

Influence of the extreme phases of the ENSO phenomenon (El Niño and La Niña) on air quality in the Metropolitan Area of the Aburrá Valley (Colombia)

C. E. Zapata, N. A. Cano, M. Ramírez, C. Rubiano & J. Jiménez
*Department of Geoscience, Environment and Development,
 National University of Colombia – Medellín, Colombia*

Abstract

The Aburrá Valley is characterized by being a narrow valley inversion problem, where monitored critical pollutants are less than 2.5 microns (PM_{2.5}) and there are inhalable particulate matter particles smaller than 10 micrometers (PM₁₀). In this study, the values of annual average concentrations for PM₁₀ and PM_{2.5} are addressed during the period 2007–2013. These concentrations were compared with the annual standard (Resolution 610 of 24 March 2010 issued at that time by the Ministry of Environment, Housing and Territorial Development (MAVDT)), for PM_{2.5} equal to 25.0 µg/m³, and for PM₁₀ equal to 50 µg/m³ respectively. Additionally, the influence of the ENSO phenomenon is analyzed in normal and extreme conditions: El Niño and La Niña during the period 2007–2013, regarding the diurnal cycle, annual cycle and the annual cycle of the diurnal cycle for both air pollutants. In order to analyze the variability exerted by the ocean-atmospheric phenomena occurring in the Pacific Ocean on the dispersion of breathable and inhalable particulate matter the Multivariate ENSO Index (MEI) is used.

Keywords: inhalable particulate matter (PM_{2.5}), breathable particulate matter PM₁₀, ENSO phenomenon, Multivariate ENSO Index (MEI), diurnal cycle, annual cycle, annual cycle of the diurnal cycle.

1 Introduction

El Valle de Aburrá, which is characterized for being a narrow valley with thermal inversion problems, is located in the Colombian Andean mountains. The



valley lies at an altitude of between 1,300 and 1,580 meters above sea level. The mountains surrounding the valley reach up to 2,100 meters above sea level, creating a complex pattern of winds and low pollution dispersion. The valley extends for approximately 60 kilometers in length and has a variable width.

This valley is formed by ten municipalities, nine of which are under the jurisdiction of the Environmental Authority of the Metropolitan Area of the Aburrá Valley (AMVA).

Since about 14 years ago, the Air Quality Network of The Metropolitan Area of the Aburrá Valley (Colombia) has been monitoring air quality.

Currently, such monitoring is carried out at 22 fixed measuring sites, and a mobile station, distributed over the municipalities that are under the jurisdiction of the Environmental Authority (AMVA). Among the monitored quality variables are: acid rain, total suspended particles (TSP), particulate matter less than 10 micrometers (PM10), particulate matter less than 2.5 microns (PM2.5) particles smaller than one micrometer, (PM1), carbon monoxide (CO), ozone (O₃), nitrogen oxides (NO_x) and sulfur dioxide (SO₂). The monitored meteorological variables are: wind speed and direction, temperature, relative humidity, precipitation, global radiation and atmospheric pressure [1].

Since the critical pollutant monitored in the Metropolitan Area of the Aburrá Valley is the inhalable particulate matter less than 2.5 micrometers (PM2.5) and particles smaller than 10 micrometers (PM10) in the present only the results of measurements of these two pollutants as such are addressed, and the influence of the ENSO phenomenon in its extreme phases: El Niño and La Niña during the period 2007–2013. To analyze the variability exerted by ocean-atmospheric phenomena that occur in the Pacific Ocean on the dispersion of breathable and inhalable particulate matter the Multivariate ENSO Index (MEI) is used.

Additionally, in order to assess improvement or deterioration of air quality, indicators that allow addressing different aspects associated with air pollution are used. Compliance with the maximum permissible emission levels defined in the Colombian standard (Resolution 610 of 2010, Ministry of Environment, Housing and Territorial Development, today the Ministry of Environment, Housing and Territorial Development) is a relevant indicator in the management task, since it reflects both the capacity of government institutions in the ongoing monitoring of those pollutants that pose a risk to the health of the population, and the impact of the efforts aiming at reducing pollution levels. Therefore, the values of annual average concentrations are presented for the period 2007–2013; these concentrations were compared with the annual standard (Resolution 610 of 24 March 2010 issued at that time by the Ministry of Environment, Housing and Territorial Development (MAVDT)) for PM2.5 equal to 25.0 mg/m³ and equal to PM10 50 g/m³ respectively, at reference conditions (atmospheric pressure of 760 mm Hg and ambient temperature of 25°C) [2].

The measurement of PM10 is justified by its association with data concerning mortality and morbidity in the population, epidemiological evidence indicates that an increase of 10 g/m³ in PM10 is associated with an increase by about 1% in mortality from all causes [3]. Regarding the measurements of PM2.5, in

recent years there has been found evidence of stronger associations between PM_{2.5} and data of morbidity and mortality, which led to certain US states to set a standard for PM_{2.5} in order to reduce the health risks associated with this pollutant [4], this evidence is based on the fact that PM_{2.5} particles are breathable. However, toxicological studies have shown that there are particles less than 0.1 microns which cause toxic responses such as irritation and alveolar inflammation, which has led to suggest that measuring PM_{2.5} will not effectively replace measuring PM₁₀ [5].

1.1 Breathable (PM₁₀) and inhalable (PM_{2.5}) particulate matter

The particulate material is an indicator used in the evaluation of air quality, comprising a mixture of solids and liquids suspended in the air. Particles whose aerodynamic diameter is less than 10 microns are so small that they can enter the lungs causing health risks.

They are generated in the processes of mechanical disintegration and due to the resuspended dust on roads because of bearing vehicles, therefore fraction having a predominantly natural origin [6].

The fine fraction of PM₁₀ are particles smaller than 2.5 microns or PM_{2.5}, directly emitted in all combustion processes (including motor vehicles, some industrial processes, forest fires, thermoelectric plants) and also generated by chemical transformation of combustion gases such as sulfur oxides, nitrogen oxides and volatile organic compounds in the air, which is called secondary particulate material.

For its forming characteristics and size, the PM_{2.5} is able to enter the alveoli, causing a greater health risk, hence its control has been prioritized in the definition and implementation of strategies to reduce air pollution in the Aburrá Valley [6].

1.2 El Niño Southern Oscillation

El Niño and La Niña are the extreme phases of the ocean-atmosphere phenomenon known as El Niño Southern Oscillation (ENSO). This natural phenomenon is associated with the hydrological anomalies in the South American tropics, on time scales ranging from monthly to yearly [7]. This phenomenon is the result of the nonlinear interactions of two components: an oceanic component (El Niño and La Niña) and an atmospheric component (Southern Oscillation: fluctuation of atmospheric pressures), it can be said that this phenomenon is the main modulator of the Earth's climate at an interannual scale. Basically, El Niño is a warming of the waters of the central-eastern Pacific and La Niña refers to the cooling of these waters. In Colombia, El Niño is associated with decreased precipitation (dry periods) and La Niña amplifies the rains in Colombia.

2 Methodology

2.1 Air quality in the Metropolitan Area of the Aburrá Valley

As it was mentioned before, the following methodology for monitoring the air quality for breathable particulate matter (PM10) and inhalable (PM2.5), as they are the two pollutants causing the greatest deterioration of air quality in the Aburrá Valley only applies to Medellín during the period 2007–2013. The stations in Medellín that were sampled are: Éxito San Antonio (MED-EXSA) and Museum of Antioquia (MED-MANT); it is worth noting that both stations are automatic. The sampling for the determination of the concentration of particles smaller than 10 μm (PM10) in ambient air is done by the equivalent method EPA EQPM-0798-122.

Samples for determining the concentration of particles smaller than 22.5 μm (PM2.5) in ambient air is performed according to the EPA EQPM-0308-170 method [4, 8, 10, 11]. Notably, the Air Quality Laboratory CALAIRE has a quality management system based on the ISO17025 NTC standard for sampling.

2.2 MEI (Multivariate ENSO Index)

The method used to characterize the climatic conditions that contribute to the development and physiology of El Niño Southern Oscillation events (ENSO) was the MEI (Multivariate ENSO Index), since the ENSO arises from a complex interaction of a variety of climate systems, the MEI is considered to be one of the most comprehensive indexes for the control of ENSO, as it combines the meteorological analysis of multiple components.

The MEI is composed of six different variables: the pressure at sea level, zonal and meridional components, sea surface temperature, surface air temperature and South Pacific Ocean cloud cover.

3 Results

3.1 Air quality in the Metropolitan area of the Aburrá Valley

3.1.1 Breathable particulate matter (PM10)

The maximum annual average concentration of PM10 during the period 2007–2013 was presented in 2007 with an approximate value equal to 87.8 $\mu\text{g}/\text{m}^3$ as shown in Figure 1(a). In 2012, the lowest average concentration of PM10 with a value below 55.0 $\mu\text{g}/\text{m}^3$ was presented. Nevertheless, in all the years of the period 2007–2013 the Colombian annual standard for particulate matter PM10 (50 $\mu\text{g}/\text{m}^3$) was exceeded, although a tendency to decrease in the concentration of PM10 during the registration period is clearly displayed.

However, in Figure 1(b), the diurnal cycle of PM10 is presented in the Municipality of Medellín during the period 2007–2013. This diurnal cycle presents an essentially bimodal behavior with a maximum approximately equal to 82.0 $\mu\text{g}/\text{m}^3$ in the morning between 07:00 and 9:00; since in this time of the

day the largest traffic flow in the Valle de Aburrá is recorded, and a second maximum approximately equal to $75.0 \mu\text{g}/\text{m}^3$ less heavy in the afternoon between 18:00 and 19:00.

The decrease of the diurnal cycle of PM₁₀ during the afternoon time can be partly explained because the atmosphere in the afternoon is generally unstable, favoring greater dilution of pollution.

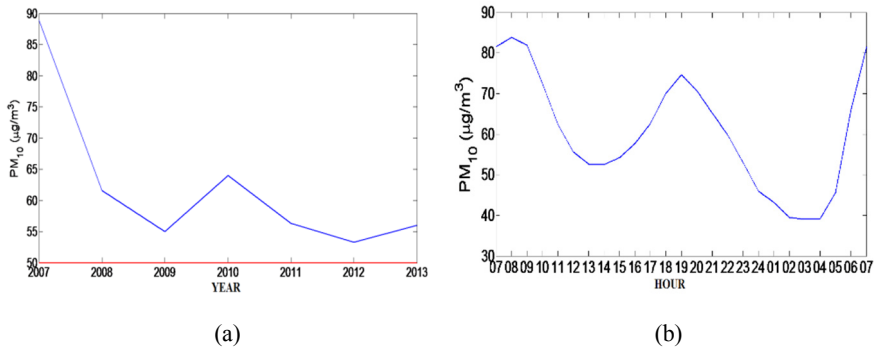


Figure 1: (a) Annual average PM₁₀ concentration for the period 2007–2013. (b) Diurnal cycle of PM₁₀ in the Municipality of Medellin during the period 2007–2013.

In Figure 2, the annual cycle of PM₁₀ in Medellin during 2007–2013 is presented. This annual cycle has a maximum concentration in the months of October and November with an approximate value equal to $63.0 \mu\text{g}/\text{m}^3$ and $65.0 \mu\text{g}/\text{m}^3$. Also in January during the period 2007–2013, the minimum concentration approximately equal to $52.0 \mu\text{g}/\text{m}^3$ occurs. These values are higher than the Colombian annual standard for particulate matter PM₁₀ ($50.0 \mu\text{g}/\text{m}^3$) for the recording period.

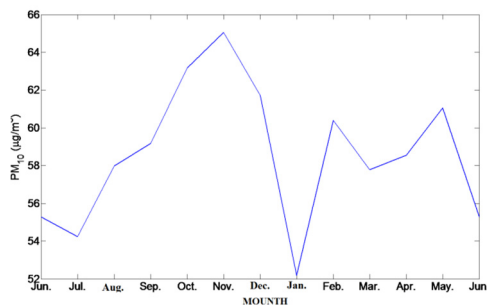


Figure 2: Annual cycle of PM₁₀ in the Municipality of Medellin during the period 2007–2013. (Note: averages were calculated from the available data; that is, it was not taken into account if for each year of the registration period 75% of valid data were available.)

3.1.2 Inhalable particulate matter (PM_{2.5})

The maximum annual average concentration of PM_{2.5} during the period 2007–2013 was presented in 2008 with an approximate value equal to 34.5 $\mu\text{g}/\text{m}^3$ (as shown in Figure 3(a)).

In 2010 and 2012 the lowest average concentrations of PM_{2.5} with a value approximately equal to 26.3 $\mu\text{g}/\text{m}^3$ and 26.8 $\mu\text{g}/\text{m}^3$ respectively were presented.

Even so, in all the years of the 2007–2013 period, the Colombian annual standard for particulate matter PM_{2.5} (25 $\mu\text{g}/\text{m}^3$) was exceeded, although a tendency to decrease in the concentration of PM₁₀ during the registration period is clearly displayed. It is important to clarify that in 2013 an increase in the average concentration of PM_{2.5} was recorded, since this measuring station changed from being on the 9th floor of a building, to start measuring from the ground in the parking lot of the same building, somehow data measured at the first location had already suffered dispersion.

Additionally, averages were calculated using available data; thus they were not taken into account if for each year of the registration period 75% of valid data was available.

Also in Figure 3(b), the diurnal cycle of PM_{2.5} is presented in Medellin during 2007–2013. Where a bimodal behavior with a maximum approximately equal to 54.0 $\mu\text{g}/\text{m}^3$ in the morning between 08:00 and 9:00, and a second weaker maximum approximately equal to 31.0 $\mu\text{g}/\text{m}^3$ presents in the evening between 18:00 and 20:00. The decrease of the diurnal cycle of PM_{2.5} in the afternoon can be partly explained because the atmosphere in the afternoon is generally more unstable favoring greater dilution of pollution.

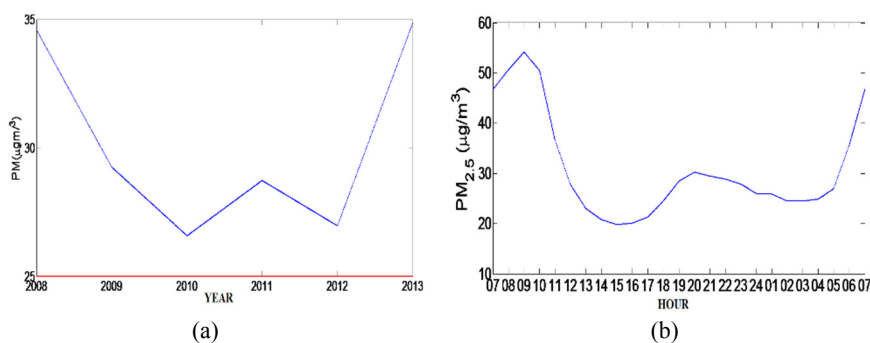


Figure 3: (a) Annual average concentration for PM_{2.5} during 2007–2013. (b) Diurnal cycle of PM_{2.5} in the Municipality of Medellin during the period 2007–2013. (Note: no data was recorded in 2007 since the data for PM_{2.5} at this station were on trial test.)

In Figure 4, the annual cycle of PM_{2.5} during 2007–2013 in Medellin is presented. Where maximum concentration occurs in the months of February and December, with an approximate value equal to 34.7 $\mu\text{g}/\text{m}^3$ and 33.5 $\mu\text{g}/\text{m}^3$. Also during June and July in the 2007–2013 period, the minimum concentration approximately equal to 26.8 $\mu\text{g}/\text{m}^3$ and 26.3 $\mu\text{g}/\text{m}^3$ is presented, these values are

higher than the Colombian annual standard for particulate matter PM_{2.5} ($25 \mu\text{g}/\text{m}^3$) in the recorded period.

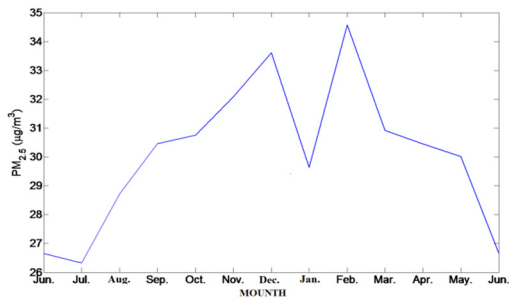


Figure 4: Annual cycle of PM_{2.5} in the Municipality of Medellin during the period 2007–2013.

3.2 MEI (Multivariate ENSO Index)

Taking standardized indexes from the MEI, it has classified the Niña conditions 1-19, normal conditions 20-45, and Niño conditions 46-64, the Niño, Niña and normal conditions were discretized for each month of the 2007–2013 period.

3.2.1 Breathable particulate matter (PM₁₀)

In Figure 5(a) and 5(b) diurnal and annual cycle of discretized PM₁₀ occurs in Niño, Niña, and normal conditions in the Municipality of Medellin during the period 2007–2013. In the diurnal cycle, a bimodal behavior with a first peak in

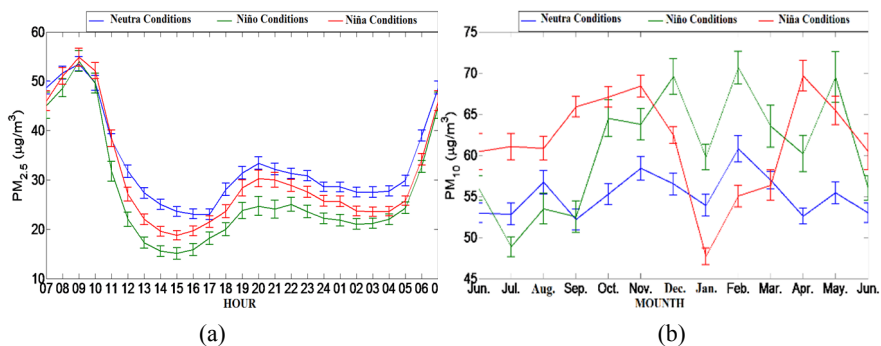


Figure 5: (a) Diurnal cycle of PM₁₀ in the Municipality of Medellin in Niño, Niña and normal conditions for the period 2007–2013. (b) Annual cycle of PM₁₀ in the Municipality of Medellin in Niño, Niña, and normal conditions for the period 2007–2013. (Note: it is taken as an error: $t \cdot St / (N^{0.5})$ where t is the statistic of the t-student distribution; St , the standard deviation of the sample; and N is the number of data.)

the morning, between 07:00 and 08:00 hours, and a weaker second maximum in the afternoon between 18:00 and 19:00 occurs for the three tested conditions (Niño conditions, Niña conditions and Normal conditions).

These two peaks correspond to the greatest traffic hours in the Aburrá Valley. Under Niña conditions, the PM₁₀ concentration values over the period 2007–2013 are slightly higher than under Niño and Normal conditions, due to the phenomenon of resuspension of particulate material presented in short periods of drought after periods of rainfall where there is washing of such particulate material. Also in Niño conditions, the values of the concentrations are slightly higher than under normal conditions, since during times when there is a lack of rainfall there is no washing of particulate matter, being resuspended in the lower atmosphere.

With regard to the annual cycle of PM₁₀, discretized in Niño, Niña, and normal conditions (as shown in Figure 5); it cannot be said that the Niño phenomenon directly affects the concentration of particulate matter in the Aburrá Valley, it is necessary to analyze a wider time record (more than 5 years); registration which is not available in the Aburrá Valley.

Additionally, it is required to make a broader analysis, associated to traffic variables and meteorological variables such as wind speed and precipitation, as they have a great influence on the dispersion of particulate matter in the atmosphere.

3.2.2 Inhalable particulate matter (PM_{2.5})

Also as for PM₁₀, Figure 6(a) presents the diurnal cycle of PM_{2.5} discretized in Niño, Niña and normal conditions in the Municipality of Medellin during the period 2007–2013. In the diurnal cycle, there is a bimodal behavior with a first peak in the morning, between 07:00 and 09:00 hours, and a weaker second

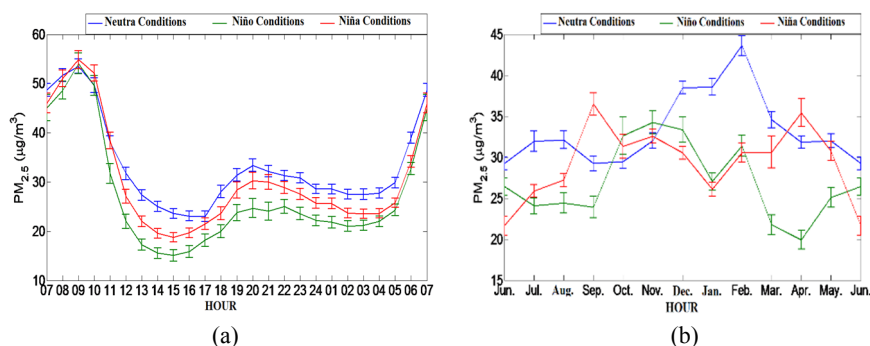


Figure 6: (a) Diurnal cycle of PM_{2.5} in the Municipality of Medellin in Niño, Niña, and normal conditions for the period 2007–2013. (b) Annual cycle of PM_{2.5} in the Municipality of Medellin in Niño, Niña, and normal conditions for the period 2007–2013. (Note: it is taken as error: $t \cdot St / (N^{0.5})$ where t is the statistic of the t-student distribution; St , the standard deviation of the sample; and N is the number of data.)

maximum in the evening between 18:00 and 20:00 hours for the three tested conditions (Niño, Niña, and normal conditions). These two peaks correspond to increased vehicular traffic hours in the Aburrá Valley.

For PM_{2.5} under Niña conditions, concentration values during 2007–2013 are higher compared to Niño conditions, due to the phenomenon of particulate material resuspension explained in advance. However, with respect to Normal conditions, these concentrations are about 5% lower; this behavior can take place because resuspension of particles is presented, as there are times of very high rainfall where there are no short periods of drought, but there is a complete washing of the inhalable particulate matter PM_{2.5} found in the environment.

With regard to the annual cycle of PM₁₀, discretized in Niño, Niña, and normal conditions; as it is shown in Figure 6(b), it cannot be said that El Niño phenomenon directly affects the concentration of particulate matter in the Aburrá Valley due to what was previously explained in the sections above.

3.3 Annual cycle of the diurnal cycle

3.3.1 Breathable particulate matter (PM₁₀)

In Figures 7(a), (b), (c), and (d), the annual cycle of the diurnal cycle conditions without discretization, Niño conditions, conditions Niña and neutral conditions for PM₁₀, respectively, are presented.

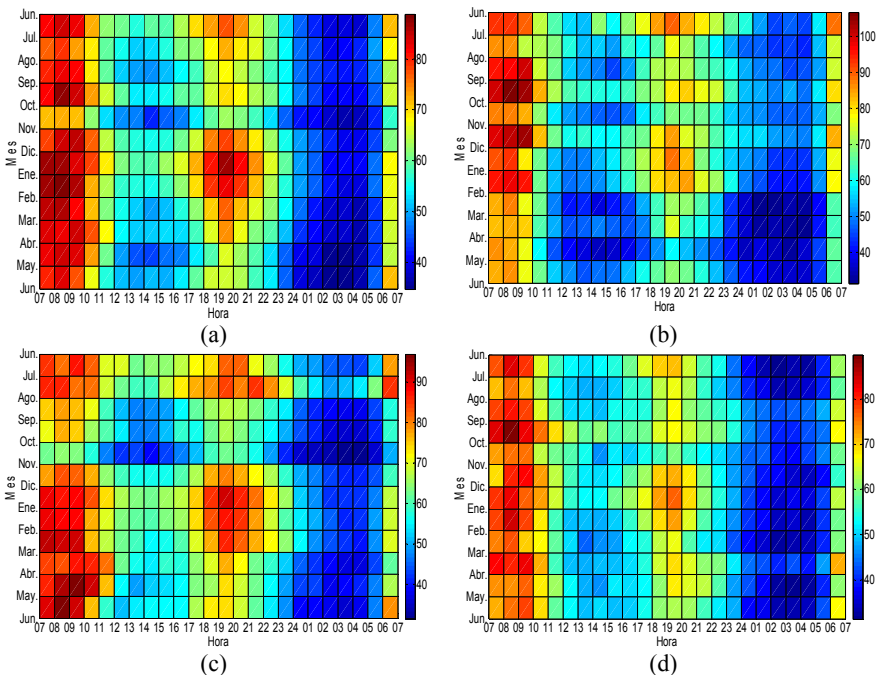


Figure 7: (a) Annual cycle of diurnal cycle for PM₁₀ in the Municipality of Medellin; (b) Niño conditions; (c) Niña conditions; (d) normal conditions.

As it has been addressed in previous sections, in these figures it is evident that for each of the months of the 2007–2013 period, the highest concentrations of PM10 are presented between 07:00 and 09:00 and the lowest concentrations are presented between 23:00 and 06:00 hours for all the studied conditions studied. Additionally, mainly for the period December, January and February high concentrations of PM10 are also present; not only in the morning but also in the afternoon between 18:00 and 21:00.

It can be said that there is a tendency to bimodal behavior in the annual cycle of the diurnal cycle. The maximum concentrations of PM10 in conditions without discretizing occurred in the months of September, December and January at 08:00 hours, and in December at 19:00. In Niño conditions they were presented in September between 08:00 and 09:00, and in November at 09:00 hours. In Niña conditions they were presented in May and June between 08.00 and 09:00. Finally, under normal conditions, they are presented in September at 8:00 pm.

3.3.2 Inhalable particulate matter (PM2.5)

In Figures 8(a), (b), (c), and (d) the annual cycle of the diurnal cycle for conditions without discretization, Niño conditions, Niña conditions and neutral conditions for PM2.5 respectively are presented. The highest concentrations of

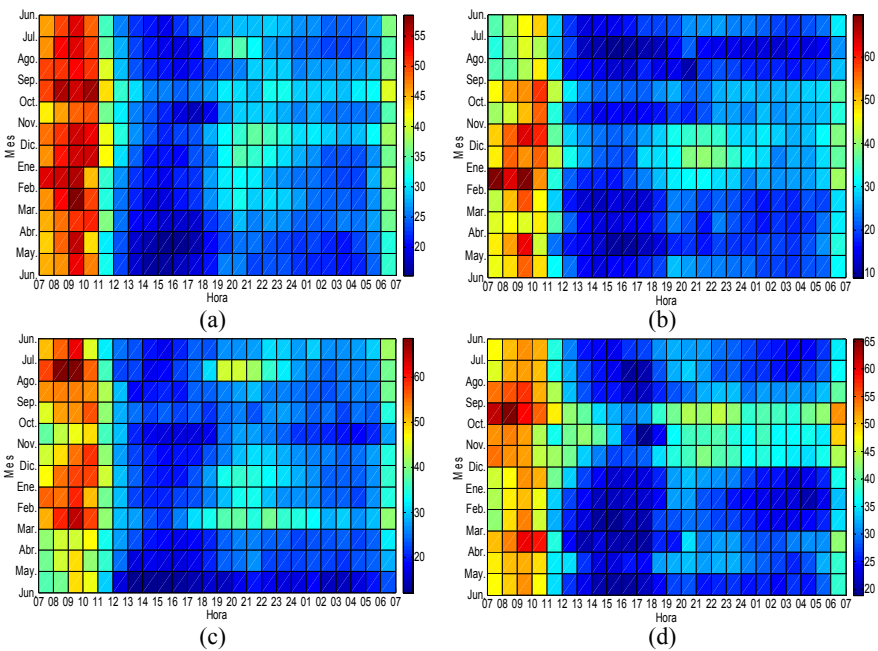


Figure 8: (a) Annual cycle of diurnal cycle for PM2.5 in the Municipality of Medellin; (b) Niño conditions; (c) Niña conditions; (d) normal conditions.



PM_{2.5} are presented from the range of 7:00 to 9:00 hours in every month of the period 2007–2013 still not as high in some months of the registration period. The lowest concentrations occur approximately between 12:00 and 19:00, and in the early morning hours (24:00 to 06:00) for all the studied conditions.

It is worth highlighting that low and/or moderate concentrations are present during most of the day (12:00 to 6:00 pm) in all months of 2007–2013: it cannot be said that there is a tendency to a bimodal behavior the annual cycle of the diurnal cycle. The highest concentrations of PM_{2.5} under conditions without discretizing occurred in the months of September and February between 07:00 and 09:00. Under Niño conditions, they occurred in January between 07:00 and 09:00. In Niña conditions, they were presented in July between 08:00 and 09:00. Finally, under normal conditions, they occur in September between 07:00 and 8:00.

4 Conclusions

- The Aburrá Valley is characterized for being a narrow valley with thermal inversion problem, whose critical pollutants are PM₁₀ and PM_{2.5}; both pollutants exceed the Colombian annual standard for PM₁₀ (50 µg/m³) and PM_{2.5} (25 µg/m³) during the registration period 2007–2013; although a tendency to decrease can be clearly seen for both pollutants along time, this because the decontamination programs and campaigns being conducted by the Environmental Authority (The Metropolitan Area of the Aburrá Valley) such as: integrated transport (Metro Plus, Metro sit, Metro cable, no-car day, 'pick and plate', etc.).
- The diurnal cycle for PM₁₀ and PM_{2.5} during the period 2007–2013 shows a bimodal behavior with a maximum in the morning and a weaker second maximum in the afternoon, this can be partly explained because the atmosphere in the afternoon is generally more unstable favoring greater dilution of pollution.
- The annual cycle for PM₁₀ during the period 2007–2013 has a maximum concentration in the months of October and November, with an approximate value equal to 63.0 µg/m³ and 65.0 µg/m³; and the minimum concentration approximately equal to 52.0 µg/m³ is presented in January. For PM_{2.5}, the maximum concentration occurs in the months of February and December, with an approximate value equal to 34.7 µg/m³ and 33.5 µg/m³; and the minimum concentration approximately equal to 26.8 µg/m³ and 26.3 µg/m³ occurs in the months of June and July respectively.
- In Niña conditions (diurnal cycle), values for PM₁₀ concentrations over the period 2007–2013 are slightly higher than under el Niño and normal conditions due to the resuspension of particulate material phenomenon presented in short periods of drought after periods of high rainfall where there is a washing of such particulate material.
- The values of PM_{2.5} under Niña conditions regarding normal conditions are about 5% lower; this behavior can take place due to the fact that resuspension of particles is not presented, as they are times of very high

rainfall where there are no short periods of drought, but there is a complete washing of the inhalable particulate matter PM2.5.

- To see a clear annual cycle behavior for PM10 and PM2.5, a broader analysis associated with a historical record of variables and data traffic and meteorological variables such as wind speed and precipitation needs to be carried out.

Acknowledgements

To the Working Group of the Air Quality Laboratory of the National University of Colombia – Faculty of Mines.

To the Environmental Authority of Valle de Aburrá (*Autoridad Ambiental del Valle de Aburrá - Área Metropolitana del Valle de Aburrá*).

To the Faculty of Mines – National University of Colombia. A la Universidad Nacional de Colombia Facultad de Minas.

References

- [1] AMVA – UNAL, operar la red de monitoreo de la calidad del aire, meteorología y ruido, en el valle de aburrá. Informe Técnico. Enero de 2014.
- [2] Colombia. Ministerio de Ambiente, Vivienda y Desarrollo Territorial. Resolución Número (610) del 24 de marzo de 2010. Norma de calidad del aire o nivel de inmisión (marzo 2010).
- [3] HO, Air quality Guidelines. World Health Organization, 2000.
- [4] Harrison R, Deacon A. “Sources and Processes Affecting Concentrations of PM10 and PM2.5 Particulate Matter in Birmingham (UK)”. *Atmospheric Environment* 31, pp. 4103-4117, 1997.
- [5] U.S. Environmental Protection Agency. “Air Quality Criteria for Particulate Matter”. National Center for Environmental Assessment-RTP Office. Office of Research and Development, Vol. 1, 2003.
- [6] AMVA – UPB, operar la red de monitoreo de la calidad del aire, en el Valle de Aburrá. Informe Técnico convenio 243 de 2012 Abril de 2013.
- [7] G. Poveda, O. Mesa. Las fases extremas del fenómeno ENSO (El Niño y La Niña) y su influencia sobre la hidrología en Colombia. *Ingeniería Hidráulica en México*, vol XI, no. 1, pp. 21-37, 1996.
- [8] IDEAM. “Protocolo para la Vigilancia y Seguimiento de Módulo Aire del Sistema de Información Ambiental”. Bogotá, septiembre del 2005.
- [9] Instituto Colombiano DE Normas Técnicas y Certificación. *Sistemas de Gestión de la Calidad. Fundamentos y vocabulario. NTC-ISO 9000*. Bogotá D.C. El Instituto, 29 pp., 2005.
- [10] Instituto Colombiano de Normas Tecnicas Y Certificación. *Requisitos generales para la competencia de los laboratorios de ensayo y calibración. NTC-ISO/IEC 17025*: 2005.

- [11] Instituto Colombiano de Normas Tecnicas y Certificación. Sistemas de Gestión de la Calidad. Requisitos. NTC-ISO 9001. Bogotá D.C.: El Instituto, 35 pp., 2008.
- [12] EPA, United States Environmental Protection Agency. Code of Federal Regulations, CFR. Book 40. Protection of Environment. Parts 50. Appendix A. Washington. www.epa.gov 1990.
- [13] AMVA – UPB, Clasificación estaciones de monitoreo de calidad del aire. Informe Técnico. Diciembre de 2012.
- [14] Palacio, Carlos Alberto and Jiménez Mejía, José Fernando. Climatología urbana y de montañas. Dyna, 79. pp. 61-69. ISSN 0012-7353, 2012.
- [15] C. Echeverri, and G. Maya, “Relación entre las partículas finas (PM_{2.5}) y respirables (PM₁₀) en la ciudad de Medellín,” Revista Ingenierías Universidad de Medellín, vol. 7, no. 12, pp. 23-42, 2008.

