IJSRM
INTERNATIONAL JOURNAL OF SCIENCE AND RESEARCH METHODOLOGY
An Official Publication of Human Journals

Human Journals
Review Article
April 2020 Vol.:15, Issue:2

Relations between Atmospheric Pollution and Climate for the Aburrá Valley in Colombia

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Submission: 22 March 2020
Accepted: 29 March 2020
Published: 30 April 2020

HUMAN JOURNALS
www.ijsrm.humanjournals.com

Keywords: Environmental study, Traffic, Health, $PM_{2.5}$, Climate monitoring

ABSTRACT

The Aburrá Valley region in Colombia has a population approaching four million people, which occupy a somewhat narrow valley high in the Andean mountains. The region has been experiencing high atmospheric pollution episodes in recent years, quite related to increasing vehicle and motorcycle traffic and special climate conditions. To respond to this in a preventive way, the local authorities have established advanced pollution and climate monitoring system and systems to interpret conditions and give early alerts and establishing recommended and obligatory actions for the population. This article describes the situation as a valid example of this type of work, applicable to large cities in developing countries and establishes simplified correlations between climate parameters, the valley geography and particulate matter pollution for the last five years starting in 2015.

1. INTRODUCTION AND CONTEXT

The region to be studied is the Metropolitan Area of the Valley of Aburrá [1] [2](AMVA by its acronym in Spanish) that is made up by the municipalities of Caldas, Itagüí, Sabaneta, Bello, Copacabana, Girardota, Barbosa, La Estrella, Envigado, and Medellín (which is the major city, with 65% of the population). This is the second largest metropolitan area of Colombia, after the metropolitan area of Bogotá, the capital city. In total, it has approximately 3.8 million inhabitants and urban and rural areas of 102 km2 and 1054 km2, respectively. It is in the center of the department of Antioquia, on the central chain of the Andes mountain range with an average elevation of 1538 m. Located on the tropic; it has quite constant temperatures and small climate variations throughout the year. The area is located in a valley formed by two mountain ranges one to the east and the other one to the west and is crossed by the Medellín river, as shown in Figure 1. The following descriptions of the Aburrá Valley show that is a clearly enclosed region.

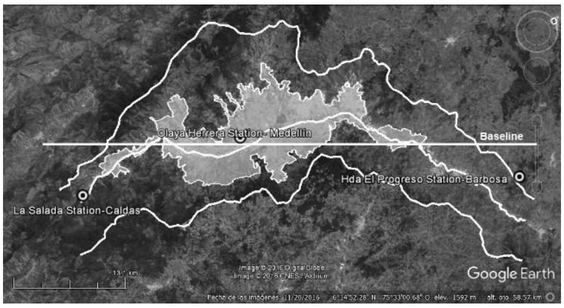


Figure 1: The Aburrá Valley, south to the left

In Figure 1, three irregular lines are observed, two representing the crests of the mountain ranges on each side of the valley, and a third one, the river that runs through the middle of the valley. A fourth straight line is a reference, called "baseline", which is formed by joining a point in the south with coordinates 6 ° 02'18.51 "N 75 ° 41'38.70"O with a point in the north with coordinates 6 ° 28 ' 47.19 "N 75 ° 24'58.90"O, this line serves as the axis for the location of distances from south to north. The Figure also shows a clear demarcated (light in shade) area that is the urban area and shows the sites for three traditional meteorological stations.

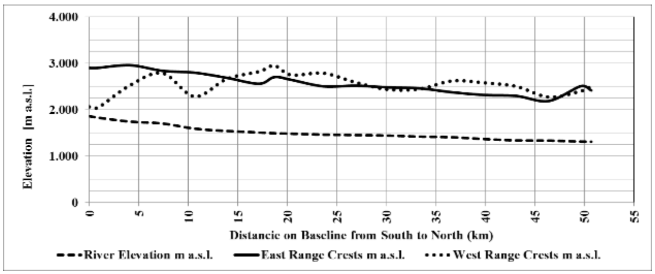


Figure 2: Elevation profile for the Aburrá Valley

It is observed in Figure 2 that the river descends 552 meters in the 51 kilometers of the baseline, going from 1,862 m to 1,301 m, with an average height of 1,505 m as it passes through the valley. The two mountain ranges have maximum heights of around 3,000 m. The average elevation of the eastern mountain range is 2,584 m and for the western one is 2,529 m. The average elevation in relation to the river is 1,078 m and 1,024 for the eastern and western ranges respectively.

In Figure 3, the width of the valley at different elevations, 50, 100 and 200 meters above the level of the river, is shown, as well as in the ridges of the mountain ranges that form the valley. This was done for different points along the baseline that connects two reference points of the valley from south to north. It can be seen that the valley it is relatively enclosed, with total areas of 108 km^2 in the flat zone near the river less than 50 m above the level of the same; of 166 km^2 in the zone of less than 100 m above the level of the River; of 227 km^2 for the zones of less than 200 m above the level of the river, and of 718 km^2 between the ridges of the two mountain ranges that form the valley. The fact that the valley is a box-like system allows it to be considered as a volume of control in which mountains act as clear boundaries through which energy and air do not flow significantly. On the other hand, the southern and northern ends are inlets and outflows, especially if taken into account that the winds have predominant directions from the north, following the direction opposite to the flow of the river.

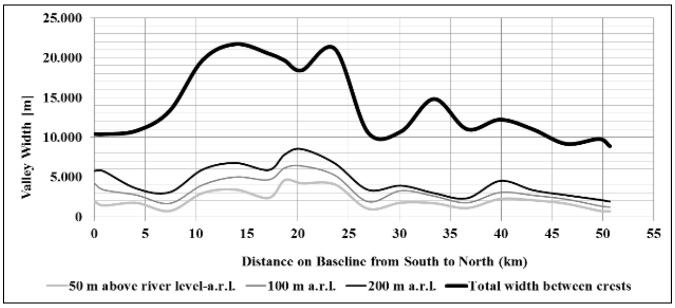


Figure 3: Width of the valley in different points, at different heights

Citation: Enrique Posada et al. Ijsrm.Human, 2020; Vol. 15 (2): 49-97.

Of course, this Valley experiences variables and meteorological phenomena that condition the dispersion of air pollutants, such as radiation, atmospheric stability, humidity, wind speed and direction. These factors, added to its special topography, make it necessary to correlate the meteorological information of the region with the data of the stations that monitor pollutants in the territory.

There is a local environmental authority, called Área Metropolitana del Valle de Aburrá (The Metropolitan Area of the Aburrá Valley) which works closely with the so-called *Sistema de Alertas Tempranas* – SIATA [3]Early Warning System) and the local municipalities of the Aburrá Valley. They monitor pollution and atmospheric conditions and take decisions in such a way that they control the situations of possible air-pollution episode periods. According to their experience, these periods occur between February-April and October-November, which coincide with the transitions of the climatic seasons, where there is a low cloudiness that prevents pollutants from dispersing, which causes higher concentrations of pollutants.

These authorities have established some especial measures to manage and control as effectively as they deem it possible, the atmospheric contingencies present at those times of year. The major instrument they have is a vehicle mobility rotation system, "peak and plate", which restrings vehicle mobility at certain days and hours during the week, applicable to specific zones of the cities. During the episodes, these are more stringent. Figure 4, Figure 6a and 6b compare normal and more stringent (PREVENCIÓN) peak and plate rules.

Vehículos particulares Desde 4 de febrero **Motos** 2 tiempos

Último dígito de la placa		Primer dígito de la placa
6-7-8-9	Lunes	4-5
0-1-2-3	Martes	6-7
4-5-6-7	Miércoles	8-9
8-9-0-1	Jueves	0-1
2-3-4-5	Viernes	2-3

7:00 a.m a 8:30 a.m
5:30 p.m a 7:00 p.m

Taxis Desde 1 de febrero
Placa - Mes - Día

	Feb	Mar	Abr	May	Jun	Jul
0	14-28	15-29	8-22	7-21	5-19	4-18
1	8-22	4-18	2-16-30	15-29	13-27	12-26
2	1-11-25	12-26	10-24	16-30	14-28	8-22
3	5-19	6-20	4	2-17-31	10	9-23
4	6-20	7-21	5	3-13-27	11-25	10-24
5	7-21	8-22	1-15-29	14-28	12-26	11-25
6	15	1-11	9-23	8-22	6-20	5-19
7	4-18	5-19	3-17	9-23	7-21	5-19
8	12-26	13-27	11-25	10-24	17	2-16-30
9	13-27	14-28	12-26	6-20	4-18	3-17-31

Último dígito de la placa

6:00 a.m a 8:00 p.m

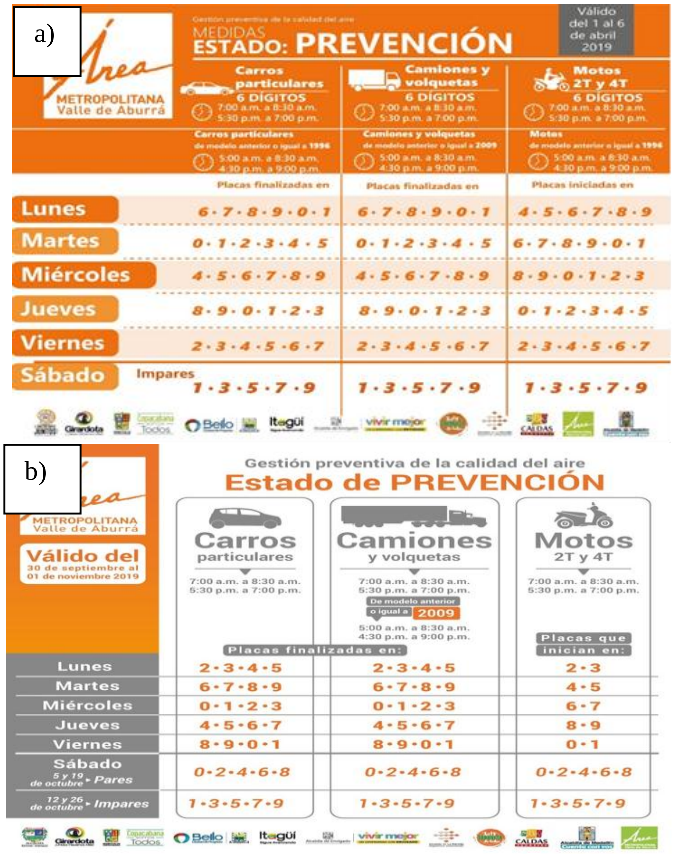
Figure 4: For the normal times, the peak and plate restrictions apply to private cars (twice a week) and 2T motorcycles, from 7 to 8:30 am, and from 5.30 to 7:00 pm, from Monday to Friday; and to taxis during 6 am to 8 pm twice a month.

Figure 5: Zone where the rotation restrictions to vehicle circulation apply

The rotation restrictions do not apply to all streets and Medellin city zones, only to the ones close to downtown, to the river (Río Medellín) and to the more crowded traffic zones, as shown in Figure 5. The colored zone is the one being restricted.

For all vehicles, three times a week, from 5 to 8:30 am and from 4.30 to 9:00 pm and include also Saturdays. In October, the restrictions are less severe and apply to trucks and motorcycles and include restrictions for cars on Saturday.

In general, there is a Comprehensive Air Quality Management Plan -PIGECA [4]- which includes medium and long-term measures that seek to mitigate unfavorable air quality conditions. States of Prevention are declared in accordance with the so called POECA [5] (Operational Plan to face Episodes of Air Pollution) under the recommendation of the Early Warning System [3]– SIATA, based on the analysis of technical tools that performs the monitoring and follow-up of air quality and weather in the Aburrá Valley [6].



Gestión preventiva de la calidad del aire

MEDIDAS
ESTADO: PREVENCIÓN

Válido del 1 al 6 de abril 2019

	Carros particulares 6 DÍGITOS 7:00 a.m. a 8:30 a.m. 5:30 p.m. a 7:00 p.m. Carros particulares de modelo anterior o igual a 1996 5:00 a.m. a 8:30 a.m. 4:30 p.m. a 9:00 p.m.	Camiones y volquetas 6 DÍGITOS 7:00 a.m. a 8:30 a.m. 5:30 p.m. a 7:00 p.m. Camiones y volquetas de modelo anterior o igual a 2009 5:00 a.m. a 8:30 a.m. 4:30 p.m. a 9:00 p.m.	Motos 2T y 4T 6 DÍGITOS 7:00 a.m. a 8:30 a.m. 5:30 p.m. a 7:00 p.m. Motos de modelo anterior o igual a 1996 5:00 a.m. a 8:30 a.m. 4:30 p.m. a 9:00 p.m.
	Placas finalizadas en	Placas finalizadas en	Placas iniciadas en
Lunes	6·7·8·9·0·1	6·7·8·9·0·1	4·5·6·7·8·9
Martes	0·1·2·3·4·5	0·1·2·3·4·5	6·7·8·9·0·1
Miércoles	4·5·6·7·8·9	4·5·6·7·8·9	8·9·0·1·2·3
Jueves	8·9·0·1·2·3	8·9·0·1·2·3	0·1·2·3·4·5
Viernes	2·3·4·5·6·7	2·3·4·5·6·7	2·3·4·5·6·7
Sábado Impares	1·3·5·7·9	1·3·5·7·9	1·3·5·7·9

Gestión preventiva de la calidad del aire

Estado de PREVENCIÓN

Válido del 30 de septiembre al 01 de noviembre 2019

	Carros particulares 7:00 a.m. a 8:30 a.m. 5:30 p.m. a 7:00 p.m.	Camiones y volquetas 7:00 a.m. a 8:30 a.m. 5:30 p.m. a 7:00 p.m. De modelo anterior o igual a 2009 5:00 a.m. a 8:30 a.m. 4:30 p.m. a 9:00 p.m.	Motos 2T y 4T 7:00 a.m. a 8:30 a.m. 5:30 p.m. a 7:00 p.m.
	Placas finalizadas en:		Placas que inician en:
Lunes	2·3·4·5	2·3·4·5	2·3
Martes	6·7·8·9	6·7·8·9	4·5
Miércoles	0·1·2·3	0·1·2·3	6·7
Jueves	4·5·6·7	4·5·6·7	8·9
Viernes	8·9·0·1	8·9·0·1	0·1
Sábado 5 y 19 de octubre ▸ Pares	0·2·4·6·8	0·2·4·6·8	0·2·4·6·8
12 y 26 de octubre ▸ Impares	1·3·5·7·9	1·3·5·7·9	1·3·5·7·9

Figure 6: For the prevention times, during February - April, the restrictions are more severe and apply not only to cars, but to all type of vehicles (excepting taxis, which maintain the normal rotation).

The POECA is structured with an Operational Plan with five components as follows:

- **Monitoring** of meteorological and air quality variables

- **Application of tools for forecasting air quality and meteorology** and their relationships. This include using models to perform prediction of episodes of pollution: Photochemical, meteorological and statistical models and application of expert criteria.

- **Application of special measures** during pollution episodes, aimed at indicating guidelines to the population to reduce exposure to high pollution and giving mandatory actions to the responsible of emission sources.

- **Application of a communications plan**, in order to inform the community in a timely and effective way and facilitate receptivity and compliance of the restriction measures and

- **Promote** behaviors aimed at reducing the exposure levels of the sensitive population.
- **Control and monitoring** focused on the evaluation of the effectiveness of the measures.

To define when to apply POECA and what measures to implement, there are four levels that depend on the indicators emitted continuously by SIATA, and that monitor the state of air quality in the metropolitan territory. The general implications for health issues for each level are as follows [7]:

Normal level (Level I): a level of absolute normality in which the concentration of pollutants in the air and their exposure time or duration are such that they do not produce harmful effects, direct or indirect, on the environment or health.

Level of Prevention (Level II): in this scenario, the concentrations of pollutants in the air and their exposure time or duration, cause adverse and manifest, albeit mild, effects on the health. Under this situation, it is recommended to limit prolonged outdoor activities of vulnerable populations: pregnant women, children, older adults, people with cardiovascular and respiratory diseases.

Alert Level (Level III): It occurs when the concentration of pollutants in the air and their duration or exposure time, can cause manifest changes in the environment or human health. Recommendations for vulnerable populations become more rigorous.

Emergency Level (Level IV): State of emergency in which the concentration of pollutants in the air and their exposure or duration, can cause acute or serious illnesses and even cause the death of living organisms.

Besides the actions related to restrictions on urban traffic (which account for almost 80 % of the particulate matter emissions in the region [8] [9]), there are other actions applicable to industries and companies. For example, companies are not allowed to carry on preventive maintenance of atmospheric emission control equipment during the episode management period and industries are subjected to some restriction if their emissions exceed some given limits. In addition, companies must train employees and encourage them to be part of a of sustainable mobility scheme.

In the case of fixed emission sources (industrial sources), once the Alert level has been declared and a level of Particulate Matter of less than 2.5 micrograms, $PM_{2.5}$ concentration greater than or equal to 106 µg / m^3 kas been reached, any fixed sources that emit at concentrations larger than 100 mg / m^3 of particulate material must stop working. If the Emergency level is declared, any fixed sources that emit at concentrations larger than 80 mg / m^3 of particulate material, must also stop working. This is determined according to a list of companies officially reported with these levels of concentrations in their fixed sources.

The concentration ranges and the exposure times for the levels of prevention, alertness or emergency, are established based on established air quality standards and color codes of Table 1 [10].

Table 1: Ranges of pollutant concentrations (µg / m^3) for the different alertness levels in the Aburrá Valley

Pollutant	Exposure time	Level I		Level II	Level III	Level IV
		Good green	Acceptable yellow	Prevention orange	Alert Red	Emergency purple
PM_{10}	24 h	0-54	55-154	155-254	255-354	>355
$PM_{2.5}$	24 h	0-12	13-37	38-55	56-150	>151
Ozone (O_3)	8 h	0-106	107-138	139-167	168-207	>208
SO_2	1 h	0-93	94-197	198-486	487-797	>798
NO_2	1 h	0-100	101-189	190-677	678-1221	>1222
CO	8 h	0-5094	5095-10819	10820-14254	14255-17688	>17689

The study of the SIATA results clearly indicate that the worst atmospheric conditions favoring pollution episodes occur in the period from February to April. A second, less critical period occurs in October. After applying the protocols, authorities report clear improvements, even though vehicles (including motorcycles) are growing annually at more than 5 % in recent years in the city. Figure 7 and Figure 8 show the results obtained during years 2015 to 2019. In 2017 the especial protocols started to be enforced. Figure 9 and Figure 10 resume the results obtained, according to the public reports generated by local authorities.

It is evident the increase in the number of monitoring stations and the attainment of better air quality indexes after applying the POECA prevention protocols.

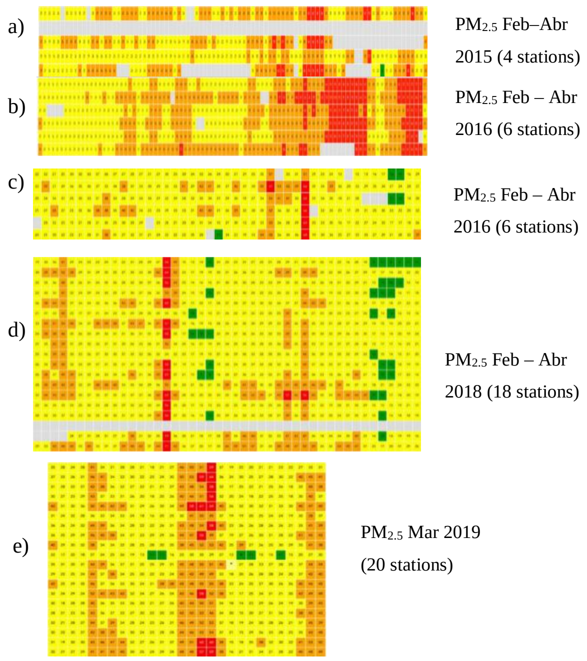


Figure 7: Air quality levels registered in the PM$_{2.5}$ monitoring stations from 2015 to 2019 during the period from February to April.

In the Figure 7 the horizontal direction, monitoring days are shown; in the vertical direction, monitoring stations are indicated. Gray colors indicate no data was taken. Green, yellow, orange and red colors assigned according to the color codes of Table 1.

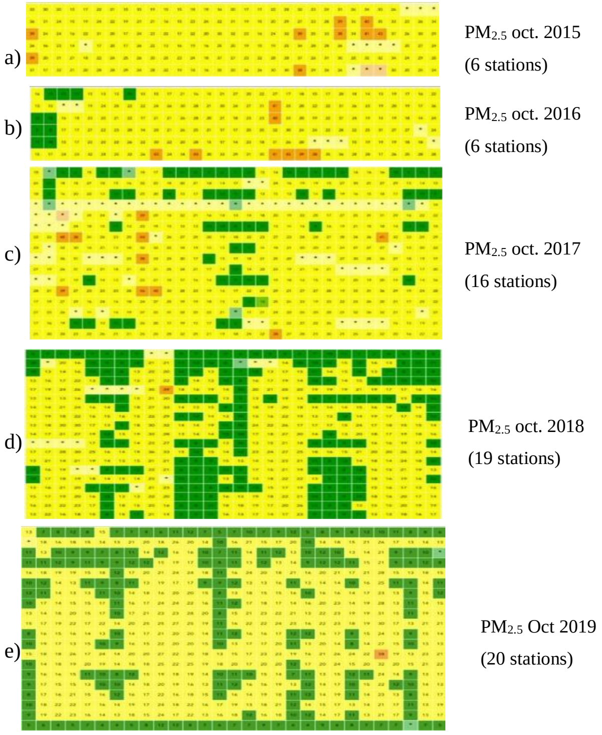


Figure 8: Air quality levels registered in the $PM_{2.5}$ monitoring stations from 2015 to 2019 during October.

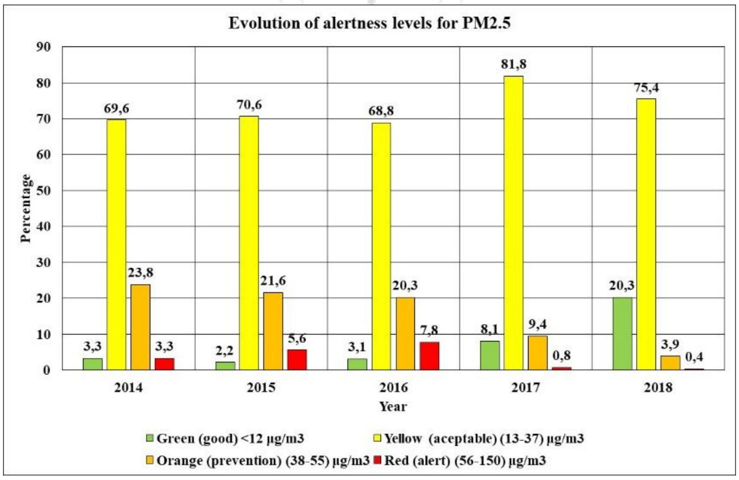


Figure 9: Evolution of alertness levels for PM2.5 since 2014 for the Aburrá Valley region.

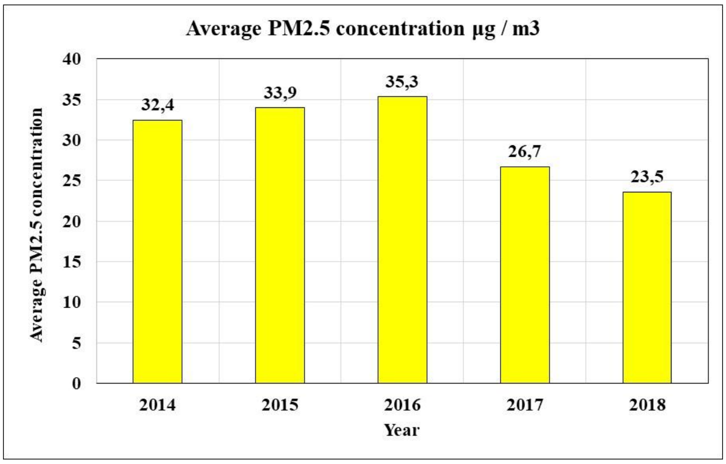


Figure 10: Evolution of estimated $PM_{2.5}$ concentrations since 2014 for the Aburrá Valley region.

The Aburrá Valley air quality monitoring network has monitoring stations for different air pollutants such as ozone, nitrogen oxides, carbon monoxide, sulfur dioxide, particulate matter (PM_{10}, $PM_{2.5}$). Measurement data is available for consultation for the people at the web site www.siata.gov.co [Accessed: Jan. 15, 2020]. (General Internet site) and are presented using several tools, so that municipalities, the Metropolitan Area and citizens may have accurate data about what happens in terms of air quality in the territory.

This is network that have been working for long time, with modernizations and systematizations started around 2000. Initially operated in collaboration with a network of universities and government monitoring stations since the 1980´s, it has been operated since 2016 by the Early Warning System of Medellín and the Aburrá Valley – SIATA. This is done with the supports of a group of professionals and scientist with permanent maintenance of the stations, and analysis and processing of the data they record, performing research on the behavior of air quality in the region, associated with weather contaminants are monitored following reference and equivalence EPA methods: NOx by chemiluminescence, SO_2 by fluorescence, CO by non-dispersive infrared, O_3 by photometry, and PM by manual gravimetric (24 hours) and attenuation of beta rays (continuous, hourly report). Automatic stations allow the hourly display of pollutant concentrations, information that is available in real time in www.siata.gov.co and the SIATA application. Data from manual stations are collected every three days and weights are determined and recorded in an accredited laboratory. This data is available for verification the automatic stations. Figure 11 shows the location of the monitoring stations, which are distributed along the valley.

Figure 11: Monitoring stations on the Aburrá Valley (SIATA). The lines indicate the limits of the ten localities of the Aburrá Valley.

SIATA has sensors that monitor meteorological conditions directly related to the dispersion of pollutants in the Aburrá Valley, as follows [11]:

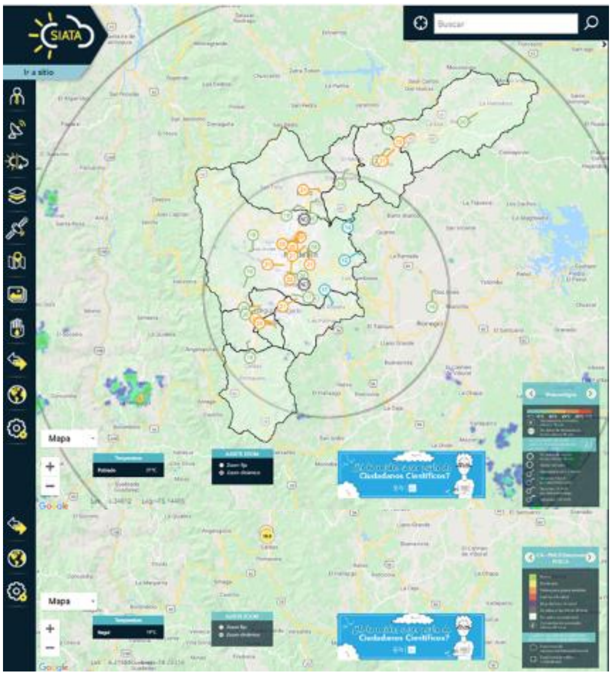
Radiometer: monitors thermodynamic variables such as temperature, humidity, water vapor in the atmosphere, allowing to determine variability profile up to 10 km above the surface.

Wind profiler radar offers information on the vertical structure of winds in the Aburrá Valley by means of electromagnetic waves that interact with the humidity present in the atmosphere, recording information from the surface up to 8 km high.

Ceilometers: a laser sensor designed to take vertical profiles of the atmosphere to determine the height of the Atmospheric Boundary Layer and give information on aerosols present in the lower part of the troposphere.

Pyranometer: used to measure the amount of total solar radiation that reaches the surface.

The following graphs, obtained in given days and hours, show how the information is reported to the citizens at https://siata.gov.co/sitio_web/index.php/calidad_aire [Accessed: Jan. 14, 2020]. (General Internet site).



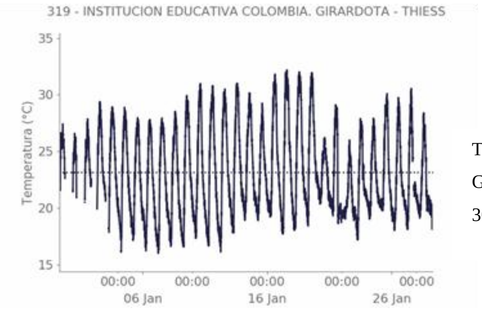
Temperatures 9:10 am Jan 28/2020

$PM_{2.5}$ 9:25 am Jan 28/2020

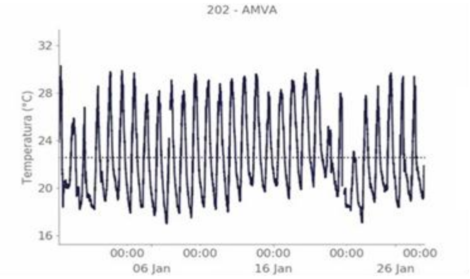
Figure 12: Displays of the SIATA web page

Using the tabs or buttons on the left line of the displays, specific information is displayed that allows access to curves and averages for each parameter, at different time periods and for the different monitoring stations.

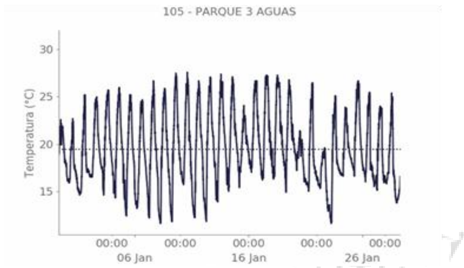
Below is a variety of information obtained in specific days and times for three stations and parameters of interest. The three stations were taken at the center of the valley and city (AMVA), at the northern zone (Giradota) and at the south (Caldas), to have a glimpse of the way parameters are presented. In the next section, a complete graphical and statistical presentation and analysis of the data for five years will be included.



Temperature
Girardota Station 319 (north)
30 days (Jan 29/2020)

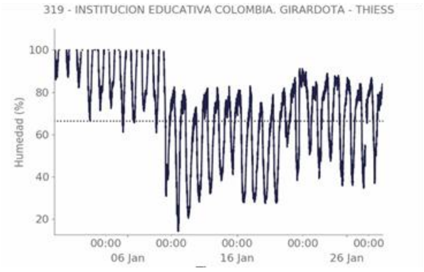


Temperature
AMVA Station 202 (center)
30 days (Jan 28/2020)

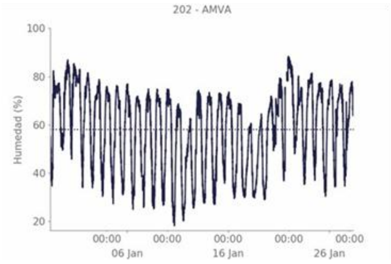


Temperature
Caldas Station 105 (south)
30 days (Jan 29/2020)

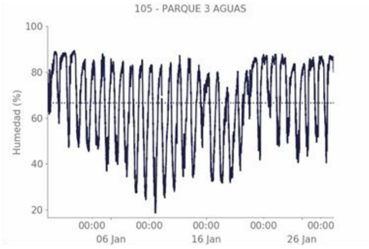
Figure 13: Temperature results (30 days) for three of the stations. Temperatures are coupled and diminish in the north-south direction.



Relative humidity
Girardota Station 319 (north)
30 days (Jan 29/2020)

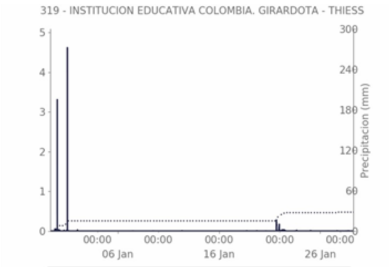


Relative humidity
AMVA Station 202 (center)
30 days (Jan 28/2020)



Relative humidity
Caldas Station 105 (south)
30 days (Jan 29/2020)

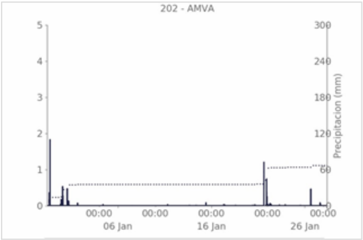
Figure 14: Relative humidity results (30 days) for three of the stations. Humidity is less coupled and diminish in the central zone.



Precipitation

Girardota Station 319 (north)

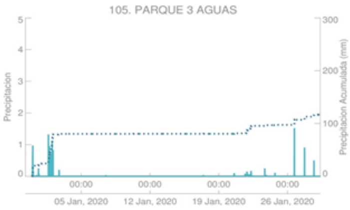
30 days (Jan 29/2020)



Precipitation

AMVA Station 202 (center)

30 days (Jan 28/2020)

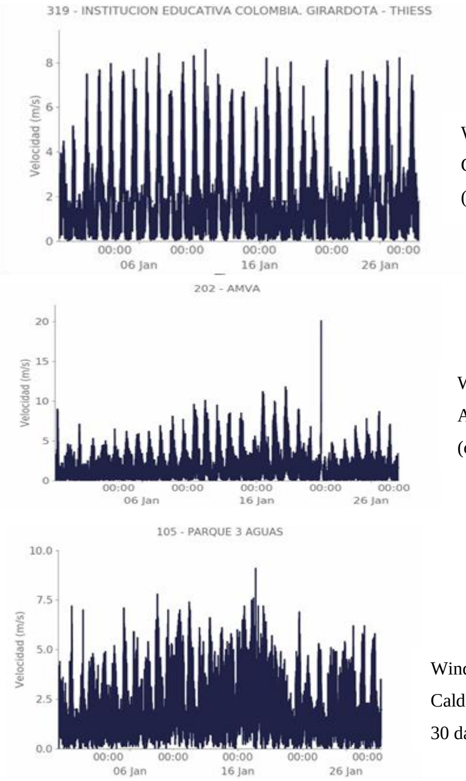


Precipitation

Caldas Station 105 (south)

30 days (Jan 29/2020)

Figure 15: Precipitation results (30 days) for three of the stations. Precipitations are somewhat coupled and increase to the south.

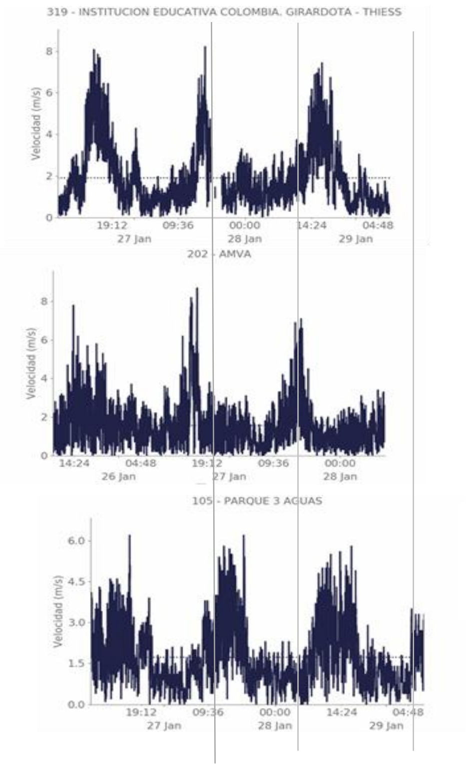


Wind speed
Girardota Station 319
(north)

Wind speed
AMVA Station 202
(center)

Wind speed
Caldas Station 105 (south)
30 days (Jan 29/2020)

Figure 16: Wind speed results (30 days) for three of the stations. Wind speeds are low, very variable, somewhat coupled.



Wind speed
Girardota Station
319 (north)

Wind speed
AMVA Station 202
(center)

Wind speed
Caldas Station 105
(south)

Figure 17: Wind speed results (3 days) for three of the stations. Wind speeds are low, very variable, somewhat coupled and similar in average.

Wind speed
Girardota Station
319 (North)

Wind speed
AMVA Station 202
(Center)
24h (Jan 28/2020)

Wind speed
Caldas Station
105(South)
24 h (Jan 29/2020)

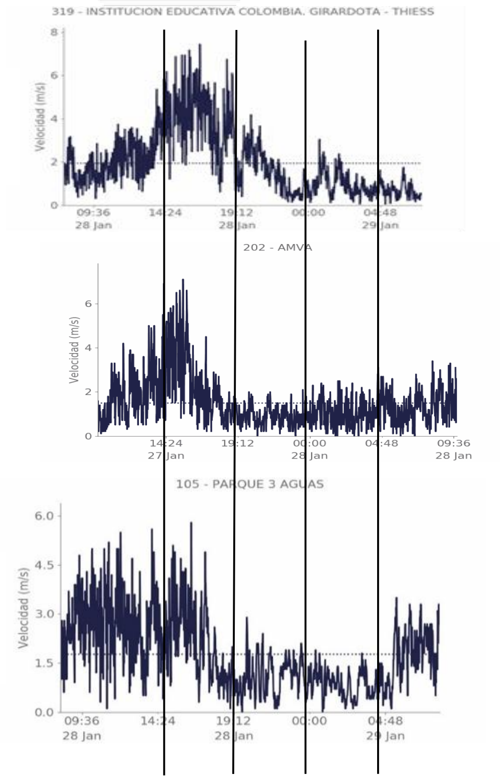
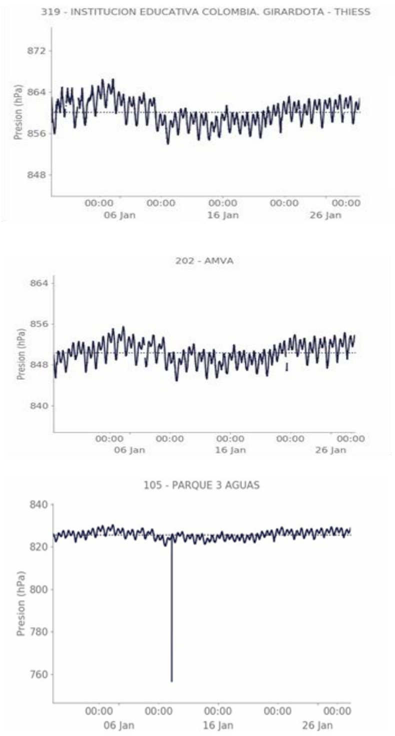


Figure 18: Wind speed results (24 h) for three of the stations.



Atmospheric pressure
Girardota Station 319 north)
30 days (Jan 29/2020)

Atmospheric pressure
AMVA Station 202 (center)
30 days (Jan 28/2020)

Atmospheric pressure
Caldas Station 105(south)
30 days (Jan 29/2020)

Figure 19: Atmospheric pressure results (30 days) for three of the stations.

Figure 18 shows how wind speeds are low, very variable, lower at night times, somewhat coupled and similar in average.

Figure 19 shows how atmospheric pressures are somewhat coupled and increase to the north, following the height above the sea levels of the valley.

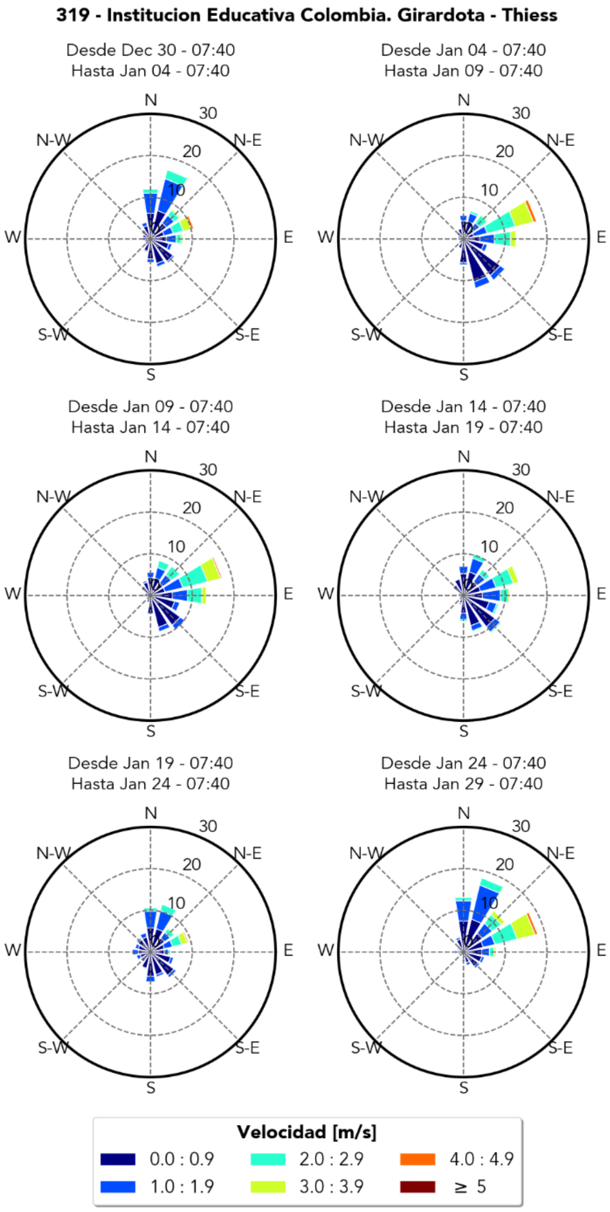


Figure 20: Wind direction and average speed - Girardota Station 319 (North) – 30 days (Jan 29/2020)

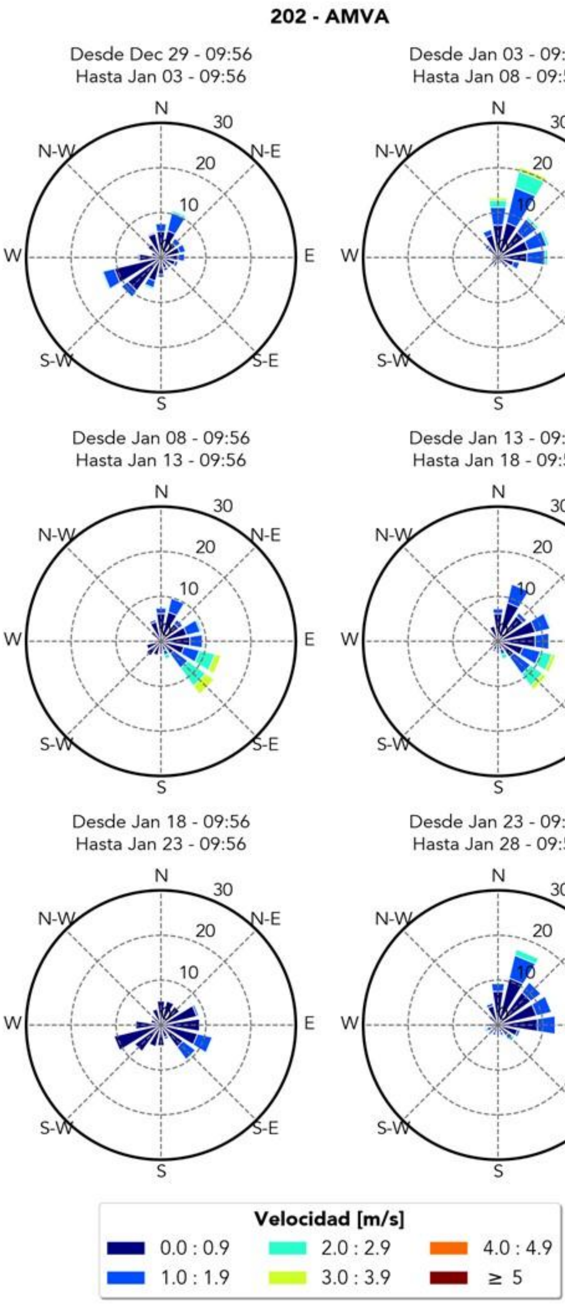


Figure 21: Wind direction and average speed – AMVA station 202 (Center) - 30 days (Jan 28/2020)

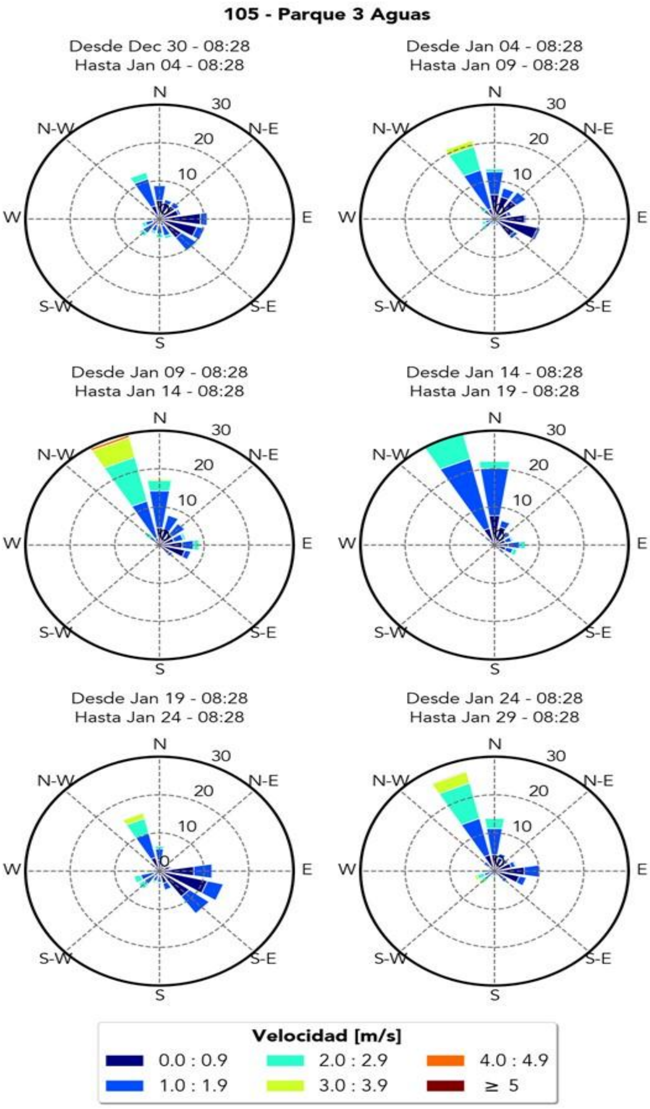


Figure 22: Wind direction and average speed – Caldas Station 105 (South) – 30 days (Jan 29/2020)

Wind directions tend to follow the orientation of the river channel in the Valley, as should be expected, with a preferred direction against the river flow. In Girardota station (North in the Valley), they mostly come from the North-East quadrant, with smaller frequencies from the South-East. Winds coming from the West are quite rare. In the AMVA station (situated in downtown Medellin, center, winds tend to come mostly from de North-East directions with occasional frequencies coming from the South-West directions. In the Caldas station (South), winds come mostly from the North West direction, with much fewer frequencies coming from the south. Figure 21, Figure 22 and Figure 22shows how this information is presented for 30 day-data, shown in six graphs with cumulative averages for six velocity ranges.

Information on reflectivity and precipitation formation in presented to the public by means of color-coded radar images of the skies, instantaneous and cumulated. A ground-based radar that bounces radar waves from precipitation measures precipitation intensity. I register base reflectivity as a display of echo intensity (reflectivity) measured in dBz (decibels). This reflectivity is the amount of transmitted power returned to the radar receiver after hitting precipitation, compared to a reference power density at 1 meter from the radar antenna. Base reflectivity images are available at several different elevation angles of the antenna. There is a colored dBz Scale, related to the different echo intensities (reflectivity) measured on a decibel (logarithmic) scale.

The scale of dBz values is also related to the intensity of rainfall. Typically, light rain is occurring when the dBz value reaches 20. The higher the dBz, the stronger the rain rate.

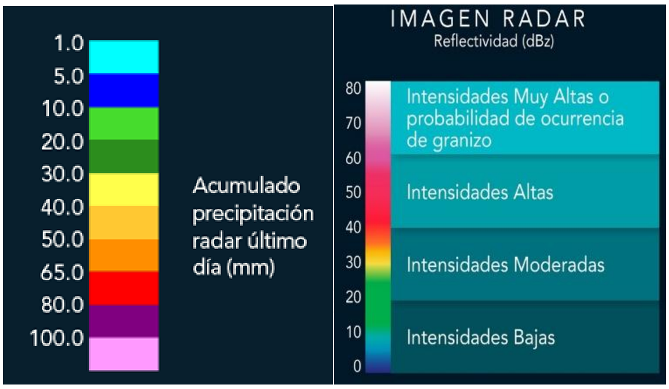
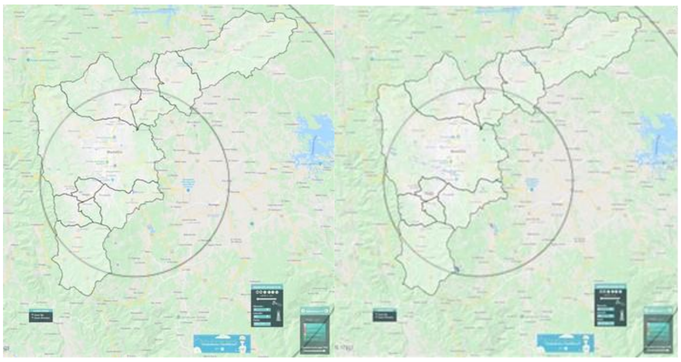
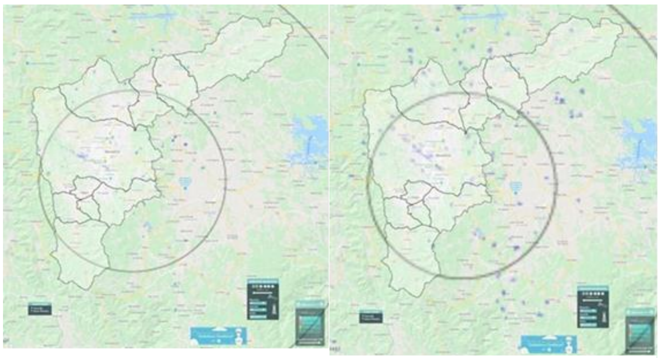


Figure 23: Radar scales Left, cumulated precipitation, based on the last day (mm). Right, radar image (reflectivity dBz) scale, going from very high insensitivities, high, moderate to low ones

The next figures show representations generated by the radar at four angles.



Reflectivity 4° Reflectivity 2°



Reflectivity 1° Reflectivity 0.5°

Figure 24: Reflectivity at four angles, Jan. 2020, 12:00

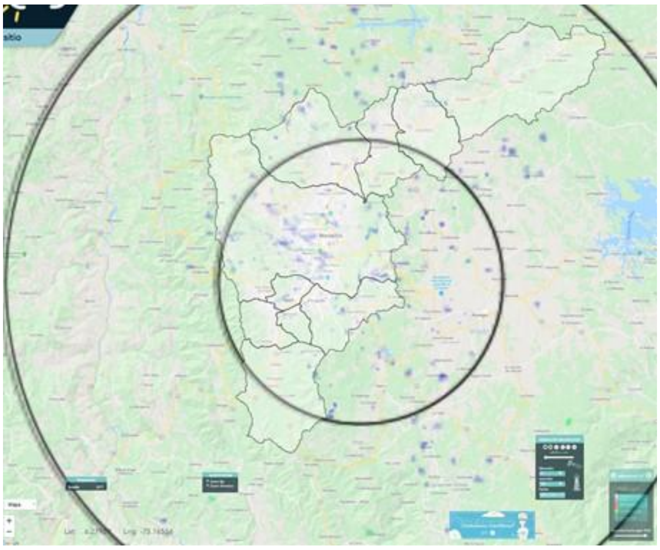


Figure 25: Reflectivity 0.5°, 1°,2°,4° Jan. 2020, 12:00

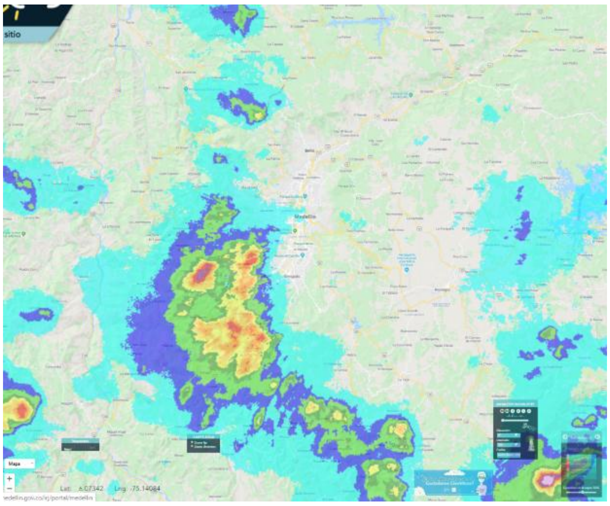


Figure 26: Reflectivity, cumulated 24 h, Jan. 2020, 12:00

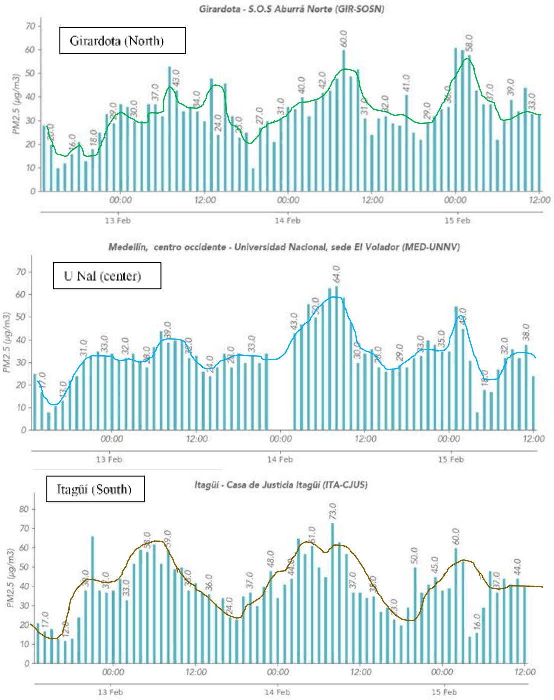


Figure 27: PM$_{2.5}$ 72 h for three stations, Feb 15. 2020, 12:00 There is some coupling in the concentrations.

Figure 27 show one of the ways PM$_{2.5}$ data is presented to the public.

2. Analysis of the environmental situation in the region

The focus of this work will be centered on particulate matter in the air, as represented by $PM_{2.5}$ concentrations. The region is very keen on this subject, as can be evidenced by the very complete network of sampling stations that exists in the Aburrá Valley. Table 2 Table 3 and Table 4 show the stations, their geographical situation and the parameters that are measured in them.

Table 2: List of Stations

Station	Name	Long.	Lat.
3	Girardota - S.O.S Aburrá Norte	-75,45	6,38
6	Politécnico Colombiano Jaime Isaza Cadavid - Medellín	-75,58	6,21
11	Institución Educativa Colombia. Girardota	-75,44	6,38
12	Estación Tráfico Centro	-75,57	6,25
25	Medellín, centro occidente - Universidad Nacional, sede El Volador	-75,58	6,26
28	Itagüí - Casa de Justicia Itagüí	-75,60	6,19
31	Caldas - Corporación Universitaria Lasallista	-75,64	6,10
37	Universidad San Buenaventura	-75,57	6,33
38	Itagüí - I.E. Concejo Municipal de Itagüí	-75,64	6,17
40	Parque de las Aguas	-75,42	6,41
41	Universidad de Medellín	-75,61	6,23
43	Tanque Miraflores	-75,55	6,23
44	Medellín, El Poblado - Tanques La Ye EPM	-75,55	6,18
46	Exito San Antonio - Medellín	-75,57	6,25
48	Estación Tráfico Sur	-75,63	6,15
69	Caldas - E U Joaquín Aristizabal	-75,64	6,09
74	Institución Universitaria ITM Robledo	-75,59	6,28
78	La Estrella - Hospital	-75,64	6,16

Station	Name	Long.	Lat.
79	Medellín, Altavista - I.E. Pedro Octavio Amado	-75,61	6,22
80	Medellín, Villahermosa - Planta de producción de agua potable EPM	-75,55	6,26
81	Barbosa - Torre Social	-75,33	6,44
82	Copacabana - Ciudadela Educativa La Vida	-75,50	6,35
83	Medellín, Belén - I.E Pedro Justo Berrio	-75,61	6,24
84	Medellín, El Poblado - I.E INEM sede Santa Catalina	-75,56	6,20
85	Medellín, San Cristóbal - Parque Biblioteca Fernando Botero	-75,64	6,28
86	Medellín, Aranjuez - I.E Ciro Mendía	-75,56	6,29
87	Bello - I.E. Fernando Vélez	-75,57	6,34
88	Envigado - E.S.E. Santa Gertrudis	-75,58	6,17
90	Sabaneta - I.E. Rafael J. Mejía	-75,62	6,14
92	Itagüí - Estación de Policía Los Gómez	-75,61	6,19
94	Medellín - Santa Elena	-75,50	6,24

Table 3: Environmental parameters measured in each station

Station	PM$_{2.5}$	PM$_{10}$	PM$_1$	NOx	Ozone	CO	SO$_2$
3	x			x	x	x	x
6	x	x	x	x		x	
11		x					
12	x	x		x	x	x	x
25	x			x	x		
28	x			x			
31	x				x		
37		x		x	x		
38	x	x			x		
40					x		
41					x		
43					x		
44	x				x		
46		x					

Station	$PM_{2.5}$	PM_{10}	PM_1	NOx	Ozone	CO	SO_2
48	x	x	x	x	x	x	
69	x	x					
74		x		x			
78	x						
79	x						
80	x						
81	x						
82	x						
83	x						
84	x						
85	x						
86	x						
87	x						
88	x						
90	x						
92		x					
94	x						

Table 4: Climate parameters measured in each station

Station	Wind dir	Humidity	Bar. Pres.	Precipit.	Radi-ation	Temp	Wind vel.
3	x	x	x	x	x	x	x
6	x	x	x	x	x	x	x
11	x	x	x	x	x	x	x
12	x	x	x	x	x	x	x
25	x	x	x	x	x	x	x
28	x	x	x		x	x	x
31	x	x	x		x	x	x
37	x	x	x		x	x	x
38	x	x	x	x	x	x	x
40	x	x	x		x	x	x
41	x	x	x		x	x	x
43							
44	x	x	x	x	x	x	x
46							
48	x	x	x	x	x	x	x

2.1.Behavior of $PM_{2.5}$

$PM_{2.5}$ concentrations in the Aburrá Valley behave in a seasonal manner, as seen in the following Figure 27, which shows a very complete set of measurements that have been made in the Aburrá Valley since January 1, 2015 for eight of the stations, which are the ones that have been monitored during the whole period.

It is easy to recognize that there are five large peaks (2015, 2016, 2017, 2018 and 2019) between late February and early April and much smaller peaks in some of the years in the month of October. In the figure, vertical lines are drawn, enclosing nine of these episodes.

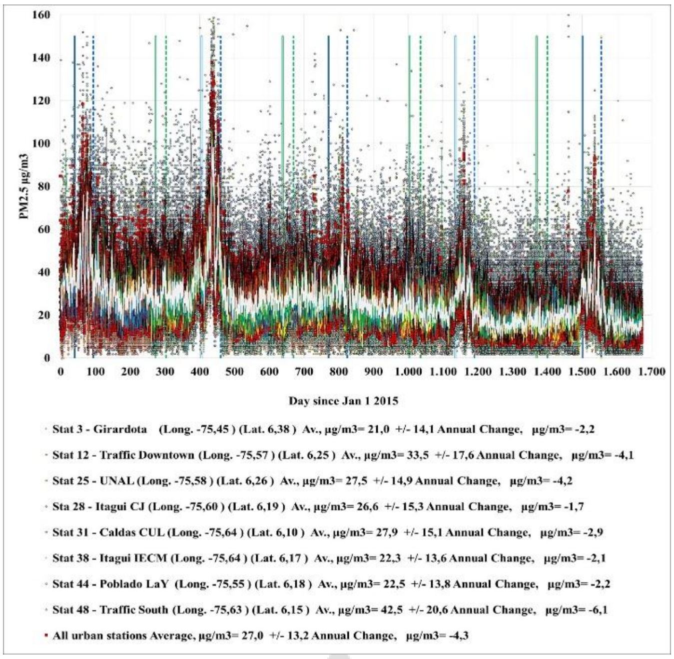


Figure 28: PM$_{2.5}$ concentrations for eight stations since January 1, 2015. Vertical lines enclose major pollution episodes. 24 hr. continuous averages are included and appear as colored lines. The white lines are the ones for the average of all data.

Table 5 shows the average results for all 23 urban stations and for the Santa Elena station, which is situated in the eastern rural region, on a much higher altitude as compared to the populated zone of the Aburrá Valley. There are ample variations as indicated by the standard deviations, which in average are 47 % of the medium value.

Table 5: Stations and PM2.5 data for each station

Station	Long.	Lat.	Average PM2,5, µg/m^3	Standard Deviation, µg/m^3	Annual change, µg/m^3/ year	Number of hourly data points
Stat 3 - Girardota	-75,45	6,38	21,0	14,1	-2,2	32.999
Stat 6 - Poli JIC	-75,58	6,21	21,6	14,4	2,7	3.186
Stat 12 - Traffic Downtown	-75,57	6,25	33,5	17,6	-4,1	36.934
Stat 25 - UNAL	-75,58	6,26	27,5	14,9	-4,2	38.265

Station	**Long.**	**Lat.**	**Average PM2,5, µg/m^3**	**Standard Deviation, µg/m^3**	**Annual change, µg/m^3/ year**	**Number of hourly data points**
Sta 28 - Itagui CJ	-75,60	6,19	26,6	15,3	-1,7	36.457
Stat 31 - Caldas CUL	-75,64	6,10	27,9	15,1	-2,9	37.861
Stat 38 - Itagui IECM	-75,64	6,17	22,3	13,6	-2,1	37.800
Stat 44 - Poblado LaY	-75,55	6,18	22,5	13,8	-2,2	32.384
Stat 48 - Traffic South	-75,63	6,15	42,5	20,6	-6,1	38.257
Stat 69 - Caldas EU	-75,64	6,09	20,9	11,5	0,4	12.395
Stat 78 - La Estrella H	-75,64	6,16	19,2	10,8	1,5	17.297
Stat 79 - Altavista	-75,61	6,22	21,4	10,8	1,2	16.639
Stat 80 - Villahermosa	-75,55	6,26	19,9	11,8	-1,9	16.439
Stat 81 - Barbosa	-75,33	6,44	13,8	10,0	0,6	15.808
Stat 82 - Copacabana	-75,50	6,35	16,3	10,2	0,0	15.861
Stat 83 - Belén	-75,61	6,24	22,0	12,7	-0,9	15.663
Stat 84 - INEM	-75,56	6,20	18,2	10,4	-1,2	15.657
Stat 85 - San Cristobal	-75,64	6,28	16,2	9,3	-0,3	15.716
Sta 86 - Aranjuez	-75,56	6,29	23,1	12,2	-1,8	15.137
Stat 87 - Bello	-75,57	6,34	16,7	9,9	-0,7	14.427
Stat 88 - Envigado	-75,58	6,17	18,4	10,4	-0,9	15.120
Stat 90 - Sabaneta	-75,62	6,14	18,3	10,8	3,2	11.037
All urban stations			27,0	13,2	-4,3	491.339
Stat 94 - Santa	-75,50	6,24	12,3	10,2		3.616

Station	Long.	Lat.	Average PM2,5, µg/m^3	Standard Deviation, µg/m^3	Annual change, µg/m^3/ year	Number of hourly data points
Elena (rural area)						

It is observed that the average daily concentrations are continuously decreasing for all the eight stations, as indicated by the annual changes given by the lineal adjustment for each one, which are negative and oscillate between -1.7 and -6.1 µg/m^3 per year with an average change of -4.3 µg/m^3 per year for the eight stations.

Figure 28 shows the average situation for all stations. It shows the average hourly data and the daily average data. It should be noted that daily averages are the ones to look at when comparing with the country's regulations and alert levels presented at Table 1. The concentrations are diminishing continuously, reaching average values of acceptable or good quality (less than 25 micrograms per m^3 of air). The average daily concentrations have gone from an average of 36.5 micrograms per m^3 (slightly below the alert level) to an average situation of 20.25 micrograms per m^3 (which is within acceptable level). This reduction is remarkable, of 16.25 µg / m^3 since January 2015, a reduction of 3.5 µg/m^3 per year, especially if it is considered that the number of vehicles and motorcycles has increased significantly during this time. Only during the five peaks referred to, are the levels exceeded and the average daily prevention or alert situations are reached,

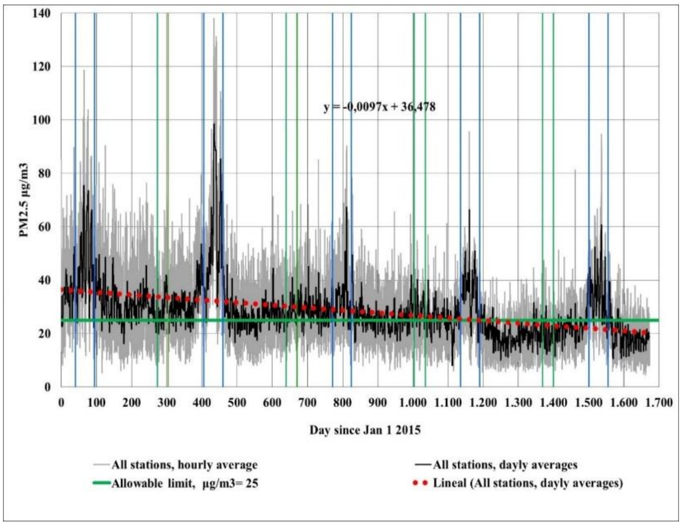


Figure 29: PM$_{2.5}$ average daily and hourly concentrations for all stations since January 1, 2015. Vertical lines enclose major pollution episodes.

This is remarkable and it should not be undervalued or demerited. The Aburrá Valley region is well focused on the environment, on behalf of both the public and the productive sectors.

Understanding the hourly behavior of $PM_{2.5}$ concentrations and of its associated influences It has been demonstrated by various means that vehicles and traffic are the major sources of urban emissions. This has been found by:

- Chemical balances of particulate material and sources, using source-receiver models.
- By emission models.
- By behavior analysis of the hourly data.

This last method will be used to model the situation based on clime variables and traffic flow patterns. Figure 28 shows the average behavior of the last five years for all urban sources. There are two daily peaks, one high in the early morning, one much lower at the end of the night and a minimum at around 5 pm. These cyclical $PM_{2.5}$ concentration behaviors can be associated with the largest daily cycle which is that of vehicular mobility and all that it implies (gas emissions, tire and road wear, among others). But there are also important cycles associated to the climate variables, which can be also explain the particulate matter concentration behavior.

Figure 28 also compares the situations of the five major episodes with those of normality. Similar behavior is evident, with much greater contamination during the peaks.

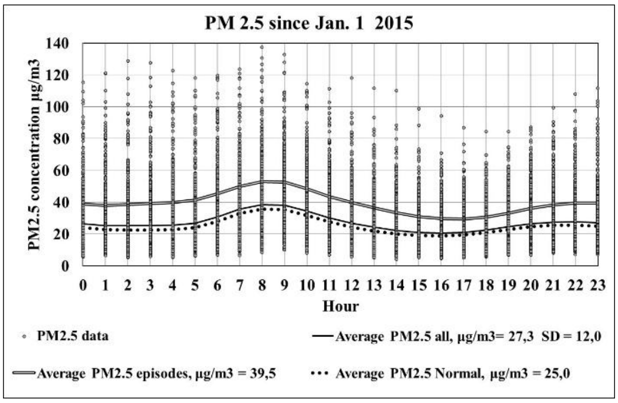


Figure 30: $PM_{2.5}$ hourly concentrations for all stations according to the hour of the day for all data, normal days and episodes (February to April peaks) since January 1 2015

Figure 30 shows a typical traffic frequency for the Aburrá Valley for the different hours of the day. Of course, these frequencies change a lot, according to the sites, the type and kind of urban streets and other variables. However, the curve presented is the best available experimental data.

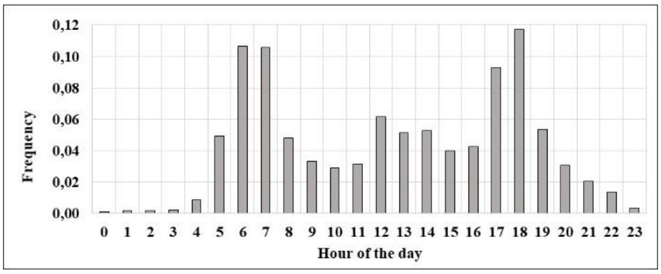


Figure 31. Traffic frequency considered for the Aburrá Valley

The reductions in the afternoon cannot be justified by the traffic frequencies. These can be attributed to the positive effect of increases in solar radiation, temperature and wind and the decrease in relative humidity, which are climate changes that contribute to lower pollution. This can be understood based on the following Figure 32, Figure 33, Figure 34, Figure 35 and Figure 3636, that show the behavior of wind speed, humidity, temperature, precipitation and solar radiation for the average of all stations considering all data, normal, and episode data. All of them, except precipitation, exhibit daily cycles, which, of course, could be associated to the $PM_{2.5}$ cycles already described, and this will be considered to elaborate a predictive model of the behavior of $PM_{2.5}$ concentrations in the Aburrá Valley.

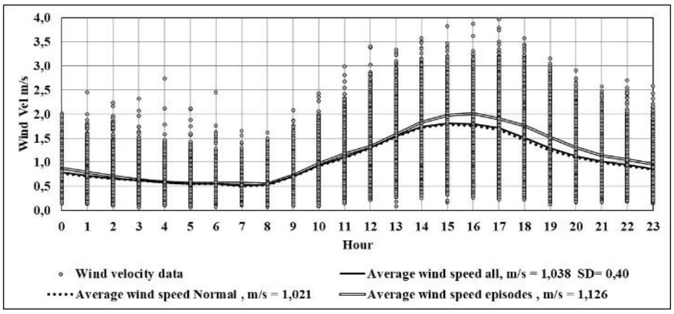


Figure 32: Wind velocity for the average of all stations, for each hour. A peak is observed in the afternoon, around 3 to 4 pm. Minimum values occur around 5 to 7 am. During episodes, wind speeds tend to be slightly higher.

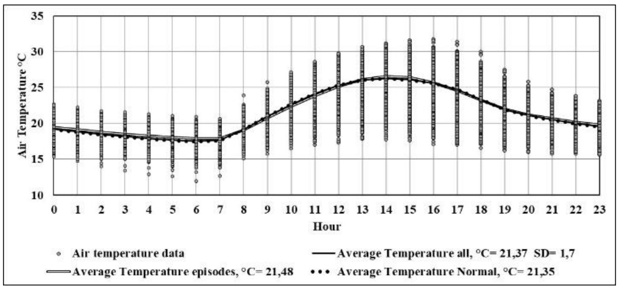


Figure 33: Air temperatures for the average of all stations, for each hour. A peak is observed in the afternoon, around 2 to 3 pm. Minimum values occur around 5 to 7 am. During episodes, temperatures are very slightly higher.

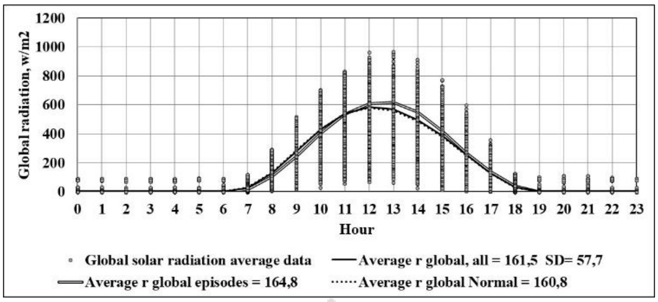


Figure 34: Global solar radiation for the average of all stations, for each hour. A peak is observed at noon, around 12 m. Cero values occur between 7 pm and 6 am. During episodes, radiation values are slightly higher.

It seems as if the air temperature, influenced by solar radiation, helps controlling wind speed and relative humidity, with average hourly values clearly consistent during the five years studied [12]. The behavior of precipitation is much more variable and unpredictable, as seen in figure 34. Most of the data correspond to cero values. There are also heavy rains.

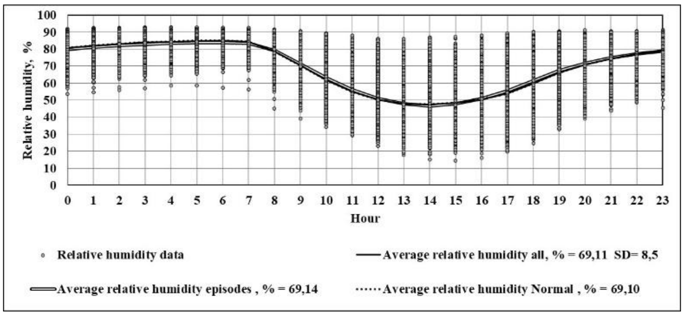


Figure 35: Air relative humidity for the average of all stations, for each hour. A minimum value zone is observed in the afternoon, around 1 to 3 pm. Maximum values occur around 5 to 7 am. During episodes humidity is very similar.

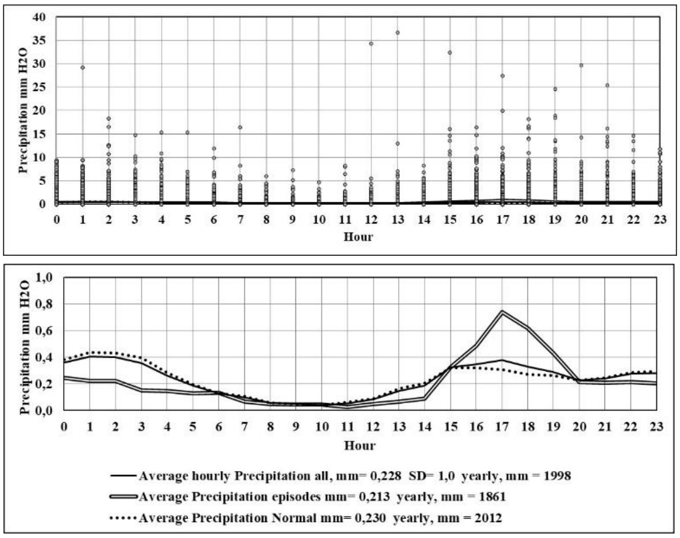


Figure 36: Precipitation data for the average of all stations, for each hour. A minimum value zone is observed between 8 am to 11 am.

Figure 36 shows that maximum average precipitation values occur twice, around 1 to 2 am and in the afternoon, around 5 pm. During episodes precipitations tend to be smaller, but not in the afternoon.

To better understand the influences of climate variables on $PM_{2.5}$, a study was made of the correlations between the five climate variables and the $PM_{2.5}$ concentrations for the different sampling stations. Figures 35 to 39 show the results obtained for the averages of all data, considering in the correlations only the cases in which all variables were taken.

It was found that the best correlations were gotten using exponential adjustments for the lines of tendency. In addition, time lags were tested between the climate variables and the $PM_{2.5}$ concentrations. It was found that better correlations were obtained in this form, which seems reasonable, as the resulting effect of the climate variable will take some time to be felt.

The linear correlations slope gives a physical sense of the influence of the climate variable on the concentration, of course considering that concentrations will depend on other influences: size of sources, atmospheric inversions and background pollution, among others.

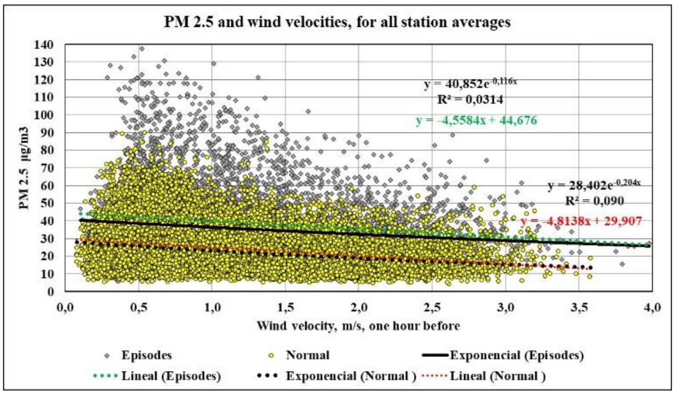


Figure 37: Higher wind velocities tend to lower concentrations, with similar tendency for normal situations and episodes. Time lag is one hour.

During low wind velocities and normal conditions, in the average, concentrations are around 28,9 μg/m^3. At high wind speeds they will diminish to 13,1 μg/m^3. This means an influence factor of -4.8 μg/m^3 per each m/s. During low wind velocities and episode conditions, in the average, concentrations are around 43,8 μg/m^3. At high wind speeds they will diminish to 28,7 μg/m^3. This means an influence factor of -4.6 μg/m^3 per each m/s.

During low temperatures and normal conditions, in the average, concentrations are around 31,0 μg/m^3. At high temperatures, they will diminish to 16,7 μg/m^3. This means an influence factor of -0.95 μg/m^3 per each centigrade degree. During low temperatures and episode conditions, in the average, concentrations are around 45,2 μg/m^3. At high temperatures, they will diminish to 32,1 μg/m^3. This means an influence factor of -0.88 μg/m^3 per each centigrade degree.

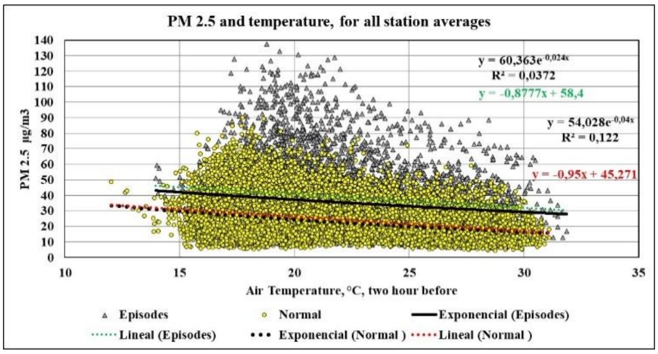


Figure 38: Higher temperatures tend to lower concentrations, with similar tendency for normal situations and episodes. Time lag is two hours.

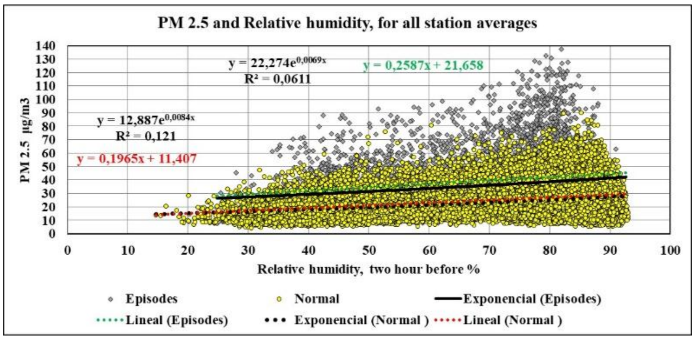


Figure 39: Lower relative humidity tends to lower concentrations, with similar tendency for normal situations and episodes. Time lag is two hours.

During high relative humidity and normal conditions, in the average, concentrations are around 29,1 µg/m^3. At lower relative humidity they will diminish to 15,3 µg/m^3. This means an influence factor of 0.20 µg/m^3 per each percentage change in relative humidity.

During high relative humidity and episode conditions, in the average, concentrations are around 45,0 µg/m^3. At lower relative humidity they will diminish to 26,9 µg/m^3. This means an influence factor of 0.26 µg/m^3 per each percentage change in relative humidity.

During low solar radiation and normal conditions, in the average, concentrations are around 27,3 µg/m^3. At high solar radiation, they will diminish to 15,0 µg/m^3. This means an influence factor of -0.015 µg/m^3 per each w/m2 change in solar radiation. During low solar radiation and episode conditions, in the average, concentrations are around 43,2 µg/m^3. At high solar radiation they will diminish to 24,4 µg/m^3. This means an influence factor of -0.022 µg/m^3 per each w/m2 change in solar radiation. In the case of the influence of the solar radiation, the time lag is four hours.

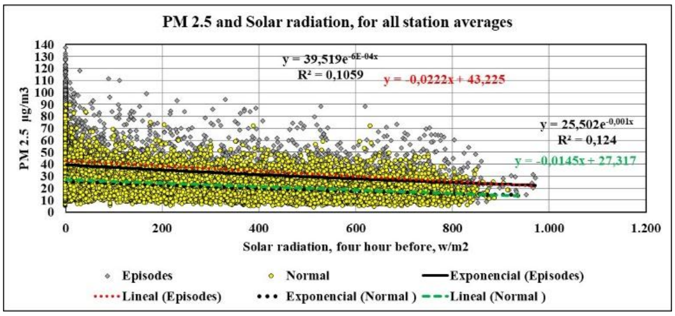


Figure 40: High solar radiation tends to lower concentrations, with similar tendency for normal situations and episodes. Time lag is four hours.

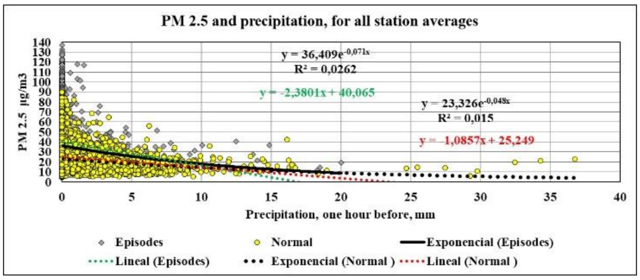


Figure 41: High precipitations tend to lower concentrations, being higher the tendency for episodes. Time lag is one hour.

During low precipitations and normal conditions, in the average, concentrations are around 25,2 µg/m^3. At higher precipitations they will diminish to 14,4 µg/m^3. This means an influence factor of -1.09 µg/m^3 per each hourly mm. During low precipitations and episode conditions, in the average, concentrations are around 40,1 µg/m^3. At higher precipitations they will diminish to 16,3 µg/m^3. This means an influence factor of -2.38 µg/m^3 per each hourly mm of precipitations.

3. Analysis of the data - Understanding the behavior of PM$_{2.5}$ and climate variables along the Aburrá Valley

Table 6 resume the situations found for the climate variables and the PM$_{2.5}$ concentrations for all the studied stations. They are ordered by latitude, this is, by south to north position. Winds tend to flow coming from the north, as shown in Figure 20**Error! Reference source not found.**, Figure 21 and Figure 22.

Table 6: Climate variables, average values, for all stations

	Station Name	Long.	Lat.	PM2,5, µg/m^3	Hum. %	Preci. mm	Rad. w/m2	Temp °C	Wind vel. m/s
3	Girardota - Aburrá Norte	-75,45	6,38	21,0	61,49	0,20	229,0	22,52	2,10
6	Politécnico Col JIC	-75,58	6,21	21,6	51,12	0,18	174,5	23,19	0,71
11	IE Colombia. Girardota	-75,44	6,38		69,88	0,16	182,1	22,23	1,71
12	Estación Tráfico Centro	-75,57	6,25		62,29	0,13	159,5	22,48	1,01
25	Universidad Nacional, Vol	-75,58	6,26	27,5	66,91	0,18	200,6	22,45	1,35
28	Itagüí - Casa de Justicia	-75,60	6,19	26,6	63,58		134,9	22,13	0,95
31	Caldas - CUL	-75,64	6,10	27,9	76,25		154,3	19,94	1,01
37	Bello U San Buenaventura	-75,57	6,33		68,36		163,6	21,42	1,36
38	Itagüí - I.E.C. Municipal	-75,64	6,17	22,3	65,36	0,22	180,5	20,14	0,62

	Station Name	**Long.**	**Lat.**	**PM2,5, µg/m^3**	**Hum. %**	**Preci. mm**	**Rad. w/m2**	**Temp °C**	**Wind vel. m/s**
40	Parque de las Aguas	-75,42	6,41		76,28		286,7	21,94	1,62
41	Universidad de Medellín	-75,61	6,23		63,56		233,0	22,74	0,73
43	Tanque Miraflores	-75,55	6,23						
44	El Poblado - La Ye EPM	-75,55	6,18	22,5	78,06	0,21	151,4	18,11	0,78
46	Exito San Antonio	-75,57	6,25						
48	Estación Tráfico Sur	-75,63	6,15		66,76	0,20	148,5	20,97	1,09
69	Caldas – IE J Aristizabal	-75,64	6,09	20,9					
74	ITM Robledo	-75,59	6,28						
78	La Estrella - Hospital	-75,64	6,16	19,2					
79	I.E. Pedro Octavio Amado	-75,61	6,22	21,4					
80	Villahermosa - Planta EPM	-75,55	6,26	19,9					
81	Barbosa - Torre Social	-75,33	6,44	13,8					
82	Copacabana – C. La Vida	-75,50	6,35	16,3					
83	Belén - I.E P Justo Berrio	-75,61	6,24	22,0					
84	I.E INEM	-75,56	6,20	18,2					
85	Parque Biblioteca F Botero	-75,64	6,28	16,2					
86	Medellín, I.E Ciro Mendía	-75,56	6,29	23,1					
87	Bello - I.E. Fernando Vélez	-75,57	6,34	16,7					
88	Envigado - Santa Gertrudis	-75,58	6,17	18,4					
90	Sabaneta - I. Rafael J. Mejía	-75,62	6,14	18,3					
92	Itagüí – Est. Los Gómez	-75,61	6,19						
94	Medellín - Santa Elena, rural	-75,50	6,24	12,3					

To better visualize the behavior, the following Figure 42 to Figure 47 show how they change with the south-north position along the valley, as indicated by latitude, understanding that the river follows this direction, while the wind generally goes against the river.

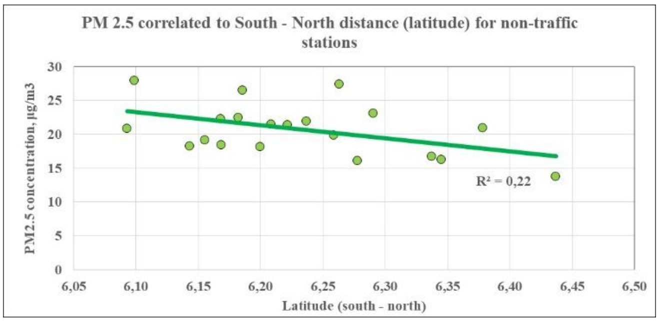


Figure 42: PM2.5 concentrations tend to increase towards the south. This should be expected, as the air (wind) comes from the north along the valley, bringing background pollution from the north entering contact with the city activities and emissions, the air should get more polluted adding to the background pollution those emissions.

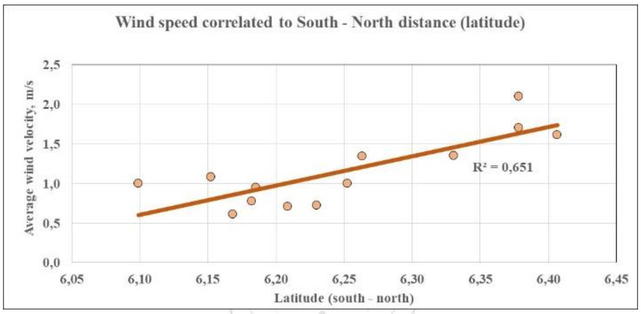


Figure 43: Wind velocities tend to increase towards the north and are also somewhat larger in the south.

This should be related to the width of the valley, which stretches in the south and in the north and widens in the center. Higher temperatures in the north probably favor having larger wind velocities there**.**

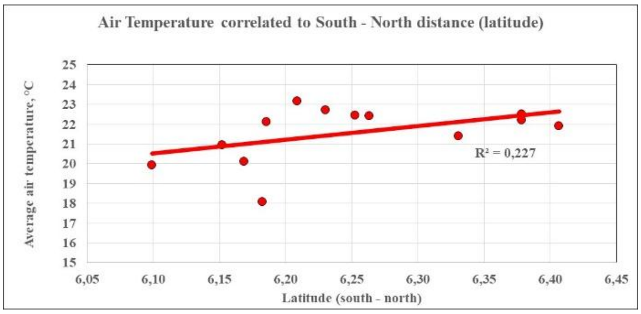


Figure 44: Figure No. 42: Air temperatures tend to increase towards the north. This should be related to the changes in altitude above the sea level. Higher temperatures in the north probably favor having larger wind velocities there.

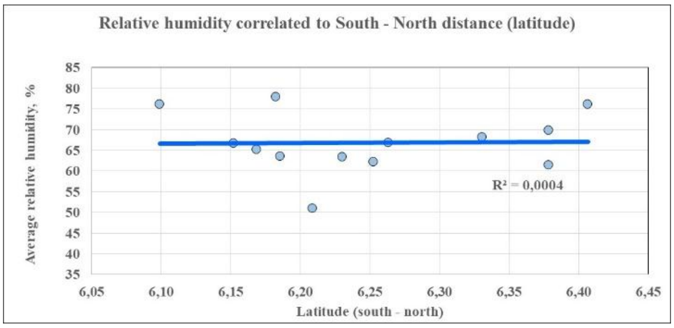


Figure 45: Air relative humidity does not exhibit a tendency to change along the valley in a systematic way.

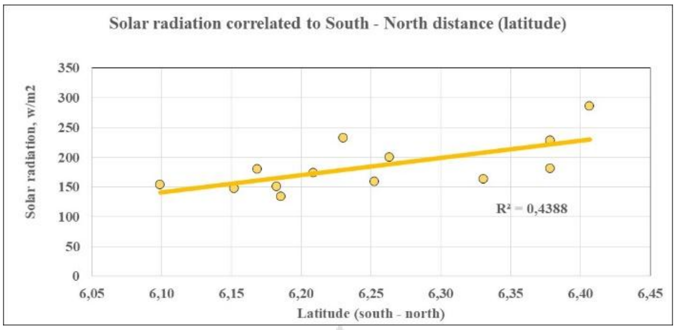


Figure 46: Solar radiation tends to increase towards the north. This should be related to cloudiness, which tends to be higher towards the south.

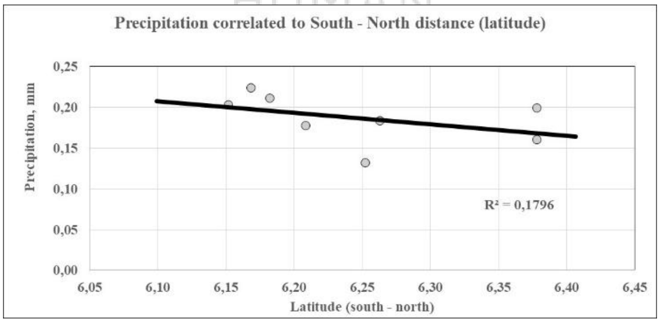


Figure 47: Average precipitation tends to increase towards the south. This should be related to cloudiness, which tends to be higher in this direction.

It is evident after examining the previous figures, that the region, being a relatively narrow valley is subjected to a pattern of climate variables that can be related to the geography of the valley, dominated by a south west-north east alignment.

4. Modeling behavior of $PM_{2.5}$ concentrations

One important aspect to be considered is that of background pollution. The air that enters the Aburrá Valley transport $PM_{2.5}$ material, as evidenced by measurements carried on nearby rural areas in several directions. The results shown in Table 7 were obtained in studies done by the author as background references for urban $PM_{2.5}$ pollution analysis in the locations of San Jerónimo (west), Jardín (southwest) and Santa Elena (east).

Table 7: PM2.5 concentrations in rural areas (to get approaches to background concentration)

Number of samples	#	24
Sites	#	3
Average concentration	$\mu g/m^3$	9,7 +/- 4,1
Maximum concentration	$\mu g/m^3$	17,2
Minimum concentration	$\mu g/m^3$	3,2
Sampling periods	Dates	May 2010 to June 2015
Months	Months	January, June, October

The data being reported by SIATA and AMVA includes a station situated in the rural area of Medellín, The Santa Elena sampling station. This information will serve well to help interpret both background $PM_{2.5}$ concentrations and the impact of episodes. Figure 48 and Figure 49show the $PM_{2.5}$ concentrations during 2019 and the hourly averages. It shows both normal weather and the episode situation for the period of February to April. It is observed that similarly to what happens with the urban area sampling stations, peaks also occur due the episode.

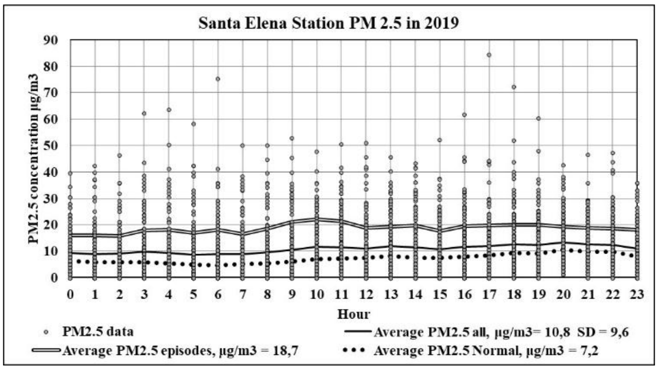


Figure 48: PM2.5 hourly concentrations for Santa Elena station according to the hour of the day for all data, normal days and episodes (February to April peaks) during 2019.

As seen in Figure 48, the daily cyclical variations are not present as is the case in the urban area, given that the effect of vehicular traffic is not as significant in Santa Elena. This zona has very small traffic load.

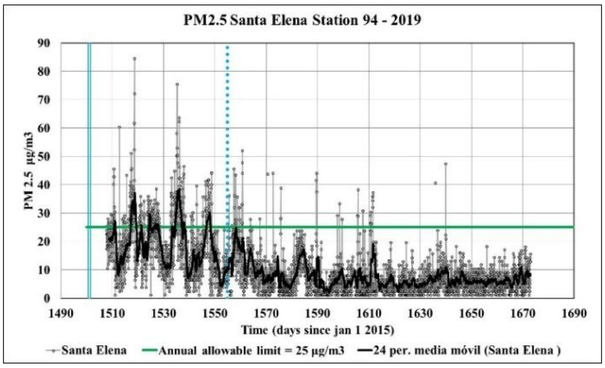


Figure 49: PM2.5 hourly concentrations and 24h averages for Santa Elena station. Days start in January 1, 2015. Data starts in day 16/02/2019 and ends in 1/08/2019. Vertical lines enclose the pollution episode of February to April.

As the Santa Elena is a low populated rural sector, with ample woods and the site of the huge Arvi Ecological Park, situated up in the eastern mountains surrounding the urban zones, the pollution there should not be rightly attributed to the urban sources (heavy traffic, industrial and other urban activity sources). This area can be considered as an indication of background effects affecting the urban sites and sampling stations. As should be expected, concentrations in the Santa Elena station are significantly lower than at the urban stations, both for episodes and for normal situations.

Table 8 compares the average urban station concentrations to the ones for Santa Elena.

Table 8: Comparison rural (Santa Elena) to urban (2019)

Station	**Units**	**Ave. All**	**Ave. Normal**	**Ave. Episode**	**Episode to normal**
S Elena, rural	µg/m^3	10,8	7,2	18,7	2,59
Average urban (2019)	µg/m^3	23,2	19,8	33,2	1,68
Relation urban to rural	times	2,15	2,74	1,78	

It seems that Santa Elena, representing rural areas, in relative terms, is more affected by episodes than the urban areas. This could be related to fact that the mitigation efforts undertaken by authorities and the community do not apply to the rural areas.

It is observed that this background contamination also increases in the episodes and high levels can also be reached. In no way would it be reasonable to attribute these increases to the impact of the urban area.

It can be concluded that the episodes have two origins: One due to climatic phenomena that generate an atmospheric inversion, which causes a lowering of the atmospheric mixing height; this increases the concentrations to much higher values than normal. Another factor has to do with significant increases in the background pollution, which goes from the order of 7-10 µg / m^3 to values of the order of 18-20 µg / m^3 during the episodes.

With all the given considerations, as expounded, based on impact of traffic, effect of temperature, wind velocities, solar radiation, relative humidity and precipitation; background pollution; impact of episodes; a predictive model was built as follows.

Based on data for station 38 (Itagüí - I.E.C. Municipal) the model constants were determined, to consider effect of climate variables. The relative impact of climate variables was assumed to be proportional to the correlation factors for the exponential correlations. The specific impact was based on the exponential adjustment, such as the ones presented in Figure 37 to Figure 41, obtained for the station 38 data. Table 9 presents the exponential coefficients for the climate variables and the correlation coefficients for the expression:

$$PM_{2.5} \text{ concentration} = A * e^{(B*\text{variable})}$$

The contribution to the PM2.5 concentration of each climate variable was obtained multiplying the expressions of Table 9 by a multiplier for each climate variable. Each of the five-climate contribution so calculated add 20 % to the total.

Table 9: Correlations between climate variables and PM2.5 concentrations

Variable	Corr. factor	A Coef.	Expon. Coefficient B
Solar radiation	0,0592	21,48	-0,0006
Wind speed	0,0342	21,71	-0,1910
Temperature	0,0491	42,24	-0,0390
Humidity	0,0492	10,53	0,0086
Precipitation	0,0103	19,49	-0,0441

Table 10 shows factors found for the traffic impact and a multiplier for the radiation impact. The multipliers for the other climate variables are calculated in proportion to the correlation factors of Table 9 once the M_r is known. The factors and multipliers of Table 10 were obtained calibrating them to get the actual concentrations for the set of data for station 38 for each hour of the day.

Table 10: Traffic contributions and radiation multiplier for each hour of the day

Hour	**0**	**1**	**2**	**3**	**4**	**5**
Traffic FC	1,15	0,38	0,29	0,38	0,83	3,84
Rad. (M_r)	1,38	1,37	1,34	1,33	1,32	1,15
Hour	6	7	8	9	10	11
Traffic FC	10,50	16,67	16,60	11,92	7,02	5,98
Rad. (M_r)	0,84	0,66	1,02	1,55	1,85	1,69
Hour	12	13	14	15	16	17
Traffic FC	7,78	9,23	10,58	9,19	8,62	11,19
Rad. (M_r)	1,34	1,11	0,84	0,89	0,85	0,59
Hour	18	19	20	21	22	23
Traffic FC	16,14	16,86	12,88	6,70	4,15	2,40
Rad. (M_r)	0,24	0,30	0,64	1,10	1,25	1,35

In this way, expected PM2.5 concentrations are calculated as follows:

$$PM_{2.5} \text{ concentration} = FE * (FC + FB + 1/5 * \Sigma\, M_i A_i * e^{(B_i * \text{variable}_i)})$$

Where i applies to the five climate variables

FE (episode factor) and FB (base or background factor) were determined by calibration, adjusting to the real situations for the average of the stations during normal and episode situations using a solver routine minimizing the weighted errors.

FB values varied during the studied period and were estimated by the expression:

$$FB = -0{,}009835 * (\text{day since Jan 1, 2015}) + 11{,}44$$

This factor is diminishing with time, going from 11.4 to -5.0. reflecting the fact that emissions are going down notably during the period of study.

FE were values, see Table 11, which varied according to the episodes. This must be so, as the circumstances for each episode vary. They have to do with particular external impacts and atmospheric inversions that are not predicted by traffic factors or by the climate variables studied, as should be evident from Figure 32 to Figure 36. For the normal situations, FE was taken as 1.0.

Table 11: Episode factors.

Episode	1	2	3	4	5
Year	2015	2016	2017	2018	2019
FE	1,38	1,83	1,23	1,37	1,73

Figure 50 shows the results of the predicting modeling, compared to the average actual concentrations. For this adjustment, the average deviations were 2.38 %. The average actual PM2.5 concentration was 27,32 μg/m^3, while the model predicted an average concentration of 27,97 μg/m^3.

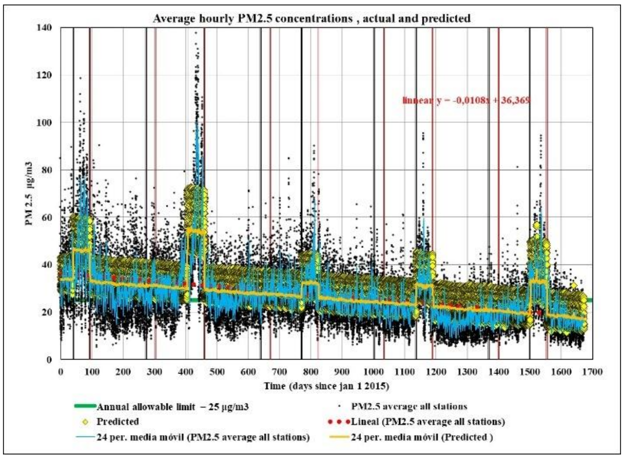


Figure 50: PM2.5 hourly concentrations and 24h continuous media fir the averages of all stations, actual and predicted by the model presented in this work. Vertical lines enclose pollution episodes.

5. CONCLUSIONS

It has been possible to get a reasonable approach to understanding the relationships between climate variables and pollution (characterized by $PM_{2.5}$ concentrations) for the case of the Aburrá Valley, at Colombia. A model was built, capable of giving good approximations at the described and studied phenomena.

This has been possible because the region counts with a very complete system to measure and register variables.

It can be concluded that the region is doing well the task of systematically controlling emissions and improving air quality. This has been attained by several means:

- A reasonable knowledge and understanding of climate and episodes.

- Greater emphasis on electric public transport systems and large investments in these systems

- Change and modernization of public transport diesel buses run by private companies.

- Modernization of a large part of the fleet of trucks and dump trucks

- Fuel improvements. Diesel fuel and gasoline have undergone significant reductions in sulfur content.

- Increasing use of additives such as the Green plus catalyst

- Best driving practices, facilitated by the photo fine system, the growing use of the Waze tool, the application of emission controls and the generation of cultural campaigns and actions. It is important to note that the impact of good practices and the attainment of greater fluency in the street traffic is very significant, much more than people might be tempted to think since traffic jams and bad practices can lead to doubling vehicle emissions.

- Actions to raise awareness on the part of the authorities and of many entities and human groups.

- New vehicles with greater efficiency and lower emissions.

- Continuous and verifiable business and industrial companies, looking for strategies and actions to control their emissions and improve on processes.

- Development of many urban green corridors and a huge campaign for tree planting.

- Significant improvements in bicycle and pedestrian paths.

Unfortunately, when there are contingency situations and episodes, even as they occur recurrently based on external situations, people tend to attack the productive sector and to scandalize and exaggerate the situations. It is important to understand the situations and to have available models and explanations, such as the ones presented here.

It is vital to understand well what is really happening and be aware that everything constitutes an interconnected system and that the generation of added value in a society should not be put at excessive risk, labeling the productive sector as indifferent to health and the environment and only interested in making a profit.

6. ACKNOWLEDGMENTS

The Authors thank to the local environmental institutions for the information binged for this study.

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