



Research article

Changes in ambient particulate matter during the COVID-19 and associations with biomass burning and Sahara dust in northern Colombia

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ABSTRACT

The restriction of mobility due to preventive social isolation has improved air quality in many regions of the world. At the same time, global and regional atmospheric phenomena such as biomass burning or dust transport from Sahara can exacerbate particulate matter (PM) mass. In this study, PM₁₀ and PM_{2.5} concentrations were evaluated in industrial and urban areas during the lockdown period due to COVID-19 in northern Colombia. Aerosol Optical Depth (AOD) observations obtained from the spaceborne MODIS (MOD04-3k) and the active fire data was obtained from VIIRS Active Fire. We measured surface contamination at several stations to quantify the PM₁₀ and PM_{2.5} changes associated with the general closure of anthropogenic and industrial activities driven by COVID-19 and by the macroscale and/or mesoscale contributions. In the industrial zone, a slight decrease in daily concentrations was detected at the stations located near the mining operations. In the urban area, the decrease is more salient in COVID-19 lockdown. A reduction rate in the daily averages of PM₁₀ of 23.3%, 6.0%, and 19.0% was observed in the Sca, Sbi, and Sun stations, respectively. The biomass burning episode has contributed 52% to the daily average of PM₁₀ and 45% to the daily average of PM_{2.5}. The episode due to the passage of Saharan dust through the Caribbean Sea has contributed 79% to the daily average of PM₁₀ (150.75 µg/m³) and on 57% to the daily average of PM_{2.5}.

1. Introduction

In December 2019, a local outbreak of pneumonia was determined to be caused by a new coronavirus that occurred in Wuhan, China. The virus was subsequently called severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (WHO, 2020). In February, it was named coronavirus disease or COVID-19 by the director-general of the WHO (World Health Organization) (Cascella et al., 2020). COVID-19 was declared a pandemic by WHO on 11 March 2020 (Sohrabi et al., 2020). Since then, the outbreak has spread to 192 countries, leading to 149,718,851 confirmed cases and 3,153,418 global deaths by April 29, 2021 (CRC, 2021). The first two confirmed cases of COVID-19 in Colombia occurred on March 6, 2020 (Mendez-Espinosa et al., 2020). On March 25, the government established obligatory preventive isolation (lockdown) across the country until April 13, 2020. The lockdown triggered the reduction of economic activities and vehicular traffic. Thus far, Colombia has established mandatory preventive isolation in places where the occupancy of intensive care units (ICUs) exceeds 70%. Many studies have analyzed the changes in air quality due to social isolation measures imposed during the

pandemic (Mininterior, 2020; MinSalud, 2020). Some studies concluded that the reduction in pollutant concentrations (PM₁₀, PM_{2.5}; SO₂ or NO₂), can be mainly attributed to the measures that have limited civic logistics and industrial activities (Faridi et al., 2020; Mendez-Espinosa et al., 2020; Rodriguez-Urrego and Rodriguez-Urrego, 2020). However, some activities or phenomena have not changed during or as a result of lockdown. For instance, air quality reports from Colombia concluded about excessively bad air quality at the beginning of the COVID-19 lockdown. In certain cases, bad air quality events were driven by the forest fires that had occurred geographically upwind of these cities (Mendez-Espinosa et al., 2020; SIATA, 2020). PM_{2.5} and PM₁₀ are the pollutants of the greatest concern in Colombia due to their tendency to exceed maximum permissible levels (IDEAM, 2019). In La Guajira, in northern Colombia, the open-pit coal mining is ongoing in one of the largest mines in the world. Previous studies have reported that aerosols generated due to extraction operations can be a major contributor to PM₁₀ and PM_{2.5} in ambient air in their zone of influence (Rojano et al., 2018, 2020). During the period, when the COVID-19 lockdown was enacted in Colombia, extractive mining has been halted. However, mines are located in the dry

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lowland with grassland forests, where land-use practices are associated with cattle ranching and agriculture. These activities and warmer, drier climate conditions have led to increased wildfire activity (Hoyos et al., 2017). Wildfires can increase levels of PM, especially, PM_{10} and $PM_{2.5}$ (Manousakas et al., 2020; Uttajug et al., 2020). This fact has become the main motivation to investigate the impact of COVID-19 in La Guajira, including the industrial extraction zone and highly populated urban area of the city. Colombia's legislation has outlined six targeted pollutants that are mandated for systematic monitoring. All of these air pollutants adversely affect human health, but the most severe effects have been attributed to PM (Hendryx and Zullig, 2009; Wu et al., 2018). The studies linking increased contagion from airborne aerosols also cause further concerns (Ge et al., 2020; Wang and Du, 2020). This study reviewed and analyzed the impact of low socioeconomic activities on particulate matter before, during and after of COVID-19 lockdown in a region north of Colombia, including regional and global episodes.

2. Methods

2.1. Study site

The study was conducted in two areas (industrial and urban), located in the region of La Guajira, northern Colombia (Figure 1). The industrial area (InA) is located in the largest open-pit coal mining area in Colombia (Cerrejón, $11^{\circ} 5' 2'' N$; $72^{\circ} 40' 31'' W$). The InA hosts the companies Carbones del Cerrejón Limited (Cerrejón) and Carbones Colombianos del Cerrejón (Caypa). The InA borders three municipalities in La Guajira including Barrancas, Hatonuevo and Albania. Nearly 74,000 people live within 30 km of the mining site, of whom 34% are ethnic minorities (DANE, 2019). For the urban area sampling, the urban area of the city of Riohacha (RuA) was elected. This is the regional capital (Riohacha, $11^{\circ} 32' 40'' N$; $72^{\circ} 54' 26'' W$), ~100 km northwest of the mine. The RuA has nearly 177,573 inhabitants (20% of the population of the department of La Guajira). The RuA is the most populated and the most commercially active area in the region (DANE, 2019).

2.2. PM_{10} , $PM_{2.5}$, and meteorological data

In surface monitoring the PM_{10} and $PM_{2.5}$ data were obtained from the 8 monitoring stations that belong to the Air Quality Surveillance System (SVCA) of the Environmental Corporation of La Guajira. The five stations located in the InA and the four stations from the RuA were selected. The seven stations were operated with manual PM_{10} and $PM_{2.5}$ equipment, while one station featured automated PM_{10} and $PM_{2.5}$ hourly measurement equipment. Table 1 shows the names, geographical coordinates, and method of measurement of the particulate material in industrial and urban zones. The topography and geographic location of the area are illustrated in Figure 2. The PM_{10} samples were collected every third day from December 19, 2019 to April 30, 2020. Mandatory preventive isolation (lockdown) forced the manual equipment to stop. The manual stations deployed Tisch Environmental (Cleves, OH, USA) brand TE-6070 (Hi-Vol) high-volume samplers. The PM_{10} samples were processed and analyzed using gravimetric techniques, following the Environmental Protection Agency of America (EPA, 2011) reference methods for determining suspended PM. At the Nuevo Espinal (SNe) station, the $PM_{2.5}$ and PM_{10} samples were collected using a Fidas 200 fine PM (Palas GmbH, Germany) (Automatic Station). The Fidas 200 is an optical instrument that measures aerosol concentration by light scattering using a white LED and a scattering angle of 90° (PALAS, 2015). It provides continuous and simultaneous measurements of PM_{10} and $PM_{2.5}$. The Fidas is a European Union-approved instrument (EN 16450: 2017). The Fidas 200 enabled the collection of hourly data of PM_{10} and $PM_{2.5}$ during the period 08/03/2020-08/03/2021. For the manual PM_{10} and $PM_{2.5}$ samplers, valid daily concentrations were accepted for a sampling time greater than 23 h. For continuous PM_{10} and $PM_{2.5}$ instruments, 45-minute records were considered for a valid hour. For daily concentrations, sampling times greater than 18 h were accepted for 24-hour sampling periods. For manual and continuous samplers, a minimum of at least 75% of the days within the PM_{10} y $PM_{2.5}$ monitoring season in any one year (MADS, 2010). In the same time period, hourly meteorological parameters of temperature (T), relative humidity (RH),

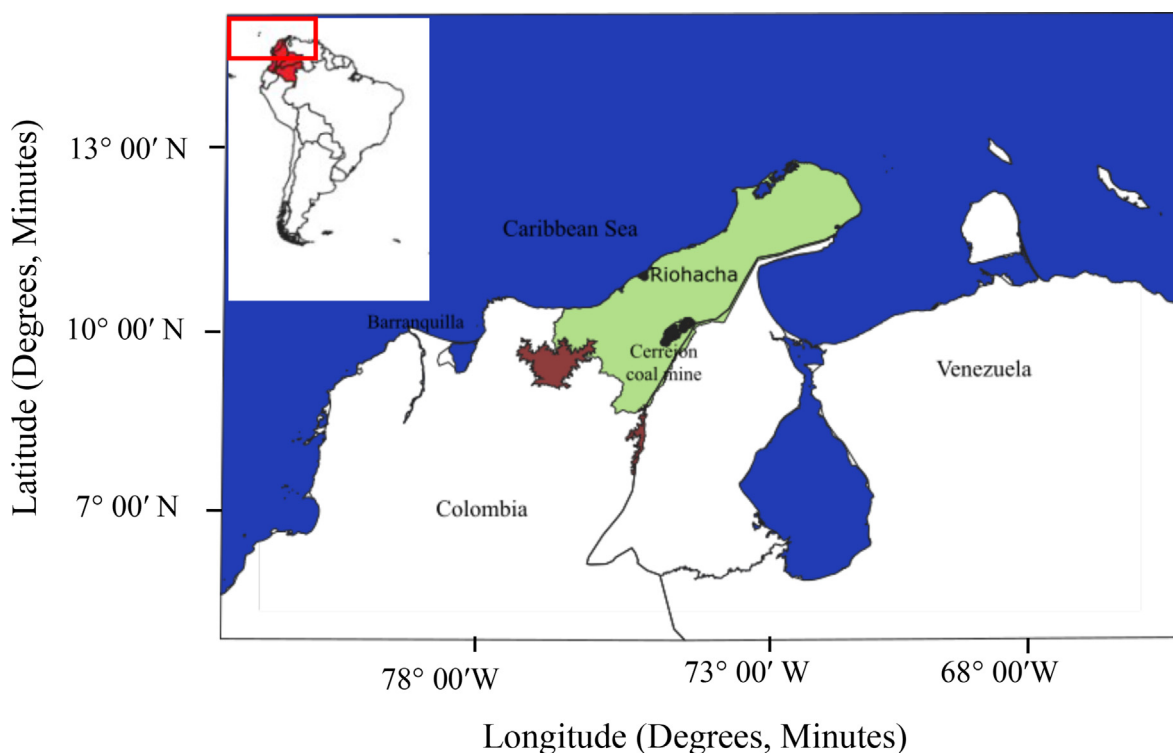


Figure 1. Reference map of the study area. Location of the area of La Guajira Colombia (green). The urban area is located in Riohacha city and the industrial area is located in Cerrejón coal mine.

Table 1. Geographical coordinates and characteristics of the sampling sites in the industrial area (InA) and urban area (RuA).

Site ID	Site name	Lat	Long	Elevation (m)	Variables measured	Measurement Method	Location
SBa	Barrancas	10°57'40.1" N	72°46'41.5" W	141	PM10	Manual - Hi-Vol	InA
SPa	Papayal	10°59'43.5" N	72°46'26.4" W	155	PM10	Manual - Hi-Vol	InA
SPr	Provincial	11°01'26.5" N	72°44'15.2" W	130	PM10	Manual - Hi-Vol	InA
SLr	Los Remedios	11°05'57.6" N	72°32'31.3" W	155	PM10	Manual - Hi-Vol	InA
SHa	Hatonuevo	11°03'50.3" N	72°45'58.6" W	201	PM10	Manual - Hi-Vol	InA
SNe	Nuevo Espinal	10°57'9.95" N	72°42'6.89" W	197	PM10, PM2.5, T, Pp, RH, ws, wd	Automatic- Fidas 200	InA
SUn	Uniguajira	11°30' 44.24" N	72°52'16.93" W	15	PM10	Manual - Hi-Vol	RuA
SBi	Bienestar	11°32' 19.38" N	72°55'1.44" W	13	PM10	Manual - Hi-Vol	RuA
SCa	Cámara de Comercio	11°32' 50.85" N	72°54'24.50" W	8	PM10	Manual - Hi-Vol	RuA
SCo	Corpoguajira	11° 32'47.15" N	72°54'27.47" W	8	T, Pp, RH, ws, wd	Automatic-Davis	RuA

precipitation (Pr), wind speed (ws) and wind direction (wd), were obtained in each study area (InA and RuA). In InA and RuA, one site was selected for measuring meteorological parameters (i.e. SCo and SNe).

2.3. Satellite data

To evaluate the potential impact of biomass burning on PM₁₀ and PM_{2.5} concentrations, satellite remote sensing was used. Namely, it was used to retrieve data on active fires in the study period. Satellite imagery of active burning was downloaded from FIRMS (Fire Information for Resource Management System; accessed from <https://firmsmodaps.eosdis.nasa.gov/>). The dates of the data were chosen by detecting the maximum levels of PM₁₀ and PM_{2.5}. A polygonal area was delineated to include the province of La Guajira. Only the access point counts with a confidence level >50% were included in this study. The single trajectories were analyzed using The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPPLIT) platform (<https://www.ready.noaa.gov/gdas1.php>). From May 1 to May 27, 2020, 584-h trajectory analysis was computed three times a day. The trajectories were computed using global meteorological data input from the National Center for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR). The data downloaded from FIRMS and HYSPPLIT were processed in QGIS (Quantum Geographic Information System; Free Software Foundation, Inc.) and customized in accordance with the researchers' criteria.

The aerosol optical depth (AOD) images were obtained from MODIS (MODerate Resolution Spectroradiometer) instrument onboard Terra, (MOD04-3k) at 550 nm with a spatial resolution of 3 km (<https://modis.gsfc.nasa.gov/data/dataproduct/mod04.php>). An area of approximately 2400 × 1600 km² was established, between the coordinates of 9° N to 17° N and -67° W to -79° W. The selected area embraces the entire Caribbean region of Colombia, with more than ten million inhabitants. The entire peninsula of La Guajira was included in the final domain. Statistical analysis of the data was performed for the days from June 22 to 25, 2020, due to the Saharan dust dispersion passing through the Colombian Caribbean region.

2.4. Data analysis

To estimate the influence of lockdown on PM₁₀ and PM_{2.5} particulate matter, the concentrations in the manual stations were analyzed before and during the lockdown by Covid-19 (December 19, 2019, to April 30, 2020). The impact of biomass burning on PM₁₀ and PM_{2.5} particles was estimated by studying the concentrations of the continuous and simultaneous measurements, from May 1 to May 27, 2020. Finally, to analyze the impact due to the Saharan dust dispersion were studied the PM₁₀ and PM_{2.5} concentrations of the continuous and simultaneous measurements, from June 22 to 25, 2020. Google Mobility datasets were used to analyze changes in mobility before, during and after the COVID-

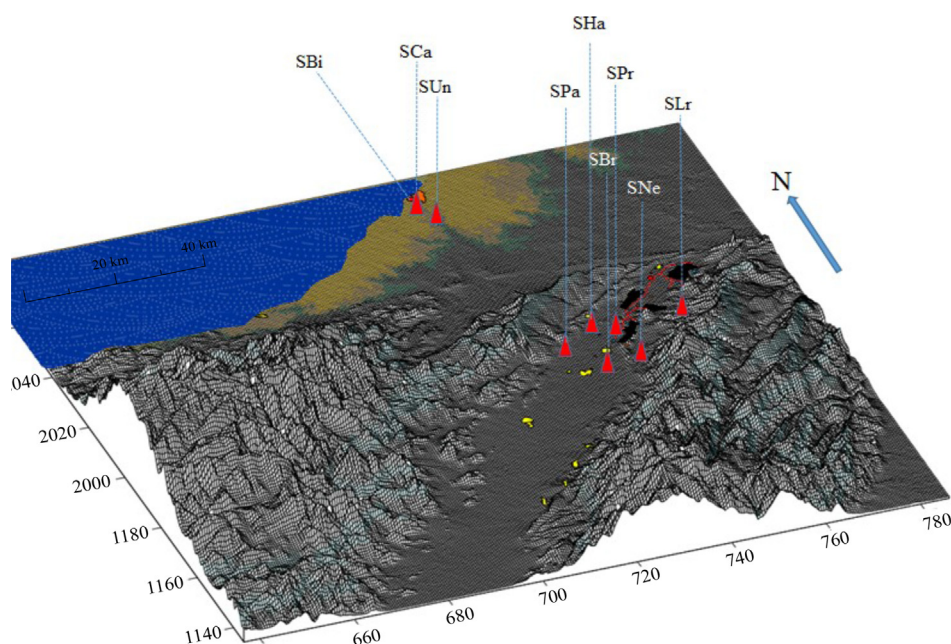


Figure 2. Topography and location of the monitoring stations in the urban area of Riohacha (RuA) and the industrial area of Cerrejón (InA).

19 lockdown and the periods of occurrence of the episodes of biomass burning and Saharan dust. This dataset measures mobility to specific categories for each day and compares this change relative to baseline day before the pandemic outbreak. The difference is expressed as a percentage (Li and Tartarini, 2020; Munir et al., 2021). Data analysis was performed with Microsoft Excel® 2013 (Microsoft Corp., Santa Rosa, CA) and the free software OpenAir air quality tool (Carslaw and Ropkins, 2012). The correlation between PM₁₀ and PM_{2.5} concentrations in the industrial and urban areas was retrieved using Pearson's coefficients.

3. Results and discussion

Meteorological parameters influence the concentration and dynamics of pollutants in the air. Temperature is a catalyst for environmental chemical reactions while precipitation and relative humidity tend to remove pollutants from the atmosphere. Wind speed and direction are used to assess relationships between sources and pollutant levels. Figure 3 shows the daily variability of meteorological parameters in the two study areas during the COVID-19 lockdown.

Table 2 shows the daily averages during the study period of temperature, precipitation, wind speed, and relative humidity in the InA and RuA. For the study period, the temperature ranged between 25 and 30 °C. The average temperature was lower in industrial areas (InA) than in urban areas (RuA). Average temperatures were 26.70 °C (CI 95%: 26.28–27.11 °C) in InA and 28.08 °C (CI 95%: 26.28–27.11 °C) in RuA. Wind speed exhibited a daily average of 3.90 m/s (CI 95%: 3.63–4.19 m/s) in InA and 2.42 (CI 95%: 2.55–2.30 m/s) in RuA. The maximum velocities of 5.7 m/s were registered at the study sites with a predominance of NEE and E wind directions in InA and RuA. Calm wind (0 m/s) was observed during the night hours. Relative humidity exhibited mean estimate of 68.50% (CI 95%: 65.27–71.43%) in InA and 77.30% (CI 95%: 75.20–79.42%) in RuA, respectively. Higher RH was observed in the area near the sea, following the natural regional pattern observed in the dry season. In RuA, there was no rainfall during the study period. In InA, there was an average of 0.14 mm daily, with a maximum value of 7.40 mm. Precipitation affects PM concentrations in the air (Olszowski and Ziemcik, 2018). In general, the behavior of meteorological parameters is

similar to those reported by other regional studies conducted in the same season (Arregocés et al., 2021; Rojano et al., 2020).

Colombia's mandatory lockdown as a result of COVID-19 has reduced transportation activities in urban areas and open-pit coal mine excavations located in La Guajira. These changes in transportation and industrial activities have significantly impacted air quality. Figure 4 shows the box plot of daily PM₁₀ concentrations at the two sampling sites. The daily average considering all samples ranged from 29.61 µg/m³ to 43.32 µg/m³ for InA and from 37.67 µg/m³ to 33.21 µg/m³ for RuA. Table 3 illustrates the descriptive statistics for the average daily PM₁₀ and PM_{2.5} concentrations before and during the COVID-19 lockdown. Figures 5 and 6, show the daily variation of PM₁₀ and PM_{2.5} concentrations for the InA and RuA sites, respectively. In InA, a slight decrease in daily concentrations is observed at stations located in towns near the mining site. In RuA, the decrease is more salient in the COVID-19 lockdown. A reduction rate in the daily averages of PM₁₀ of 23.3%, 6.0%, and 19.0% was observed in the SCA, SBI, and SUN stations, respectively. Figure 4 shows box plots of monthly PM₁₀ and PM_{2.5} concentrations before and after of the COVID-19 lockdown.

At the InA site, the intervals between the third and first quartiles of PM₁₀ and PM_{2.5} are higher before of the lockdown than during the lockdown for three stations (i.e. SBA, SHA, and SPA). Two stations exhibited the opposite pattern, (i.e. SLR and SPR) with lower interquartile ranges before the lockdown than during the lockdown. From an environmental perspective, the SLR and SPR stations have been historically the most exposed by open-pit mining excavations (Arregocés et al., 2020; Rojano et al., 2018). The interquartile ranges of PM₁₀ and PM_{2.5} at all stations at the RuA site were higher before the lockdown than during the lockdown. The lower daily averages were observed than those reported in the previous studies (Argumedo and Castillo, 2016; Rojano et al., 2015). The lockdown due to COVID-19 was observed with greater rigidity in urban areas of Colombian cities. Levene's test was applied to assess the homogeneity of group variances. One group was taken in the period before of the lockdown and group 2 during the lockdown. The daily averages of PM₁₀ and PM_{2.5} remained relatively stable for the InA and RuA. As the p-values at all stations were greater than 0.05 ($p > 0.05 = \alpha$). Table 4 shows all the estimates which satisfy the assumption of homogeneity of variances.

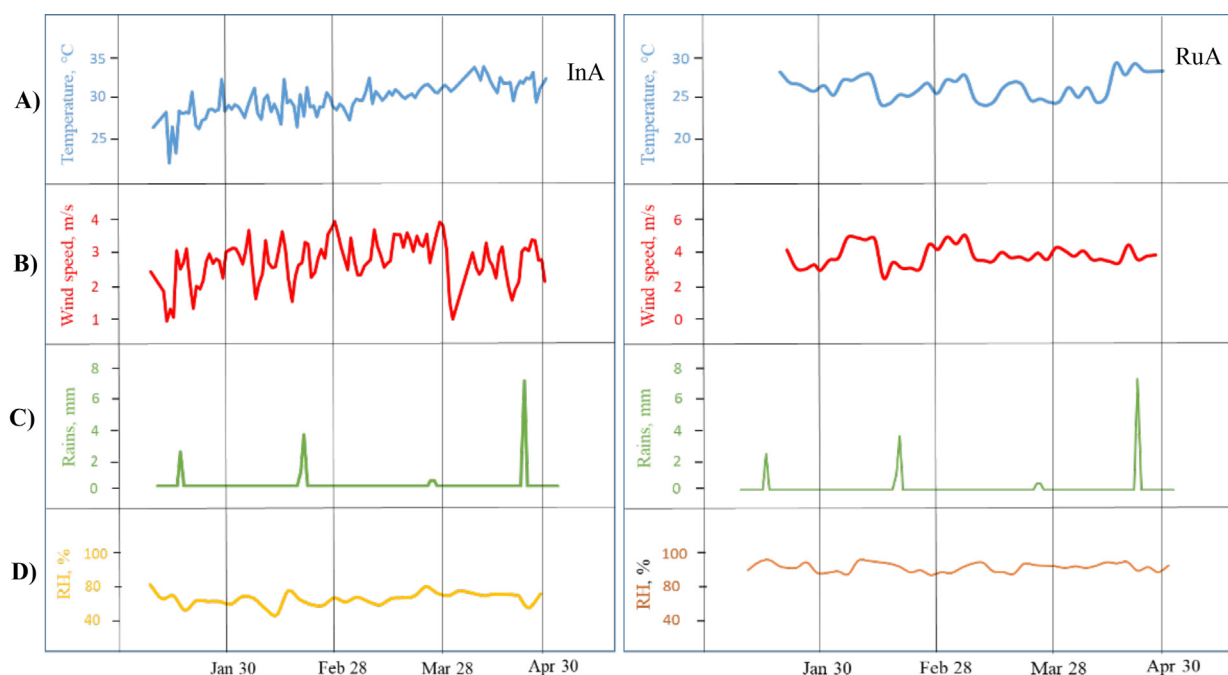


Figure 3. Daily variability of meteorological parameters in the industrial area (InA) and urban area (RuA) before and during COVID-19 lockdown. A) temperature: in °C; B) wind speed: in m/s; C) rain: in mm and D) relative humidity in %.

Table 2. Descriptive statistics of averages of the daily values of meteorological parameters of temperature (T), relative humidity (RH), wind speed (ws) and precipitation (Pp).

Parameters	InA					RuA				
	Mean	SD	CI _{95%}	Max	Min	Mean	SD	CI _{95%}	Max	Min
T, °C	28.08	1.57	3.37	37.15	21.95	26.70	1.37	0.41	29.50	24.95
ws, m/s	2.42	0.71	0.13	2.55	0.45	3.90	0.92	0.27	5.70	1.90
RH, %	68.50	8.67	3.23	78.45	57.98	67.30	7.00	2.10	69.49	54.83
Pp, mm	0.14	0.08	0.15	7.40	0.00	0.00	0.00	0.00	0.00	0.00

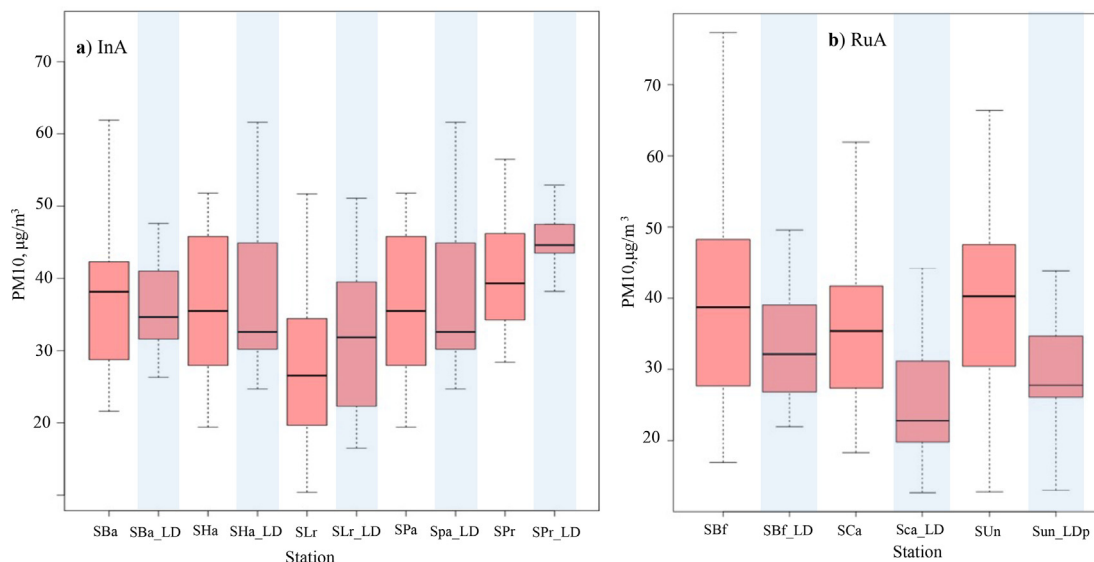


Figure 4. Daily PM₁₀ concentrations before and during the lockdown by COVID-19. Boxplot shaded in blue indicates the behavior in the lockdown. a) industrial sampling site (InA); b) urban sampling site (RuA).

Figure 7 shows the daily variation of PM₁₀ and PM_{2.5} concentrations at the Nuevo Espinal (SNe) station over one year. This station is automated and, therefore, measured the hourly concentrations of PM₁₀ and PM_{2.5} without any restrictions during the study. The annual average PM₁₀ was 27.89 µg/m³ (CI95%: 29.08–26.70 µg/m³), with a maximum concentration of 199.12 µg/m³ on June 24, 2020. The annual average does not exceed Colombia's annual legal standard for (50 µg/m³). The maximum daily level of PM₁₀ recorded in one year is nearly twofold compared with the Colombian daily legal standard (100 µg/m³) (MADS, 2017). Both concentration levels exceed the WHO guidelines (WHO, 2005). There was an average of 14.47 µg/m³ of PM_{2.5} concentrations (CI95%: 13.98–14.96 µg/m³), with a maximum value of 60.62 µg/m³.

For PM₁₀, the annual average of PM_{2.5} does not exceed the annual Colombian legal standard (25 µg/m³). However, the maximum daily level of PM_{2.5} exceeds the Colombian daily legal standard (50 µg/m³) by 17%.

The Pearson correlation between daily PM₁₀ and PM_{2.5} concentrations is significant and positive (R = 0.80) for the period March 2020–March 2021 (Figure 8). This correlation potentially indicates the same source of PM.

Figure 7 shows two parallel continuous peaks in the daily variation of PM₁₀ and PM_{2.5}. The first peak is observed between May 7 and May 12, 2020. The other peak is evidenced between June 21 and June 25, 2020. These peaks in PM₁₀ and PM_{2.5} concentrations are linked to regional and global phenomena that occurred during the study period.

Table 3. Descriptive statistics for the averages of the daily concentrations of PM10 and PM2.5 before and during COVID-19 lockdown.

Site	Station ID	Station name	All the period			Pre_Lockdown			Lonkdown		
			Mean	SD	CI _{95%}	Mean	SD	CI _{95%}	Mean	SD	CI _{95%}
InA	SBa	Barrancas	37.24	10.08	3.37	37.15	9.65	4.21	37.36	11.04	5.75
	SHa	Hatonuevo	37.37	11.58	3.87	37.34	12.54	5.47	37.42	10.51	5.48
	SLr	Los Remedios	29.61	10.95	3.66	27.87	11.18	4.88	32.09	10.50	5.47
	SPa	Papayal	37.37	11.58	3.87	37.34	12.54	5.47	37.42	10.51	5.48
	SPr	Provincial	43.32	9.28	3.10	41.75	10.60	4.62	45.57	11.82	6.16
RuA	SUn	Uniguajira	36.60	13.50	4.06	39.08	13.88	5.11	31.64	11.62	6.06
	SBi	Bienestar	37.67	13.19	3.97	38.44	13.11	4.83	36.14	13.71	7.15
	SCa	Cámara de Comercio	33.21	13.16	3.96	36.00	11.74	4.33	27.63	14.47	7.54
All Mine			36.98	11.47	1.72						
All Urban			35.83	13.32	2.31						

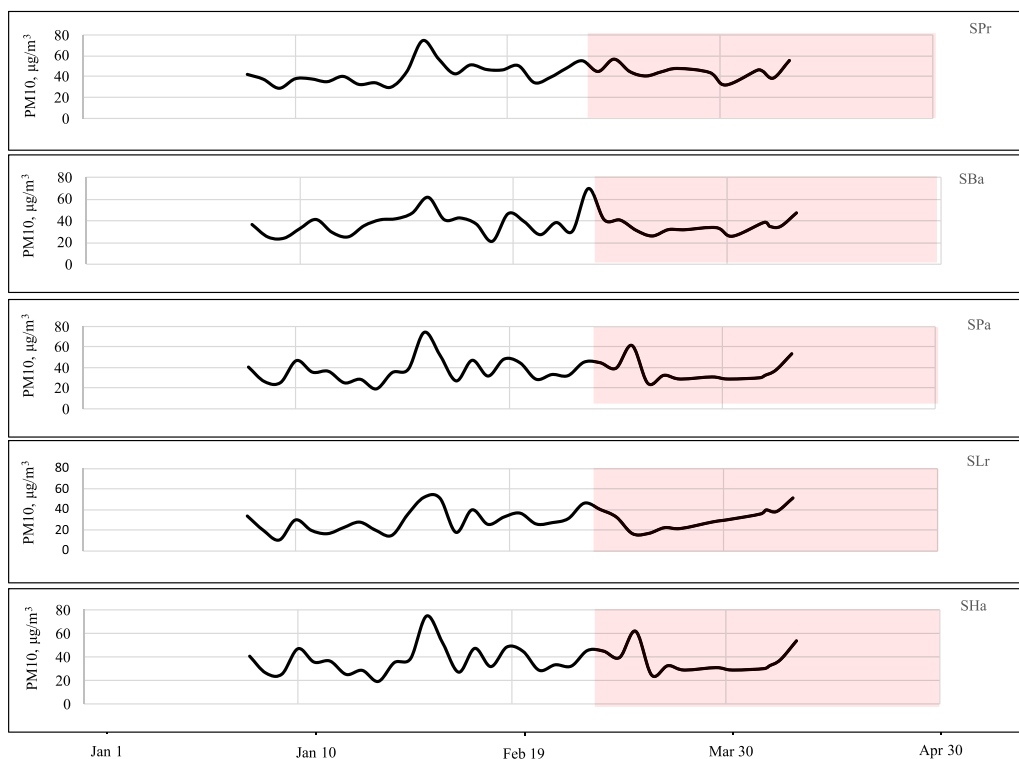


Figure 5. Daily PM10 concentrations for all selected sampling sites in the industrial area before, during and after the lockdown. Description of the sites according to Table 1. The lockdown began on March 25, 2020.

3.1. Emissions from biomass burning in industrial and urban areas

In the zone exposed by the industrial area, episodes of biomass burning were observed alongside the emissions from anthropogenic sources (mining, transport, and domestic). The hot spots coincide with the high emissions from biomass burning to the northeast and east of the SNe station location (Figure 9). The same figure shows the fire hotspots in the areas upwind of the sampling sites and surrounding areas in May 2020. HYSPLIT analysis illustrates the trajectories of particle circulation

originating from InA and RuA, the number of hot spots per day, and the PM_{2.5} emissions from biomass burning in the period.

The peak between May 7 and 12, 2020 (Figure 7), is consistent with the high level of spot burning and PM_{2.5} emissions. The biomass burning episode contributed 52% above the daily average to PM₁₀ (65.98 µg/m³) and on 45% above the daily average to PM_{2.5} (37.77 µg/m³). The contribution above the daily averages of PM₁₀ and PM_{2.5} was doubled in the lockdown period. The contribution of PM_{2.5} was higher than that reported by Bolaño-Truyol et al. (2021), in the two cities of

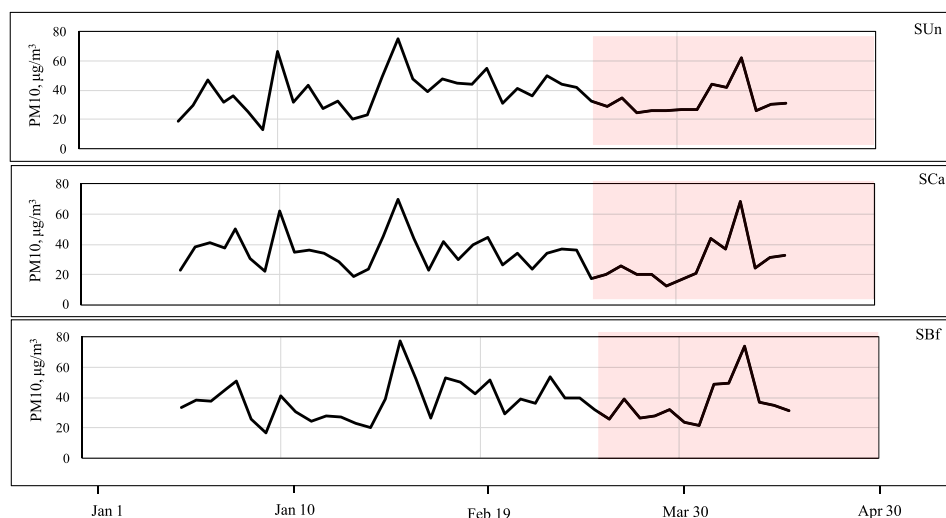


Figure 6. Daily PM10 concentrations for all selected sampling sites in the urban area before, during and after the lockdown. Description of the sites according to Table 1. The lockdown began on March 25, 2020.

Table 4. Levene's test for averages of the daily concentrations of PM10 for InA and RuA sites.

Site	Station	SD_pre_LDp	SD_LDp	p-value
InA	SBa	9.65	11.04	0.93
	SHa	12.54	10.51	0.60
	SLr	11.18	10.50	0.50
	Spa	12.54	10.51	0.60
	SPr	10.60	11.82	0.23
RuA	SUn	11.62	13.88	0.65
	SBi	13.71	13.11	0.65
	SCa	14.47	11.74	0.48

the same region (Colombian Caribbean). Since May 13, the concentration levels have returned to the geographic pattern, this area is characterized. According to the trajectories calculated for the study area, the impact of biomass burning on the level of PM in the northern part of Colombia is clear. Other studies have also reported the impact of biomass burning emissions on air quality in Colombia (Ballesteros-González et al., 2020; Bolaño-Truyol et al., 2021; Manuel Rincón-Riveros et al., 2020).

3.2. Contribution of Saharan dust to PM₁₀ and PM_{2.5} concentrations

Figure 10 shows the AOD estimates obtained from the MODIS sensor (Terra, MOD04) for June 22–25, 2020, when the second peak of PM₁₀ and PM_{2.5} shown in Figure 5 was recorded. The AOD values ranged from a

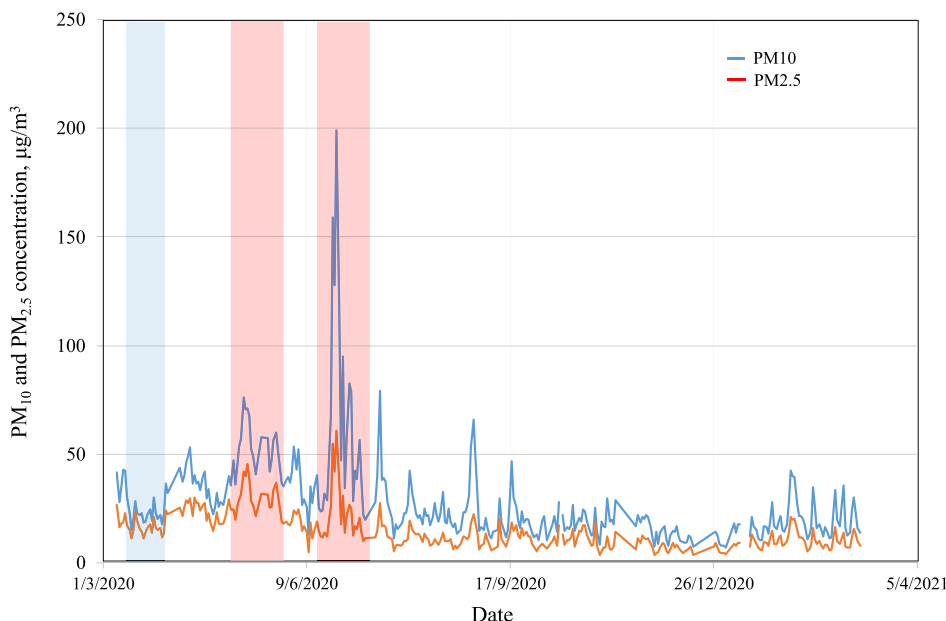


Figure 7. Daily variation of PM₁₀ and PM_{2.5} concentrations at the Nuevo Espinal (SNe) station in one year of measurement. Blue shading indicates mandatory isolation period. Red shading indicates maximum concentration levels in the year.

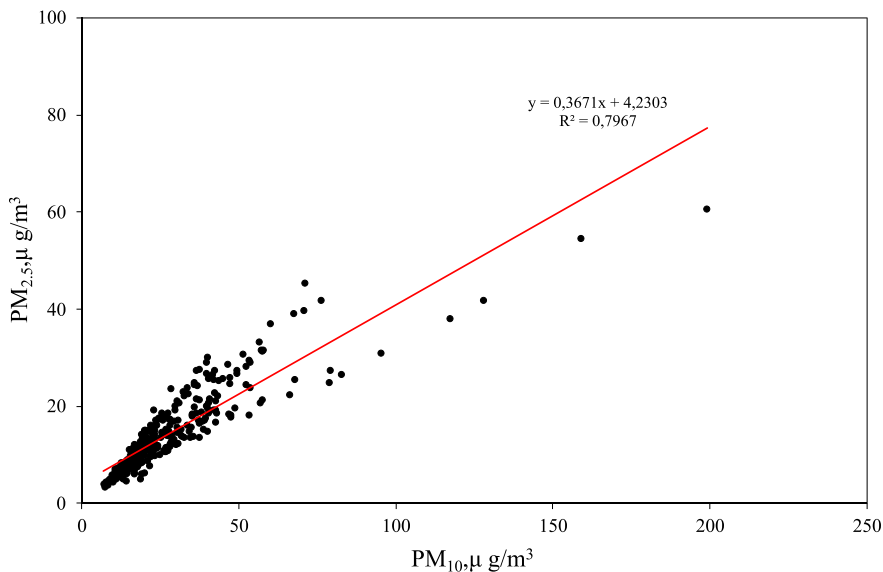


Figure 8. Pearson's correlation coefficient between the daily concentrations of PM10 and PM2.5. March 2020–March 2021. Nuevo Espinal Station. Industrial zone (InA).

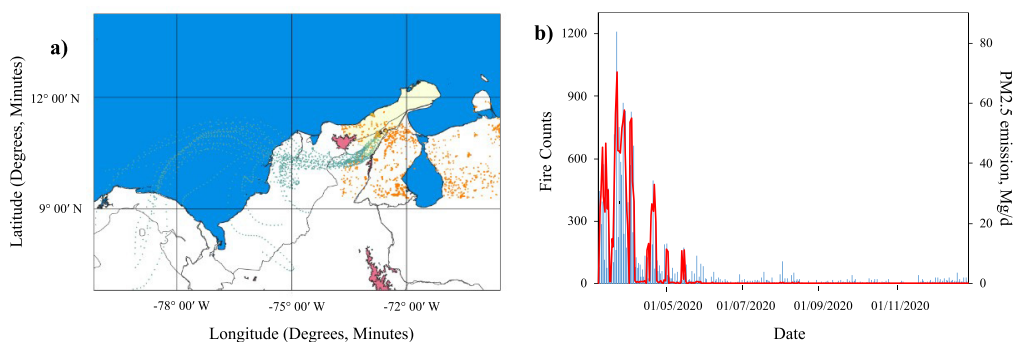


Figure 9. Fire hot spots in areas upwind of the sampling sites and their surroundings between May 5 and 12, 2020.

minimum of 0.0 to a maximum of 2.5. The AOD ranged between 0.5 and 1.0 in the Guajira peninsula, while over the Caribbean Sea, values were greater than 1.5. The maximum values of AOD in the study area (InA and RuA) occurred on June 24 and 25, which could be linked to the peaks of PM₁₀ and PM_{2.5} exhibited in that same period in the stations' measurements.

The episode of Saharan dust passing through the Caribbean Sea contributed 79% to the daily average of PM₁₀ (150.75 µg/m³) and on 57% to the daily average of PM_{2.5} (48.83 µg/m³). The dispersion of Saharan dust induced a three-fold increase in its level for PM₁₀ and a two-fold increase in its level for PM_{2.5}, compared to the averages in the lockdown period. Figure 11 shows the HYSPLIT back-trajectories analysis corresponding to the period of the Saharan dust episode in the Colombian Caribbean. The trajectories indicated potential areas

impacted in northern Colombia. Results of studies of trajectories from North Africa showed the impact on the Caribbean atmosphere due to the Saharan dust episode (Euphrasie-clotilde et al., 2020). Figure 12 shows the changes in Traffic, workplaces, parks, and recreation using Google Mobility. An immediate change in mobility (-75%) was observed since March 25, 2020, when the lockdown measures were implemented. Low economic activity is observed in La Guajira until the end of August, inclusive, after the lifting of COVID-19 lockdown. The peaks of concentrations of particulate matter (Figure 7), coincided with low traffic activity, workplaces, parks, and recreation (-58%) (Figure 12). The results showed that the impacts of Sahara dust and biomass burning influenced the high levels of PM₁₀ and PM_{2.5} in May and June.

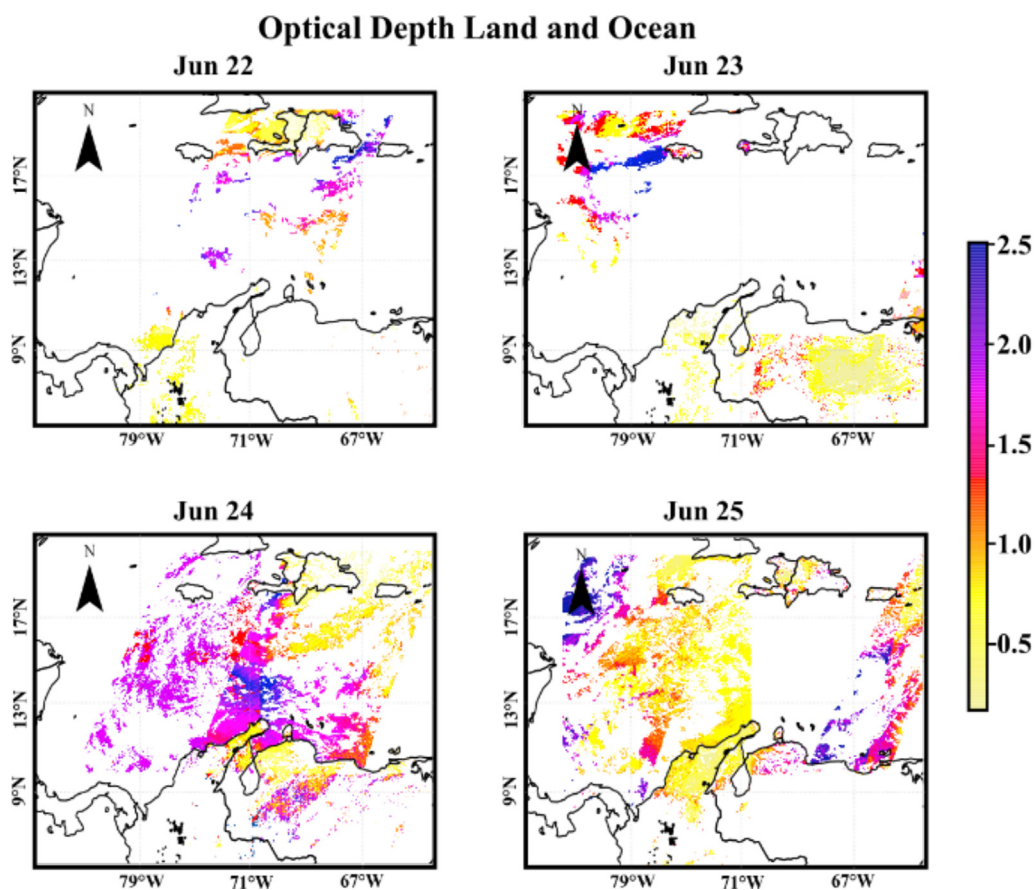


Figure 10. Spatial variation of AOD in the Saharan dust episode in the Colombian Caribbean in the period of pre-lockdown and lockdown by Covid-19.

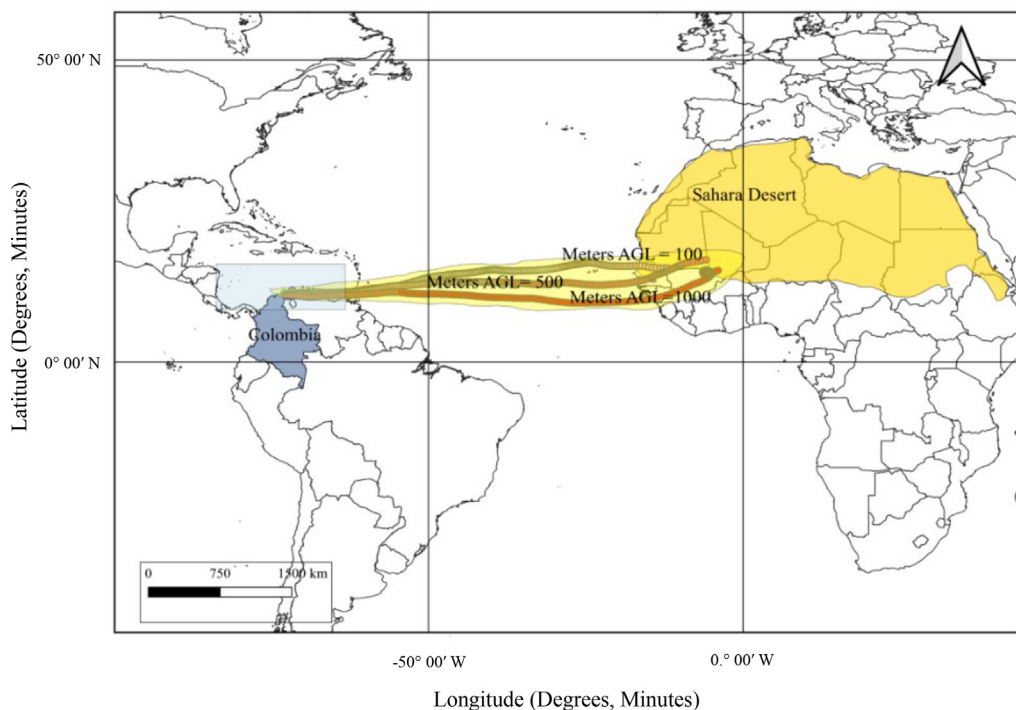


Figure 11. HYSPLIT back-trajectories corresponding to the study period in the Saharan dust episode in the Colombian Caribbean.

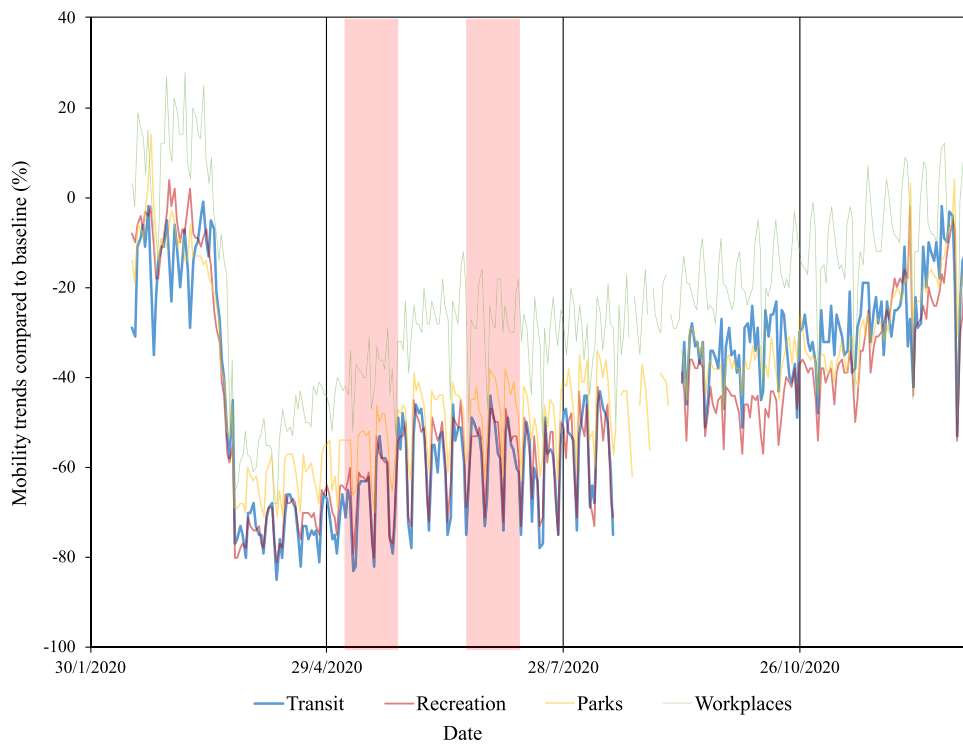


Figure 12. Mobility trends for transit, recreation, parks and workplaces, estimated for La Guajira, between 2 February and August 30, 2020, compared to baseline. Red shading indicates impacts of Sahara dust and biomass burning.

4. Conclusions

These results show the impact of the partial lockdown on air quality in an urban and industrial area of northern Colombia. The PM concentrations in the industrial area did not disclose significant changes in the

averages of PM₁₀ and PM_{2.5}. The opposite pattern was evidenced in the urban area, whereas a significant decrease in PM₁₀ and PM_{2.5} averages was detected during the COVID-19 lockdown. The high levels of PM₁₀ and PM_{2.5} measured in June 2020 in the InA, are seemingly related to the Saharan dust episode that affected the Colombian Caribbean. The

analysis of Terra MODIS provided the average AOD values in the Guajira Peninsula as well as PM₁₀ and PM_{2.5} concentrations measured at the automatic stations located in InA. The PM₁₀ and PM_{2.5} averages have increased by 79% and 57% over the daily PM₁₀ average and PM_{2.5} average, respectively, in the Saharan dust episode. The daily average PM₁₀ and PM_{2.5} have experienced a 52% increase over the daily average PM₁₀ and a 45% increase over the daily average PM_{2.5} in the periods of increased biomass burning in the study area. The characterization of PM₁₀ and PM_{2.5} particles can potentially shed light on the direct impact of these two phenomena and can be further studied in the future.

Declarations

Author contribution statement

Roberto Rojano: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Heli A. Arregocés: Performed the experiments, Analyzed and interpreted the data.

Eider Gámez Frías: Analyzed and interpreted the data.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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