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Spatial and Temporal Assessment of Particulate Matter Using AOD Data from MODIS and Surface Measurements in the Ambient Air of Colombia

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ABSTRACT

Particulate matter (PM) measurements are important in air quality, public health, epidemiological studies and decision making for short and long-term policies implementation. However, only few cities in the word have advance air quality-monitoring networks able to provide reliable information of PM leaves in the ambient air, trends and extent of the pollution. In Colombia, only major cities measure PM concentrations. Available measurements from Bogota, Medellin and Bucaramanga show that PM concentration are well above World Health Organization guidelines, but up to now levels and trends of PM in other cities and regions of the country are not well known. Satellite measurements serve as an alternative approach to study air quality in regions were surface measurements are not available. The aim of this study is to perform a spatial and temporal assessment of PM in the ambient air of Colombia. We used Aerosol optical depth (AOD) retrieved by the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite of NASA and surface measurements from the air quality networks of Bogota, Medellin and Bucaramanga. In a first step, we estimated the correlation between MODIS-AOD and monthly average surface measurements (2000 to 2015) from these three cities, obtaining correlation coefficient R values over 0.4 for the cities under study. After, we used AOD and PM_{10} measurements to study the temporal evolution of PM in different cities and regions. Finally, we used AOD measurements to identify cities and regions with the highest AOD levels in Colombia. All the methods presented in this paper may serve as an example for other countries or regions to identify and prioritize locations that require the implementation of more accurate air quality measurements.

Key words: AOD, MODIS, PM_{10}, Pollution, Measurements, Air quality, Public health

1. INTRODUCTION

Monitoring of ground-level concentrations of particulate matter is necessary for an effective evaluation of air quality and the assessment of potential health risks (Pérez P *et al*., 2016; Saunders *et al*., 2014; Verma *et al*., 2013; Fajardo and Rojas, 2012). In Latin America, countries such as Colombia, Mexico, Venezuela, Ecuador, Peru and Brazil, air quality is highly affected by PM_{10} and $PM_{2.5}$ emitted from different sources such as, biomass burning (Castellanos *et al*., 2015), vehicles emissions (Cuellar *et al*., 2016; Zárate *et al*., 2007), and industrial-agricultural activities (Kumar *et al*., 2016; Reddington *et al*., 2015; Rojas *et al*., 2015; Fajardo and Rojas, 2012). In Latin America the pollution levels are only monitoring in a few main cities, leaving most of the surface without information about its air quality. In Colombia three cities: Bogota, Medellin and Bucaramanga have AQMN (automatic air quality monitoring networks), but many cities and regions of the country has not suitable, or any AQMN.

The use of Aerosol Optical Depth (AOD) is a feasible and cheap alternative to estimate the levels of this pollutant in the region. Moderate Resolution Imaging Spectroradiometer (MODIS) on board of the orbiting satellites Terra and Aqua from NASA has enabled the retrieval of AOD data globally. Retrieval algorithms have evolved so they can process the radiance measured by the instrument. MODIS has become an important tool in the prediction of particles ground level concentration estimates (Duncan *et al*., 2014; Saunders *et al*., 2014; Vijayakumar and Devara, 2012). Previews works developed worldwide has shown this approach to be useful for air quality assessment and to complement the AQMN. In The United States of America AOD values were used to estimate $PM_{2.5}$ surface levels (Saunders *et al*., 2014). In the megacity of Beijing, AOD levels were used to evaluate the impact of PM_1 on plant leaf proteins (Yan *et al*., 2014). In India variations of aerosol levels during a particular event were studied through AOD data (Vijayakumar and Devara, 2012). In South America the effects of biomass burning was evaluated in 2015 (Castellanos *et al*., 2015). Other researches involving a new method for the use of AOD data in particular locations in South America have been published (Lanzaco *et al*., 2016). In Colombia a recent research evaluated the African dust outbreak effects in the air quality of the country (Cárdenas *et al*., 2017).

The main goal of this study is to perform a temporal and spatial analysis of air quality in Colombia using AOD and AQMN PM_{10} data in the period from 2000 to 2015. We used AOD retrieved from NASA MODIS and surface measurements from Bogota, Medellin and Bucaramanga. Correlation between AOD and monthly average surface measurements from these three cities are estimated. We used AOD and PM_{10} measurements to study the temporal evolution of PM in different cities and regions of the country. Finally, we used AOD measurements to identify cities and regions with the highest AOD levels in Colombia.

2. MATERIALS AND METHODS

Colombia is geographically located in the northern South America. It is a country divided politically and geographically in 32 departments each one with a capital city. Being Colombia's Capital Bogota, which at the same time is the capital of Cundinamarca Department. Colombia is also divided in 5 Geographical Regions: Amazonia, Andina, Pacifica, Llanos Orientales or Orinoquía and Caribe (IDEAM).

Air quality data is limited and for existent AQMN in some places. Manual monitoring systems along the country measure air quality variables but access to this information is limited or not available. Actually only Bogota, Medellin and Bucaramanga have AQMN data available for air quality studies.

2.1 Air Quality Monitoring in Colombia

In Colombia only 2 large cities have complete and fully functional AQMN: Bogota and Medellin, the city of Bucaramanga and its surroundings had an AQMN, but data is only available from 2002 to 2012. In Medellin, there is available data from August 2007 (UPB). Bogota has measurements from 2000 to 2017 in 11 monitoring stations (aqicn; IDEAM; Ramírez *et al*., 2018; SDA-RMCAB, 2016; Zimmerman *et al*., 2011). In these cities the annual average levels of PM_{10} are often above the acceptable concentrations (50 $\mu g/m^3$) established by local regulations (Ramírez *et al*., 2018), leading to public health problems and finally economic affectations (LA MINISTRA DE AMBIENTE Y DESARROLLO TERRITORIAL, 2017; Sarigiannis *et al*., 2015; Silva *et al*., 2013). Measured PM_{10} surface concentrations for this research were obtained from Bogota, Medellin and Bucaramanga AQMN. Hourly average values are available in each monitoring station, we used this information to compute monthly averages concentrations in each city.

Bogota is the largest city in Colombia with more than 10 millions of people (DANE, 2006), considered as megacity in environmental recent studies (Ramírez *et al*., 2018); due to its extension, the AQMN of the city is composed by 11 stations (SDA). Air quality data and meteorological variables are available from 2000 to present. In this study, data regarding PM_{10} surface concentration was used to be compared with AOD data.

The city of Bucaramanga had a fully functional AQMN composed by 9 stations, including the Floridablanca station in a town near the city, but the measurements were only developed from 2002 to 2012, this monitoring network is currently being upgraded and is supposes to be running in the near future.

Medellin PM_{10} data are available from August 2007. The data is measured by 10 station along the urban area. The AQMN of Medellin is being currently upgraded to assess the high pollution events in the city in recent years (Ramírez *et al*., 2018; Ramos *et al*., 2017).

Additional information regarding AQMN for Bogota, Medellin and Bucaramanga is contained in the Appendix.

2.2 AOD-MODIS Data

The AOD data was obtained from MODIS products from NASA through the GIOVANNI online platform for satellite data retrieval (NASA-a, 2017). MODIS with 1° resolution (111 km) and 0.55 Microns AOD, for land and ocean mean was the data-set used. Data were collected from 2000 to 2015 for Colombia and its neighbors, taking as analysis domain: (87.5W 6.5S 59.5W 17.5N) (Fig. 1) (Rojas *et al*., 2015; Saunders *et al*., 2014; Yan *et al*., 2014).

The data collected corresponded to monthly averaged values, directly downloaded from the GIOVANNI online interface (NASA-c, 2016). Monthly averaged values were taken due to the lack of daily datasets because of the cloudy weather in many of the different areas along the established domain.

The AOD data used were retrieved from Terra satel-

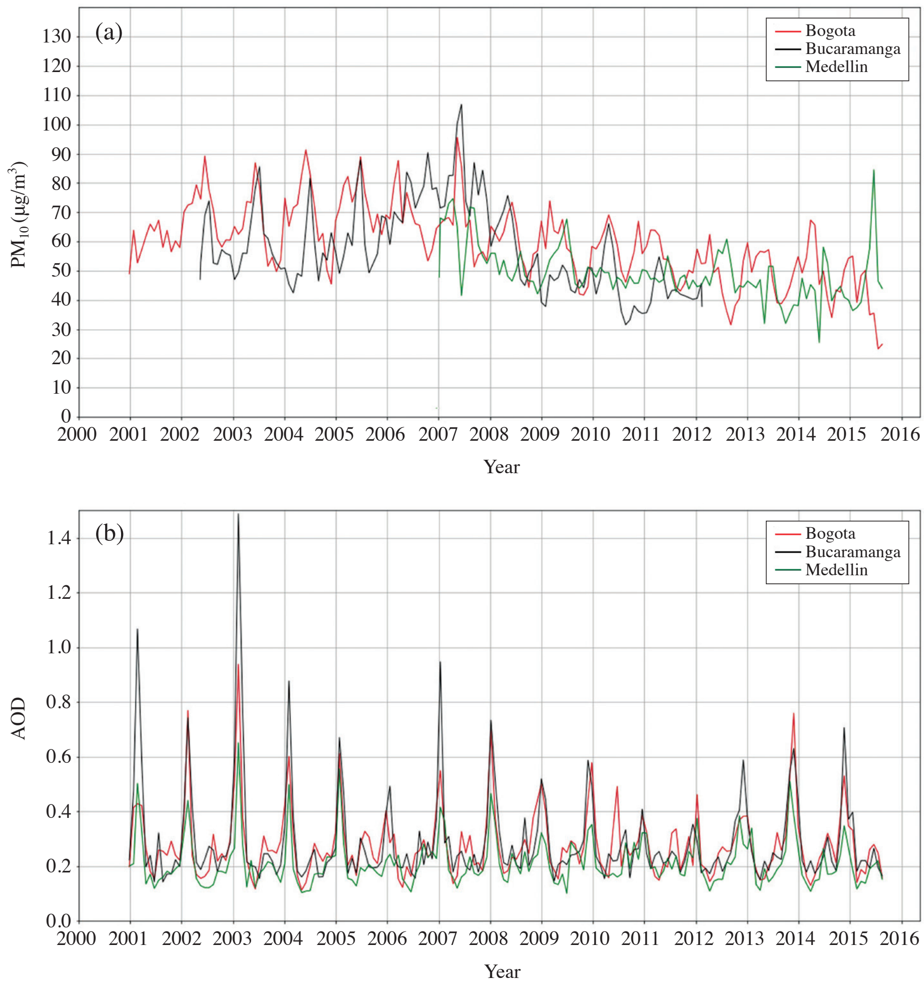

Fig. 1. Air quality data in the period between 2000 and 2015 for the Colombian cities: Bogota, Bucaramanga and Medellin. (a) Monthly averaged PM_{10} concentration data ($\mu g/m^3$) from the air quality monitoring networks, (b) Monthly averaged AOD 0.55 Microns.

lite (originally known as EOS-AM-1), due to the fact that its orbit around the Earth is a sun-synchronized polar orbit, timed so that it passes from north to south across the equator in the morning, about 10:30 am local time for the region of interest for this study; this gives more reliable data because of the more favorable weather conditions at this hour of the day for the region, while Aqua passes south to north over the equator in the afternoon. Both satellites are monitoring the whole Earth's surface every 1 to 2 days (NASA-c, 2016; Tomasi *et al*., 2012). Data for temporal analysis was downloaded monthly averaged and area averaged from GIOVANNI, meanwhile for spatial analysis time average data for the period of 2000 to 2015 was downloaded in netCDF format for the data processing (UCAR).

Data from MODIS only includes day measurements due to the nature of the AOD instrument. This passive instrument works with a remote sensor sensible to the surface irradiance, for that reason only measure during solar hours (NASA-b, 2018). The main advantage of this kind of orbit is that it keeps almost constant the angle of sunlight over the earth during the whole year. This allows to compare, during long periods of time, the AOD without getting concerned about lighting, cloudiness or shadows that can distort measurements, in order to have a nice and comparable statistic sample. This feature is important for this particular study over Colombia.

2.3 Data Processing

This research used Python V3.6® as tool for the data processing (Anaconda Python). Scripts for AOD data managing were implemented for temporal and spatial analysis. The time series were plotted using Matplotlib library for graphics. AOD maps were plotted using time averaged information in netCDF format, the Basemap library were used. Other libraries for numerical analysis were also used: Numpy, Scipy and netCDF.

3. RESULTS AND DISCUSSION

3. 1 Temporal Analysis of PM_{10} Surface Data and MODIS-AOD

The Fig. 1 shows the temporal evolution of AOD and PM_{10} values along the period of study from 2000 to 2015. Fig. 1(a) shows surface PM_{10} concentration in the time period of study, a decrease in PM_{10} is observed after 2008 when the change in the combustibles quality of the country was modified especially for diesel with sulfur content reductions from 500 ppm to 100 ppm and to ultralow sulfur diesel (less than 50 ppm), and gasoline with less than 300 ppm actually (Comisión de Regulación de Energía y Gas (CREG) and Ministerio de Minas y Energía, 1999; Congreso de Colombia; Ministerio de Ambiente).

It is important to remark that environmental policies were also changed from 70 to 50 $\mu g/m^3$ annual for PM_{10} in 2010 (EL MINISTRO DE AMBIENTE; LA MINISTRA DE AMBIENTE). Even so this values are still above the values recommended by WHO (Ramírez *et al.*, 2018; WHO, 2006). This upper limit for PM_{10} is not accomplished according with the data retrieved from AQMN in the 3 cities Fig. 1(a).

According to the Fig. 1(a), PM_{10} values in Bogota are along the period of study the highest concentration levels. Bucaramanga shows high PM_{10} with a great peak in the second half of 2006. Bucaramanga also has an unstable behavior, meanwhile Medellin presents a very stable behavior with peaks only in the second half of 2006 and the end of 2015, even so this stable behavior of PM_{10} in Medellin is varying about 50 $\mu g/m^3$, exceeding several times this limit.

In the 3 cities a seasonal pattern is observed from Fig. 1, in AOD and PM_{10}, the moths of rains have lower values than the dry month of the year in the country. Months such may, June and July consist in a valley values of the year with low PM_{10} and AOD each year, meanwhile the months of December and January presents a clear peak each year.

A small increase of the peak values of AOD in the years of 2013 to 2015 can be observed in the Fig. 1(b). AOD shows the peaks with higher values in the city of Bucaramanga, in the dry months of the year, always above the values for the other 2 cities. In the case of AOD (Fig. 1(b)) the greatest peak is observed in the end of the 2003 a year different from 2006, even so, the peak of 2006 in PM_{10} is represented also by a peak of AOD the summer of the same year. This difference in the higher peaks of each variable, PM_{10} and AOD, can be explained by the inclusion of biogenic aerosols to the AOD values measured by MODIS, in the year 2003 a particular event of biogenic aerosols over the country is clearly identified by AOD. The event in the second half of 2007 is perceived by both variables, PM_{10} and AOD.

Fig. 1(b) shows a more stable tendency than AOD in time, the change in the regulations and combustible quality improvements is not represented as clear as it is by the PM_{10} measured by the AQMN in the time series trend. Even so, the peak values are reduced in recent years if they are compared with the years before 2008.

3. 2 Correlation of AOD-MODIS with Measured PM_{10} Concentration Data and Statistical Analysis

The correlation of PM_{10} concentrations from AQMN with AOD in the 3 cities was developed using a Spearman linear correlation. Graphical results regarding dispersion of data points and statistical parameters according to a Spearman linear regression are shown in Fig. 2 as scatter plots.

Correlation coefficients (R) using Spearman linear regression are very similar in the three cities and range from 0.42 to 0.44 (Fig. 2). P-values are below 0.05, so can observe there is a statistically significance relation between AOD and PM_{10} surface concentrations measured in Bogota, Medellin and Bucaramanga.

Moreover, it was also observed that AOD values in Bogota, Medellin and Bucaramanga have a non-normal distribution, based on a Shapiro-Wilk value lower than 0.05. For PM_{10} data Bogota presented is the only city with normal distribution of the data, this due to the big amount of data from the AQMN of the city in comparison to the other 2 cities. Therefore, these results validate the use of a non-parametric approach (Spearman correlation) in the 3 cities to correlate AOD-MODIS and PM_{10} concentrations data.

3. 3 Seasonal Analysis

The detailed seasonal analysis of the data is based in the box plots of the monthly accumulated AOD values per regions in the country, and the precipitation rates, the main meteorological variable to characterize the seasons in Latin American tropical regions.

For the Caribe Region the high precipitation rates season, corresponding to months from July to January is related with the low AOD values. The same pattern is observed for Llanos Orientales Region. Other regions show a smooth relationship with a diminution of AOD values in the months of July to January. Therefore is possible to mention there is evidence of seasonal behav-

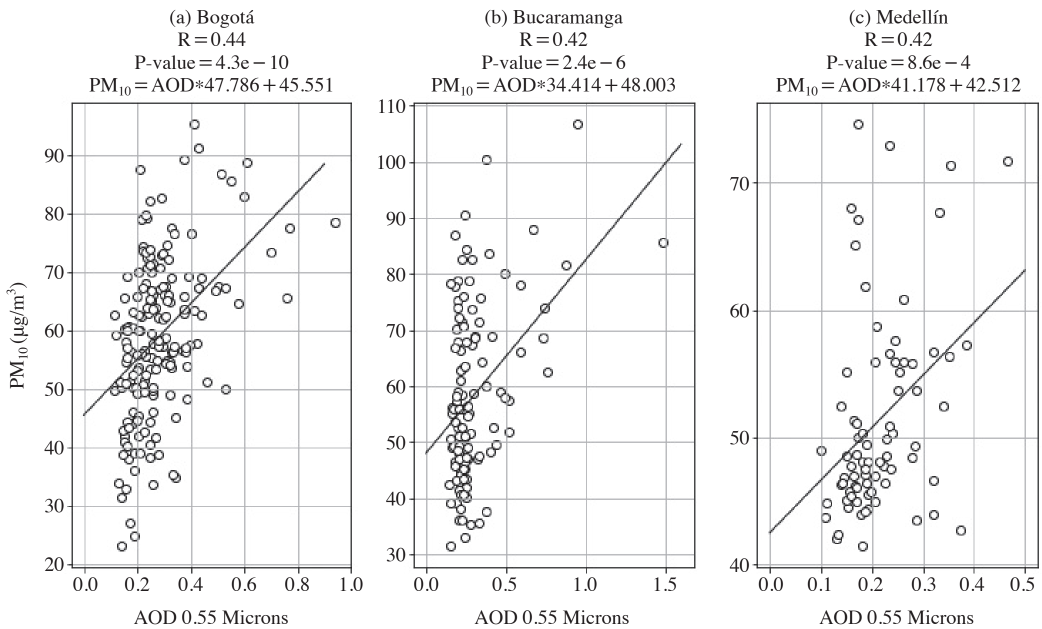

Fig. 2. Scatter plots and correlation (linear regression) of PM_{10} concentrations from measuring network and AOD 0.55 Microns data. (a) Bogota, (b) Bucaramanga and (c) Medellin.

ior in AOD levels, and these are clearly related with the summer season of the region (Northern South America).

Otherwise dry months are associated with relatively high AOD values in each region of the country. In Fig. 3 months from January to May show an increase in AOD, with peak values in March and April, about 0.8 in the Caribe and Llanos Orientales Regions, decreasing gradually in May and June.

November, December and January are the best moths in terms of AOD values for all 5 regions. Even so, those months are not strongly characterized by high precipitation rates. This behavior can be related with changes in anthropogenic effects due to different activities as industrial activities, holydays, agricultural activities, wild fires, biomass burnings and vehicular and aerial traffic. In addition, meteorological variables have a relationship with the decrease in AOD values at the end of the year, which is an interesting phenomenon.

3.4 Spatial Analysis: AOD-MODIS

Spatial Time-averaged contour maps of AOD for Colombia, and its neighbors, corresponding to region: 87.5W 6.5S 59.5W 17.5N are shown in Fig. 4. These maps also show the location of the 32 cities involved in this research. The geographical locations of the 32 departments of the country and their capital are summarizes in Table 1.

From the contour map in Fig. 4, high AOD values can be observed in the northern region, particularly in the borderlines with Panama and Venezuela. In the boundary line with Venezuela high PM_{10} and $PM_{2.5}$ concentration levels can be explained, considering the increasing amount of wildfires in Venezuela and the eastern Colombia as mentioned before in the temporal analysis (Chacón, 2015), leading this to an effective representation of this wild fires phenomena by AOD in temporal scale as well as in spatial scale.

There is also a region of high AOD values in the south-west of Colombia, near the pacific coast and over the city of Cali. This situation might be caused by "controlled" burnings in sugar cane plantations and biofuels production facilities, typical to this area of the country among other industrial and anthropogenic activities such as food industry, air and land transportation, sowing and use of fertilizers. For a deeper understanding of these phenomena, possible effects of topography of the terrain and meteorological variables should be evaluated in future studies at local and national level. Surface measurement of aerosols and pollutants related with the mentioned activities must be implemented in Valle del Cauca in order to analyze the impact on the local population public health and spatial approach of the pollution with more accuracy.

For the Caribbean coast, a great area covered by aerosols was observed, with considerably high PM_{10} levels according to the collected AOD. This area covers almost the whole country of Panama and a great part of the Caribbean and Pacific coasts of Colombia. This situa-

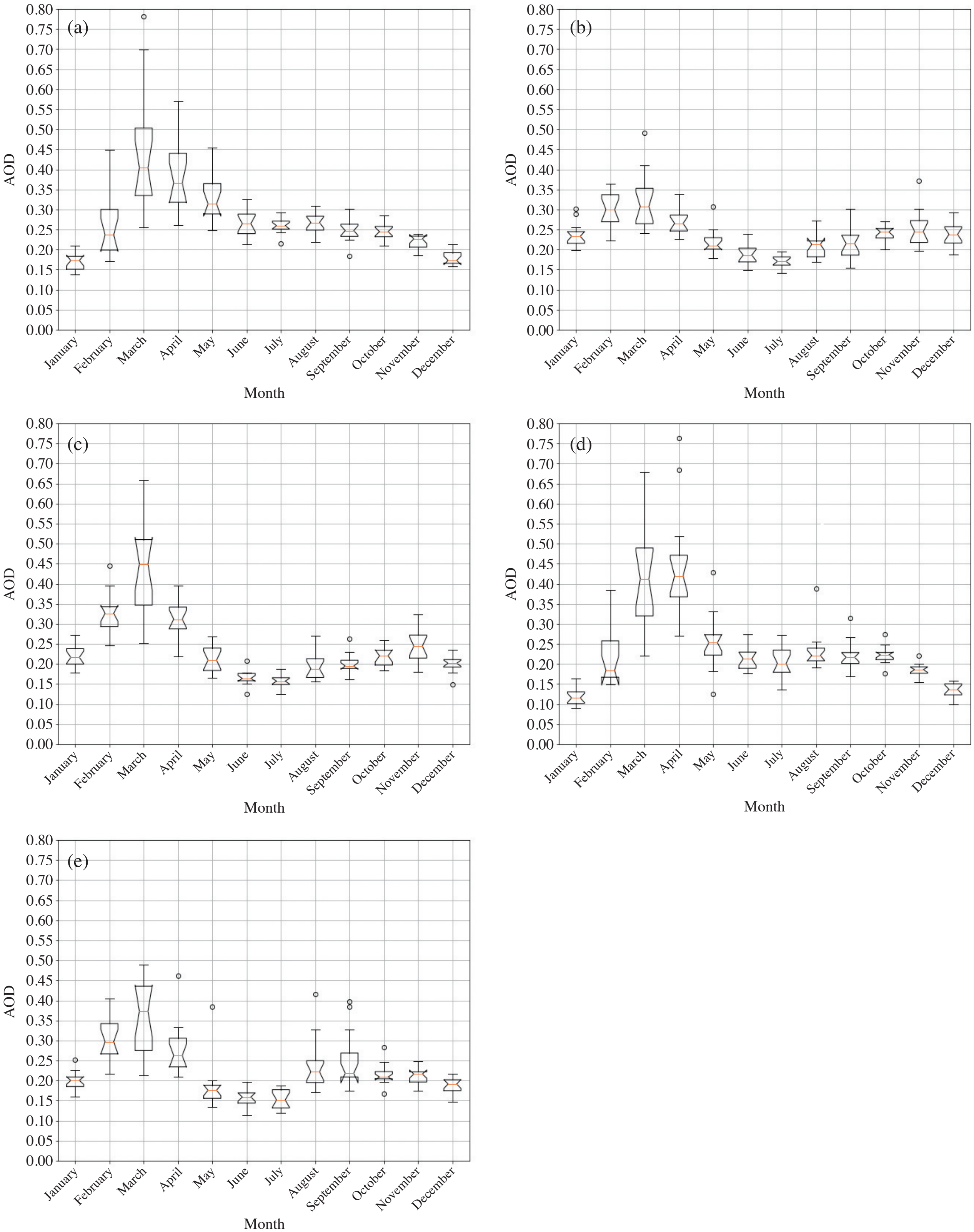

Fig. 3. Seasonal analysis boxplots: (a) Caribe Region AOD, (b) Pacifica Region AOD, (c) Andina Region AOD, (d) Llanos Region AOD, (e) Amazonas Region AOD.

Table 1. AOD levels in 32 Colombian capitals separated by region.

Region	Location		Coordinates		AOD 0.55 Microns data		
	Department	City or Place	Latitude	Longitude	Mean	Minimum	Maximum
Caribe	Bolívar	Cartagena de Indias	103.910	−754.794	0.312	0.151	0.813
	Córdoba	Montería	87.596	−758.857	0.301	0.100	1.577
	Magdalena	Santa Marta	112.331	−741.929	0.296	0.136	0.681
	Sucre	Sincelejo	93.046	−753.906	0.292	0.134	0.921
	San Andrés, Providencia and Santa Catalina	San Andrés	125.567	−817.185	0.267	0.160	0.525
	Atlántico	Barranquilla	110.041	−748.070	0.266	0.113	0.892
	La Guajira	Riohacha	115.384	−729.168	0.230	0.110	0.556
	Cesar	Valledupar	104.742	−732.436	0.213	0.066	0.698
Pacifica	Valle del Cauca	Cali	34.525	−765.358	0.378	0.208	0.643
	Cauca	Popayán	24.448	−766.147	0.196	0.082	0.438
	Choco	Quibdó	56.956	−766.498	0.191	0.079	0.590
	Nariño	Pasto	12.059	−772.858	0.186	0.081	0.528
Andina	Santander	Bucaramanga	71.173	−731.261	0.292	0.142	1.488
	Cundinamarca	Bogota	47.110	−740.721	0.280	0.112	0.938
	Quindío	Armenia	45.351	−756.732	0.251	0.124	0.624
	Risaralda	Pereira	48.048	−757.138	0.251	0.124	0.624
	Tolima	Ibagué	44.447	−752.424	0.251	0.124	0.624
	Huila	Neiva	29.376	−752.724	0.241	0.094	0.823
	Caldas	Manizales	50.672	−755.133	0.238	0.112	0.527
	Norte de Santander	Cúcuta	78.885	−725.031	0.222	0.097	0.971
	Antioquia	Medellin	62.442	−755.812	0.213	0.100	0.651
	Boyacá	Tunja	55.446	−733.576	0.168	0.081	0.315
Llanos Orientales	Arauca	Arauca	65.473	−710.022	0.286	0.092	1.266
	Meta	Villavicencio	41.515	−736.382	0.283	0.076	1.359
	Casanare	Yopal	53.489	−724.005	0.258	0.100	1.565
	Vichada	Puerto Carreño	61.848	−674.885	0.147	0.008	0.921
Amazonas	Caquetá	Florencia	16.154	−756.042	0.262	0.054	0.972
	Putumayo	Mocoa	11.523	−766.511	0.234	0.090	0.758
	Guaviare	San José	25.685	−726.417	0.232	0.053	0.669
	Amazonas	Leticia	−42.119	−699.395	0.221	0.042	0.769
	Guainía	Puerto Inírida	38.683	−679.239	0.219	0.069	0.600
	Vaupés	Mitú	12.522	−702.336	0.201	0.075	0.564

tion had affected the center of the country as well, leading to high PM_{10} levels involving 3 of the 5 regions of Colombia: Caribe, Pacifica and Andina. These phenomena can be at least partially related with the Sahara dust outbreak-effect, which affects most of the Caribbean countries in Latin America (Cárdenas *et al*., 2017). Furthermore, there are other biogenic sources of aerosols affecting air quality such as: the salt dragged by the air in the coast and PM_{10}-$PM_{2.5}$ emissions from many anthropogenic sources among others.

As further observation, high AOD values along the Pacific coast of Ecuador were observed, covering the cities of Manta, Guayaquil, La Libertad and San Lorenzo. In this case, and based on satellite observations, the Sahara dust outbreak is not the main source of aerosols. This observation is made based in the distance between this places and the influence area of the dust outbreak from Africa, which are north of Colombia and Venezuela, and part of Amazonas.

A possible explanation to this observation is the anthropogenic emissions due to agricultural, vehicular and industrial activities in the cities of Ecuador mentioned above. Particularly, the pacific coast of Ecuador has a significant petrochemical industrial activity with oil refining plants in La Libertad and Manta. Measurements and analysis involving meteorological, topographical, demographic and industrial aspects in this region are required in order to fully understand this situation.

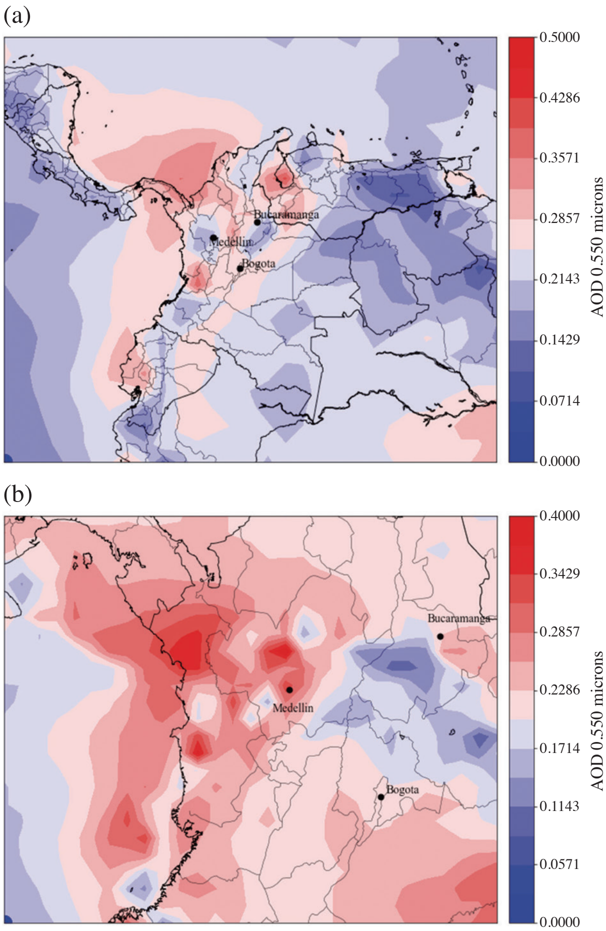

Fig. 4. AOD contour for years from 2000 to 2015 AOD-terra 0.55 Microns monthly averaged: (a) in the region of Colombia and its neighbor: 87.5W 6.5S 59.5W 17.5N, (b) Detail of the Colombia Region of the main analysis: 80.27W 2.43N 72.2W 9.8N.

Fig. 4 allows the visualization of AOD in the whole region, the figure shows the location of the capital cities of the country where most of them do not have proper AQMN or any measuring systems to assess air quality and its forward implications. Table 1 summarizes data regarding geographical location for the 32 places included in this research, and the maximum, minimum and mean values for the collected AOD data.

Cities in the center of the country also have high aerosol presence but in this case, the cause is not related to Sahara dust outbreaks, and there is other biogenic and anthropogenic aerosol sources that may be responsible for these levels as mentioned above.

Caribe Region has high values of AOD in many of its cities; mainly Cartagena presents a high mean value and Monteria the highest maximum in the region. To completely evaluate the effects of anthropogenic activities in the Caribe Region is necessary to develop future studies considering public health implications, meteorological variables and important anthropogenic activities such industry and agriculture.

Table 2. Top 10 AOD-MODIS 0.55 Microns for the Colombian Cities.

Place	City	Mean	Max.
1	Cali	0.38	0.64
2	Cartagena de Indias	0.31	0.81
3	Montería	0.30	1.58
4	Santa Marta	0.30	0.68
5	Bucaramanga	0.29	1.49
6	Arauca	0.29	1.27
7	Sincelejo	0.29	0.92
8	Villavicencio	0.28	1.36
9	Bogota	0.28	0.94
10	San Andrés	0.27	0.53

The Pacifica Region shows a high mean value for the city of Cali, even being this city the Highest mean value of the country as can be observed in the Top 10 of mean AOD values (Table 2).

Low AOD levels are observed in the Chocó department, over the city of Quibdó, this behavioral pattern of aerosols can be explained due to the high precipitation rates presence in this part of the country during the whole year. Also Amazonas has a low AOD values in comparison to other regions, but it is an observed transport of aerosols from Brazil and Venezuela. This fact can be related with biomass burning in both countries.

According to the AOD values observed, the 10 most polluted cities of Colombia are summarized in Table 2. Cali is the city with the highest mean AOD, which is the capital city of Valle del Cauca department, and represents the strongest AOD spot in the map as well (Fig. 4). After this city, other cities mainly from the Caribe Region have high mean AOD values.

Other cities from the geographical center of the country such as Bogota, Bucaramanga and Villavicencio are in the top, but bellow Cali, the case of Bucaramanga is particularly critical, this city has one the highest maximum (1.488) AOD value of the country even when it is not in the top 10 of mean AOD. Other cities all of them from Llanos Orientales in Eastern Colombia such Yopal (1.565), Monteria (1.577), Villavicencio (1.359) and Arauca (1.266) have the highest maximum values, Arauca as a not industrialized city is a clear evidence of the biomass burning and wild fires in Venezuela affecting air quality in the cities of Colombia. The number of wildfires has increased in recent years due to many causes, the first one is global warming and its increased effects due to industrial activities in developed countries; and the second is El Niño phenomena which has a great impact in this particular region.

San Andres is an island, this city located in the Atlantic Sea is included in the 10^{th} position of Table 2, there is not previous studies about the air quality of this island and its impacts in public health, and this is an important observation due to the lack of air quality measurements, research and state presence in the island.

3. 5 Suggested Places for Future Air Quality Monitoring Systems Implementation

The mean values for the 5 regions geographical regions in Table 1 are different, as well as the higher and lower values. This means that air quality in the country is highly heterogeneous. The political and economic centralization of the country at geographical and social level is notorious also through this fact.

The higher AOD values were found in the Caribe region, thus implying bad air quality in cities such as Cartagena, Barranquilla, Santa Marta, Sincelejo and Montería. Development and implementation of AQMN and air quality modeling is recommended.

The city of Bucaramanga, located in the Andina region has also shown high AOD levels; measurements of their AQMN in surface and collected AOD data support this observation. Unfortunately, air quality measurements were suspended in 2011. Even so, there is a studies about the high pollution levels impact in public health in the city of Bucaramanga, Colombia involving this period (Rodriguez-Villamizar *et al*., 2016, 2012). Re-activation of the AQMN in the city of Bucaramanga and its surroundings is highly recommended in the near future with the actual upgrade of the actual AQMN this can be successfully achieved.

For the Andina region, other cities with considerable high levels of aerosols are: Bogota, Cucuta and Neiva. The bad air quality in Cucuta, and other cities as Arauca, can be related with anthropogenic activities in Venezuela, mainly biomass burning and uncontrolled wildfires. Even so, the hydrocarbon exploitation in the Catatumbo area, and soil erosion are possible related, to fully comprehend this situation and its effects in local population AQMN design and implementations is required in the near future.

In Llanos Orientales the AOD levels are high in several cities of the region, this makes important to consider an AQMN for the whole region capable to measure the impact of the synoptic transport from Venezuela, Brazil and Africa mainly (Cárdenas *et al*., 2017), and the pollutants emitted from local biogenic and anthropogenic sources due to the large agricultural, industrial and transportation activities.

Air quality of Medellin based in AOD levels, is better than in other cities of the same region. In comparison with surface measured data AOD levels and PM_{10} concentrations have a correlation and an equal qualitative tendency, indicating this that the other towns and cities of the region have also a strong presence of aerosols a recent upgraded to the AQMN of Metropolitan Area of Valle de Aburrá (Medellin and its surroundings) was performed, this will lead to a better understanding of air quality events and their causes, and the implication in terms of public health.

In the region of Amazonas the AOD values are surprisingly high in cities as Leticia, Florencia and Mocoa. Their AOD levels are comparable with central cities with a greater number of anthropogenic emissions. Based on Fig. 4, a possible cause of this behavior might be synoptic transport of pollutants. Also biogenic sources of aerosols like plantations, soil erosion and vegetal spores. This cause is based in AOD-MODIS observations but further analysis is required, and air quality data measurements in these cities and surrounding places must be implemented for many pollutants and meteorological variables to validate this hypothesis.

It is also possible to determine that anthropogenic activities such as oil refining processes in Barrancabermeja and Cartagena have important effects over the local air quality. Being these two places between the locations with high AOD values in the country. Measurements campaigns to collect data are required before taking any decisions about implementation of environmental regulations or technical modifications in the current process plants.

Based in the PM_{10} concentrations measured in Bogota, Bucaramanga and Medellin and the AOD data collected, the implementation of new air quality monitoring networks are suggested for: Montería, Sincelejo, Cartagena, Barranquilla and Santa Marta in the Caribbean region. Cucuta and Neiva in the Andina Region (The reactivation of measurements in the city of Bucaramanga and the improvement of the way the data is deliver to the public and academic community in Medellin is highly recommended). Arauca, Yopal and Villavicencio located in the region Llanos Orientales; Cali in the Pacific region, and Leticia, Florencia and Mocoa in the Amazonas region require AQMN design and implementation in the near future.

4. CONCLUSIONS

The Information about the AQMN in Colombia was summarized and analyzed, considering the operation of the systems in the period between 2000 and 2015 for the 3 main cities of the country: Bogota, Bucaramanga and Medellin.

The PM_{10} concentration data from the AQMN (Bogota, Bucaramanga and Medellin) was compared with the

AOD data collected for the region of Colombia and its Neighbors (87.5W 6.5S −9.5W 17.5N). The data was analyzed using initially a quantitative test of normality (Shapiro-Wilk) to determine the behavior of the variables and a better approach to develop a correlation in an accurate way, leading to conclude the variables have a non-normal distribution except for Bogota's PM_{10} due to the big amount of data available for this city. The Spearman approach was defined as the best to develop a linear regression of the data obtaining R values of: 0.44 (Bogota), 0.42 (Bucaramanga) and 0.42 (Medellin).

With linear regression the P-values indicate a good enough significance (P-value $< 1 \times 10^{-5}$) for Bogota and Bucaramanga. Nevertheless, in Medellin the P-value is 8.609×10^{-4}, a value close to 1×10^{-5} leading to consider data from Medellin as a statistically significant as well.

Using the AOD data, the air quality of the 32 capital cities along Colombia was evaluated. The analysis developed leads to a possible relationship between anthropogenic activities with air quality. Furthermore, also biogenic sources of aerosols like soil erosion, marine salt, African dust, etc., can explain the low air quality in terms of AOD values for several places in Colombia, and the qualitatively difference in the behavior of the PM_{10} and AOD in the time series analyzed (Fig. 1).

This study identifies the places in Colombia where it is necessary to implement measurements with new air quality monitoring networks, or upgrade the actual ones. For the city of Bucaramanga is required to reactivate air quality variables monitoring suspended in 2011. However, in all cases further studies and measurements are required to fully understand the situation and the events, as occurs in the city of Montería and other places from Caribe region for example. Future research must consider in detail meteorology, topography and anthropogenic issues. As a recommendation there are 3 good alternatives with possibilities to be implemented as approaches in air quality modeling considering in detail the different variables involved: Air Quality Modeling (AQM), Computational Fluid Dynamics (CFD) and Artificial Neural Networks (ANN) (Lanzaco *et al*., 2016).

For the main cities of Llanos Orientales in Eastern Colombia, Villavicencio, Yopal and Arauca, high AOD values were clearly identified along the period of 2000 to 2015. This can be caused by the synoptic transport of aerosols from Venezuela, Brazil and Africa mainly, and the pollutants emitted from local biogenic and anthropogenic sources due to the large agricultural, industrial and transportation activities.

For the country of Ecuador there is a region of poor air quality, possibly related with industrial activity Nevertheless further studies are required in order to establish the cause and assess the public health implications.

Studies regarding the $PM_{2.5}$ are also required to analyze in a deeper way air quality in Colombia and other South American countries. To develop such studies, implementation of new air quality monitoring systems capable of measure variables as $PM_{2.5}$ in many places in Colombia and the places of interest, as the recommended above, is required in the short term.

Industrial, vehicular air quality stations are required to obtain PM_{10} detailed local surface data. This methodology by other hand is useful for upgrading or updating planning of existent AQMN, and for planning of new AQMN design due to the possibility of considering synoptic effects.

This study points to an important approach for air quality measurement and assessment in Colombia using satellite data. This study can be reproduce in other countries of the region to assess air quality patterns based in aerosols from biogenic and anthropogenic sources.

The approach suggested in this first study can be used by developing countries worldwide, mainly African and Latin American Countries, as an alternative to complement surface air quality measurements, or for investment planning in Air quality monitoring systems upgrading or in new implementation.

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APPENDIX

Supplementary Information: Air Quality Monitoring Networks of Bogota, Medellin and Bucaramang

This additional section summarizes the Air Quality Monitoring Networks (AQMN) for the cities of Bogota, Medellin and Bucaramanga.

Table A-1. Stations of the air quality monitory network of Bogota (aqicn; SDA-RMCAB, 2016).

Station name	Latitude	Longitude	Zone type	Station type
Guaymaral	4°47′1.52″N	74°2′39.06″W	Sub-Urban	Background
Usaquén	4°42′37.26″N	74°1′49.50″W	Urban	Background
Suba	4°45′40.49″N	74° 5′36.46″W	Sub-Urban	Background
Bolivia	4°44′9.12″N	74°7′33.18″W	Sub-Urban	Background
Las Ferias	4°41′26.52″N	74°4′56.94″W	Urban	Taffic
P. Simón Bolívar	4°39′30.48″N	74°5′2.28″W	Urban	Background
Sagrado Corazón	4°37′31.75″N	74°4′1.13″W	Urban	Taffic
Fontibón	4°40′12.36″N	74°8′29.58″W	Urban	Industrial
Puente Aranda	4°37′54.36″N	74°7′2.94″W	Urban	Industrial
Kennedy	4°37′30.18″N	74°9′40.80″W	Urban	Background
Carvajal	4°35′44.22″N	74°8′54.90″W	Urban	Industrial
Tunal	4°34′34.41″N	74°7′51.44″W	Urban	Background
San Cristóbal	4°34′21.19″N	74°5′1.73″W	Urban	Background

Table A-2. Stations of the air quality monitory network of Bucaramanga (SIAC and IDEAM, 2015).

Station name	Latitude	Longitude	Zone type	Station type
Cabecera	7°07′16.40″N	73°06′30.51″W	Urban	Traffic
Centro	7°07′08.84″N	73°07′21.79″W	Urban	Traffic
Ciudadela	7°05′57.30″N	73°07′53.69″W	Urban	Background
Norte	7°08′34.82″N	73°07′43.24″W	Urban	Background
Cra 21	7°07′29.55″N	73°67′24.01″W	Urban	Taffic
Diag. 15-Cra. 17	7°06′46.96″N	73°07′19.78″W	Urban	Background
Joya	7°06′57.23″N	73°07′49.83″W	Urban	Background
Floridablanca	7°04′15.68″N	73°06′21.61″W	Urban	Background

Table A-3. Stations of the air quality monitory network of Medellin (SIATA, 2016; UPB).

Station name	Latitude	Longitude	Zone type	Station type
U. Nacional	6°16′23.5″N	75°35′30.02″W	Urban	Background
Museo de Antioquia	6°15′08.61″N	75°34′08.04″W	Urban	Background
Tanques la Ye	6°10′57.91″N	75°33′02″W	Urban	Traffic
Casa de Justicia	6°16′04.69″N	75°33′56.16″W	Urban	Traffic
I.E. Consejo	6°15′26.56″N	75°36′21.05″W	Urban	Background
Lasallista	6°05′58.94″N	75°38′19.63″W	Sub-Urban	Background
Metro	6°19′53.42″N	75°33′13.11″W	Urban	Traffic
SOS-Girardota	6°22′40.48″N	75°27′04.22″W	Sub-Urban	Background