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Air pollution and COVID-19 lockdown in a large South American city: Santiago Metropolitan Area, Chile

Richard Toro A. [a], Francisco Catalán [a], Francesco R. Urdanivia [b], Jhojan P. Rojas [b], Carlos A. Manzano [a,c], Rodrigo Seguel [d,e], Laura Gallardo [d,e], Mauricio Osses [f], Nicolás Pantoja [f], Manuel A. Leiva-Guzman [a,*]

[a] *Department of Chemistry, Faculty of Sciences, University of Chile, Santiago, Chile*
[b] *National Service of Meteorology and Hydrology, Lima, Peru*
[c] *School of Public Health, San Diego State University, San Diego, USA*
[d] *Center for Climate and Resilience Research (CR)2, Santiago, Chile*
[e] *Department of Geophysics, School of Physical and Mathematical Sciences, University of Chile, Santiago, Chile*
[f] *Departamento Ingeniería Mecánica, Universidad Técnica Federico Santa María (UTFSM), Santiago, Chile*

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ABSTRACT

The implementation of confinement and physical distancing measures to restrict people's activities and transit in the midst of the COVID-19 pandemic allowed us to study how these measures affect the air quality in urban areas with high pollution rates, such as Santiago, Chile. A comparative study between the concentrations of PM10, PM2.5, NOx, CO, and O3 during the months of March to May 2020 and the corresponding concentrations during the same period in 2017–2019 is presented. A combination of surface measurements from the air quality monitoring network of the city, remote satellite measurements, and simulations of traffic activity and road transport emissions allowed us to quantify the change in the average concentrations of each pollutant. Average relative changes of traffic emissions (between 61% and 68%) implied statistically significant concentrations reductions of 54%, 13%, and 11% for NOx, CO, and PM2.5, respectively, during the pandemic period compared to historical period. In contrast, the average concentration of O3 increased by 63% during 2020 compared to 2017–2019. The nonlinear response observed in the pollution levels can be attributed to the changes in the vehicular emission patterns during the pandemic and to the role of other sources such as residential emissions or secondary PM.

1. Introduction

The spread of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which causes coronavirus disease 2019 (COVID-19), has put everyone on alert (Harapan et al., 2020; Sohrabi et al., 2020; WHO, 2020a; WHO, 2020b). It was in December 2019 in the city of Wuhan, China, where the first cases were reported, and it then it spread to almost the entire world (Sohrabi et al., 2020; Cui et al., 2020). To slow down the advance of SARS-CoV-2 and thereby avoid a collapse of the health system, local governments have taken measures to control the pandemic by generating effective physical distancing among people (Pradhan et al., 2020). One of these

* Corresponding author.
E-mail address: manleiva@uchile.cl (M.A. Leiva-Guzman).

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measures has been the application of partial or total lockdowns in cities. This, in addition to generating the desired effect of distancing, has produced a reduction of some air pollutants and the increase of others in some urban areas (Anjum, 2020; Bao and Zhang, 2020; Chen et al., 2020; Dutheil et al., 2020; Muhammad et al., 2020; Seguel et al., 2020a).

In many cities around the world, significant reductions in particulate matter (PM), carbon monoxide (CO) and nitrogen dioxide (NO_2) levels have been observed during periods of city lockdown (Bao and Zhang, 2020; Chen et al., 2020; Abdullah et al., 2020; Berman and Ebisu, 2020; Collivignarelli et al., 2020; Dantas et al., 2020; He et al., 2020; Mahato et al., 2020; Nakada and Urban, 2020; Sharma et al., 2020; Siciliano et al., 2020; Tobías et al., 2020; Wang et al., 2020). For example, in 44 cities in China, the concentrations of sulfur dioxide (SO_2), PM with an aerodynamic diameter of <2.5 μm ($PM_{2.5}$), and of <10 μm (PM_{10}), NO_2, and carbon monoxide (CO) have decreased 7%, 6%, 14%, 25%, and 5%, respectively, compared to previous years (Bao and Zhang, 2020). This was mainly associated with a drop in vehicular flow, which was estimated to have reduced by up to 70% (Bao and Zhang, 2020). Likewise, of the 324 cities in China where lockdown measures were applied, 95 of them showed improvements in their air quality indices due to $PM_{2.5}$ concentration reductions of 25% (the cities with total lockdown) or 8% (the more industrialized cities or those with partial lockdowns) (He et al., 2020). These improvements implied a substantial benefit to the health of local people, since air pollution in general, and particle air pollution in particular, are associated with higher mortality and morbidity rates in humans (He et al., 2020). In 22 cities in India, reductions of 43%, 31%, 10%, and 18% have been observed for $PM_{2.5}$, PM_{10}, CO, and NO_2, respectively, compared to previous years; while there was an increase of 17% in ozone (O_3) (Sharma et al., 2020). In New Delhi, it was estimated that the concentrations of PM_{10}, $PM_{2.5}$, and NO_2 were reduced by 50%, while CO was reduced by 31%, NH_3 was reduced by 4%, and O_3 showed a slight increase (0.3%) (Mahato et al., 2020).

In European cities, the reduction in atmospheric pollutant concentrations during lockdown periods has also been reported. In the city of Milan, Italy, significant concentrations reductions were observed for PM_{10} and $PM_{2.5}$ (up to 47%), black carbon (BC, up to 71%), benzene (up to 65%), CO (up to 49%), and NO_X (nitrogen oxides: $NO_X = NO_2 + NO$, up to 58%). Meanwhile, O_3 increased by up to 20% (Collivignarelli et al., 2020). In the city of Barcelona, Spain, similar results have been reported. The mean concentrations of PM_{10} decreased by 31% during the lockdown period compared to previous weeks without lockdown (Tobías et al., 2020). For BC, the reduction was 45%, and for NO_2, it was up to 51%. The average daily concentrations of O_3 increased markedly (up to 58%) (Tobías et al., 2020).

Cities in Latin America have also recorded this reduction in air pollutants during the lockdowns motivated by the COVID-19 pandemic (Seguel et al., 2020a; Mendez-Espinosa et al., 2020), such as the metropolitan areas of Sao Paulo (Nakada and Urban, 2020) and Rio de Janeiro (Dantas et al., 2020; Siciliano et al., 2020) in Brazil and Lima-Callao in Peru (Rojas et al., 2021). In Brazil, the city of Sao Paulo, under partial lockdown, showed a decrease of 65%, 77%, and 54% in the concentrations of CO, NO, and NO_2, respectively, when compared to a 5-years monthly average. In contrast, O_3 showed an increase of 30% (Nakada and Urban, 2020). In Rio de Janeiro, reductions have been smaller than in Sao Paulo: the CO concentrations were reduced by up to 49%, NO_2 decreased less, and PM_{10} decreased 24%, during the fourth of six partial lockdown weeks. O_3 increased 48% on average (Dantas et al., 2020). In Lima-Callao the concentrations decreased during the six weeks of lockdown compared to the previous six weeks, with PM_{10}, $PM_{2.5}$, and NO_2 reducing up to 40%, 31%, and 46%, respectively (Rojas et al., 2021). Again, O_3 increased by approximately 13%.

All the examples above show how the physical confinement of the population combined with the reduction in vehicular traffic and other anthropogenic activities, in general reduced the concentrations of primary atmospheric pollutants in urban areas. The increases observed for O_3, a secondary pollutant of complex chemistry, can be explained by the fact that the decreases in NO_2 and NO lead to the production and accumulation of O_3 (Seguel et al., 2020a). Studies under these highly unusual conditions of partial or total confinement during the current COVID-19 pandemic, allow us to evaluate the effects of reduced emission sources on the local urban air quality, providing vital information for designing policies and strategies for the prevention and control of air pollution (Anjum, 2020; Dutheil et al., 2020).

In the case of Chile, to our knowledge, the effects of lockdown measures in the Santiago Metropolitan Area (SMA) have only been assessed for a relatively short period in late summer and early fall (Seguel et al., 2020a). The objective of this study is to evaluate and discuss the impact of the lockdown strategies adopted during the COVID-19 pandemic on the air quality of the SMA by comparing the concentrations of PM_{10}, $PM_{2.5}$, NO_X, CO, and O_3 during this period with those obtained during the same period between 2017 and 2019. Furthermore, we investigated the transit from strong-to-weak photochemical activity and provide a quantification of the role played by mobile sources in the environmental concentrations of pollutants.

2. Materials and methods

2.1. Study area

The SMA (33.5° S, 70.6° W), encompassing the Chilean capital city of Santiago, has 40% (7.4 million) of the country's population. In addition, it concentrates a significant portion of the economic activity, accounting up to 45% of the national gross domestic product (OL, 2020). It has a fleet of more than 2 million motorized vehicles. The city has atmospheric pollution levels that are reported to regularly exceed the National Ambient Air Quality Standards (NAAQS) for PM_{10}, $PM_{2.5}$, and O_3 on more than 35, 80 and 40 days of the year, respectively (Seguel et al., 2020a; Seguel et al., 2020b; Seguel et al., 2012; Gallardo et al., 2018; Toro et al., 2019; Toro et al., 2014). Therefore the city has been designated a nonattainment area for PM_{10}, CO, O_3, and "latent" nonattainment area (pollutant concentrations are between 80 and 100% of the standard) for NO_2 in 1996 (D131, Declares ozone saturated zone, respirable particulate matter, suspended particulate matter and carbon monoxide, and nitrogen dioxide latent zone, to the area that indicate (in Spanish), 1996) and nonattainment area for $PM_{2.5}$ in 2014 (D67, Declares a saturated zone for fine respirable particulate matter mp2.5, as a 24-

hour concentration, to the metropolitan region, 2014).

The high levels of air pollution result from a combination of anthropogenic activity, its geographic location and local and synoptic meteorological conditions inhibiting pollutant dispersion (Toro et al., 2019). The city lies in a valley in the central zone of Chile between two rivers, the Maipo and the Mapocho, surrounded by mountains (the Andes the Coastal Range running north to south, and the Cordón de Chacabuco running east to west). The urban area covers approximately 776 km^2 (Gallardo et al., 2018) and is 500 m above sea level on average (Toro et al., 2014). The climate in the SMA is Mediterranean, with an average temperature of approximately 14 °C and an annual average rainfall of 350 mm (DMG, Climatology, Dirección Meteorológica de Chile, 2013). The SMA has a system of persistent valley and mountain breezes, with a complex pattern associated with topography and urban surface roughness. The SMA has prevailing anticyclonic weather conditions throughout the year, so a subsidence inversion layer is observed (Toro et al., 2019), which varies from 400 m in winter to 1000 m in summer (Gramsch et al., 2014). Vertical ventilation in the basin is impeded by this stability, and there are recurring unfavorable conditions for the dispersion of air pollutants (Toro et al., 2019; Muñoz and Undurraga, 2010; Saide et al., 2011).

2.2. Air pollution database and statistical analysis

The SMA has an Air Quality Pollution Watch Program (SINCA, 2020) run by the Ministry of the Environment. Surveillance stations are distributed throughout the city and comprise the Air Quality Monitoring Network (AQMN) of the SMA, measuring the concentrations of atmospheric aerosols and pollutants (CO, NOx, O_3, PM_{10}, and $PM_{2.5}$), as well as meteorological data, which are reported online in the National Air Quality Information system (SINCA, 2020).

The experimental data obtained by the surveillance stations were initially analyzed to identify spurious data. The descriptive statistical analysis was carried out in Microsoft Excel (M. Excel®, Microsoft Corporation®, 2017) and in the R programming language, a free software environment (R Core Team, R, 2020). Some of the analyses were performed with the OpenAir software package (Carslaw, 2019; Carslaw and Ropkins, 2020; Carslaw and Ropkins, 2012) for the R programming language. Time plots of hourly-averaged concentrations were prepared using local time.

The air quality in the SMA is influenced by short-term local emissions and by synoptic and local meteorological variations with marked seasonality and diurnal behavior. Therefore, a comparison of the concentrations of pollutants in three historical years in the months of March, April, and May with the corresponding ones of the current year (2020) would show the effect of the physical distancing measures (closed schools, universities and shopping centers, curfews, and partial quarantines) on the air quality of the SMA during the COVID-19 pandemic. In this study, we deemed that the average of a three-year reference period (2017–2019) was long enough to be used as a reference, after minimizing the interannual variability of air pollution levels. Consequently, through the estimation of the relative changes between the historical period and the current year, its confidence interval and its statistical significance, quantitative information was obtained on the effect of the physical distancing measures on the levels of PM_{10}, $PM_{2.5}$, NO_X, CO, and O_3 in the SMA during COVID-19 pandemic.

2.3. Spatial distribution analysis

A spatial distribution analysis was performed on NO_2 in the 2017–2019 and 2020 periods from remote monitoring data. The spatial distribution were obtained from remote sensing and were provided by the Copernicus Sentinel-5 Precursor Tropospheric Monitoring Instrument (S5p/TROPOMI), developed by the European Space Agency (ESA, 2018), at a spatial resolution of 0.01° x 0.01° and daily temporal resolution. The satellite data were downloaded in NetCDF format and then processed in R (R Core Team, R, 2020) and/or Python (Python, 2020) programs.

2.4. Traffic activity and road transport emissions

Baseline traffic emissions in Santiago were obtained for the period 2017–2019, averaging monthly regional results for NOx, $PM_{2.5}$, volatile organic compounds (VOC), and CO_2. These emissions have been calculated using a bottom-up methodology (Tolvett Caro et al., 2016), adapting the calculation of air pollutant emissions from road transport (COPERT) of the European emission factors to the conditions of fleet technology, fuel quality, environmental conditions and vehicle activity existing in SMA. CO_2 emissions were converted into fuel consumption to compare with the official transport-related fuel sales in the SMA, for validation. Other authors have used these on-road transport emissions as input for air quality modelling analysis in Santiago (Huneeus et al., 2020a; Mazzeo et al., 2018).

The effect of lockdown strategies in vehicle traffic for the period March-May 2020 wasobtained from the Tomtom traffic index (TomTom, 2020) and Google mobility reports (Google, 2020). In addition, information from the Operational Transit Control Unit (UOCT, 2020) has been considered, comprising 49 traffic-count stations, reporting 24 h for 5 communes in the SMA, for the periods between March 2 to 8 (before the COVID-19 restrictions) and from March 30 to April 5, 2020 (during the first partial lockdown restrictions).

To estimate the variations in the emissions during the lockdown scenario, the traffic flow variation in each commune and the associated speed increase were considered, both generating a reduction in traffic flow compared to the emission base scenario. The results were calculated by the hour and distributed over the SMA using a network of cells of 0.001 × 0.001 degrees latitude/longitude, using the Open Street Map road network vector tiles for Chile (OSM, 2020).

3. Results and discussion

3.1. COVID-19 in SMA, Chile

After the first cases of COVID-19 were confirmed in December 2019, the virus spread rapidly around the world (WHO, 2020a; WHO, 2020b). Its arrival in South America was confirmed by the diagnosis of the first case on February 26, 2020 in Brazil (WHO, 2020b). Soon after, cases were confirmed in Ecuador (Feb 29), Argentina (Mar 03), and Colombia (Mar 06). In Chile, the first confirmed case was reported on March 3, 2020, in Talca (35°25′35″ S - 71°39′19″ W), a city in the Maule Region, 255 km south of Santiago, and the next day the first case in the SMA was reported (see Fig. 1) (MINSAL, 2020). On March 11, 2020, the WHO declared that the spread of SARS-CoV2 was already a pandemic (WHO, 2020a). On March 16, there were more than 100 confirmed cases in Chile, 80% of them in the SMA. On March 15, classes were suspended at schools and universities. On March 18, a State of Constitutional Exception of Catastrophe, due to public calamity was declared in the territory of Chile (MINSAL, 2020). On March 25, Chile exceeded 1000 confirmed cases, 60% of which were in the SMA. The following day, the areas of the SMA with the highest rates of infection were put under partial lockdown, confining approximately 1.3 million people to their homes (MINSAL, 2020). Since the beginning of the contagion and the implementation of physical distancing measures, travel via public transportation had declined approximately 70% (see Fig. 1).

The number of confirmed cases of COVID-19 has evolved rapidly, reaching 10,000 cases on April 19 (53% of which were reported in the SMA). Seventeen days later, in May 4, cases exceeded 20,000 (65% in the SMA). By May 15, total cases exceeded 40,000, with 30,000 of them in the SMA, and the authorities decided to implement a total lockdown strategy for most of the SMA (affecting more than 6.5 million people) in what they called "the battle of Santiago". By May 31, Chile reached the psychological barrier of 100,000 confirmed cases, 80% of them in SMA (MINSAL, 2020).

3.2. Relative changes in pollutant concentrations

Table 1 shows the average concentrations of PM_{10}, $PM_{2.5}$, NO_x, NO_2, NO, O_3, and CO measured at the stations of the SMA monitoring network (SINCA, 2020) comparing the historical period (2017–2019) and 2020. The results showed that the concentration of all pollutants in the SMA decreased during the lockdown period compared to the average values observed in the historical period, except for O_3, which increased. PM_{10} concentrations decreased 5.2%, while $PM_{2.5}$ decreased by 11%, and CO by −13%. The largest percent change was observed for NO_x (NO_2 + NO), with values of −54%, −42%, and − 66% for NO_x, NO_2, and NO, respectively.. In contrast, the average concentration of O_3 increased by 63%. The confidence intervals and associated *p*-values for these relative changes are shown in Table 1.

Table 1 also shows the average, the 99% confidence interval, and the relative percent change for temperature, relative humidity, and wind speed in the historical and current periods. The meteorological variables did not change significantly (*p*-values >0.01), and the 99% confidence intervals of the relative changes contained the value 0 (Table 1). These results imply that the changes observed in the concentrations of pollutants in the current period with respect to the historical period can not be attributed to interannual variations in meteorological conditions (temperature, relative humidity, and wind speed),but rather to the effect of the change in the emission patterns and emission rates of pollutants and their precursors during the pandemic.

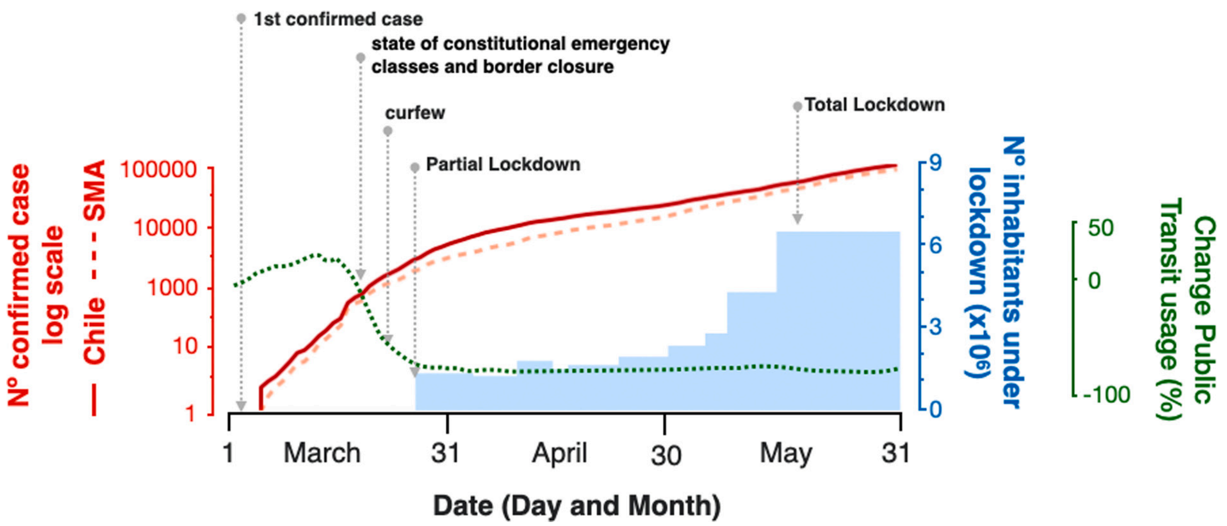


Fig. 1. Evolution of the number of confirmed cases of COVID-19 infections in Chile (red) and in the Santiago Metropolitan Area (SMA, dashed orange) and the percentage change in the use of public transport (dotted green). Source data: MINSAL 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Average concentrations and 99% confidence intervals for the selected atmospheric pollutants, and local meteorological data during March to May 2017–2019 vs. 2020, and the respective relative changes.

Pollutant	A: Mean 2017–2019 (CI) (historical)	B: Mean 2020 (CI) (current)	Relative Change (B-A)/A, %
PM_{10} ($\mu g \cdot m^{-3}$)	75 (73 – 77)	71 (69 – 73)	−5.2 (−13 – 2.1)*
$PM_{2.5}$ ($\mu g \cdot m^{-3}$)	27 (26 – 28)	24 (23 – 25)	−11 (−18 – −3.6)**
NOx ($\mu g \cdot m^{-3}$)	113 (109 – 117)	52 (49 – 55)	−54 (−63 – −45) **
NO_2 ($\mu g \cdot m^{-3}$)	57 (56 – 58)	33 (32 – 34)	−42 (−49 – −36) **
NO ($\mu g \cdot m^{-3}$)	56 (53 – 59)	19 (17 – 21)	−66 (−79 – −52) **
CO ($mg \cdot m^{-3}$)	0.96 (0.93 – 0.99)	0.83 (0.80 – 0.87)	−13 (−22 – −3.9) **
O_3 ($\mu g \cdot m^{-3}$)	25 (24 – 26)	41 (38 – 43)	63 (41 – 84) **
T (°C)	16 (15 – 16)	16 (16 – 17)	4.3 (1.3 – 10) *
HR (%)	58 (58 – 59)	57 (55 – 58)	−3.0 (−7.9 – 1.9) *
Ws (m s^{-1})	1.01 (0.98 – 1.03)	0.92 (0.88 – 0.97)	−8.2 (−18 – 1.7) *

*$p > 0.01$ **$p < 0.001$.

Table 2 shows the Pearson correlation coefficients between the pollutant concentrations for both the historical and current periods. High correlations between PM_{10}, $PM_{2.5}$, NOx and CO were observed, indicating that they shared common emission sources with similar emission patterns. On the other hand, O_3 is a secondary pollutant and not directly related to $PM_{2.5}$ and PM_{10} emissions, but related to NOx and CO. Hence, an inverse correlation was observed, which can be attributed to the fact that the SMA is a VOC-limited area (Seguel et al., 2020a; Seguel et al., 2020b). In addition, a consistent decrease in all correlation coefficients was observed in the current period with respect to the historical period. This could be due to changes in the source apportionment and/or emission patterns in the SMA during partial or total lockdowns.

The relative changes during this pandemic year indicated that the confinement and physical distancing measures have influenced the main sources of pollutants to the SMA. The largest PM_{10} and $PM_{2.5}$ emission sources in the SMA are mobile transport sources and residential emissions, which contribute approximately with 40% and 30% of the annual budget respectively on, but they increase in the winter season reaching values of over 50% (Mazzeo et al., 2018; Mena-Carrasco et al., 2012). The positive effect of reductions in transport-related emissions can be counterbalanced by an increase in residential emissions due to the confinement, partial quarantines and total lockdowns implemented in the SMA. The decrease in PM_{10} concentrations was not significant in 2020 compared to the historical period ($p > 0.01$), while the $PM_{2.5}$ concentration was significantly reduced ($p < 0.001$). These can be attributed to combined local factors such as a decline in mobile sources emissions and relatively similar wind conditions throughout the years.. Another contributing factor is the reduction from precursors of secondary particulate matter, such as NO_x, whose neutralization products mainly contribute to the <2.5 μm accumulation fractions of PM (Menares et al., 2020). NO_x showed the greatest decreases among all the pollutants studied, which can be attributed to the reduced emissions associated to land traffic, which emit more than 70% of the total NO_x in the SMA (private land traffic was reduced by 30–50%) (ISCI, 2020). Additionally, financial reports showed that passenger traffic at Santiago Airport decreased by 95% in April, while the main airline operating in Chile stopped all its international flights on April 13, 2020, to concentrate all its operations on local flights.. However, during partial and total quarantines, industrial activity, and public transport were not been restricted at all. The reductions in CO concentrations were also counterbalanced by a potential increase in emissions associated with the use of firewood for residential heating during the confinement.

O_3 is the only pollutant that increased during the lockdown period, compared to the same months of the historical period. This increase can be explained by considering the complex atmospheric photochemistry involving VOC–NO_x mixtures (Finlayson-Pitts and Pitts, 2000). The SMA is a VOC-limited area, and under these conditions, a reduction in NO_x generates a greater reserve of OH radicals to react with the VOC, which generates more O_3 (Seguel et al., 2020b; Seguel et al., 2012). Furthermore, the significant decrease in NO implies a lower rate of O_3 titration and its consequent accumulation in the atmosphere.

Table 2
Pearson's correlation coefficients between pollutants for the historical (2017–2019) and current (2020) periods.

Pollutant	PM_{10}	PM_{25}	NOx	CO	O_3
A: 2017–2019					
PM_{10}	1.00	0.72	0.71	0.64	−0.08
PM_{25}		1.00	0.82	0.83	−0.39
NOx			1.00	0.93	−0.59
CO				1.00	−0.60
O_3					1.00
B: 2020					
PM_{10}	1.00	0.63	0.61	0.56	0.14
PM_{25}		1.00	0.57	0.72	−0.23
NOx			1.00	0.82	−0.42
CO				1.00	−0.45
O_3					1.00

Thus, the relative changes in the concentrations of pollutants in the SMA in 2020 showed that confinement and mobility restrictions had an impact decreasing the emissions of air and land transport–related pollutants, but increasing the emissions associated with residential sources. This fact can be related to socioeconomic aspects i.e., people with higher incomes can stay at home through remote work but not those with lower incomes, who must work every day to survive. The SMA is a very segregated area from the point of view of income and urban infrastructure (the north-eastern zone concentrates the population with the highest incomes compared to the southern and western zones). A detailed analysis of this factor is beyond the scope of this study.

3.3. Daily variations

Fig. 2 shows the daily variations in the concentrations of PM_{10}, $PM_{2.5}$, NO_2, NO, and O_3 for the periods 2017–2019 (historical, blue) and 2020 (current, red). In general, PM_{10}, $PM_{2.5}$, NO_2, and NO followed a pattern of two maximums, at 7:00 and 21:00. This pattern can be explained by both the vehicular emission in the morning and afternoon rush hours and the diurnal cycle of the atmospheric boundary layer (which has a higher mixing height at midday). In the case of PM_{10} and PM_{25}, the morning and afternoon maximum concentrations were lower in 2020 compared to the historical period. However, at midday, the PM_{10} concentrations were higher in 2020, though the $PM_{2.5}$ concentrations were similar. This behavior may reflect a change in the rush hour pattern of emissions, a product of the confinement and social distancing measures, such as suspending classes in schools and universities and implementing telework. These measures changed the movement pattern in the city, reducing trips during the morning and afternoon rush hours and shifting them to midday. NO_2, NO, and CO were drastically reduced in 2020 compared to the historical period, but the diurnal behavior was still seen. This, as mentioned in the previous section, would correspond to the decrease in emissions associated vehicle emissions in the SMA. The observed reductions in ambient concentrations of pollutants resulting from changes in vehicle emissions are discussed in the section Vehicle emissions and COVID-19 countermeasures below.

In the case of O_3, the characteristic pattern of a daily maximum associated with the increases in precursor emissions over the course of the morning and the increase in photochemical activity in the middle of the day are maintained. Here, an increase was seen in the maximum concentration in 2020, typical of a VOC-limited area where the environmental concentrations of NO_x decline.

3.4. Spatial pattern

Fig. 3 shows the spatial variability over the studied area of the concentrations of NO_2 (μmol/cm^2) during the historical (2017–2019)

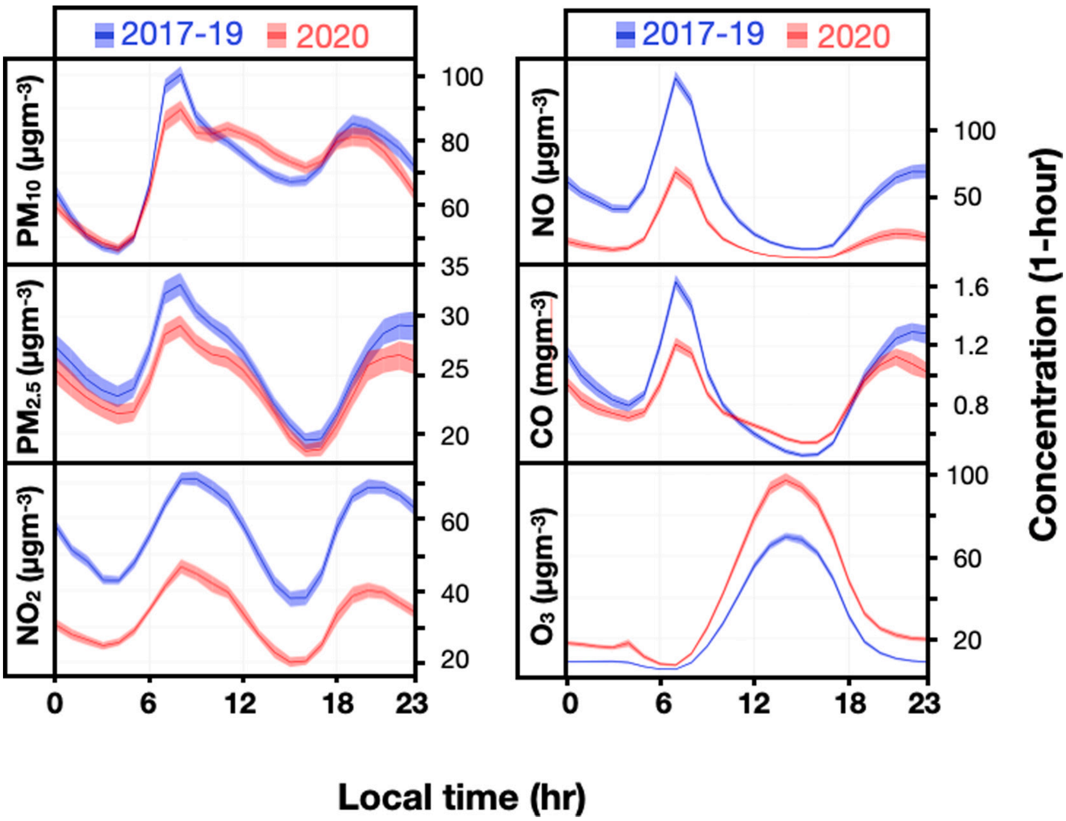


Fig. 2. Daily variability of pollutants concentrations for the historical (2017–2019) and current periods (2020).

and current periods (2020) and the percentage change between them. The relative changes in the NO_2 tropospheric column in the SMA were estimated to be between −10% and − 50%, with changes as large as −40% in most of the studied area, which was consistent with surface measurements. The spatial variability of the concentrations showed that the most significant reductions occurred in the southwest and northeast areas of the SMA. The northeast area was the first in which lockdowns were implemented (March 26), while the western area was the latest (May 17), when a total lockdown of all the SMA was implemented (see Fig. 1). The partial lockdown of the city during the first month of the pandemic could explain the reductions observed in the northeast, especially in terms of reduced transit emissions. However, the greatest reductions during the pandemic have occurred in the western sector of the city, which did not enter quarantine until mid-May, showing the effect that partial lockdowns had in other areas, which are generally more affected by poor air quality, due to local wind patterns (Toro et al., 2019).

3.5. Vehicular emissions and COVID-19 countermeasures

In the SMA, COVID-19 official restrictions have been changing over time produced different types of behaviors in vehicle flows, which could be classified into two: one of them with mandatory lockdown (red zones) and the other with a partial or voluntary lockdown (blue zones) (Fig. 4).

From the analysis of vehicle flows, daily emissions of four polluting compounds were calculated for the historical period (2017–2019) and 2020 (current), considering the average of a typical business day in the months of March, April and May. The average reduction for traffic activity in 2020 was 49.6%, both for public and private transport. This brought about a reduction in emissions from mobile sources in the city. The average reduction in this same period for $PM_{2.5}$, NOx, CO and CO_2 was 62%, 61%, 68% and 47%, respectively.

Comparing the first partial lockdown with the fourth, a greater reduction in emissions was observed during the former (March 27). Although the number of communes affected with mandatory confinement was similar (7 and 8), the traffic generated or attracted by the northeast zone is greater than that of the southern zone.

Fig. 4 shows the change in $PM_{2.5}$ vehicle emissions for the baseline period (Fig. 4a), at the beginning of lockdown measures in some areas of the SMA on March 17, 2020 (Fig. 4b) and April 23, 2020 (Fig. 4c) and for total lockdown in May 15, 2020 (Fig. 4d). The figure shows a reduction in $PM_{2.5}$ vehicle emissions in zones with mandatory lockdown (red zones) that reached 50% between noon and rush hour traffic (07:00 AM). Meanwhile, in the rest of the city, with voluntary lockdown, reductions in the order of 20% were observed (Huneeus et al., 2020b). $PM_{2.5}$ levels increased from the first partial lockdown of March 17, 2020 in the rush traffic hours and at noon in the three monitoring stations. A similar behavior was observed from the fourth partial lockdown at April 23, which seems to indicate that the partial lockdowns had a significant effect on reducing emissions from vehicular traffic (Fig. 4 and Table 3) that did not imply significant and sustained reductions in ambient concentrations of $PM_{2.5}$ in the SMA. Instead, $PM_{2.5}$ variations seems to be driven by other factors such as other sources of pollution and/or variations in the atmospheric stability and ventilation conditions in the SMA basin. Finally, another peak was measured at the three monitoring stations a few days before May 15, when a total lockdown was implemented (see Fig. 5), a measure that did seem to have an effect of reducing concentration levels during the following week. However, during the last week of May, concentrations increased again in the middle of total lockdown, confirming the influence of other factors on air quality.

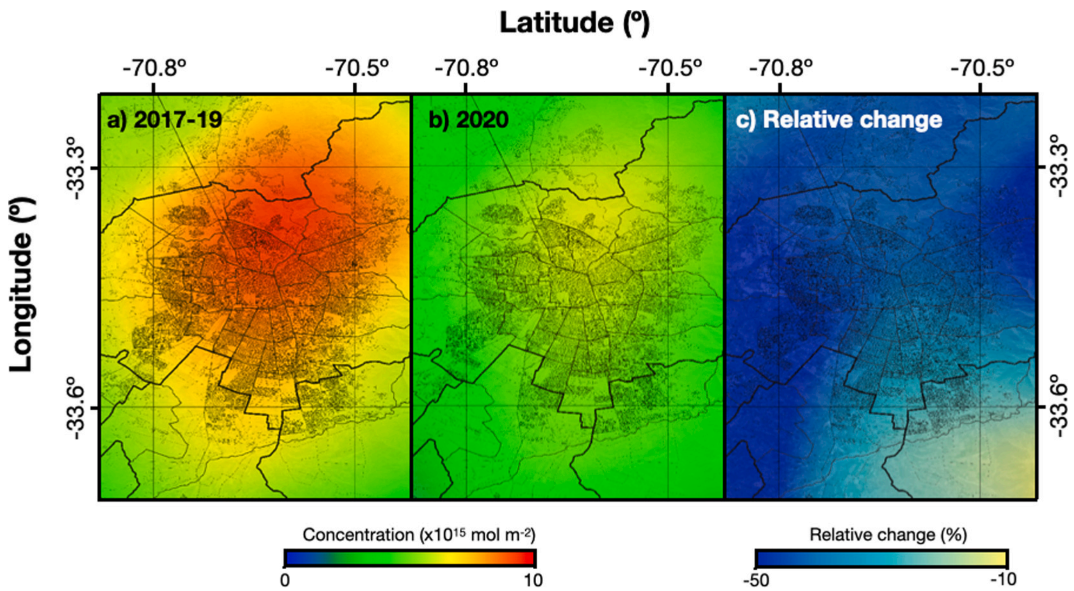
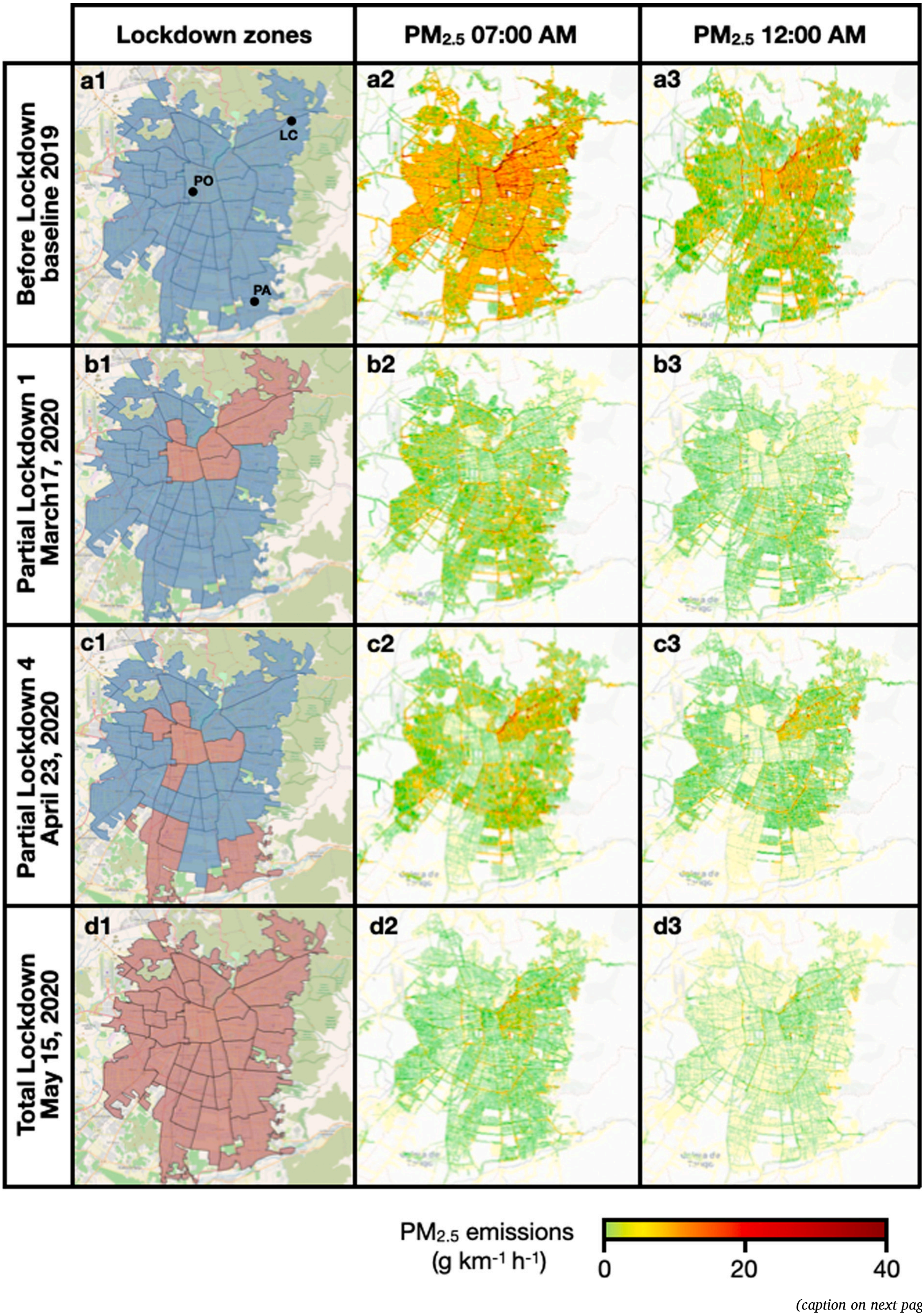


Fig. 3. Spatial distributions of the mean concentrations of NO_2 (satellite data) in SMA during March 15 to May 31, 2017–2019 (a) and March 15 to May 31, 2020 (b), along with the percentage changes (c).



(caption on next page)

Fig. 4. Lockdown geographical coverage and differences in $PM_{2,5}$ emissions comparing 2020 and 2019 in the SMA.. Colour legend: blue means zones (communes) without mandatory confinement, red indicates zones with mandatory confinement. Mandatory lockdowns started on March 27 for 7 northeast communes (partial lockdown 1). On April 23 a group of 8 central-southern communes were under confinement (partial lockdown 4), moving into total lockdown from May 15 onwards. Black dots in figure a1 show three areas of the city (LC: Las Condes; PO: Parque O'Higgins and PA: Puente Alto). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Average values for the emission of pollutants produced by traffic activity for March-April-May (M-A-M) 2017–2019 and 2020 and average relative changes of emissions produced by traffic activity between both periods.

Average emission (March-April-May 2017–2019 and 2020)					
Pollutant	A: Daily Mean M-A-M 2017–2019	B: Daily Mean M-A-M 2020	C: Daily Mean March 2020	D: Daily Mean April 2020	E: Daily Mean May 2020
$PM_{2.5}$ (t/d)	1.4	0.5	0.8	0.4	0.5
NOx (t/d)	76	30	44	20	25
CO (t/d)	86	28	40	18	24
CO_2 (kt/d)	28	9.9	15	6.3	8.8
Average relative changes of emissions (March-April-May 2017–2019 and 2020)					
Pollutant	Relative change (B-A)/A %	Relative change (C-A)/A %	Relative change (D-A)/A %		Relative change (*E*-A)/A %
$PM_{2.5}$	−62%	−44%	−75%		−68%
NOx	−61%	−42%	−74%		−66%
CO	−68%	−53%	−80%		−72%
CO_2	−47%	−47%	−77%		−68%

3.6. *Air pollution and COVID-19 countermeasures around the word*

Fig. 6 shows the relative changes observed in the concentrations of different pollutants as a result of SARS-CoV-2 prevention and control measures, mainly aimed at reducing social contact. The impact on air quality in these cities has been widespread, and what is observed in the SMA is consistent with what has been observed in different cities around the world. That is, decreases in PM_{10} and $PM_{2.5}$, which are quite variable and depend on the patterns of the emission sources in each city. In the SMA, the reductions in PM_{10} concentrations have been one-tenth as strong as those observed in Milan, Lima, and Delhi. The patterns of $PM_{2.5}$ are similar to those recorded in Dubai (United Arab Emirates) and Mumbai (India). For NO_2 and CO, similar relative changes have been observed in other cities, which may be associated with measures to reduce the movement of inhabitants that have led to significant reductions in emissions from air and land vehicles. The changes observed for NO_2 in the SMA are similar to those observed in cities such as Lima, Barcelona, and Delhi.

4. Conclusions

The confinement and physical distancing measures implemented in the SMA from March 2020 onward by the Chilean government in response to the COVID-19 pandemic, such as the suspension of classes in schools and universities, restricting the movement of people inside and outside a defined geographic area during partial and then total lockdowns, night curfews, and limiting gatherings of more than 50 people in closed spaces such as restaurants and shows, have resulted in large reductions in traffic emissions and statistically significant reductions in the average ambient concentrations of PM_{10}, $PM_{2.5}$, NO_2, NO, and CO in the period March–May 2020 compared to the average concentrations in the same period in 2017, 2018, and 2019. O_3 is the only pollutant studied that increased its concentrations. This trend is consistent with the observations made in different urban areas around the world during the current pandemic. The highest relative reductions are recorded in the pollutants associated with vehicular traffic, such as NOx, CO, and $PM_{2.5}$. The average increase recorded for O_3 is the most significant change among all the air pollutants studied. The relative changes in the local meteorological variables in SMA showed no significant difference between the year of the pandemic and the historical records, so the changes in the concentrations of pollutants can be attributed to changes in the patterns and rates of pollutant and precursor emission during the pandemic. Is noteworthy that such a high reduction in traffic emissions ($>$ 75%) implies reductions of only 5% and 11% of PM_{10} and $PM_{2.5}$, respectively, which indicates the relative importance of other emission sources of PM in the SMA, such as burning firewood for residential heating, construction and industry, or contribution of secondary aerosol.

The SMA showed similar behaviors, but with different intensity, in the relative change of the concentration of air pollutants to what has been observed in more than 15 cities around the world. This showed the impact of COVID-19 prevention and control measures on the environment, and specifically on local air quality. The detailed study of emission patterns and emission rates of pollutants and its effect on air quality in urban areas during the pandemic conditions, can provide information of interest for designing policies and strategies to prevent and control air pollution.

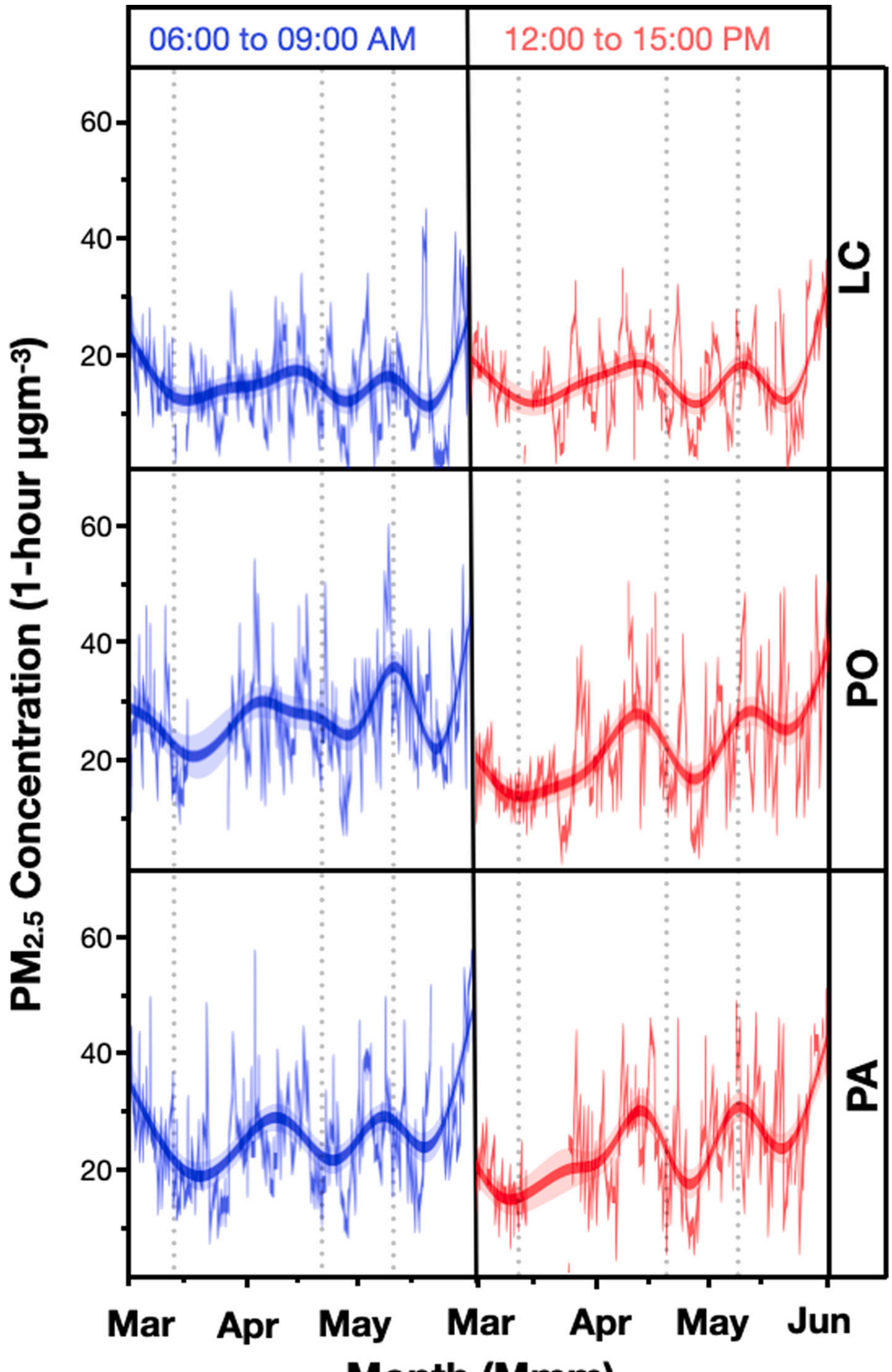


Fig. 5. Time series of 1-h $PM_{2.5}$ concentrations from March to May 2020; in the morning (06:00 to 09:00 AM) and afternoon (12:00 to 15:00 PM) periods at three air quality monitoring stations of the SMA (LC: Las Condes; PO: Parque O'Higgins and PA: Puente Alto, see Figure 4a1). Dotted gray lines indicate the days March 17, April 23 and May 15.

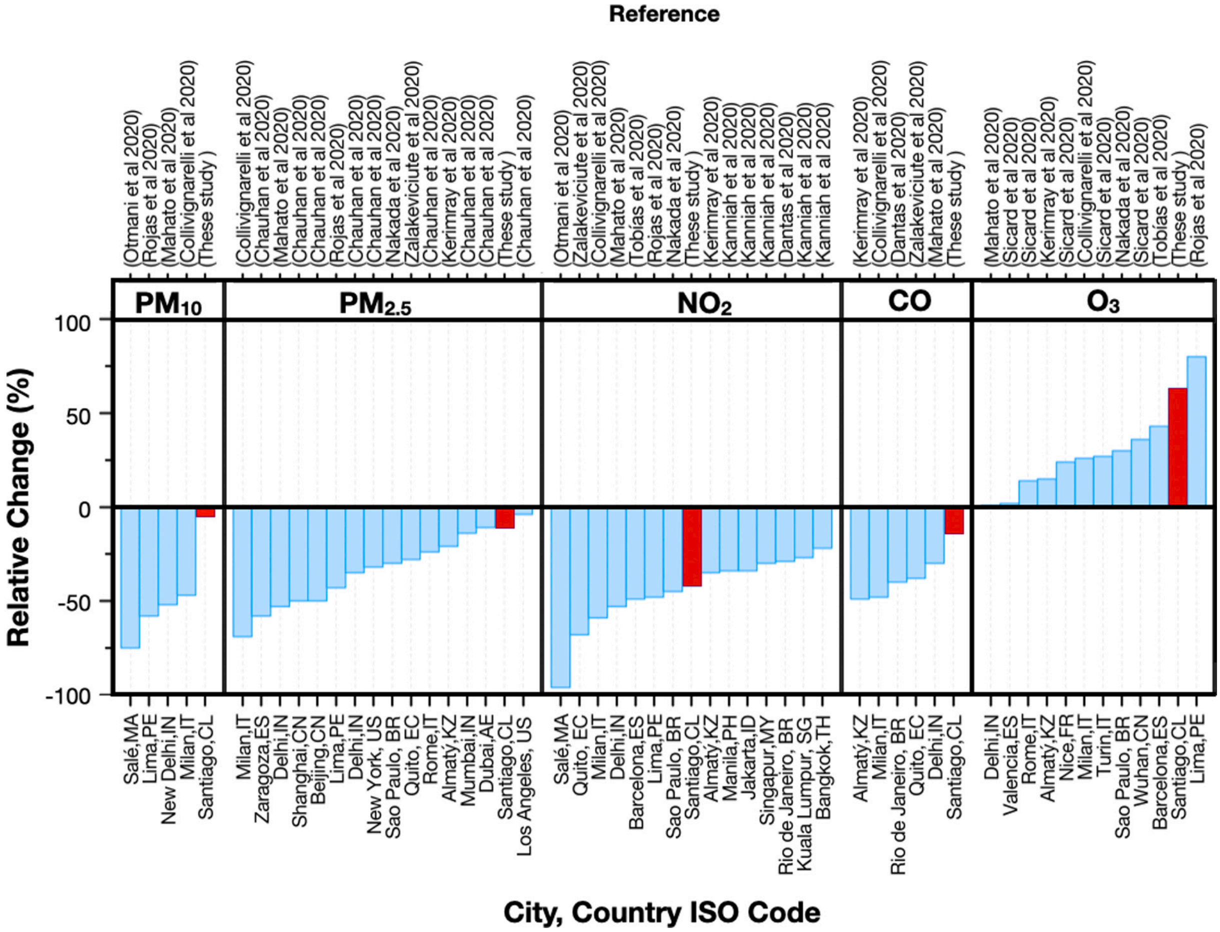


Fig. 6. Comparison of relative changes in the concentration of atmospheric pollutants due to countermeasures against COVID-19 in cities around the world (SMA in red). (Collivignarelli et al., 2020; Dantas et al., 2020; Mahato et al., 2020; Nakada and Urban, 2020; Tobías et al., 2020; Rojas et al., 2021; Chauhan and Singh, 2020; Kanniah et al., 2020; Kerimray et al., 2020; Otmani et al., 2020; Sicard et al., 2020) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Credit author statement

Richard Toro A.: Methodology, Investigation, Writing - Review & Editing; **Francisco Catalan**: Formal analysis, Data Curation, Visualization; **Francesco R. Urdanivia:** Visualization; **Jhojan P. Rojas:** Visualization; **Carlos Manzano:** Review & Editing; **Rodrigo Seguel**: Review & Editing; **Laura Gallardo**: Conceptualization, Review & Editing; **Mauricio Osses:** Methodology, Conceptualization, Writing - Review & Editing; **Nicolás Pantoja:** Data Curation, Visualization **Manuel. A. Leiva-Guzmán:** Conceptualization, Methodology, Investigation, Writing - Review & Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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