentrations for the 3 years (2018, 2019 and 2020) in each analyzed station and Table S6 shows the absolute differences in concentrations compared to historical data, both in Supplementary material. The 3 stations with significant results showed reductions, and are located in HUWMR 6, which comprises the SPMR. The biggest reduction was verified at the Congonhas Airport station (SP_20) (35%), accompanied by a reduction of 20% in NO_2. The station located at Osasco (SP_31) also showed an important reduction of 45% and the concomitant reduction of 17% in $NO_{2.}$

3.1.5. Exceedances to the WHO guideline concentrations

Comparing the number of exceedances concerning the standards recommended by the WHO for PM_{10} daily concentration (50 µg m^{-3}), the complete results by station comparing 2020 to 2019 and 2019 to 2018 are shown in Table S7 (Supplementary Material). When comparing 2020 with 2019, the number of PM_{10} exceedances increased in 14 of the 29 stations (from 1% to 35%) and decreased in 6 (from -1% to -9%). Particularly, the stations of Piracicaba (SP_10) and Santa Gertrudes (SP-12) from interior sites, and Cubatão – Vila Parisi (SP_41) a coast site showed the highest increases in the PM_{10} exceedances in 2020 compared to 2019 (32%, 35% and 19%, respectively). Still, while Piracicaba station (SP_10) also had a relevant increase in the number of exceedances from 2018 to 2019 (19%), the other two stations had relevant decreases (-34% and -39%, respectively for SP_12 and SP_41).

Table S8 (Supplementary Material) shows the comparison of the concentration of $PM_{2.5}$ with the values recommended by the WHO (25 µg m^{-3}). It is possible to observe the number of exceedances increased in 4 of the 13 stations (1% to 4%) and decreased in 6 of them (-1% to -16%) from 2020 to 2019. The decrease in the number of exceedances was higher from 2018 to 2019 than from 2019 to 2020 in the same period. However, concerning SO_2, the WHO standard (20 µg m^{-3}) was exceeded more times in 2020 than in the same period in 2019 in 2 of the studied stations located in Cubatão (SP_41 and SP_42), respectively 5% and 3% more (Supplementary Material Table S9).

3.2 Social isolation index and association with air pollutant differences

Figure S7 (Supplementary Material) shows the time trends of the isolation index in Sao Paulo state during the mobility restrictions due to the COVID-19 pandemic, from 24th March to 31st May 2020. There was a pattern in the weekly variation of the social isolation index, being lower on Thursday and higher on weekends [Figure S7 (a)]. It is also noted that there was a reduction in adherence to these measures gradually over time during the study period [Figure S7 (b)].

Figure 1 shows the time trends of the isolation index in Sao Paulo by location of the monitoring station, showing that the same pattern can be observed for all cities, although there were important differences in the adherence to the mobility restrictions in each analyzed station. For example, in Presidente Prudente (SP_55) and Guaratingueta (SP_04), the isolation index showed results below and above 50%, respectively.

Figure 2 shows the social isolation index according to the air quality monitoring stations in the state of Sao Paulo. In terms of location, it was possible to identify that the capital, the metropolitan region and the coast presented higher levels of isolation when compared to the interior, with a decreased as the distance from the capital increased.

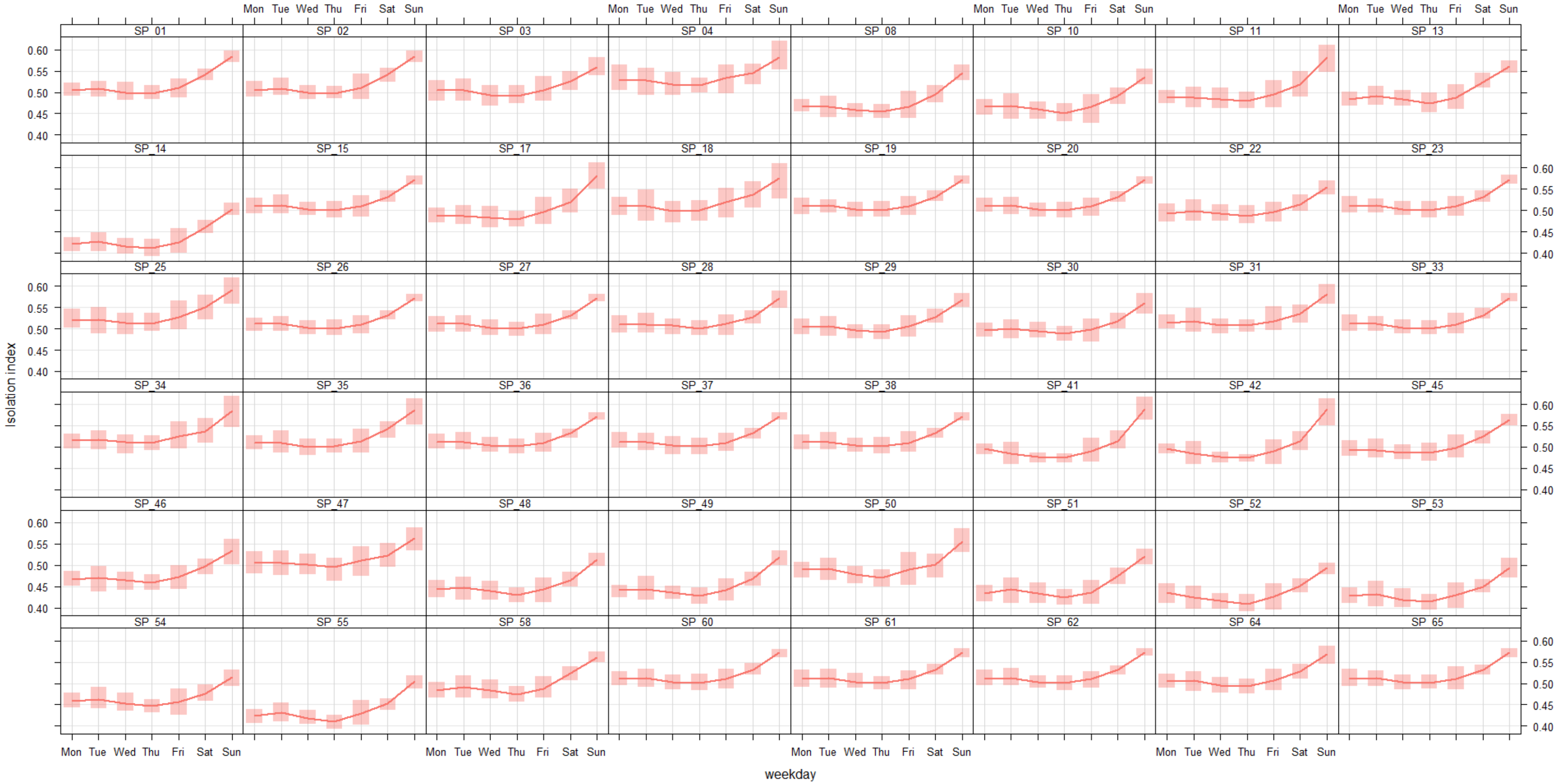

Figure 1 – Daily mean time trends by weekday of isolation index in the state of Sao Paulo during the COVID-19 mobility restrictions, from 24th March to 31st May 2020, per location of each studied air quality monitoring station

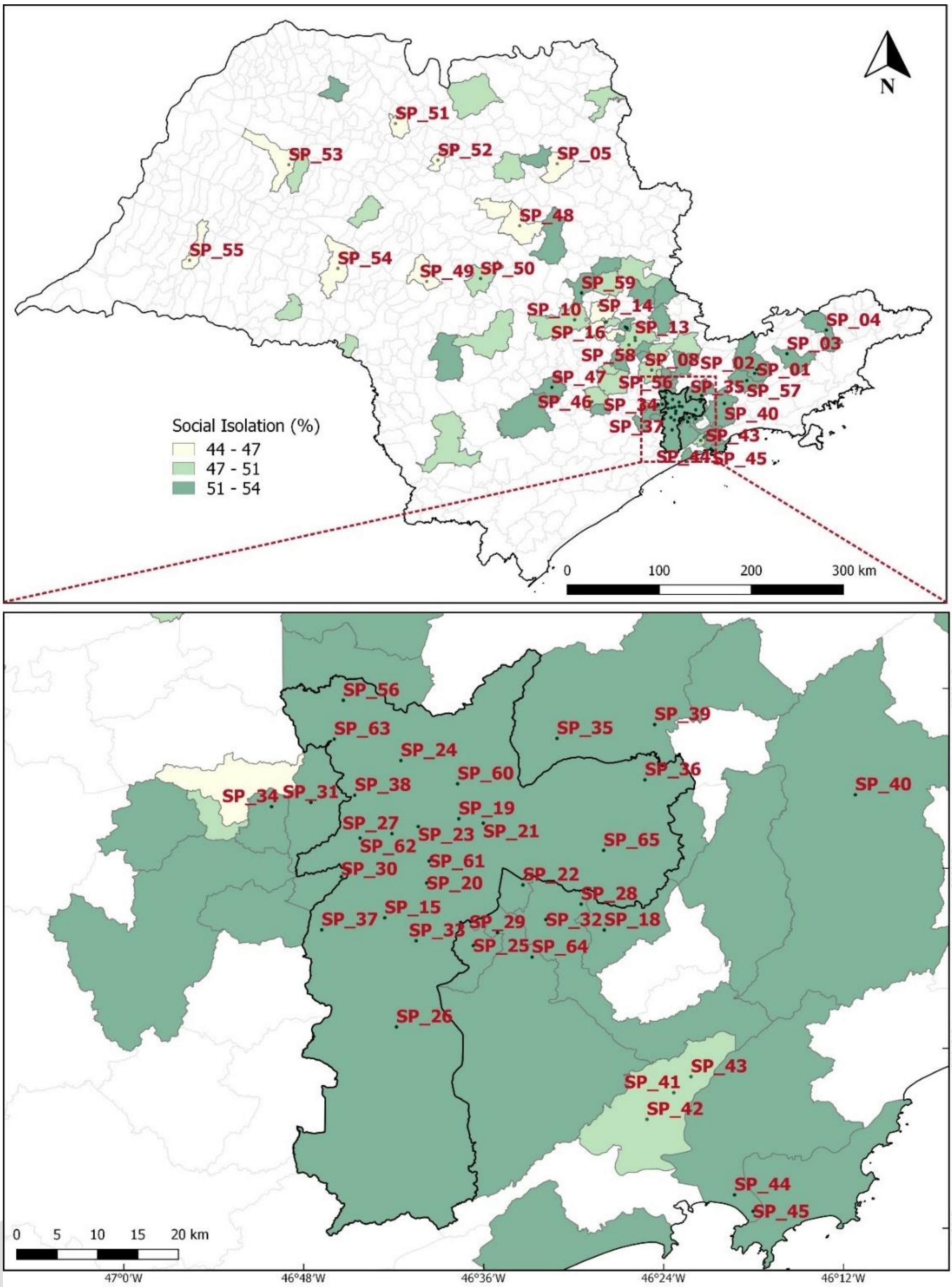

Figure 2 – Social isolation index according to the air quality monitoring stations in the state of Sao Paulo.

Figures 3-7 represent the geographical distribution of the differences (compared to the historical data) in NO_2, O_3, PM_{10}, $PM_{2.5}$ and SO_2 concentrations, respectively, in the studied period, compared to the historical years, and the social isolation index in the respective municipalities.

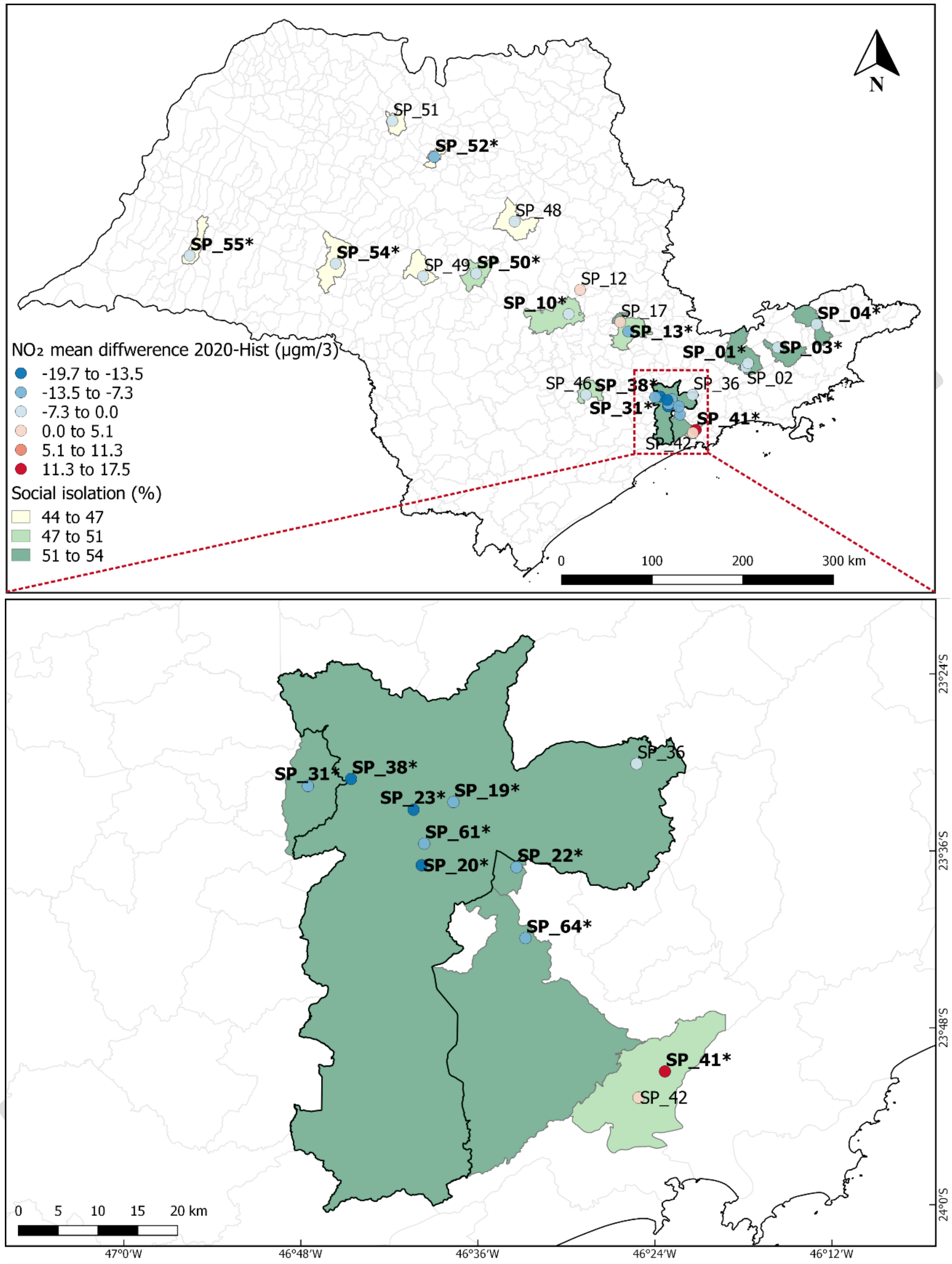

Figure 3 – Geographical representation of the differences in nitrogen dioxide (NO_2) concentration in the studied period (24/03-31/05) compared to the historical years (2019 and 2018) and social isolation index in the respective municipalities of Sao Paulo state. Air quality station with bold* showed significant reductions ($p\text{-value} < 0.05$).

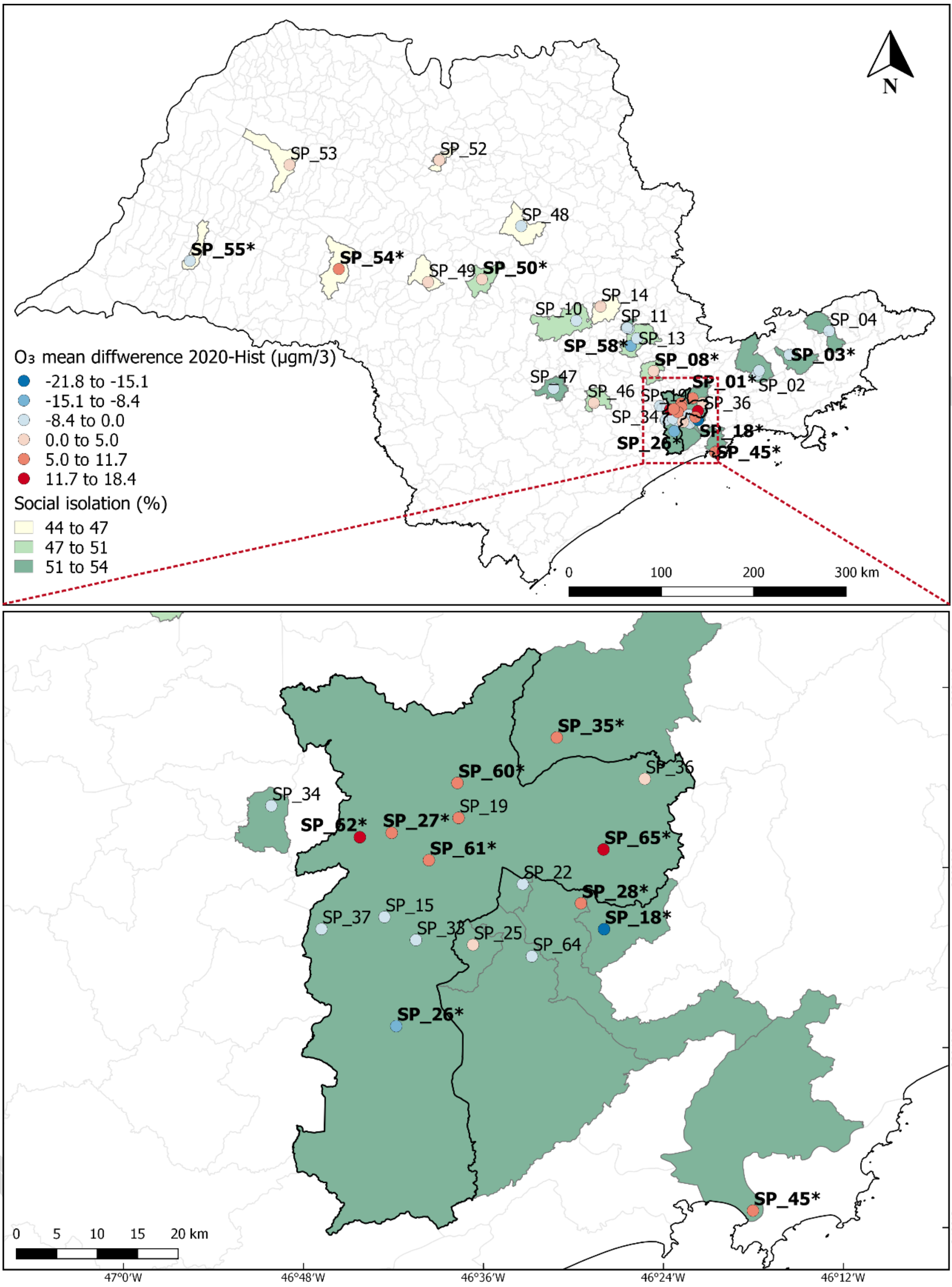

Figure 4 – Geographical representation of the differences in ozone (O_3) concentration in the studied period (24/03-31/05) between 2020 and the historic years (2019 and 2018), and social isolation index in the respective municipalities of Sao Paulo state. Air quality station with bold* showed significant reductions (p-value < 0.05).

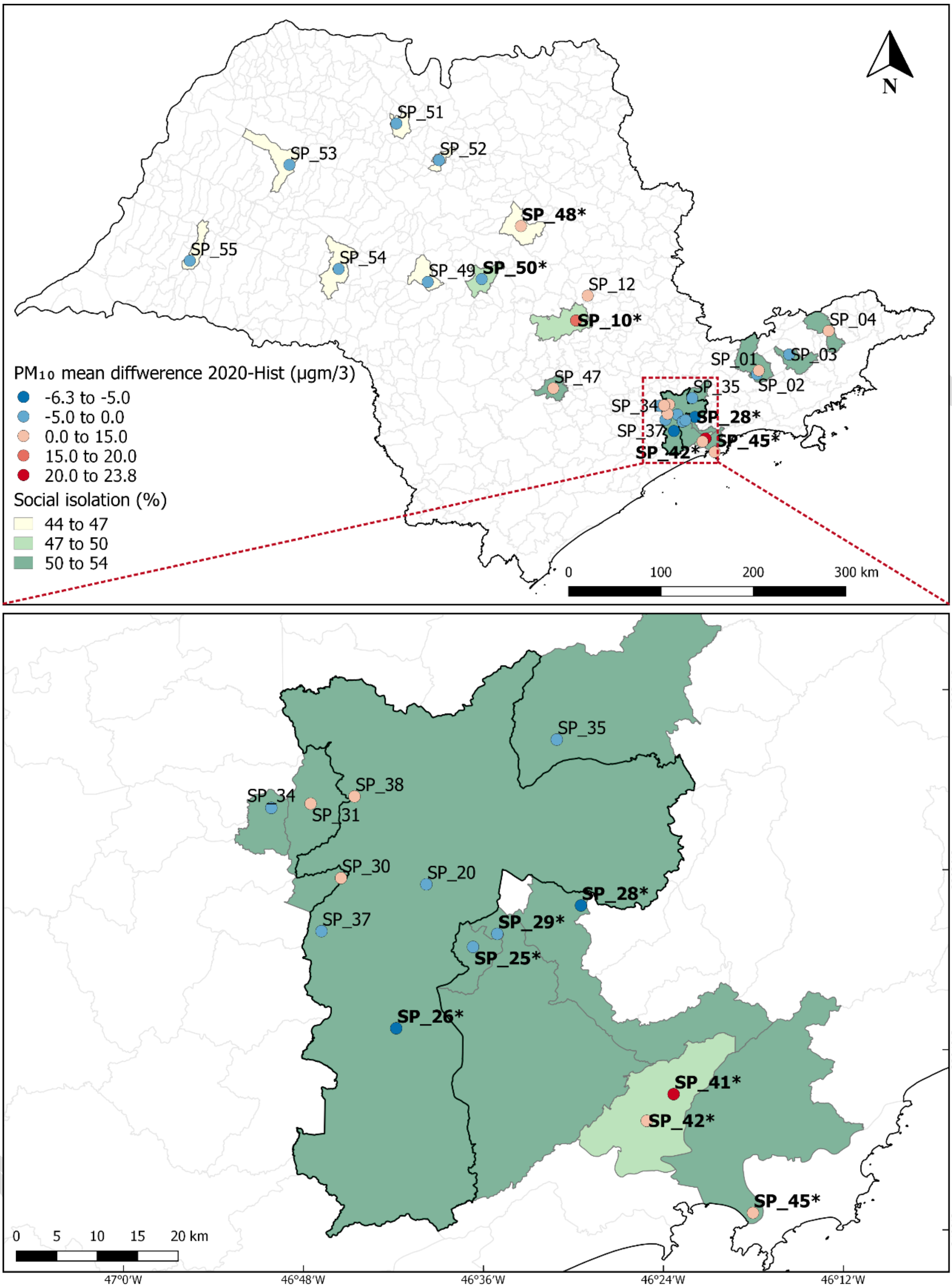

Figure 5 – Geographical representation of the differences in particulate matter (PM_{10}) concentration in the studied period (24/03-31/05) between 2020 and the historic years (2019 and 2018), and social isolation index in the respective municipalities of Sao Paulo state. Air quality station with bold* showed significant reductions (p-value < 0.05).

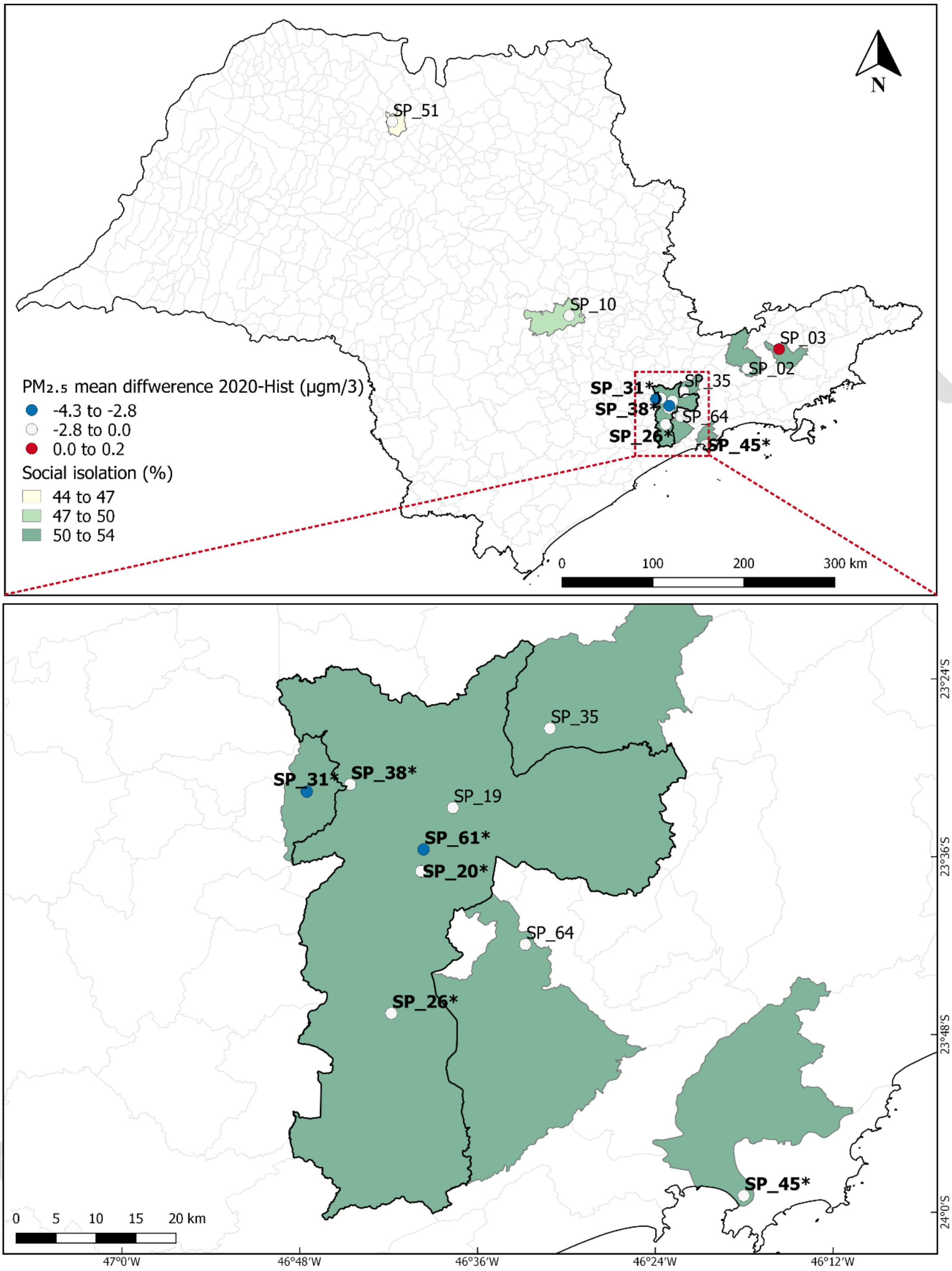

Figure 6 – Geographical representation of the differences in particulate matter (PM$_{2.5}$) concentration in the studied period (24/03-31/05) between 2020 and the historic years (2019 and 2018), and social isolation index in the respective municipalities of Sao Paulo state. Air quality station with bold* showed significant reductions (p-value < 0.05).

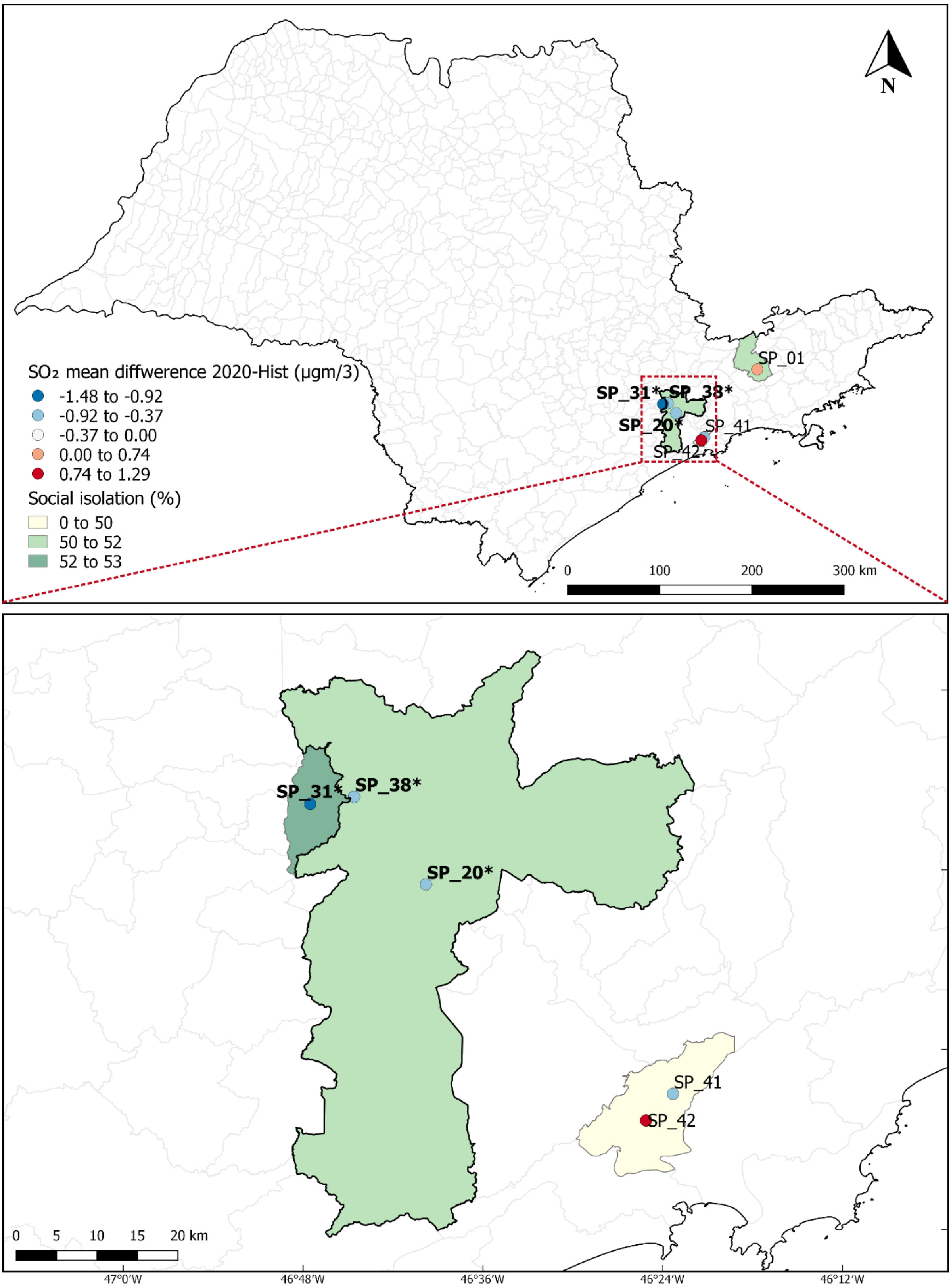

Figure 7 – Geographical representation of the differences in sulfur dioxide (SO_2) concentration in the studied period (24/03-31/05) between 2020 and the historical years (2019 and 2018), and social isolation index in the respective municipalities of Sao Paulo state. Air quality station with bold* showed significant reductions (p-value < 0.05).

Table 1 summarizes all the results found for significant or non-significant changes in pollutants, the respective percentage variation by station and the missing data (whether they are supposed to be available or not being measured by a particular station). It also shows the exceedances to the WHO standards for PM_{10}, $PM_{2.5}$ and SO_2 for all the stations where data where available.

Table 1 – Summary of main results for NO_2, O_3, PM_{10}, $PM_{2.5}$, and SO_2 measures in the 65 stations of the state of Sao Paulo, comparing average daily concentrations from 24th March 2020 to 31st May 2020 (first social isolation measures imposed by the State Government during COVID outbreak). Stations with missing data and not measuring specific pollutants are also represented. Exceedances of the WHO standards for PM and SO_2 are also shown for the historical years.

HUWRM	Station Number	Station Name	Vocational Unity	Location	Escale/Traffic Influence	NO_2 variation	O_3 variation	PM_{10} variation	$PM_{2.5}$ variation	SO_2 variation	exceedance PM_{10} WHO guidelines		exceedance $PM_{2.5}$ WHO guidelines		exceedance SO_2 WHO guidelines	
											(2019-2018)	**(2020-2019)**	**(2019-2018)**	**(2020-2019)**	**(2019-2018)**	**(2020-2019)**
2	**SP_04**	Guaratinguetá	Industrial	Paraiba Valley	Urban/N	**↓(17%)**	−	−	**M**	**M**	0%	0%				
	SP_57	Jacareí	Industrial	Paraiba Valley	Neighborhood/N	**M**	**M**	**M**	▨	▨						
	SP_01	São José dos Campos	Industrial	Paraiba Valley	Neighborhood/N	**↓(13%)**	**↓(12%)**	−	**M**	−	0%	0%			0%	0%
	SP_02	São José dos Campos - Jd Satelite	Industrial	Paraiba Valley	Neighborhood/N	−	−	−	**−**	**M**	0%	0%	3%	3%		
	SP_03	Taubaté	Industrial	Paraiba Valley	Neighborhood/N	**↓(19%)**	**↓(10%)**	−	**−**	**M**	1%	1%	1%	1%		
4	**SP_05**	Ribeirão Preto	In industrialization	Interior	Neighborhood/N	**M**	**M**	**M**	**M**	▨						
5	**SP_16**	Americana	Industrial	Close Interior	Neighborhood/N	▨	▨	**M**	**M**	▨						
	SP_07	Americana-Vila Santa Maria	Industrial	Close Interior	Neighborhood/N	▨	▨	**M**	**M**	▨						
	SP_06	Campinas - Centro	Industrial	Close Interior	Micro/Y	▨	▨	**M**	▨	▨						
	SP_13	Campinas - Taquaral	Industrial	Close Interior	Neighborhood/N	**↓(21%)**	−	**M**	**M**	**M**						
	SP_58	Campinas - Vila União	Industrial	Close Interior		**M**	**↓(13%)**	**M**	**M**	**M**						
	SP_08	Jundiaí	Industrial	Close Interior	Urban/N	**M**	**↓(6%)**	**M**	**M**	**M**						
	SP_14	Limeira	Industrial	Close Interior	Neighborhood/N	**M**	−	**M**	**M**	**M**						
	SP_11	Paulínia	Industrial	Close Interior	Neighborhood/N	**M**	−	**M**	**M**	**M**						
	SP_17	Paulínia - Santa Terezinha	Industrial	Close Interior	Neighborhood/N	−	−	**M**	**M**	**M**						
	SP_09	Paulínia-Sul	Industrial	Close Interior	Neighborhood/N	**M**	**M**	**M**	**M**	▨						
	SP_10	Piracicaba	Industrial	Close Interior	Neighborhood/N	**↓(12%)**	**↓(7%)**	**↑(75%)**	−	**M**	19%	32%	0%	0%		
	SP_59	Rio Claro - Jardim Guanabara	Industrial	Close Interior	Neighborhood/N	▨	**M**	**M**	**M**	▨						
	SP_12	Santa Gertrudes	Industrial	Close Interior	Neighborhood/N	−	**M**	**−**	**M**	**M**	-34%	35%				

↓ Statistically different and lower concentration; ↑ Statistically different and higher concentration; − Monitoring station without statistically significant differences; **M,** missing data; gray cells highlight pollutants not being measured by a particular station; **N**, no direct influence of traffic; **Y**, direct influence of traffic.

Table 1 (cont.) – Summary of main results for NO_2, O_3, PM_{10}, $PM_{2.5}$, and SO_2 measures in the 65 stations of the state of Sao Paulo, comparing average daily concentrations from 24th March 2020 to 31st May 2020 (first social isolation measures imposed by the State Government during COVID outbreak). Stations with missing data and not measuring specific pollutants are also represented. Exceedances of the WHO standards for PM and SO_2 are also shown for the historical years.

HUWRM	**Station Number**	**Station Name**	**Vocational Unity**	**Location**	**Escale/Traffic Influence**	**NO_2 variation**	**O_3 variation**	**PM_{10} variation**	**$PM_{2.5}$ variation**	**SO_2 variation**	**exceedance PM_{10} WHO guidelines**		**exceedance $PM_{2.5}$ WHO guidelines**		**exceedance SO_2 WHO guidelines**	
											(2019-2018)	**(2020-2019)**	**(2019-2018)**	**(2020-2019)**	**(2019-2018)**	**(2020-2019)**
6	**SP_37**	Capão Redondo	Industrial	Capital	Neighborhood/N	**M**	−	−	**M**	**M**	0%	0%				
	SP_34	Carapicuíba	Industrial	Capital	Neighborhood/N	**M**	−	−	**M**	**M**	-3%	1%				
	SP_23	Cerqueira César	Industrial	Capital	Micro/Y	**↓(31%)**	**M**	**M**	**M**	**M**						
	SP_62	Cidade Universitária - IPEN	Industrial	Capital	Neighborhood/N	**M**	**↑(29%)**	**M**	**M**	**M**						
	SP_20	Congonhas Airport	Industrial	Capital	Micro/Y	**↓(20%)**	**M**	−	**↓(15%)**	**↓(35%)**	3%	4%	-22%	-4%	0%	0%
	SP_25	Diadema	Industrial	SPMR	Neighborhood/N	**M**	−	**↓(9%)**	**M**	**M**	3%	3%				
	SP_26	Grajaú - Parelheiros	Industrial	Capital		**M**	**↓(14%)**	**↓(15%)**	**↓(15%)**	**M**	-45%	-9%	-24%	-8%		
	SP_35	Guarulhos - Paço Municipal	Industrial	SPMR	Urban/N	**M**	**↑(11%)**	−	−	**M**	4%	7%	-7%	4%		
	SP_39	Guarulhos - Pimentas	Industrial	SPMR	Neighborhood/N	**M**	**M**	**M**	**M**	**M**						
	SP_61	Ibirapuera	Industrial	Capital	Meso/N	**↓(21%)**	**↑(10%)**	**M**	**↓(28%)**	**M**			-10%	-1%		
	SP_33	Interlagos	Industrial	Capital	Neighborhood/N	**M**	−	**M**	**M**	**M**						
	SP_36	Itaim Paulista	Industrial	Capital	Neighborhood/N	**↓(13%)**	−	**M**	**M**	**M**						
	SP_65	Itaquera	Industrial	Capital	Meso/N	**M**	**↑(23%)**	**M**	**M**	**M**						
	SP_38	Marginal Tietê - Ponte dos Remédios	Industrial	Capital	Micro/Y	**↓(15%)**	**M**	−	**↓(13%)**	**↓(19%)**	-4%	1%	-28%	0%	0%	0%
	SP_18	Mauá	Industrial	SPMR	Neighborhood/N	**M**	**↓(34%)**	**M**	**M**	**M**						
	SP_40	Mogi das Cruzes	Industrial	SPMR												
	SP_21	Mooca	Industrial	Capital	Meso/N		**M**	**M**	**M**							
	SP_24	Nossa Senhora do Ó	Industrial	Capital	Meso/N		**M**	**M**								
	SP_31	Osasco	Industrial	SPMR	Micro/Y	**↓(17%)**	**M**	−	**↓(19%)**	**↓(45%)**	-13%	-2%	-42%	-16%	0%	0%
	SP_19	Parque Dom Pedro II	Industrial	Capital	Neighborhood/N	**↓(19%)**	−	**M**	−	**M**			-13%	0%		
	SP_56	Perus	Industrial	Capital			**M**	**M**	**M**							
	SP_63	Pico do Jaraguá	Industrial	Capital												
	SP_27	Pinheiros	Industrial	Capital	Micro/Y	**M**	**↑(15%)**	**M**	**M**	**M**						
	SP_60	Santana	Industrial	Capital	Meso/N	**M**	**↑(17%)**	**M**	**M**	**M**			-10%	-1%		
	SP_15	Santo Amaro	Industrial	SPMR	Meso/N	**M**	−	**M**	**M**	**M**						
	SP_28	Santo André - Capuava	Industrial	SPMR	Neighborhood/N	**M**	**↑(10%)**	**↓(23%)**	**M**	**M**	0%	0%				
	SP_32	Santo André - Paço Municipal	Industrial	SPMR	Meso/N			**M**								
	SP_64	São Bernardo - Centro	Industrial	SPMR	Micro/Y	**↓(18%)**	−	**M**	−	**M**			-16%	-3%		
	SP_29	São Bernardo - Paulicéia	Industrial	SPMR	Neighborhood/N	**M**	**M**	**↓(12%)**	**M**	**M**	-7%	-3%				
	SP_22	São Caetano do Sul	Industrial	SPMR	Meso/N	**↓(21%)**	−	**M**	**M**	**M**						
	SP_30	Taboão da Serra	Industrial	Capital	Meso/N	**M**	**M**	−	**M**	**M**	-9%	-9%				

↓ Statistically different and lower concentration; ↑ Statistically different and higher concentration; − Monitoring station without statistically significant differences; **M,** missing data; gray cells highlight pollutants not being measured by a particular station; **N**, no direct influence of traffic; **Y**, direct influence of traffic.

Table 1 (cont.) – Summary of main results for NO_2, O_3, PM_{10}, $PM_{2.5}$, and SO_2 measures in the 65 stations of the state of Sao Paulo, comparing average daily concentrations from 24th March 2020 to 31st May 2020 (first social isolation measures imposed by the State Government during COVID outbreak). Stations with missing data and not measuring specific pollutants are also represented. Exceedances of the WHO standards for PM and SO_2 are also shown for the historical years.

HUWRM	**Station Number**	**Station Name**	**Vocational Unity**	**Location**	**Escale/ Traffic Influence**	**NO_2 variation**	**O_3 variation**	**PM_{10} variation**	**$PM_{2.5}$ variation**	**SO_2 variation**	**exceedance PM_{10} WHO guidelines**		**exceedance $PM_{2.5}$ WHO guidelines**		**exceedance SO_2 WHO guidelines**	
											(2019-2018)	**(2020-2019)**	**(2019-2018)**	**(2020-2019)**	**(2019-2018)**	**(2020-2019)**
7	**SP_42**	Cubatão - Centro	Industrial	Baixada Santista	Neighborhood/N	**–**	**M**	**↑(12%)**	**M**	–	-3%	-1%			3%	2%
	SP_43	Cubatão - Vale do Mogi	Industrial	Baixada Santista	Neighborhood/N	**M**	**M**	**M**	▨	**M**						
	SP_41	Cubatão - Vila Parisi	Industrial	Baixada Santista	Neighborhood/N	**↑(22%)**	**M**	**↑(35%)**	**M**	–	-39%	19%			5%	-3%
	SP_44	Santos	Industrial	Coast	Neighborhood/N	▨	**M**	**M**	▨	▨						
	SP_45	Santos - Ponta da Praia	Industrial	Coast	Neighborhood/N	**M**	**↑(17%)**	**↑(62%)**	**↓(15%)**	**M**	16%	16%	-5%	-3%		
10	**SP_46**	Sorocaba	Industrial	Close Interior	Neighborhood/N	–	–	**M**	**M**	**M**						
	SP_47	Tatuí	Industrial	Close Interior	Neighborhood/N	**M**	–	–	**M**	**M**	4%	6%				
13	**SP_48**	Araraquara	In industrialization	Countryside	Neighborhood/N	–	–	**↑(15%)**	**M**	**M**	3%	3%				
	SP_49	Bauru	In industrialization	Countryside	Neighborhood/N	–	–	–	**M**	**M**	0%	0%				
	SP_50	Jaú	In industrialization	Countryside	Neighborhood/N	**↓(13%)**	**↑(3%)**	**↓(10%)**	**M**	**M**	-1%	0%				
15	**SP_52**	Catanduva	Farming	Countryside	Urban/N	**↓(18%)**	–	–	**M**	**M**	-16%	3%				
	SP_51	São José do Rio Preto	Farming	Countryside	Urban/N	–	**M**	–	–	**M**	-10%	-3%	0%	4%		
19	**SP_53**	Araçatuba	Farming	Countryside	Urban/N	**M**	–	–	**M**	**M**	-3%	1%				
21	**SP_54**	Marília	Farming	Countryside	Neighborhood/N	**↓(16%)**	**↑(13%)**	–	**M**	**M**	0%	0%				
22	**SP_55**	Presidente Prudente	Farming	Countryside	Urban/N	**↓(16%)**	**↓(6%)**	–	**M**	**M**	0%	0%				

↓ Statistically different and lower concentration; ↑ Statistically different and higher concentration; − Monitoring station without statistically significant differences; **M,** missing data; gray cells highlight pollutants not being measured by a particular station; **N**, no direct influence of traffic; **Y**, direct influence of traffic.

4. Discussion

As shown in figures 1 to 7, the behaviour of the social isolation index varies over the weeks for each location considered, but with a similar pattern for the entire state. This behaviour was observed in other countries and have been attributed to different economic, cultural, political and emotional factors (Ajzenman, Cavalcanti, and Da Mata 2020; Bavel et al. 2020; Hoeben et al. 2021). But it is worth noting that adherence to social isolation measures is lower the greater the distance from the capital. This fact was reported during the isolation measures in Brazil and showed to be a reflection of two components: the distance from the decision-making centre and political reasons. As decisions are taken independently at the federal, state and municipal levels and there was a discrepancy in the understanding between the federal government and the state government, it caused many mayors in the interior areas to be resistant to state decrees (Varella, Zeine, and Ribeiro 2020). Those discrepancies make the establishment of the correlation with the social isolation index very difficult to be evaluated, showing a weak and variable correlation even when an analysis is done week by week, for all pollutants (data not shown). Part of this impossibility of correlation is also due to the small sample size (69 days) and the lack of data in many stations, as can be seen in Table 1. (Rudke, Martins, de Almeida, Martins, Beal, Hallak, Freitas, Andrade, Foroutan, Baek, and de A. Albuquerque 2021) found similar results when trying to correlate air quality changes with mobility reduction in the state of Sao Paulo, using mobility data from Apple "Mobility Trends Reports" obtained from information of anonymous smartphone users during their displacements. Although data is disaggregated by transport mode type, representativeness of mobility can be very low, as the navigation function should be enabled and the market share of iOS (Apple operational system for mobile) in Brazil for the considered period is only 14% (Statista 2021). In addition, Apple data was not disaggregated by municipality and is only available at the state level.

However, although it was not possible to establish a clear correlation with the social isolation index, some stations are known to receive direct influence from traffic, as it is the case of micro-scale stations.

Congonhas Airport (SP_20), Marginal Tiete – Ponte dos Remédios (SP_38) and Osasco (SP_31) are micro-scale stations that had data for NO_2, $PM_{2.5}$ and SO_2 and showed an important decrease in those pollutants, indicating the influence of traffic reduction. It is worth mentioning that the station located at Congonhas is probably indicating also a reduction in emissions from airplanes (Shikwambana and Kganyago 2021).

In the specific case of NO_2, a reduction can be seen in all stations in the state, except for Cubatão, even those located in regions of low industrialization or with agricultural predominance such as Cataduva (SP_52), Marília (SP_54), Presidente Prudente (SP_55). This shows that the concentration of this pollutant in the local atmosphere is greatly affected by restrictions in mobility, even when they are of short duration. This was also demonstrated by (Briz-Redón, Belenguer-Sapiña, and Serrano-Aroca 2021) for most important Spanish cities. Since NO_2 comes essentially from the oxidation of NO by O_3 and NO comes from the combustion process, this reduction is chemically expected (Tobías et al. 2020). This pattern is in agreement with the findings of all studies carried out for São Paulo.

(Nakada & Urban, 2020) e (Rudke, Martins, de Almeida, Martins, Beal, Hallak, Freitas, Andrade, Foroutan, Baek, and de A. Albuquerque 2021) also verified the increase of this pollutant in the Cubatão-Vila Parisi (SP_41), a station that is strongly marked by industrial activities and do not have influence of local traffic. The industrial activity in this area did not suffer interruptions (FIESP 2020), but due to the pandemic, there was a reduction in industrial production activities, especially in the fertilizer units (CETESB 2020). Despite this, in the last four years, the average concentrations of stations Cubatão-Vila Parisi remained practically stable. The drop that occurred in previous years, as well as the maintenance in recent years, may be related to the more favourable meteorological conditions observed in the region (CETESB 2020), explaining also the significant increase in PM_{10} at this station, of around 35%.

The almost homogeneous results for the reduction of NO_2 cannot be verified for the O_3. Although there is a chemical relationship, and the reduction of NO_2 means greater availability of O_3, in many stations reductions were verified in this pollutant, and this result was observed consistently across HUWRM 2 and HUWRM 5. There is an overall reduction trend, but it is small compared to the reduction of NO_2. This shows that the weather and conditions for the formation of precursors cannot be ignored (Adams 2020). As O_3 is not directly emitted but rather produced in the presence of NOx, VOCs and solar radiation, there are more factors that need to be considered. The mismatch of this association with the results should be highlighted and can be attributed to the capability of the meteorological variables to affect the formation of O_3, among others, especially when most of the stations for which this pollutant has been reported are not micro-scale stations, as can be seen in Table 1. According to CETESB, (2020) only April had weather conditions favourable to the formation of high concentrations of ozone. Exceedance of this pollutant was verified in five days, all of which at the Itaquera (SP_65) station, when, in most cases, the state was under the influence of an area of continental instability, on days with high temperatures and high incidence of solar radiation. In addition to the meteorological effect, the effect of the mobility restriction measure may have been the reduction of precursors from the transport sector, industrial processes and the use of solvents (Adams, 2020). Particularly in the Paraiba Valley region, although industrial activity has not been halted, many companies that make heavy use of solvents, such as car and aircraft manufacturers, chose to give collective vacations to their employees in the initial three weeks of the isolation measures established by the state government (Rodrigues 2020).

Ibirapuera (SP_61), Itaquera (SP_65) and IPEN - Cidade Universitaria (SP_62) were the stations with the highest number of exceedances for ozone for 2020 (data not shown). This high number of exceedances comes from the transport of ozone or its precursors from more distant locations, by the action of the winds of the ES quadrant (CETESB 2020). Pinheiros (SP_27) station is the only one on a micro-scale that has data for this pollutant, and shows an increase, in agreement with what is reported in the literature.

Regarding PM_{10}, although there is a large number of stations that measure this pollutant in the state of São Paulo (57 in total), only about half of them (28) had data available for the analyses, which in itself brings an important limitation for the study. Among these, only 10 bring significant results, and HUWMR 7 (Baixada Santista) presents this pollutant increased in all stations. HUWMR 6, on the other hand, shows a reduction in all stations, indicating that it may be associated with vehicle circulation reduction, the main source of PM_{10} in the capital and metropolitan region.

It is worth mentioning the increase in Piracicaba (SP_10), which belongs to the Santa Gertrudes Ceramic Pole. The PM_{10} is therefore strongly associated with industrial activity in this region, but the increase in concentration in 2020 is probably associated with the absence of precipitation and the increased number of fire outbreaks in the state, that tends to affect more the cities in the countryside area (Rudke, Martins, de Almeida, Martins, Beal, Hallak, Freitas, Andrade, Foroutan, Baek, and de A. Albuquerque 2021)

Also in Santos (SP_45), the average concentration increased in 2020 compared to 2019, inflecting the downward curve that had been observed in previous years. This increase in concentrations may be associated with port activity, especially the intense movement of grains that took place in 2020, since, based on port movement reports, there were monthly records in grain exports (CODESP 2020). The reduction in concentrations at the Santos-Ponta da Praia station, observed in previous years, was associated with the improvement of operating procedures in the handling of grains and cereals at the Port of Santos, as well as the more favorable meteorological conditions for the dispersion of pollutants observed in those years (CETESB 2020).

Regarding $PM_{2.5}$, all stations showed a reduction in this pollutant, but the large number of stations from which it was not possible to recover the data is also noteworthy. Of 31 stations measuring this pollutant,only 18 had data and only 6 showed significant reduction, 5 of them in the RMSP and 1 in Santos (SP_45).

The SO_2 concentrations in the few stations presenting significant results were lower than the historical years. Despite being an expected result, it is worth noting that the emission control plans for this pollutant, both vehicular and industrial, have already caused, in recent years, a significant reduction in emissions throughout the state (CETESB 2019).

5. Conclusions

65 stations throughout the State of São Paulo were used to assess changes in air quality in 31 municipalities during the first general State plan of mobility restrictions due to the COVID-19 pandemic (24th March to 31st May 2020). Nitrogen dioxide (NO_2), ozone (O_3), particulate matter PM_{10} and $PM_{2.5}$ and sulphur dioxide (SO_2) concentrations were assessed. Although the reduction of pollutants such as NO_2, SO_2 and $PM_{2.5}$ is very clear, the economic and climatic characteristics of each region were decisive in the general behaviour of O_3 and PM_{10}.

Even with the availability of data to assess the mobility of individual municipalities, it was not possible to establish a correlation between the pollutants and the social isolation index, partly due to the lack of data, partly due to the compliance of the population to those measurements, which was variable over time. It is also important to highlight that each municipality in the state had the autonomy to assess its own restriction measures, and there was no mandatory lockdown, making the isolation index variable in each municipality. Another important limitation factor was the absence of data related to the pollutants of interest in many of the stations.

Even so, the isolation measures carried out in the state opened the opportunity to individually assess the air quality measurements in each of the stations, allowing, in the future, that air quality policies be designed together with local sanitary policies.

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