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Air quality variations in Northern South America during the COVID-19 lockdown

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HIGHLIGHTS
• Short-term NO2, PM10, PM2.5 decreased by 60%, 44%, and 40% respectively during the strict lockdown.
• Short-term NO2, PM10, PM2.5 decreased by 62%, 58%, and 69% respectively for the relaxed lockdown.
• Long-term NO2, PM10, PM2.5 reductions were of 50%, 32%, and 9% respectively for the strict lockdown.
• Regional biomass burning increased PM2.5 concentrations by 20 μg/m³ during the strict lockdown.
• Policies equivalent to reduced lockdown mobility could bring pollution close to WHO guidelines.

ABSTRACT
Lockdown measures led to air pollution decrease in several countries around the world such as China and India, whereas other regions experimented an increase in pollutant concentrations. Northern South America (NSA) was one of those areas where pollution changed during lockdown due to high fire activity. This study aims to analyze, for the first time in NSA, the behavior of selected criteria air pollutants during the implementation of the SARS-CoV-2 lockdown in two high populated cities of the region: Bogotá and Medellín in Colombia. A set of tools including surface measurements, as well as satellite and modeled data were used. 24-hour average concentrations of PM10, PM2.5, and NO2 were collected from air quality stations for the lockdown period ranging from February 21 to June 30, 2020. The Copernicus Atmosphere Monitoring Service (CAMS) was used to analyze the fire flux OC as a biomass burning (BB) indicator, and tropospheric NO2 concentrations were retrieved from TROPOMI. The HYSPLIT model was used to analyze back trajectories and fire data were obtained from MODIS sensor measurements. Our analysis shows short-term background NO2, PM10, and PM2.5 concentration reductions of 60%, 44%, and 40%, respectively, for the strict lockdown; and 62%, 58%, and 69% for the relaxed lockdown. Corresponding long-term reductions were of 50%, 32%, and 9% for the strict lockdown; and 37%, 29%, and 19% for the relaxed lockdown. Regional BB increased PM10 concentrations by 20 μg/m³ during the strict lockdown, and the Saharan dust event increased PM10 concentrations up to 168 μg/m³ in Bogotá, and 104 μg/m³ in Medellín, bringing an additional risk of morbidity and mortality for population. Regional BB has several causes that need to be properly...
managed to benefit local air quality improvement plans. Future cleaner transport policies equivalent to reduced lockdown mobility could bring pollution close to WHO guidelines.

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1. Introduction

The Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) pandemic, a new human-infecting betacoronavirus (Lu et al., 2020), was identified in Wuhan, China in December 2019. The city was placed under quarantine on January 23 and the World Health Organization (WHO) declared the outbreak to be a public health emergency of international concern on January 30 (WHO, 2020a). The number of infected people and the lethality of the novel coronavirus (COVID-19) increased exponentially between February and March of 2020, forcing most cities around the world to be under some form of lockdown (Muhammad et al., 2020). Citizen mobility was notably restricted to reduce the spread of COVID-19. Consequently, commercial, industrial and entertainment activities were closed, and transport was one of the most affected sectors due to the lockdown, which necessarily reduced the number of cars on the road.

A relationship between air pollution and COVID-19 infections has been explored in several regions of the world in two ways. On the one hand, some studies have analyzed how air pollution is related to the spread of the disease. In this way, Wu et al. (2020) found that an increase in 1.0 μg/m³ of PM2.5 concentrations resulted in an 8% increase in the mortality rate by COVID-19 in the United States. Other researchers have reported a positive association of PM2.5, PM10, NO2, and O3 with COVID-19 confirmed cases (Coccia, 2020; Ogen, 2020; Zhu et al., 2020). On the other hand, some studies have evaluated changes in air quality due to the lockdown. As a result of the drastic closure of economic and social activities, variations in concentrations of atmospheric pollutants such as NO2, PM10, PM2.5, SO2, and O3 have been reported in European (Muhammad et al., 2020; Tobías et al., 2020), Asian (Jain and Sharma, 2020; Xu et al., 2020), African (Otmani et al., 2020), Latin American (Dantas et al., 2020; Nakada and Urban, 2020), and United States cities (Muhammad et al., 2020). Furthermore, Chauhan and Singh (2020) reported PM2.5 changes during lockdowns in 9 selected major cities in Asia, Europe, and the USA. Our study contributes to this second approach.

The first detected case of COVID-19 in South America was reported in Sao Paulo, Brazil on February 26 (WHO, 2020b). Later, the first two confirmed cases in Colombia (the most populous country in Northern South America - NSA) (CIA, 2019) were reported on March 6, 2020, in Bogotá. A third case was confirmed on March 9 in Medellín. Starting on March 20, Bogotá implemented an obligatory local lockdown during a three-day holiday weekend to test how the city would cope with a possible COVID-19 outbreak. As of March 25, as a consequence of an increasing number of confirmed cases of COVID-19, a national lockdown was in place in Colombia that restricted most of the economic activities, excepting the provision of basic products and services, such as food and medicines, energy (electricity and fuels), human and animal health, home, banking, public transportation, sanitation and emergency services, among others. Therefore, the main sources of urban emissions were cut to historically low levels. The lockdown was relaxed on April 27 to reactivate economic sectors such as construction and manufacturing, including textiles, leather, wood, paper, chemicals and metals industries, and some commercial activities (Ministerio del Interior, 2020).

These conditions would lead to better air quality as found in several regions, especially for those most polluted countries such as China (Isaifan, 2020; Wang et al., 2020) and India (Mahato et al., 2020; Sharma et al., 2020). However, some areas in the world recorded high levels of pollutants during the lockdown (Schiermeier, 2020).
representing an additional risk of morbidity and mortality for its population (Conticini et al., 2020; Zhu et al., 2020). In NSA, two events of long-range pollution transport to the most populated areas of the country were observed during the lockdown: regional biomass burning (BB) at the end of March and in April 2020, and a Saharan dust intrusion at the end of June. Hence, we aimed to analyze the behavior of selected criteria air pollutants during the implementation of the COVID-19 lockdown in two high populated cities of NSA: Bogotá and Medellín. A set of tools including surface measurements, satellite images, and modeled data was used.

2. Methods

2.1. Area of study

NSA covers an area of nearly 3.9 million km² (longitude = −79.0, latitude = −4.4 as the bottom left; longitude = −51.7, latitude = 13.1 as top right) with strategic ecological zones and around 100 million inhabitants (Mendez-Espinosa et al., 2019). This region (Fig. 1) includes five countries, namely Ecuador, Venezuela, Colombia, northern Peru, and northern Brazil.

2.2. Surface monitoring

To assess the changes in air quality levels, 24-hour average concentrations of PM$_{10}$, PM$_{2.5}$, and NO$_{2}$ were collected in Bogotá (latitude: 4.624, longitude: −74.063, altitude: 2640 m above sea level, m.a.s.l) and Medellín (latitude: 6.230, longitude: −75.5905, altitude: 1495 m. a.s.l) for the period ranging from February 21, 2020, to June 30, 2020. These cities are within the most populated and polluted cities in NSA (Pachón, 2018; Aguiar-Gil et al., 2020; Ramírez et al., 2020), and are located in the Andes mountain range with nearly 8 million and 3 million inhabitants, respectively. Air quality data was collected from the public monitoring networks such as SDA (http://201.245.192.252:81/) in Bogotá and SIATA (https://siata.gov.co/siata_nuevo/) in Medellín. Pollutant concentrations were reported at standard conditions (1 atm and 25 °C) by local environmental authorities. For each city, we selected one traffic station and one urban/suburban background station (Table 1). Analyses were conducted for the periods before the lockdown (February 21 to March 19), during the strict lockdown (March 20 to April 26), and during the relaxed lockdown (April 27 to June 30), assessing temporal pollution events, and comparing their relative change (%).

A comparison with concentrations during the same periods of the previous 5 years (2015 to 2019) was also performed to control for meteorological conditions and the average BB effects. In addition, concentrations were compared between days with high and low fire activity, as well as the Saharan dust intrusion event that took place on June 24th and 25th, to estimate the contribution of regional sources to local PM$_{2.5}$ pollution during the lockdown. High fire activity days were defined as the days with a number of fires above the 75th percentile.

2.3. Satellite monitoring and active fire analysis

Data from the TROPOMI monitoring instrument were used to analyze changes of NO$_{2}$ concentrations during the studied period. Tropospheric NO$_{2}$ columns (levels 2 and 3) were retrieved from the Sentinel 5p platform (https://s5phub.copernicus.eu/dhus/) and further processed and analyzed with the Phyton HARP package. Changes on air quality were assessed on one day per each of the lockdown periods. On the other hand, Organic Carbon emissions from the Copernicus Atmospheric Monitoring Systems and associated with wildfires (fire flux OC emissions) were used as an indicator of BB (CAMS, 2019). Changes in fire flux OC emissions were assessed for the three periods: before the lockdown, during the strict lockdown, and during the relaxed lockdown. Finally, active fires were retrieved from FIRMS (https://firms.modaps.eosdis.nasa.gov/). Only fires with a confidence equal or greater than 75% were selected. The open-source programing language R and the OpenAir package (http://www.openair-project.org/) were used to analyze results.

2.4. Back trajectory analysis

The Hybrid Single-Particle Lagrangian Integrated Trajectory Model HYSPLIT (Stein et al., 2015) was used to establish the origin of air masses arriving at Bogotá and Medellín before the lockdown, during the strict lockdown, and during the relaxed lockdown. HYSPLIT has been used in previous studies to analyze the impact of medium and long-range transport of pollution to cities in NSA (Ramírez et al., 2018; Méndez et al., 2018; Méndez-Espinosa et al., 2019). Trajectories were calculated for eight arrival times daily in order to consider medium-range transport, and each trajectory was computed 72 h before the arrival. Receptors were located at the background air quality monitoring station, 500 m above ground level. The National Center for Atmospheric Research (NCEP) provided the GDAS1 meteorological fields (https://www.ready.noaa.gov/archives.php). The meteorological dataset was used in the model set up since it can be useful for regional analyses without high computational power and storage due to its horizontal resolution of 1° and its 23 vertical levels. In addition, a comparison of concentrations on days with high and low fire activity was performed, to estimate the impact of fires on air quality during the lockdown period.

3. Results

3.1. Variations in pollutant concentrations during the lockdown

Particulate matter concentrations were reduced significantly as a consequence of the lockdown in both cities with respect to the preceding month (Table 2, Fig. 2).

At Bogotá’s background station, PM$_{10}$ and PM$_{2.5}$ average concentrations were approximately 40 μg/m$^3$ and 30 μg/m$^3$ before the lockdown. The decline was slow during the strict lockdown, as it took nearly 10 days to achieve low concentrations, and high values occurred again during the third week of lockdown. This was followed by oscillations at lower values during the relaxed lockdown. In average, a decline of approximately 16 μg/m$^3$ and 25 μg/m$^3$ of PM$_{10}$ (39% and 63% reduction) was achieved during the strict lockdown and the relaxed lockdown, respectively. For PM$_{2.5}$, reductions were of 10 μg/m$^3$ and 22 μg/m$^3$ (34% and 75%), respectively. The traffic station showed similar relative reductions for both pollutants.

Reductions of PM$_{10}$ were greater for Medellín during the strict lockdown, approximately 30 μg/m$^3$ (50% reduction) in the background station and 43 μg/m$^3$ (52%) in the traffic station but did not change much more during the relaxed lockdown. Reductions of PM$_{2.5}$ in the background station were of 19 μg/m$^3$ (45%) and 26 μg/m$^3$ of PM$_{10}$ (62%) during the lockdown and the relaxed lockdown, respectively, with larger reductions in the traffic station. Similar reductions in PM$_{10}$ (59%) and PM$_{2.5}$ (60%) were found in Asian and European cities (Tobías et al., 2020; Zhao et al., 2020).

Variations of NO$_{2}$ concentrations during the lockdown showed a different behavior, with similar or higher reductions during the strict lockdown than the relaxed lockdown (Table 2, Fig. 2). At the traffic station in Bogotá, average NO$_{2}$ concentration was around 49 μg/m$^3$ before the lockdown. A sharp decline and later oscillations resulted in a reduction of 31 μg/m$^3$ (63% reduction) during the strict lockdown and a similar figure during the relaxed lockdown.

In Medellín, NO$_{2}$ concentration was around 45 μg/m$^3$ before the lockdown and declined sharply at the beginning of the strict lockdown, then increased. A similar situation was observed during the relaxed lockdown. As a result, the average reduction was of approximately 30 μg/m$^3$ (65%) during the strict lockdown, and of 13 μg/m$^3$ (28%)
during the relaxed lockdown. NO$_2$ represents a good tracer for traffic emissions (Ogen, 2020), activity that was substantially diminished during the lockdown. According to Google COVID-19 Community Mobility Report (https://www.google.com/covid19/mobility/), traffic activity in Bogota and Antioquia (where Medellin is located) decreased by an average of 70% during the strict lockdown and 49% during the relaxed lockdown. Although reduction percentages in observed NO$_2$ were different-age of 70% during the strict lockdown and 49% during the relaxed lockdown. According to Google COVID-19 Community Mobility emissions (Ogen, 2020), activity that was substantially diminished during

3.2. Comparison with previous years

The comparison of lockdown concentrations with those measured during equivalent periods of the previous years is useful to control for meteorological conditions and examine the effect of the changes occurred during 2020 from a wider perspective. In Bogota, NO$_2$ was 22% (background station) to 5% (traffic station) higher before the lockdown in 2020 than in previous years (Table 3). A similar situation occurred for PM$_{2.5}$, with concentrations 13% and 29% higher before the lockdown, which indicates an increased activity of combustion sources, particularly BB. In contrast, PM$_{10}$ concentrations, more closely associated with the resuspension of particulate matter, were 7% and 2% lower before the lockdown in 2020 than in previous years’ equivalent period. During the strict lockdown, the reduction in pollutant concentrations was substantial: >50% in NO$_2$, around 30% in PM$_{10}$, and 13% (background station) to 5% (traffic station) in PM$_{2.5}$. During the relaxed lockdown, reductions were lower for NO$_2$ (<50%), but higher for PM$_{10}$ (-36%) and PM$_{2.5}$ (-33%) than for the strict lockdown period. This can be explained by the increase in vehicle emissions, especially heavy-duty diesel, and the lower contribution of combustion sources such as BB during the relaxed lockdown, compared with the strict lockdown period.

In Medellin, NO$_2$ concentrations at the traffic station were 16% lower before the lockdown period in 2020 than the equivalent period in previous years, suggesting lower vehicle emissions. PM$_{2.5}$ concentrations were about the same (2% variation) and PM$_{10}$ increased 10% suggesting more resuspension emissions. For the same period, PM$_{2.5}$ was significantly higher (19%) in the background station, associated with the increased activity of regional sources such as BB. During the strict lockdown in 2020, NO$_2$, PM$_{10}$ and PM$_{2.5}$ concentrations at the traffic station were sharply reduced by 69%, 33% and 35%, respectively, with respect to previous years.

During the relaxed lockdown, long-term reductions in NO$_2$ and PM$_{10}$ were lower (35% and 19%, respectively) than short-term ones. Long-term PM$_{2.5}$ reductions did not change during the relaxed lockdown, indicating that PM$_{2.5}$ was not only affected by vehicle emissions, but also by regional sources such as BB, which were more active during the strict lockdown period. The background station, in fact, showed higher concentrations of PM$_{2.5}$ during the period before the lockdown in 2020 than the average of the equivalent period in the last 5 years, which can be associated with higher regional source emissions in 2020 than in previous years (ECMWF, 2020) registering just a 6% reduction during the strict lockdown (because of lower vehicle emissions but higher regional emissions) and just a 3% reduction during the relaxed lockdown (due to slightly lower vehicle emissions and much lower regional activity). PM$_{10}$ reductions at the background station were 2%, 33%, and 25% before the lockdown, during the strict lockdown, and during the relaxed lockdown, respectively. This suggests that particulate matter resuspension, partly associated with traffic, is a significant source of PM$_{10}$ in Medellin, especially its coarse fraction.

### Table 1

Air quality monitoring stations. NA: Not available.

| City       | Station                  | Type of station     | Location | Background PM$_{10}$ | Background NO$_2$ | Background PM$_{2.5}$ | Traffic PM$_{10}$ | NO$_2$ | PM$_{2.5}$ |
|------------|--------------------------|---------------------|----------|----------------------|--------------------|----------------------|-------------------|--------|------------|
| Bogotá     | Centro de Alto Rendimiento | Urban background | 4.6585   | 74.0840              | 74.0824            |                      | x                  | x      | x          |
|            | Las Feras                | Traffic             | 4.6907   | −74.0824             | −75.644            |                      | x                  | NA     | x          |
| Medellín   | Concej de Itagüí         | Suburban background | 6.1685   | 75.5695              | 75.6443            |                      | x                  | x      | x          |
|            | Estaciones Tráfico Centro | Traffic             | 6.2525   | 75.6443              | 75.6443            |                      | x                  | x      | x          |

### Table 2

Average concentrations of PM$_{10}$, PM$_{2.5}$, and NO$_2$ for the periods before lockdown (February 21 to March 19), strict lockdown (March 20 to April 26), and relaxed lockdown (April 27 to June 30), and their relative variation between periods. NA: Not Available.

| Station | Pollutant | Concentration (μg/m$^3$) | Variation | Traffic variation (%) |
|---------|-----------|---------------------------|-----------|----------------------|
|         |           | Before lockdown | Strict lockdown | Relaxed lockdown       |
|         |           | μg/m$^3$ | % | μg/m$^3$ | % | μg/m$^3$ | % | μg/m$^3$ | % |
| Bogotá  | NO$_2$    | 42.6 ± 6.2    | 17.0 ± 6.9    | 16.4 ± 8.0  | −25.6 | −60 | −26.2 | −62 | −73 | −50 |
|         | PM$_{10}$ | 40.2 ± 12.1   | 24.4 ± 13.2   | 14.8 ± 12.8 | −15.8 | −39 | −25.4 | −63 |
|         | PM$_{2.5}$| 29.6 ± 10.1   | 19.4 ± 12.4   | 7.4 ± 5.5   | −10.2 | −34 | −22.2 | −75 |
| Traffic | NO$_2$    | 48.7 ± 8.4    | 18.0 ± 8.1    | 18.7 ± 10.2 | −30.8 | −63 | −30.0 | −62 |
|         | PM$_{10}$ | 47.2 ± 12.7   | 29.9 ± 13.6   | 16.0 ± 13.5 | −17.3 | −37 | −31.1 | −66 |
|         | PM$_{2.5}$| 32.3 ± 9.9    | 20.7 ± 13.9   | 7.9 ± 5.0   | −11.6 | −36 | −24.5 | −76 |
| Medellín | NO$_2$    | 61.8 ± 14.2   | 31.6 ± 16.1   | 29.1 ± 10.0 | −30.2 | −49 | −32.8 | −53 |
|         | PM$_{10}$ | 41.9 ± 11.6   | 23.1 ± 14.7   | 15.9 ± 4.3  | −18.8 | −45 | −26.0 | −62 |
|         | PM$_{2.5}$| 45.3 ± 13.4   | 15.8 ± 10.5   | 32.6 ± 10.4 | −29.6 | −65 | −12.7 | −28 |
| Traffic | NO$_2$    | 81.9 ± 17.0   | 38.9 ± 17.5   | 40.8 ± 13.5 | −42.9 | −52 | −41.1 | −50 |
|         | PM$_{10}$ | 50.6 ± 12.0   | 25.6 ± 15.4   | 18.5 ± 5.7  | −25.0 | −49 | −32.1 | −63 |
The fulfilment of the WHO air quality guidelines, especially during the relaxed lockdown period, represents a reduction in the additional risk of morbidity and mortality due to the COVID-19 pandemic (Conticini et al., 2020; Zhu et al., 2020).

3.3. Back trajectory analysis and effects of long-range transport

The lockdown was a natural experiment of historical importance to assess the impact of local sources, especially vehicle emissions, as
well as the regional impact of BB and the Saharan dust intrusion on air quality. The beginning of the lockdown occurred in the middle of a high air pollution event that had caused increased restrictions to the use of private vehicles and cargo trucks. High concentrations of air pollutants at the beginning of the lockdown can be associated with BB in the Orinoco basin and the Magdalena Valley, as indicated by the HYSPLIT back trajectories of air masses from high fire activity areas arriving at Bogotá and Medellín (Fig. 3). The main impacts during the lockdown occurred from March 20 to April 1st and from April 14 to May 1st.

The comparison between the days of high and low fire activity (Table 4) shows that the increase in background concentrations associated with BB was as high as 20 μg/m³ of PM₁₀ in Bogotá and 19 μg/m³ of PM₁₀ in Medellín. The impact of BB on air quality has

### Table 3

Average concentrations of PM₁₀, PM₂·₅, and NO₂ for the equivalent periods before lockdown (February 21 to March 19), strict lockdown (March 20 to April 26), and relaxed lockdown (April 27 to June 30) from 2015 to 2019, and the relative variation with 2020. NA: Not Available.

| Station | Pollutant | Before lockdown eq. | Strict lockdown eq. | Relaxed lockdown eq. | Variation: 2020 – (2015 to 2019) |
|---------|-----------|---------------------|---------------------|----------------------|----------------------------------|
|         | NO₂       | μg/m³ ± %           | μg/m³ ± %           | μg/m³ ± %            | μg/m³ ± %                        |
| Bogotá  | Background NO₂ | 35.0 ± 7.9 | 33.9 ± 6.9 | 25.9 ± 6.1 | 7.6 ± 22 | −16.9 ± −50 | −9.6 ± −37 |
|         | PM₁₀      | 43.5 ± 7.5 | 35.4 ± 5.8 | 22.3 ± 5.2 | −3.3 ± −7 | −11.0 ± −31 | −7.5 ± −34 |
|         | PM₂·₅    | 26.1 ± 3.7 | 22.2 ± 3.3 | 11.4 ± 2.2 | −3.4 ± 13 | −2.8 ± −13 | −4.0 ± −35 |
| Traffic | NO₂       | 47.0 ± 9.3 | 47.8 ± 8.9 | 36.8 ± 7.0 | −1.7 ± 4 | −29.8 ± −62 | −18.4 ± −49 |
|         | PM₁₀      | 48.2 ± 8.3 | 41.3 ± 6.3 | 26.1 ± 5.0 | −1.1 ± −2 | −11.5 ± −28 | −10.0 ± −38 |
|         | PM₂·₅    | 25.1 ± 4.5 | 21.0 ± 3.4 | 11.4 ± 2.3 | −7.2 ± 29 | −1.2 ± −5 | −3.5 ± −31 |
| Medellín| Background NO₂ | NA | NA | NA | NA | NA | NA |
|         | PM₁₀      | 62.9 ± 13.1 | 47.4 ± 8.7 | 38.6 ± 9.6 | −1.1 ± −2 | −15.7 ± −33 | −9.5 ± −25 |
|         | PM₂·₅    | 35.1 ± 6.6 | 24.6 ± 4.5 | 16.3 ± 4.5 | −8.7 ± 19 | −1.5 ± −6 | −0.5 ± −3 |
| Traffic | NO₂       | 54.2 ± 13.0 | 51.2 ± 12.1 | 50.4 ± 11.6 | −8.9 ± −16 | −35.5 ± −69 | −17.8 ± −35 |
|         | PM₁₀      | 74.2 ± 11.1 | 58.5 ± 10.7 | 50.1 ± 11.7 | −7.6 ± 10 | −19.6 ± −33 | −9.4 ± −19 |
|         | PM₂·₅    | 49.4 ± 7.9 | 39.3 ± 7.3 | 27.9 ± 6.9 | −1.1 ± 2 | −13.8 ± −35 | −9.5 ± −34 |

**Fig. 3.** Back trajectories density of air masses calculated with HYSPLIT and MODIS fires (orange dots) for (a.) Before lockdown, (b.) Strict lockdown, and (c.) Relaxed lockdown. The arrival points of air masses were at 500 m AGL.
been identified in previous studies, especially in the first quarter of the year (Méndez-Espinosa et al., 2019; Hernandez et al., 2019; Rincón-Riveros et al., 2020).

On the other hand, the Saharan dust intrusion event caused a spike in PM10, which increased from an average of 37 μg/m³ during the relaxed lockdown period to 85 μg/m³ (an increase of 48 μg/m³ or 130%) in Bogotá, and a similar increase in Medellín (48 μg/m³ or 123%). Events of Saharan dust intrusion to the Andes are rather scarce but have affected air quality in these two cities previously. Méndez et al. (2018) showed that the 2014 event increased PM10 concentrations up to 168 μg/m³ in Bogotá, and 104 μg/m³ in Medellín.

### 3.4. Spatial analysis of fire flux OC emissions and tropospheric NO2

The fire flux OC assimilated data confirmed the changes in emissions from BB in NSA during the lockdown period (Fig. 4). Not only Bogotá and Medellín were affected, but other major cities such as Barranquilla in the Caribbean coast, and regions located northeast of Ecuador (such as Nueva Loja), western Venezuela (such as Barinas), and northeastern Colombian including Bucaramanga and Cúcuta, close to the border with Venezuela. These regions comprise millions of people that could be exposed to high levels of pollutants (PM10 up to 95 μg/m³ and PM2.5 up to 60 μg/m³), especially during the first three months of the year (fire season). Fire flux OC emissions before and during the strict lockdown were higher than during the relaxed lockdown, especially in the north and southwest of Colombia, the Amazon region in Ecuador and Peru, and the northwest of Venezuela. This result was consistent with the results obtained from ground observations. Recently, the CAMS confirmed that fire activity and emissions from BB in NSA during 2020 were overall above the 2003–2019 average (ECMWF, 2020), accordingly they need to be properly managed to benefit local air quality improvement plans.

The major reductions described in Table 2 for NO2 were also observed by analyzing tropospheric NO2 data supplied by TROPOMI. A notable reduction in NO2 concentrations was observed between one day before the lockdown (March 6th), and two days during the lockdown: one day of low fire activity during the strict lockdown (April 7th), and one day during the relaxed lockdown (June 26th) (Fig. 5). In Bogotá, the reductions were 82% and 90% for the strict and relaxed lockdown periods, respectively, higher than those obtained from ground observations at the background station (60% and 62%, Table 2). In Medellín, the respective reductions were 37% and 19%, lower than those from ground observations at the traffic station (65% and 28%, Table 2). Urban NO2 is emitted from combustion processes, mainly from road traffic. Therefore,

### Table 4

Average concentrations of PM10 and PM2.5 during the lockdown (March 20 to June 30) and the relative variation between days with high and low fire counts. NA: Not Available.

| Station | Pollutant | Concentration (μg/m³) | Variation (Low – High) | % |
|---------|-----------|-----------------------|------------------------|---|
|         |           | High fire count        | Low fire count          |    |
|         |           | (647 ± 290 fires/day)  | (97 ± 82 fires/day)     |    |
| Bogotá  | Background PM10 | 33.8 ± 10.4 | 14.2 ± 8.8 | −19.6 | −58 |
|         | PM2.5     | 27.9 ± 10.5 | 9.4 ± 7.8 | −18.5 | −66 |
| Traffic | PM10      | 38.2 ± 11.3 | 15.9 ± 9.2 | −22.3 | −58 |
|         | PM2.5     | 29.6 ± 11.2 | 9.1 ± 7.8 | −20.4 | −69 |
| Medellín| Background PM10 | 45.4 ± 15.4 | 26.6 ± 10.0 | −18.8 | −41 |
|         | PM2.5     | 35.0 ± 14.6 | 16.6 ± 9.0 | −18.3 | −52 |
| Traffic | PM10      | 54.6 ± 19.4 | 35.8 ± 12.3 | −18.8 | −34 |
|         | PM2.5     | 38.6 ± 17.0 | 18.5 ± 9.6 | −20.2 | −52 |

*Fig. 4.* Organic Carbon fluxes in the NSA region for (a.) Before Lockdown, (b.) Strict lockdown, and (c.) Relaxed lockdown.
the tropospheric NO2 was at its minimum level during the lockdown in NSA as a consequence of social isolation. These results concurred with the behavior of NO2 observed in China, Europe, and northeastern USA (Muhammad et al., 2020).

4. Discussion

Previous sections showed that concentrations of PM10, PM2.5, and NO2 in Bogotá and Medellín decreased during the COVID-19 lockdown. In average, the variations were −60% for NO2, −44% for PM10, and −40% for PM2.5 during the strict lockdown, and −62% for NO2, −58% for PM10, and −69% for PM2.5 during the relaxed lockdown. The decrease in NO2 was associated with the reduction in traffic, as has been documented in other cities in South America and around the world. PM10 and PM2.5 also decreased, although BB events affected these reductions during the strict lockdown.

The comparison with variations during the equivalent period of the previous 5 years (long-term variations) showed that concentration reductions were only partly due to the changes in meteorological conditions that usually occur at this time of the year. In average, taking the previous years as baseline, the variations were −50% for NO2, −32% for PM10, and −9% for PM2.5 during the strict lockdown, and −37% for NO2, −29% for PM10, and −19% for PM2.5 during the relaxed lockdown.

For policy-making purposes, these figures offer a more realistic scenario, because policymakers should consider long-term variations and different factors that affect them, avoiding misleading artifacts. Using a similar approach, Zangari et al. (2020) showed that, even though PM2.5 and NO2 concentrations in New York decreased during the lockdown, no reductions were observed in the long-term analysis.

To compare lockdown impacts on air quality with those achieved in other cities around the world, the short- and long-term pollutant concentration changes in Bogotá and Medellín were considered as upper and lower limits. Fig. 6 shows that, in general, reductions in these cities were higher than the average of those found in Asian, European, North American, and South American cities, when the short-term changes are considered, but lower than the average for the long-term changes. The reduction in PM2.5 at Bogotá achieved during the relaxed lockdown was higher than the average of the other cities for both short- and long-term changes. The same occurred for NO2 at both cities during the relaxed lockdown, with the highest reductions in mobility.

It can be expected that policies aiming to reduce traffic emissions will have significant improvements on air quality. If emissions reductions equivalent to those during the relaxed lockdown, with a 50% reduction in mobility and without the strong influence of BB emissions, were achieved through better vehicle technologies, increase use of bicycles and electric scooters, teleworking, and better transit, the annual average in pollutant concentrations at the background station in Bogotá used for this study would be around 12 µg/m³ for PM2.5 (20% over the

Fig. 5. Tropospheric NO2 column in Bogotá and Medellín for (a.) March 6, 2020 (Before lockdown), (b.) April 7, 2020 (Strict lockdown), and (c.) June 26, 2020 (Relaxed lockdown). Data obtained from ESA Sentinel 5p/TROPOMI.
WHO guidelines), 19 μg/m³ for PM₁₀, and 17 μg/m³ for NO₂. Further reductions in PM₂.₅ sources would, therefore, be needed to meet WHO PM₂.₅ annual average guidelines.

5. Conclusions

This study analyzed the behavior of selected criteria air pollutants during the implementation of the COVID-19 strict and relaxed lockdown periods, starting on 20 March 2020, in two major cities in NSA, for which a set of tools including surface measurements, satellite images, and modeled data was used. Background PM₁₀ concentrations decreased on average by 44% for the strict lockdown and 58% for the relaxed lockdown, while PM₂.₅ decreased by 40% and 69%, respectively. The highest reductions were obtained on urban NO₂ with 60% and 62% during the strict and relaxed lockdown, respectively. Reductions were generally lower when comparing lockdown levels with the equivalent periods of previous years, because of higher pollution levels before the lockdown: for the strict and relaxed lockdown, average long-term reductions were −50% and −37% for NO₂, −32% and −29% for PM₁₀, and −9 and −19% for PM₂.₅. Also, long-range air pollution transport affected air quality during the lockdown. Biomass burning events in March and April increased PM₂.₅ pollution by almost 20 μg/m³, whereas a Saharan dust intrusion event at the end of June increased PM₁₀ by almost 50 μg/m³, at both cities. This study highlighted two important findings during the sanitary contingency: i) cities of northern South America were able to achieve the lowest level of pollutants (fulfilling WHO guidelines) during the lockdown periods, ii) air quality benefits were partially overridden by the impact of BB and a Saharan dust event. A proper management of regional BB events is of upmost importance for the NSA region.

CRediT authorship contribution statement

J.F. Mendez-Espinosa: Software, Investigation, Writing - original draft, Writing - review & editing. N.Y. Rojas: Conceptualization, Writing - review & editing. J. Vargas: Software, Investigation, Data curation. J.E. Pachón: Writing - review & editing. L.C. Belalcazar: Conceptualization, Data curation, Writing - review & editing. O. Ramírez: Conceptualization, Investigation, Writing - original draft, 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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