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Impact of lockdown on particulate matter concentrations in Colombia during the COVID-19 pandemic

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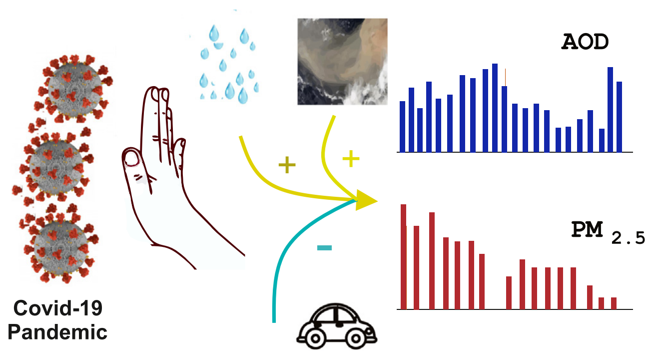
HIGHLIGHTS

- The COVID-19 pandemic triggered closures in Colombia that greatly reduced PM2.5 concentrations.
- The capital of Colombia (Bogotá) and regions in the north of the country experienced a decline (68% and 86%) in $PM_{2.5}$.
- The $PM_{2.5}$ reductions are associated with reduced vehicular traffic due to lockdown.
- The spatial and temporal values of AOD are related to regional rainfall and Saharan dust over coastal areas.

GRAPHICAL ABSTRACT



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ABSTRACT

The first confirmed case of COVID-19 in Colombia was reported on March 6, 2020. For this reason, on March 25, preventive isolation was declared mandatory. These measures involved the suspension of economic activities and drastically reduced the number of vehicles on the road. The objective of this study is to evaluate the impact of the lockdown due to the COVID-19 pandemic on $PM_{2.5}$ concentrations at 5 monitoring stations and aerosol optical depth values of the Terra/MODIS satellite. We analyzed and compared the weekly and monthly concentrations of $PM_{2.5}$ before and during the lockdown between the week of January 6 to June 22, 2020, and compared the daily values obtained from the Terra/MODIS satellite for the months of January–June during the years 2018–2020 to elucidate the effects of the lockdown. Similar to other monitored sites in the world, we observed substantial reductions in weekly $PM_{2.5}$ concentrations, from 41 to 84% (Bogotá), from 13 to 66% (Funza), from 17 to 57% (Boyacá), from 35 to 86% (Valledupar) and 31 at 60% (Risaralda). Unlike other studies, the aerosol optical depth values increased up to 59% during the months of lockdown compared to previous years and up to 70% of the weekly mean when compared to before the lockdown. These spatiotemporal behaviors of $PM_{2.5}$ and the aerosol optical depth in Colombia are influenced by reductions in vehicular flow during quarantine, regional rainfall, and height of the planetary boundary layer. Emissions from economic activities affect pollutant levels in the area. The analysis of the levels of pollutants during the lockdown provides a baseline for regulatory agencies to establish mitigation plans.

1. Introduction

Coronavirus disease 2019 (COVID-19) is a viral infection that can cause severe acute respiratory syndrome with severe pneumonia (Coccia, 2020). The disease began in the city of Wuhan, China, at the

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Nomenclature

COVID-19	COronaVirus Diseases 2019
AOD	aerosol optical depth
IDEAM	Institute of Hydrology, Meteorology and Environmental Studies (for its acronym in Spanish)
MODIS	Moderate Resolution Imaging Spectroradiometer
PM	particulate matter

end of 2019. In early 2020, the scientific community isolated a new coronavirus from patients in Wuhan. The genetic sequence of the new coronavirus allowed the rapid development of real-time diagnostic tests (C. Wang et al. 2020). The first investigations showed that the most common symptoms at the beginning of the disease are fever, cough and myalgia or fatigue. The less common symptoms were sputum production, headache and diarrhea (W. Guan et al. 2020; Huang et al., 2020). Factors such as advanced age, a history of smoking, high blood pressure and heart disease are associated with the development of the disease (Gautam, 2020; Zhou et al., 2020). Additionally, it has been found that the level of air pollution of a region and the lethality are related to COVID-19 and are positively correlated, indicating that air pollution is an elemental and hidden factor in the aggravation of the global load number of deaths related to COVID-19 (Gupta et al., 2020). Due to its high degree of contagion and its aggressive course, the WHO declares Covid-19 disease as a Public Health Emergency of International Concern, giving it the status of pandemic (WHO, 2020). According to the National Institute of Health of Colombia, the first confirmed case of COVID-19 disease in Colombia was reported from Bogotá on March 6, 2020. To try to stop the transmission of the virus, on March 25, the authorities decreed an emergency closure/lockdown. This implied that the closure of restaurants, study centers, large gatherings were restricted, public transport was suspended, and airports and train stations were closed. The term used for lockdown was mandatory preventive isolation (del Interior, 2020). Other terms frequently used in the country are quarantine, social isolation and mandatory isolation. As of September 25, 2020, 798,317 confirmed cases and 25,103 deaths have been reported in the country (Minsalud, 2020). Getting sick from COVID-19 can cause progressive respiratory failure and death with greater probability in people with comorbidities (W.J. Guan et al. 2020; Richardson et al., 2020). Many of the comorbidities in people living in urban areas are associated with respiratory diseases (respiratory disease, asthma, exacerbation of chronic obstructive pulmonary disease (COPD)) caused by exposure to poor environmental and indoor air quality.

Urban air pollution comes mainly from commuting or transport, economic activities and residential energy use (Borck, 2019; Grondys, 2019). When there are measures to control vehicular flow or industrial emissions, the levels of air pollutants are reduced. The consequences due to the pandemic are estimated to have significant social, environmental, health and economic implications (Gautam and Hens, 2020). The efforts of countries to implement measures to control the coronavirus pandemic have reduced economic activity and led to a decrease in atmospheric emissions (Dickinson, 2020). Particulate matter is classified as the main indicator of air quality in urban and industrial areas due to its composition and sources of origin. Recent research reports reduction of these pollutants due to the restrictions of mobility and productive activities caused by the pandemic. In the epicenter of the pandemic, in the city of Wuhan, the average reduction of particulate matter during the first weeks of quarantine was approximately 22 μg m^{-3} (P. Wang et al. 2020). In Delhi, Mahato et al. (2020) found during COvid-19 emergency closures a reduction of PM_{10} and $PM_{2.5}$ concentrations by more than 50% compared to historical data prior to emergency measures. Dantas et al. (2020) compared the records of 3 air quality monitoring stations located in the city of Rio de Janeiro (Brazil) during the weeks prior to and during the restrictions mandated by the government due to the health emergency, finding an increase between 25 and 30% of PM_{10} concentrations during social isolation. They attributed this behavior to the heavy rains before the measures were implemented. The studies by Nadzir et al. (2020) show that CO and particulate concentrations reduced by 40–50% and 20–60% respectively during the lockdown period in Malaysia. In many regions and cities around the world, less polluted atmospheres have been seen for the first time in several decades due to the restrictions given by the COVID-19 pandemic. Kumar et al. (2020) cited approximately 39 studies in their article on the impact of lockdown and their effects on the levels of different pollutants in the air in many of the world. Table 1 illustrates other recent studies focused on the impact of lockdown on the levels of particulate matter studied through the concentrations of PM_{10}, $PM_{2.5}$ and AOD.

Colombia faces air pollution challenges due to the massive arrival of foreigners and rapid expansion of industrial and agricultural development. Additionally, the country experiences a significant increase in vehicular flow in urban and rural areas. As a result, large cities face environmental problems related to air quality, mainly due to particulate matter (Casallas et al., 2020; Lopez-Restrepo et al., 2020). Logically, the reduction in the number of vehicles and industrial operations has an impact on air quality due to the isolation and cessation of productive activities. However, in Colombia, some cities reported levels of particulate matter exceeding the national air-quality standard during the first week of lockdown, which corresponded to forest fires in the northern part of South America (SIATA, 2020). To understand the impact of the variations of the pollutants in the country during lockdown, Mendez-Espinosa et al. (2020) analyzed the values of four stations in urban areas belonging to the cities of Bogota and Medellin. The authors show that the environmental levels of $PM_{2.5}$ and PM_{10} are reduced by 40% and 44%, respectively. However, in the country, the impact of COVID-19 on air quality has not been analyzed considering industrial, rural and residential areas. Additionally, it is necessary to determine the spatial variations of particulate matter throughout the territory because positive anomalies are reported with the detection of fires in jungle areas of the country and near the border with Venezuela (Amador-Jiménez et al., 2020). Air quality is an important factor that any government must acquire tools to manage and control. Colombia implemented an Air Pollution Prevention and Control Policy in 2010. This monitoring has revealed that of the deaths attributable to environmental risk factors, air pollution is responsible for the greatest burden of environmental disease in Colombia. The estimated environmental risk factor is approximately 88%, mainly due to coronary heart disease (CHD) and chronic obstructive pulmonary disease (COPD) (INS, 2018).

This study presents the findings of the changes in air quality observed at five sites in Colombia, which resulted from changes in the emission patterns associated with lockdown due to the COVID-19 pandemic. The analysis covers from January 6 to June 22, 2020. The purpose of this study is, first, to evaluate the extent of the reductions observed in $PM_{2.5}$ concentrations and AOD values in representative regions of the country resulting from the closing. Additionally, this research seeks to understand the impact of insulation measures on air quality in urban, rural and industrial areas. The results of this research provide information on the local and regional impacts of human activities on the values of $PM_{2.5}$ and AOD. This study will project the degree of impact of human activities on air pollutant loads and provide us with tools to develop viable procedures for the management and control of air quality.

2. Methodology

Colombia is situated in the northernmost part of South America. It lies between latitudes 12° N and 4° S and between longitudes 67° and 79° W and comprises 32 departments. It is the fourth largest country in South America. It has a population of 50,372,424 inhabitants (DANE, 2005). Geographically, the country is characterized by having a mountainous system known as the Andean system. The Andean

Table 1
Recent studies on the impact of air quality, especially considering particulate matter, during the COVID-19 pandemic.

Study area (city, country)	Key findings	Author (year)
Region of India (134 monitoring stations)	• They estimated changes in air pollution, including particulate matter ($PM_{2.5}$ and PM_{10}) during the strict lockdown phases (March 25–May 3, 2020) through an analysis of daily variation and diurnal variation. • The results show average reductions of $PM_{2.5}$ (northwest region and Indo--Gangetic plain up to 50%, southern region up to ~40% and central region up to ~25%) and PM 10 (northwest region and Indo--Gangetic plain up to 60%, southern and central region up to ~40%).	(Singh et al., 2020)
United States (California, Florida, Louisiana, North Carolina, and Alabama) and China (Hubei, Beijing, Shanghai, Guangdong, and Zhejiang).	• Through data obtained between January 1 and April 30, 2019 and 2020 from the EPA online platform (https://www.epa.gov/) and the MEE (http://datacenter.mee.gov.cn/) the concentrations of five contaminants were analyzed. • The results in general show that in the United States, $PM_{2.5}$ levels decreased by 1.10%, while PM_{10} levels increased by 3.81%. Meanwhile, in China the concentrations of $PM_{2.5}$ and PM_{10} were reduced by 17.78% and 37.85%, respectively.	(Shakoor et al., 2020)
Spain (Barcelona, Bilbao, Lleida, Madrid, Pamplona, Santander, Santiago de Compostela, Seville, Valencia, Vigo, Zaragoza)	• The study showed that short-term lockdowns (March 15 to April 12, 2020) are not sufficient to improve air quality. Although a significant decrease in the environmental levels of PM_{10} is observed during the quarantine period, the influence of meteorological factors influences surface concentration values.	(Briz-Redón et al., 2020)
India (Chandigarh)	• They investigated the impact of the emergency closure from March 25, 2020 to May 17, 2020 by examining the levels of 14 contaminants through the analysis of principal components and the combined trajectory analysis. • The results show decreases of up to 28.8% and 36.8 for $PM_{2.5}$ and PM_{10}, respectively. Identifying the greatest variations in environmental levels due to vehicular emissions.	(Mor et al., 2020)
Saudi Arabia (Jubail, Qatif, Dammam and Al Ahsa)	• Using descriptive statistical analysis, they analyzed PM_{10} and meteorological behavior during September 15, 2019 to July 18, 2020 for 7 surface stations. • The average concentrations of PM_{10} contaminants in several monitoring stations were reduced to lower levels than the WHO reference values due to the imposed lockdown. Reductions reached within the range between 21 and 70% in most monitoring sites.	(Anil and Alagha, 2020)
India	• They quantified the changes in the hourly pollution levels, as well as the weather during the 6-week lockdown of COVID-19 in 17 cities in India. • The greatest decrease is observed in Ahmedabad (68%) and Delhi (71%) for $PM_{2.5}$ and PM_{10}, respectively. The greatest decline observed • It was during the hours of the day from 7 to 10 am and from 7 to 10 pm with a reduction of more than 40%.	(Navinya et al., 2020)
China (Beijing-Tianjin-Hebei region)	• The authors explored the variability of large-scale air pollutants from January 23 to April 8, 2020 using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT), potential source contribution function (PSCF) and concentration weighted trajectory models (CWT). • The contamination by $PM_{2.5}$ was mainly affected by local emission sources that contributed from 51.6% to 60.6% of the total trajectories in the region with a concentration of $PM_{2.5}$ that oscillates between 146.2 μg m^{-3} and 196.7 μg m^{-3} during the first episode presented during this period.	(Zhao et al., 2020)
Iraq (Baghdad)	• They evaluated the concentrations of $PM_{2.5}$ and PM_{10} before the closure of January 16 to February 29, 2020, and during four partial and total closure periods from March 1 to July 24, 2020, in Baghdad. • In comparison with the period prior to the closure, the following results are presented: In the first closure, the concentrations decreased by 8 and 15% of $PM_{2.5}$ and PM_{10}, respectively. • In the second closure, $PM_{2.5}$ concentrations decreased by 2.5, while there was an increase of 56% for PM_{10}.	(Hashim et al., 2020)
New Zealand (Auckland)	• Its analysis period is focused on the time of the emergency closure that includes from March 27 to April 17, 2020. • The reductions observed in	(Patel et al., 2020)

Table 1 (*continued*)

Study area (city, country)	Key findings	Author (year)
	$PM_{2.5}$ and PM_{10} were significantly lower (8–17% for $PM_{2.5}$ and 7–20% for PM_{10}). Sea salt, traffic emissions and seasonality are significant factors in the behavior of these pollutants.	
India (Rajasthan)	• Using trend analysis for the 24-h daily average data for five pollutants, they found maximum decreases of PM_{10} and $PM_{2.5}$ in the industrial center of Rajasthan of ~58.2% (178.54 to 98.74 μg m^{-3}) and ~44.69% (95.98 to 40.09 μg m^{-3}), respectively.	(Sharma et al., 2020)
China (Wuhan)	• They evaluated the daily data of the air quality index (AQI) from January 1, 2016 to February 31, 2020. These values were compared with values from 2015 to 2020. • The AQI of Wuhan City decreased significantly, the higher the population density, the more significant the decrease.	(Lian et al., 2020)
South Korea (Seoul)	• They evaluated during the two 30-day periods before and after the onset of social distancing due to the pandemic. The mean concentration of $PM_{2.5}$ at 30 days decreased by 10.4% in 2020. The decrease in $PM_{2.5}$ concentration was more prominent during the day than at night.	(Han et al., 2020)
Western Europe	• Using the WRF-CHIMERE modeling system, they determined the impact of the measures to contain the Covid-19 pandemic on air quality during the month of March 2020. Time data for 799 stations for PM_{10} and 399 stations for $PM_{2.5}$. • Reductions in $PM_{2.5}$ concentrations are weak, between −5 and −10%. The sources of primary particle emissions from residential heating and emissions from the agricultural sector contribute to the formation of secondary fine particles in the atmosphere.	(Menut et al., 2020)
India	• They used data from the AOD product of the Terra--Agua/MODIS satellite sensors, Level 2 with spatial resolution of 1 km, to investigate the changes in the level of AOD during the lockdown phases throughout the Indian territory compared to the level of AOD medium to long-term (2000–2019) of the same periods. • Almost 45% of the level of AOD fell on the Indian territory during the periods of lockdown. The	(Ranjan et al., 2020)

Table 1 (*continued*)

Study area (city, country)	Key findings	Author (year)
	metropolitan cities showed a negative average AOD anomaly throughout the lockdown period.	
Northern South America	• For the analysis of particulate matter, 4 stations located in the cities of Medellín and Bogotá in Colombia were used. The authors show that the environmental levels of $PM_{2.5}$ and PM10 are reduced by 40% and 44%, respectively, during quarantine compared to the days previous to closure.	(Mendez-Espinosa et al., 2020)
Eastern China	• Employed MODIS-derived AOD at 550 nm obtained 154 by merging Dark Target and Deep Blue retrievals. • During the period from January 23 to April 8, 2020, it was 30% lower than the average of 2011–2019.	(Field et al., 2020)

system is divided into three mountain ranges: eastern, central and western. In this study, five regions, shown in Fig. 1, were selected to analyze the behavior of the pollutants: Bogotá, Funza, Boyacá, Valledupar and Risaralda. These regions were selected for the availability of $PM_{2.5}$ concentration data prior to and during the lockdown because of their representative geographic characteristics and land use.

Bogotá is the capital and the city with the largest population in Colombia (7,743,955 inhabitants) and is located at an average altitude of 2640 m asl within the Andean mountain range system. The city has a temperate climate. Due to its high altitude, Bogotá has a mountain climate; due to its low latitude (4°36′46″N), it shows little thermal oscillation throughout the year. The temperatures regularly oscillate between 5 and 19 °C, with an annual average of 13 °C. It has two rainy seasons and two dry seasons; precipitation is abundant from March to May (approximately 87 mm). It frequently presents mobility problems because it is estimated that approximately 2.4 million vehicles circulate. The reports of the IDEAM show frequent exceedances in PM_{10} levels during the year (IDEAM, 2016). Funza is part of the department of Cundinamarca located on the eastern mountain range of Colombia. It is located at an altitude of 2548 m asl and has an average annual temperature of 14 °C. Six percent of its territory corresponds to urban areas. Approximately 90% of its inhabitants are located in urban areas. The manufacturing industry and agriculture are the activities of the area. Boyacá is located in the center of Colombia at 2427 m asl. The city has a population of 1.3 million inhabitants. The average annual temperature in Boyacá is 19°, the average annual precipitation is 1216 mm, and the average annual relative humidity is 83%. In the area, minerals such as emeralds and coal are extracted. The city of Valledupar is located in northeastern Colombia at an altitude of 180 m asl. This city is close to the Caribbean Sea and is influenced by trade winds. The average annual temperature in the area is 28.4 °C. At the thermal level, Valledupar is the city of Colombia with the highest average temperature and with little cloudiness during the year. Large-scale open-pit mining is developed in this region. There are approximately 8 open pit mining projects. In the last decade, approximately 30 million tons of bituminous coal have been extracted. Risaralda is located in the central western region of the country, 223 km from Bogotá. It has a population of 1 million inhabitants. It is located at an average altitude of 1516 m asl The economic activities of the area are agriculture, livestock and the metal industry. Additionally, illegal gold ore and gravel extraction are recorded.

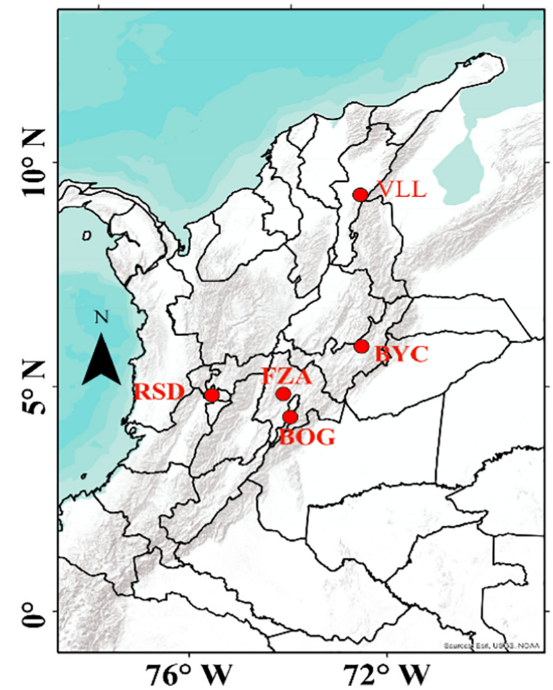

Fig. 1. Location of $PM_{2.5}$ monitoring stations in the regions of Bogotá (BOG), Funza (FZA), Boyacá (BYC), Valledupar (VLL) and Risaralda (RSD).

2.1. $PM_{2.5}$ data

The functioning and operation of $PM_{2.5}$ monitoring stations in Colombia are very limited. The $PM_{2.5}$ data were obtained from five monitoring stations in the regions of Bogotá (BOG), Funza (FZA), Boyacá (BYC), Valledupar (VLL) and Risaralda (RSD). These stations determine $PM_{2.5}$ levels using the CFR equivalent method (40 CFR Part 58) adopted by Colombian Federal Regulations. These data are freely downloadable and are recorded in the air quality subsystem regulated by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM for its acronym in Spanish) (http://www.ideam.gov.co/). Some stations of the country's air quality monitoring system were non-operative during the study period. Table 2 shows the coordinates, characteristics and some important notes regarding the stations. Weekly-monthly concentrations were analyzed and compared during the pre- lockdown and lockdown periods.

A descriptive statistical analysis and methods of analysis of outliers were performed on the $PM_{2.5}$ datasets obtained. The box plots were represented using the calculated mean, the median, the first quartile, the third quartile, the range within 1.5 times the interquartile range and the outliers of the $PM_{2.5}$ data observed weekly and monthly in each station for the phase before and during the emergency closure. The weekly and monthly precipitation values of four meteorological stations located within the study regions were used to interpret the behavior of $PM_{2.5}$ concentrations (Supplementary Tables S1 and S2).

2.2. Aerosol Optical Depth (AOD) Data

Daily data for the months of January to June of the mid-visible optical depth of aerosol in the air column were extracted at 550 nm from the Moderate Resolution Imaging Spectroradiometer (MODIS) of the Terra satellite during 2018–2020. AOD denotes the amount of aerosol in the atmosphere over the observation location. The MODIS Level-2 aerosol product over the study area was acquired from NASA's Level 1 Atmosphere Archive and Distribution System (LAADS). The Terra satellites were launched in December 1999 and cross the equator daily at approximately 10:30 local time (Remer et al., 2005). The data for used in this study were the Terra Collection 6 Dark Target AOD algorithm at a resolution of 3 km (https://modis.gsfc.nasa.gov/data/dataprod/mod04.php). Like the surface data of $PM_{2.5}$, a descriptive analysis was performed represented in box plots of the weekly and monthly values of AOD throughout the country, including land and ocean values, for the phases before and during lockdown. These average monthly AOD values were compared with previous monthly average values corresponding to the years 2018–2019.

3. Results and discussion

Fig. 2 shows the weekly concentrations of $PM_{2.5}$ in a boxplot. The time during the lockdown is highlighted in gray. The weeks of March 9 to March 23, called pre- lockdown, were used as references for the analysis. From the beginning of the lockdown (March 26) until the week of June 22, there are 13 weeks of social isolation and restrictions mandated by the Colombian government. Overall, $PM_{2.5}$ concentrations decrease during the lockdown period. A reduction in $PM_{2.5}$ levels is observed in the first week of lockdown in BOG (68.1%), FZA (24.2%), BYC (22.8%), VLL (59.2%) and RSD (30.9%) compared to the weeks of pre-lockdown.

All stations experienced reductions in $PM_{2.5}$ levels after March 30. In the BOG station, when comparing the values of $PM_{2.5}$ concentrations until the week of June 22, the reductions of $PM_{2.5}$ levels vary between 41 and 84% compared to the weeks of January, February and pre-lockdown. The greatest reductions occurred during the second week of lockdown. The stations of FZA (between 13 and 66%), BYC (between 17 and 57%), VLL (between 35 and 86%) and RSD (between 31 and 60%) showed decreasing trends after the lockdown went into effect. Significant reductions in $PM_{2.5}$ levels were recorded, most notably during the weeks of April, with the exception of the FZA station that recorded the greatest decrease in the first week of May (May 4). Studies of $PM_{2.5}$ in the Covid-19 era in urban areas show behavior patterns similar to this research. A decrease in $PM_{2.5}$ concentrations is observed during the confinement period (Chauhan and Singh, 2020; Rodríguez-Urrego and Rodríguez-Urrego, 2020).

Table 2
Description of the $PM_{2.5}$ monitoring stations in Colombia used to determine the impact pre- lockdown and during the lockdown periods.

ID	Region	Coordinates	Characteristics	Observations (01-06-2020 to 06-30-2020)
BOG	Bogota	04°32′16″N 74°08′16″W	Located in a rural area, less than 1 km from Doña Juana Landfill. Downwind from the urban area of Bogotá.	Data missing from daily concentrations was 2.84%
FZA	Funza	04°43′03″N 74°12′42″W	Located in an urban area approximately 10 km from the urban center of Bogotá.	Data missing from daily concentrations was 34.09%
BYC	Boyacá	05°46′15″N 72°56′16″W	Located downwind in an industrial zone producing construction materials and at a distance of 0.5 km from the urban center.	Data missing from daily concentrations was 31.25%
VLL	Valledupar	09°42′12″N 73°16′41″W	Located in an area influenced by the open pit coal mining industry in northern Colombia.	Data missing from daily concentrations was 76.70%
RSD	Risaralda	04°48′57″N 75°41′39″W	Station located in a residential area in the municipality of DOSQUEBRADAS (population of approximately 207,000 inhabitants) in the department of Risaralda.	Data missing from daily concentrations was 31.82%

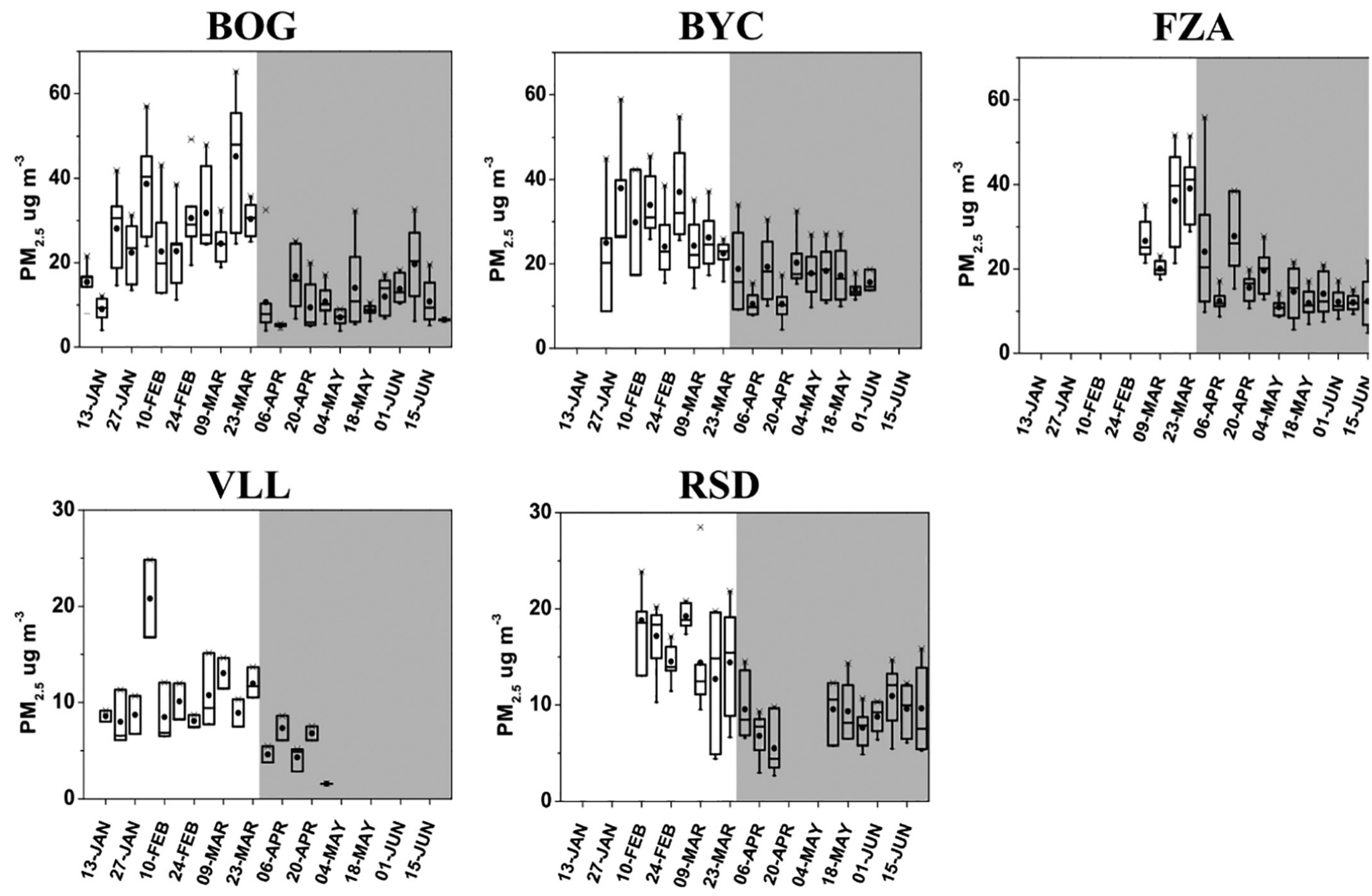

Fig. 2. $PM_{2.5}$ concentrations (μg m^{-3}) in the monitoring stations in Colombia during the weeks of January 06 to June 22, 2020. The period of preventive isolation began on March 25.

The decrease in $PM_{2.5}$ levels is related to factors such as the reduction of vehicular flow and local weather. During preventive isolation, the regions where the BOG and RSD stations are located experienced a reduction of vehicular traffic of 50–94% and 69–93%, respectively, compared to the normal patterns in recent years. Colombia in general experienced a reduction in average vehicle flow of 67% (BID, 2020).

Meteorological parameters could influence the decrease in $PM_{2.5}$ concentrations. The highest rainfall occurred in the region of the BOG and RSD stations during the lockdown period. However, before the lockdown, there was also significant precipitation (weekly rainfall of up to 30.9 mm for BOG and up to 116.3 mm for RSD). Precipitation helps wash out pollutants from the atmosphere through wet deposition of $PM_{2.5}$. The results of the monthly $PM_{2.5}$ concentrations and monthly rainfall at each station are shown in Fig. 3. The rainfall recorded for the FZA region was not obtained. For the month of March, when the lockdown began, the average $PM_{2.5}$ concentrations were classified as Pre-lockdown (Mar (B)) and during the lockdown (Mar (D)). The general trend of all stations is a reduction in $PM_{2.5}$ levels (monthly average). The monthly variations in $PM_{2.5}$, monthly precipitation and pollutant reductions vary between stations. Supplementary Table S3 shows the monthly concentrations of $PM_{2.5}$ (μg m^{-3}) in the monitoring stations for the pre-lockdown period and during the lockdown.

For the BOG station, in pre-lockdown, the monthly concentrations increase with increasing precipitation in the month. During the lockdown, a reduction in the monthly levels of $PM_{2.5}$ is observed compared to the months January, February and the pre-lockdown (Mar (B)). When comparing the concentrations of $PM_{2.5}$ for the months of January, February and Mar (B) (average values), there was a reduction of 15.9 ± 4.2 μg m^{-3}, 16.1 ± 6.0 μg m^{-3} and 12.7 ± 4.5 μg m^{-3} for the months of April, May and June at this station, respectively. For the BYC station, very little monthly precipitation was recorded compared to the records of other stations. The restrictions adopted during the lockdown influenced the monthly concentrations of $PM_{2.5}$. The greatest reductions were recorded in April with approximate values of 14.7 ± 4.9 μg m^{-3}. During this same month, the monthly precipitation was zero, according to what was recorded for this station.

At the FZA station, there was a notable reduction of $PM_{2.5}$ concentrations in the months of April, May and June compared to pre-lockdown. The effect of rainfall cannot be inferred because there is no surface data recorded at this weather station. However, monthly $PM_{2.5}$ concentrations trend downward during the lockdown period. The greatest reductions were recorded in June, with values of 41.83% compared to the pre-lockdown period. Missing records for the months of May and June at the VLL station prevents a more in-depth analysis of $PM_{2.5}$ concentration patterns in this area. However, April shows a reduction in $PM_{2.5}$ levels (5.4 ± 1.3 μg m^{-3}) compared to the previous months. The $PM_{2.5}$ levels for the RSD station reduced during the lockdown period. The greatest reductions occurred in the month of April (8.5 ± 3.8 μg m^{-3}) compared to February and pre-lockdown. During lockdown, until June, the concentrations tend to increase. Precipitation in this area has a significant effect on concentrations. During the lockdown, as precipitation decreases, $PM_{2.5}$ levels increase.

Fig. 4 shows the variations in the average AOD in land and ocean within the jurisdiction of Colombia in the first six months between 2018 and 2020. In general, the highest AOD values occur in April and June, while the lowest AOD values occur in January. When comparing interannual values, the lowest monthly AOD values correspond to 2018. Compared with 2018, the AOD values were significant for 2019 (range between 3 and 38%) and 2020 (range between 30 and 59%) during the months of April to June. In 2020, between the months of January–June, April had the highest monthly average with 0.30, followed by June with 0.28. In the month of March 2020, during the

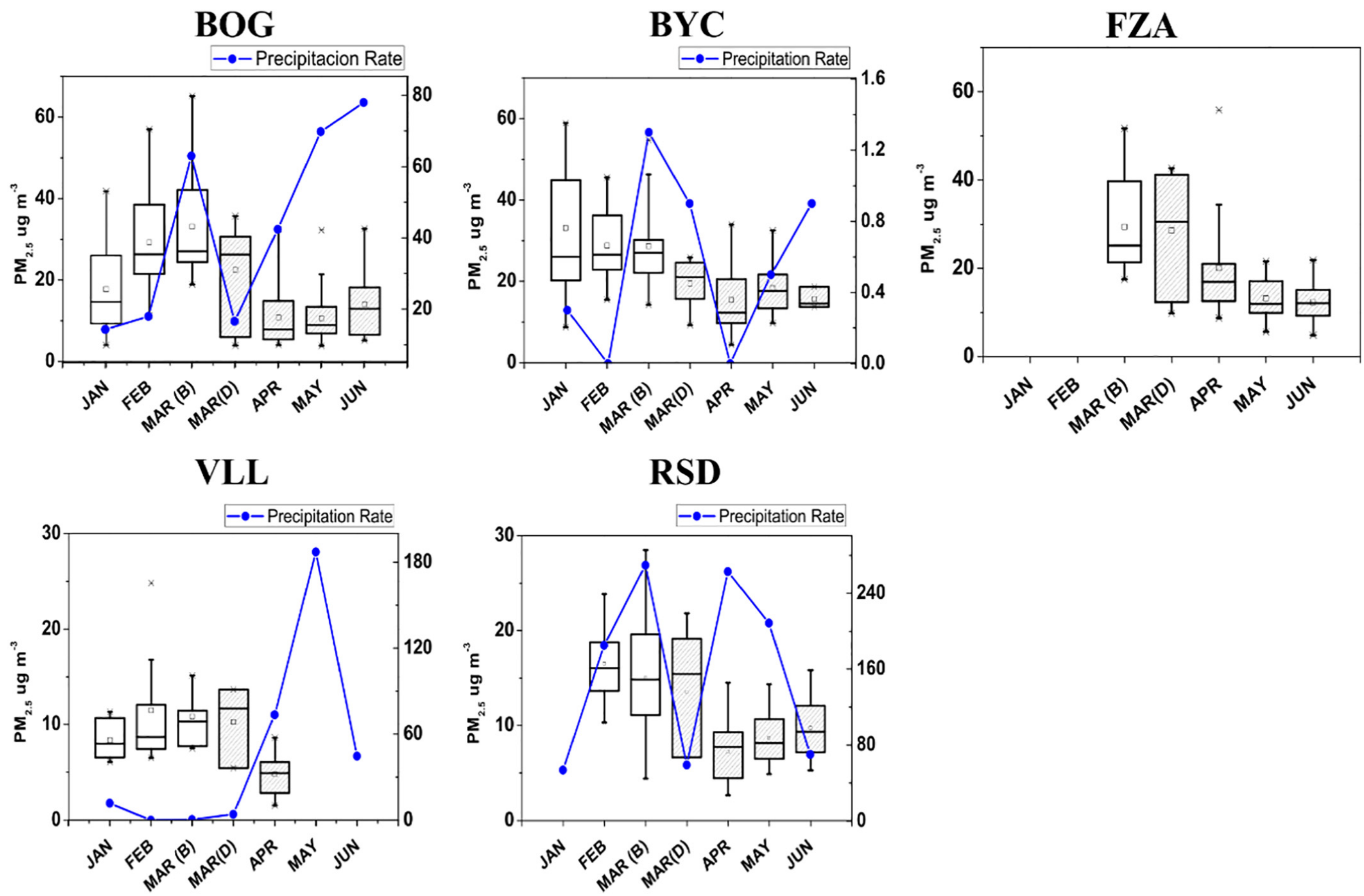

Fig. 3. Monthly concentrations of $PM_{2.5}$ (μg m^{-3}) and monthly precipitation (mm) in the monitoring stations in Colombia during January 6 to June 22, 2020. There were no rainfall records obtained from the FZA station for our analysis period.

months of the lockdown, the ADO values increased by 30%, 12% and 20% for April, May and June, respectively, compared to the pre-lockdown period.

The monthly variability of the AOD values on land and ocean in the territory of Colombia during 2018–2019 is shown in Fig. 5. The average spatial values of AOD can be observed during the months February–June of each year. In 2018, the highest monthly AOD values were recorded in June (0.23) due to the presence of aerosols in the Caribbean Sea. For 2019 and 2020, the highest monthly averages are recorded in March and April due to the high presence of aerosols in coastal areas and in

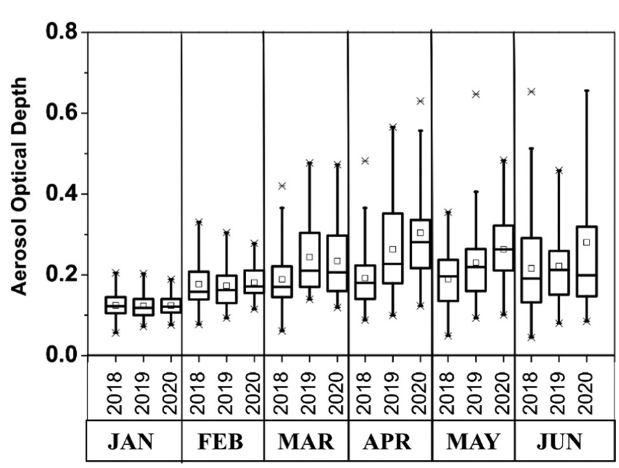

Fig. 4. Monthly AOD values in land and ocean within the jurisdictional limits of Colombia in the first six months of the years 2018–2020.

the southeast of the country. From the rainfall recorded in 2020, it is shown that in combination with the regional transport from the northeast, aerosol loading remains high in the north (the Caribbean region) and in the east (near Venezuela country) where precipitation was lower compared to central and western areas of the country for the month of March 2020. Subsequently, in April 2020, loads are reduced compared to the previous month due to the frequent precipitation in the north of the country. The AOD measured in April 2020 has a strong decline towards the center of the country compared to the previous month. During this month, the AOD on the borders with Venezuela and in the northern zone of Colombia presents the highest values (0.58) than that of the other more urbanized regions of the country. In the months of May and June 2020, there is a reduction in AOD values on land due to the reduction of vehicular traffic as a result of the measures implemented during the lockdown. However, aerosol loading over the ocean increases, especially near the coastline for these months. At the end of June, the intensification of annual winds transporting Saharan dust from Africa across the Atlantic Ocean significantly affects the atmosphere of the Colombian Caribbean (NASA, 2020).

The weekly analysis of the AOD averages in pre-lockdown and lockdown, shown in Fig. 6, reveals that during the first three weeks of the lockdown, the AOD values (weekly averages) tend to increase; then, after week five, they tend to decrease until the week of June 15. During the first weeks of lockdown, AOD levels increase (average values) by 16%, 26% and 70% in the weeks of March 30, April 6 and April 13, respectively, compared to the pre-lockdown weeks. Likewise, during the week of April 20 to May 11, the increases vary between 22%–46%. In contrast, in the first weeks of June 2020 (1, 8 and 15) there are reductions of up to 26% compared to pre-lockdown period. During the week of June 22, the AOD values are higher compared to the other weeks of the analysis. The

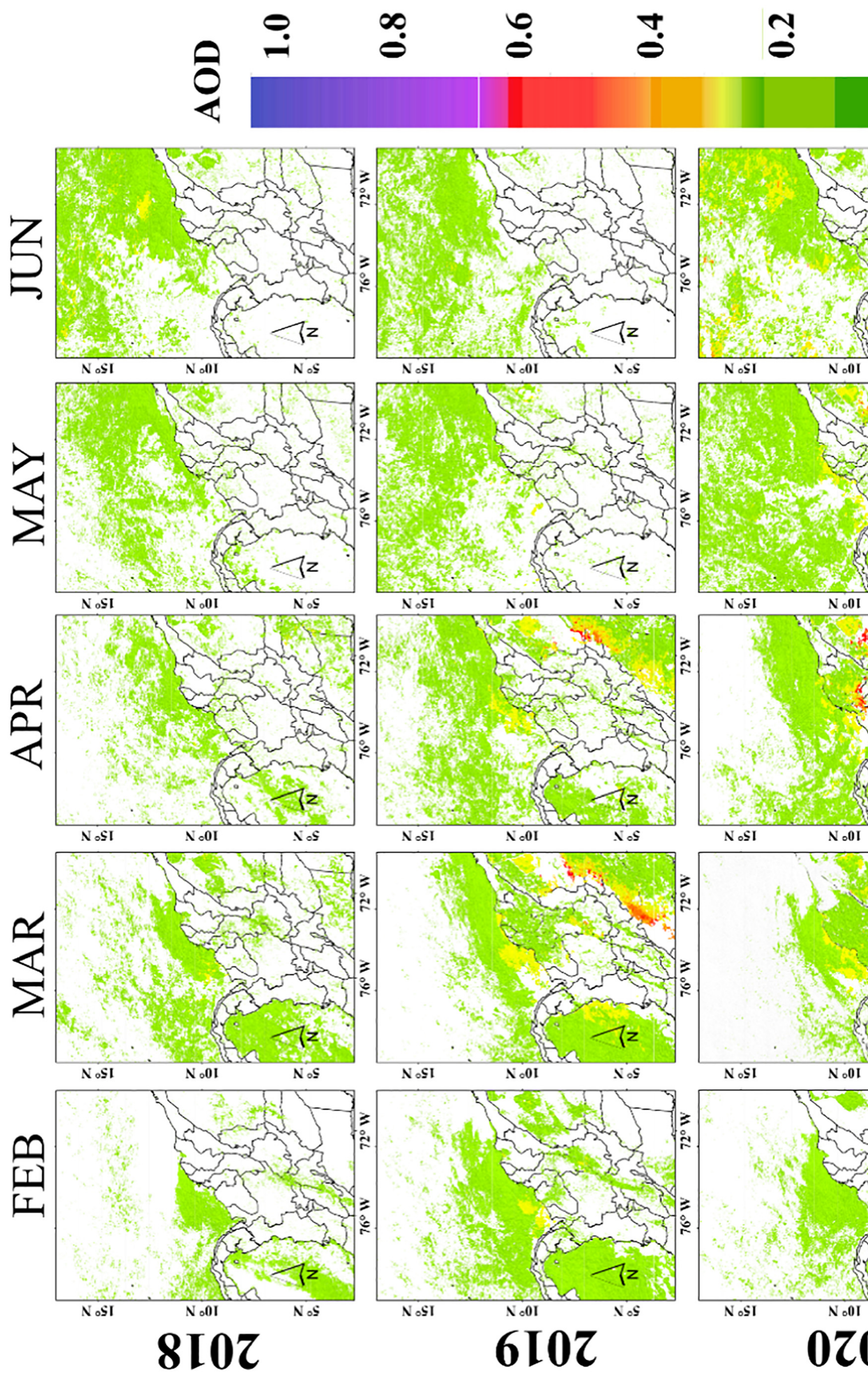

Fig. 5. Monthly distribution of AOD in land and ocean within the jurisdictional limits of Colombia during the months February–June between the years 2018–2020. The empty spaces represent AOD values less than 0.05.

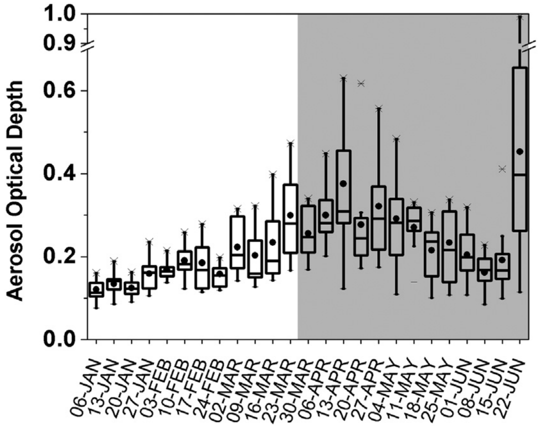

Fig. 6. Weekly AOD MODIS averages in Colombia during January 6 to June 22, 2020.

drastic increase in AOD values during the week of June 22 is due to Saharan dust masses that have crossed the Atlantic Ocean (NASA, 2020).

In general, compared to the pre-lockdown weeks, surface air quality stations show a decline (up to 86% for the VLL station) in weekly $PM_{2.5}$ levels during the lockdown. In contrast, weekly AOD values on land and ocean increase (up to 70%) during the weeks of March 30–April 20. A reduction is observed in the weeks of 1–15 June (up to 26%) compared to the reference weeks for this analysis. When analyzing the monthly values of $PM_{2.5}$ concentrations, reductions in the environmental levels of $PM_{2.5}$ are observed during the lockdown period compared to the months prior to isolation, especially during the months of April, and were significant in BOG (15.9 ± 4.2 μg m^{-3}), BYC (14.7 ± 4.9 μg m^{-3}) and VLL (5.4 ± 1.3 μg m^{-3}). In contrast, the highest values of AOD occur in April (mean value 0.30), representing an increase of 30% compared to previous months. The characteristic pattern in the weekly and monthly values of surface $PM_{2.5}$ and AOD in Colombia during the pre-lockdown and lockdown periods is a reduction of surface $PM_{2.5}$ and increased AOD values. This is explained by two factors associated with the planetary boundary layer and humidity. In the lockdown period, the reduced vehicular flow in the country (average reduction of 67%) contributed to decreased surface $PM_{2.5}$ levels. These processes occur within the boundary layer that varies according season. It has been estimated that the highest heights of the boundary layer in the country occur during the months of April–July (Nisperuza et al., 2011). Therefore, a lower local planetary boundary layer confines more particles that are concentrated near the surface, which leads to higher $PM_{2.5}$ values. The lower values of $PM_{2.5}$ in April–June 2020 are associated with restricted vehicular traffic due to the lockdown and a higher boundary layer during these months. Chauhan and Singh (2020) reported, through a short communication, that a partial or complete lockdown improves air quality by decreasing surface $PM_{2.5}$. Their analysis reveals that during the lockdown, the large cities of the United States and Spain reduced their monthly averages of $PM_{2.5}$ to 39% and 58%, respectively, compared to non-lockdown months. These reductions are related to decreased vehicular traffic and restrictions placed on industrial companies. Rodríguez-Urrego and Rodríguez-Urrego (2020) estimated that the global reduction of $PM_{2.5}$ concentrations during the first few weeks of lockdown was 12%. They report that the city of Bogotá showed a daily reduction of 57%. The value reached is 68.1%, the average weekly value estimated in our research.

The decreasing trend of weekly $PM_{2.5}$ concentrations was noted in the stations of BOG (41–84%), FZA (13–66%), BYC (17–57%), VLL (35–86%) and RSD (31–60%), which is evidence of the impact of lockdown due to the pandemic. The monthly analysis of $PM_{2.5}$ levels reveals significant reductions mainly in the BOG stations of 16.1 ± 6.0 μg m^{-3}, BYC 14.7 ± 4.9 μg m^{-3} and RSD 8.5 ± 3.8 μg m^{-3}. The reductions in the mobility of public transport and the closure of some industries reduced $PM_{2.5}$ emissions, thus reducing the levels in the low atmosphere of particulate matter levels. Meteorological elements play an important role in the formation, transport, and deposition of $PM_{2.5}$. Precipitation favors the deposition of pollutants. At the monitoring sites, rainfall of up to 62 mm/month for Bogotá occurred during the closure phase, which contributed to a decrease in $PM_{2.5}$ levels. These conditions, related to the relative humidity and the height of the boundary layer, favor the dispersion and the decline of the concentrations.

In contrast, AOD values increased up to 59% during the months of lockdown compared to previous years and up to 70% of the weekly average when compared before emergency closure. This notable increase compared to the values before closure can be attributed to regional activities such as the burning of trees and large-scale processes such as the arrival of Sahara dust to the area. During the month of April 2020, the AOD on the borders with Venezuela and in the northern zone of Colombia presents the highest values (0.58) than that of the other more urbanized regions of the country. Similar research has shown low aerosol concentrations in 2020 compared to previous years elsewhere, clearly indicating the impact of the period of Covid-19 social restrictions (Kumar et al., 2020; Lokhandwala and Gautam, 2020). During the months of March–June 2020, a significant fraction of AOD is observed along the coastline and offshore. High temperatures and relative humidity conditions facilitate the gas-to-particle process, producing more secondary sulfate particles and inducing hygroscopic growth of atmospheric particles (Achtert et al., 2009). In combination with NE regional transport, aerosol loads accumulate near coastal and offshore areas. The influences of Saharan dust significantly influenced the increase in AOD values during the month of June 2020. Ranjan et al. (2020) studied AOD variations over an urban and mining region in India during the lockdown period. Their research found that in urban areas, there are negative anomalies (up to −36.5%) and positive anomalies (up to 70%) when compared with values from 2000 to 2019 for the months of March–May. On the other hand, Filonchyk et al. (2020) found an increase in AOD values over eastern China during the lockdown period in 2020 compared to 2019. These relatively higher values are due to the operation of thermoelectric plants that continued to operate over prolonged periods.

The present research suggests the need for a more detailed study in the interpretation of $PM_{2.5}$ estimation and AOD values. The variations in AOD do not show a strictly linear relationship with the values measured by the Terra/MODIS satellite, as shown in some recent studies (Christopher and Gupta, 2020; Wang et al., 2020c) most likely due to the different measurement scales between what was recorded in the $PM_{2.5}$ surface station and the estimates given by the Terra/MODIS satellite, however, a more detailed study can reveal the factors to be considered. Additionally, it is necessary to study the variations in ozone (O3) during this phase of closure by COVID-19 in Colombia. Some studies have shown that reductions in $PM_{2.5}$ during this pandemic have favored the formation of O3 due to an increase in solar radiation and a reduction in NOx levels due to reduced transport. (Sicard et al., 2020; Siciliano et al., 2020).

4. Limitations

When interpreting the results, it should be considered that the selected monitoring sites are located in urban, rural, industrial and residential areas; therefore, the $PM_{2.5}$ data on the surface do not quantify the emissions from deforestation given by illegal activities in the vicinity to the border with Venezuela. However, these variations are recognized by the AOD values analyzed. The results of $PM_{2.5}$ levels are a combined effect of emissions, regional meteorology and atmospheric processes at large scales. For example, in northern Colombia, although a decrease in $PM_{2.5}$ levels was observed on the surface, AOD values increased due to aerosol loads from the Sahara Desert. This study provides the opportunity to more carefully study the relationships of surface $PM_{2.5}$ concentrations and AOD values. The concentrations of $PM_{2.5}$ at the surface level may not have direct relationships with the distributions of AOD, which is an integrated column index that also includes information on aerosols in the upper levels, as well as at the surface level. For example, the FZA and BYC stations show decreases in $PM_{2.5}$ concentrations in the month of June compared to May, and these variations were not noticeable by the MODIS images.

5. Conclusion

The results show that the preventive mandatory isolation adopted in Colombia due to the COVID-19 pandemic had an impact on the country's air quality. On March 25, the country entered preventive mandatory isolation. The reductions in $PM_{2.5}$ levels were significant. During the first week of restrictions, Colombia's capital Bogota experienced reductions of up to 68.1% compared to the weeks of March 9–23. The average concentrations of $PM_{2.5}$ pollutants in several monitoring stations were significantly reduced due to the lockdown imposed by COVID-19. The weekly $PM_{2.5}$ values were reduced during closure in the city of Bogotá (41–84%), Funza (13–66%), Boyacá (17–57%), Valledupar (35–86%) and in the Risaralda region (31–60%). These decreases are mainly associated with transport activities, which were substantially restricted during the closure phase. Additionally, local precipitation caused wet deposition of the particles. The results also revealed that cities such as Bogotá and Boyacá reduced monthly averages to $16.1 \pm 6.0\ \mu g\ m^{-3}$ and $14.7 \pm 4.9\ \mu g\ m^{-3}$, respectively, during lockdown. Reductions in the mobility of public transport and the closure of some industries reduced emissions compared to $PM_{2.5}$. Meteorological elements such as precipitation contributed to the moisture deposition of particulate matter, especially in the central and western zones of the country. The weekly aerosol optical depth values in Colombia increased up to 70% during emergency closure compared to the weeks prior to closure. This notable increase compared to the values before closure can be attributed to emissions at the regional scale due to active fires and large-scale processes such as the arrival of Sahara dust to the area. During the month of April 2020, the AOD on the borders with Venezuela and in the northern zone of Colombia presented the highest values (0.58) than that of the other more urbanized regions of the country. The spatiotemporal behavior of $PM_{2.5}$ and the optical depth of aerosols in Colombia during the pandemic are influenced by reductions in vehicular flow, regional precipitation, synoptic wind fields and planetary boundary layer height. These results suggest the need for a rigorous study on the effect of implementing social isolation as an alternative measure to reduce pollution, especially particulate matter. This research suggests the need to study the variations in O3 during this pandemic to expand the analysis of the impact of COVID-19 on the air quality of the country. Additionally, it suggests the need to study the various factors involved in the interpretation of $PM_{2.5}$ estimates on the surface through MODIS images.

CRediT authorship contribution statement

Heli A. Arregocés: Data curation, Conceptualization, Software, Validation, Formal analysis, Investigation, Writing - review & editing. **Roberto Rojano:** Formal analysis, Investigation, Writing - review & editing. **Gloria Restrepo:** Writing - review & editing, Resources, Supervision.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.142874.

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