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Influence of meteorology and source variation on airborne PM_{10} levels in a high relief tropical Andean city

Influencia de la meteorología y las fuentes de emisión en los niveles ambientales de PM_{10} en una ciudad tropical Andina.

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Abstract

Atmospheric particulate matter (PM_{10}) was evaluated with meteorology, mixing height and source variation over a two-year period (from January 2010 to December 2012) in the densely populated tropical Andean city of Manizales. The highest levels of PM_{10} were observed in areas with the highest vehicular density with values in a range of 18 - 69 µg m^{-3}. PM_{10} concentrations were influenced by meteorological parameters, positively associated with temperature (r = 0.40), and negatively associated with relative humidity (r = -0.47) and precipitation (r = -0.38). The effects of scavenging by precipitation were observed by analyzing PM_{10} concentrations for dry periods versus wet periods. The high sulfate PM_{10} ionic contents observed throughout the city were consistent with the influence of public transport and automobiles, which use diesel and gasoline as principal fuels, and are recognized as the main source of particulate matter emissions. Increasing midday mixing height over downtown of the city (from 900 m to 1600 m) effectively diluted peak hour emission from vehicular traffic, as observed over a 24 hour sampling period, with 30-second intervals. These preliminary data suggest factors important to modeling PM_{10} in high rainfall and densely populated tropical mountain ecosystems.

----------*Keywords:* PM_{10}, meteorological variables, scavenging, mid-sized Andean cities

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Resumen

El análisis de niveles de (PM_{10}) y su asociación con la meteorología, altura de capa de mezcla y fuentes de contaminación, se realizó en la ciudad tropical andina de Manizales durante un periodo de dos años (enero 2010 a diciembre 2012). Los mayores niveles de PM_{10} se observaron en zonas con alta influencia vehicular, con valores de PM_{10} en un intervalo de 18 - 69 µg m^{-3}. Las concentraciones de material particulado fueron influenciadas por factores meteorológicos, mostrando una asociación positiva con la temperatura (r = 0.40), y negativa con la humedad relativa (r = -0.47) y la precipitación (r = -0.38). Los efectos del fenómeno de scavenging por la precipitación fueron observados a través del análisis de concentraciones de PM_{10} para periodos secos y húmedos. Los altos niveles de sulfatos observados en el PM_{10} en comparación con los demás iones predominantes, fueron consistentes con la influencia de emisiones derivadas del transporte público y automóviles, los cuales utilizan diesel y gasolina como sus principales combustibles. Incrementos en la altura de capa de mezcla en la zona del centro histórico de la ciudad (de 900 m a 1600 m), explican la dilución efectiva de las emisiones provenientes del tráfico vehicular, tal como se observó mediante el monitoreo de PM_{10} cada 30 segundos por periodos de 24 horas. Este análisis preliminar sugiere factores de importancia para implementar a futuro técnicas de modelización del PM_{10} en ecosistemas tropicales de montaña caracterizados por su alta precipitación y alta densidad poblacional.

----------*Palabras clave:* PM_{10}, variables meteorológicas, remoción húmeda, ciudades andinas intermedias

Introduction

Understanding production, fate and transport of particulate matter is essential to managing public health risks associated with urban exposure of inhalable particulates, especially in poorly understood tropical mountain ecosystems where ambient air is influenced by factors that include strong orographic effects, wide precipitation and temperature variations. Researchers have found that particles in ambient air with diameters less than 10 µm (PM_{10}) are strongly influenced by meteorological conditions and altitude [1, 2]. Identifying the fate and transport of PM_{10} in tropical mountain cities will contribute to a growing body of knowledge that is being developed in different regions of the world [3-5].

Particulate matter is a mixture of solid and liquid droplets formed by elemental and organic carbon, ammonium, nitrates, sulfates, mineral dust, trace elements and water [6]. Aerosol particles arise from natural and anthropogenic sources such as windborne dust, volcanic emissions, vehicular fuel combustion, and industrial emission processes. These particles can be emitted directly into the atmosphere, or formed as secondary pollutants through chemical reactions of gaseous precursors [7]. Greater amounts of PM_{10} can form when vehicular combustion is incomplete, and factors like composition and mass of particulate matter are also influenced by the levels of sulfur in fuel [8].

The coarse fraction of particles less than 10 µm is normally filtered in the upper respiratory tract by nasal hairs, cilia and mucus membranes. However, these structures often do not filter fine PM_{10} fraction ($PM_{2.5}$) that can enter deep into the lungs interfering with gas exchange sites or alveoli, causing serious health problems [9, 10]. These types of particles have been linked with illnesses and deaths from heart or lung disease, which include heart failure and coronary artery disease, asthma and chronic obstructive pulmonary disease [11-13]. This finer fraction, more damaging to public health, has been found to comprise the majority of PM_{10} mass fraction ($PM_{2.5}/PM_{10} \sim 0.6$) in principal urban areas of the Colombian Andes [14].

The majority of epidemiological studies have used PM_{10} as an exposure indicator [12]. The World Health Organization (WHO) has recommended reference limit values of PM_{10} for annual mean concentrations (20 µg m^{-3}) and 24 h concentrations (50 µg m^{-3}). Current limits in Colombia for annual and 24 h means are 50 µg m^{-3} and 100 µg m^{-3}, respectively [15]. Taking into account a reduction in Colombian PM_{10} concentration limits during the last decade, it is probable that the government will adopt the lower WHO reference values in the near future.

Exposure to particulates in ambient air is influenced by various meteorological factors such as precipitation, wind velocity, relative humidity and temperature [16]. Scavenging of particles by precipitation can result in decreased concentrations [17]. Higher wind velocities disperse particles and decrease their concentration. Higher relative humidity removes atmospheric particles and diminishes the amount of re-suspended soil dust due to increases in soil humidity [2]. Temperature, solar radiation and wind velocity control vertical air movement and lower troposphere stability, resulting in changes in mixing height and effective dilution of airborne pollutants [7, 18].

The extreme Andean topography, altitude, and urban development of Manizales city become important considerations when describing the production, fate and transport of PM_{10}. Manizales (urban population 367000 [19]) is a city located on the western slopes of the central range of the Andes (2150 m.a.s.l.) in the Colombian department of Caldas. Urban zone is developed on steep slopes, and as a consequence, the area available for development is limited resulting in high urban density compared with other Colombian cities. The resulting high vehicular density (254 vehicles per 1000 inhabitants [20]) and combustion of fuels with sulfur content, justifies the monitoring, analysis and modeling of air pollution dynamics in Manizales.

Relatively high altitude of Manizales could reduce combustion efficiency of diesel fuels due to the low oxygen pressure on the air. Industrial activity, leading thermal processing of wastes, metal recycling and foods, also contributes to pollution in the city. As well as, 28 km southeast of the city, there is influence from an active volcano (Nevado del Ruiz), a natural source of reduced and oxidized forms of sulfur, nitrogen and particles. Records of air pollution monitoring in Manizales have been limited to Total Suspended Particles (TSP), monitored in three points of the city, and more recently PM_{10} has been monitored continuously, since 2000. The aim of this study is to analyze the effects of meteorology, mixing height and source variability in the production, fate and transport of PM_{10} to better understand patterns of human exposure to particulate matter.

Materials and methods

Sampling and meteorological data

The urban area of Manizales forms an elongated shape oriented northwest to southeast and occupies mostly ridge topography, changing into more valley topography in the southeastern most zone. Five stations were chosen along this axis over a total horizontal distance of approximately 6.8 km to evaluate airborne PM_{10} concentrations during January 2010 to December 2012 (Figure 1). Table 1 shows principal characteristics of the sampling sites. Three stations were located in the most densely urban downtown area (Agustinos, Gobernación and Liceo). One station was located in the central area of the Manizales ridge (Palogrande) and the fifth station was located in the southeast valley zone (Nubia). Daily mean

PM_{10} levels were compared at four stations of the city: Gobernación, Liceo, Palogrande and Nubia; while in Agustinos a real-time PM_{10} analyzer was implemented to determine peak hours of pollution. This station is influenced by high surrounding traffic emissions of public transportation. Gobernación is surrounded by vehicular traffic and little industrial activity. Liceo is characterized by high surrounding traffic emissions of public transportation and again little industrial activity. Palogrande is influenced by one of the most important avenues connecting downtown to the northwest. Cars fueled with gasoline and public transportation fueled with diesel are the principal air pollution sources. Nubia is located in the southern zone of the city, with less proximity to major transport corridors in its immediate vicinity. Nubia is adjacent to the industrial area to the southeast and it is the nearest station to the Nevado del Ruiz volcano.

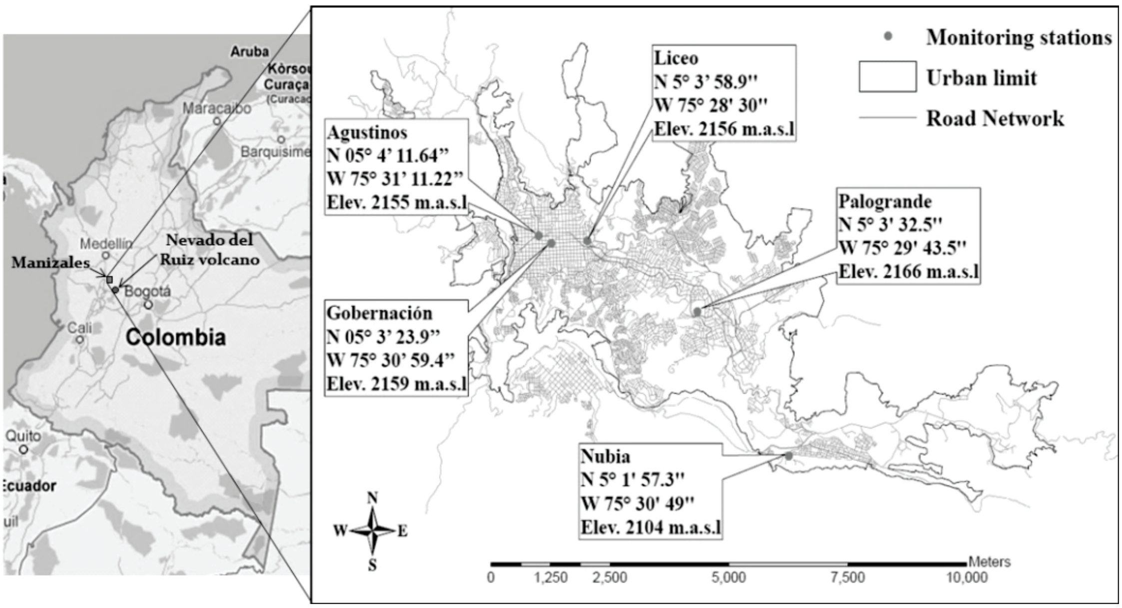


Figure 1 Map of the studied area and sampling stations

Table 1 Sampling station characteristics and summary of daily PM_{10} results

Station	*Location / characteristics*	*Sources of pollutants*	*Daily PM_{10} results (µg m^{-3})*			
			Mean	*Min*	*Max*	*Std.*
Gobernación (n=217)	Downtown / Commercial area	Vehicular traffic Little industrial activity	24	6	47	9
Liceo (n=184)	Downtown / Commercial area	High vehicular traffic - Public transportation mainly Little industrial activity	44	18	69	10
Palogrande (n=131)	Central zone / Residential area	Vehicular traffic No industrial activity	26	10	46	7
Nubia (n=120)	Southeast zone / Residential area	Low vehicular traffic Adjacent to industrial zone	26	12	45	7
Agustinos* (n=35)	Downtown / Commercial area	High vehicular traffic - Public transportation mainly Little industrial activity	50	59	38	4

Std: Standard deviation
n: Number of data
* In Agutinos station a DustTrak aerosol monitor was employed. Statistics showed for this station were calculated for daily mean values.

In Liceo, Gobernación, Palogrande and Nubia, samples were collected from January 2010 to December 2012. 24 h PM_{10} samples were collected during sampling campaign on quartz-fiber and glass-fiber filters using Hi-Vol Sampler (HVS) in Liceo, Palogrande and Nubia, and a sequential low volume sampler Partisol–FRM model 2025 in Gobernación. Samples were collected from a height of about 10 m above ground level. Information of PM_{10} concentrations in Liceo and Gobernación was supplied by Regional Environmental Authority (CORPOCALDAS). Hi-Vol sampled volumes ranged from 1226 m^3 to 1400 m^3 at a sampling flow rate of 53 - 58 m^3 h^{-1}. In the case of Partisol sequential sampler, flow rate was 1 m^3 h^{-1}. The filters were weighed before and after sampling (pre-desiccated) in an analytical balance with a precision of 0.1 mg. The PM_{10} concentrations have been performed following US EPA - 40 Method [21] and expressed in µg m^{-3}.

In Agustinos a DustTrak™ Aerosol Monitor model 8520 was used for understanding daily variation and PM_{10} exposure. The equipment was set up to analyze PM_{10} concentrations in air every 30 seconds during 24 h, at a sampling flow rate of 0.1 m^3 h^{-1}. 35 daily samples were collected during October, 2010 and April, 2011.

In order to analyze the relationship between meteorological variables and PM_{10} levels, meteorological data (total precipitation, temperature, atmospheric pressure, relative humidity, solar radiation and wind velocity) were collected from three stations located in the immediate vicinity of HVS in Liceo, Palogrande and Nubia. In this sense only these stations were used to analyze the relationships of meteorology and PM_{10}. In Gobernación, there was not meteorological station in its immediate vicinity and this station was not included in the analysis. In general, Manizales typically has low wind velocity and bi-directional daily wind pattern. This background information is important because low wind velocity limits horizontal dispersion of contaminants and diurnal flow patterns direct contaminants towards populated areas. Diurnal pattern of air movement -heating and rising during the day, cooling and falling during the night, is important for transport of sulfur gas emissions from Nevado del Ruiz volcano.

Statistical and temporal analysis

Pearson correlation coefficients were used to determine the relationships between PM_{10} and meteorological variables using simple regression model. Analysis of variance (ANOVA) was applied to determine the confidence levels between these variables. Low significant difference (LSD) Fisher test was used to estimate differences between mean concentrations of PM_{10} for wet versus dry periods. Seasonal distribution of PM_{10} concentrations (Figure 2) was performed using Openair package [22].

Results and discussion

Seasonal PM_{10} analysis

The highest average of PM_{10} was associated with high urban traffic and high density of public transportation at the downtown Liceo station (44 µg m^{-3}). Table 1 shows average PM_{10} statistics calculated in the five sampling sites. In terms of HVS stations, the PM_{10} average at downtown Liceo was 75% higher than the other three stations combined (n = 468). In previous studies, diesel and gasoline combustion was reported as principal sources of emissions around downtown Liceo [5, 23]. Among the other stations, there was little difference observed, with averages of PM_{10} ranging from 24 µg m^{-3} (Gobernación) to 26 µg m^{-3} (Palogrande and Nubia).

Liceo exhibited the greatest PM_{10} seasonal variability compared to Gobernación, Palogrande and Nubia (Figure 2). This pattern suggests that contributions of mobile sources in downtown of the city are relevant and define levels of PM_{10}. Concentrations of PM_{10} never reached the Colombian 24 h guideline value of 100 µg m^{-3}. Only downtown Liceo exceeded the Colombian annual limit of 50 µg m^{-3} for different daily measurements (Figure 2). However, if WHO annual limit is compared, all stations reported daily concentrations above WHO mean annual limit of 20 µg m^{-3}.

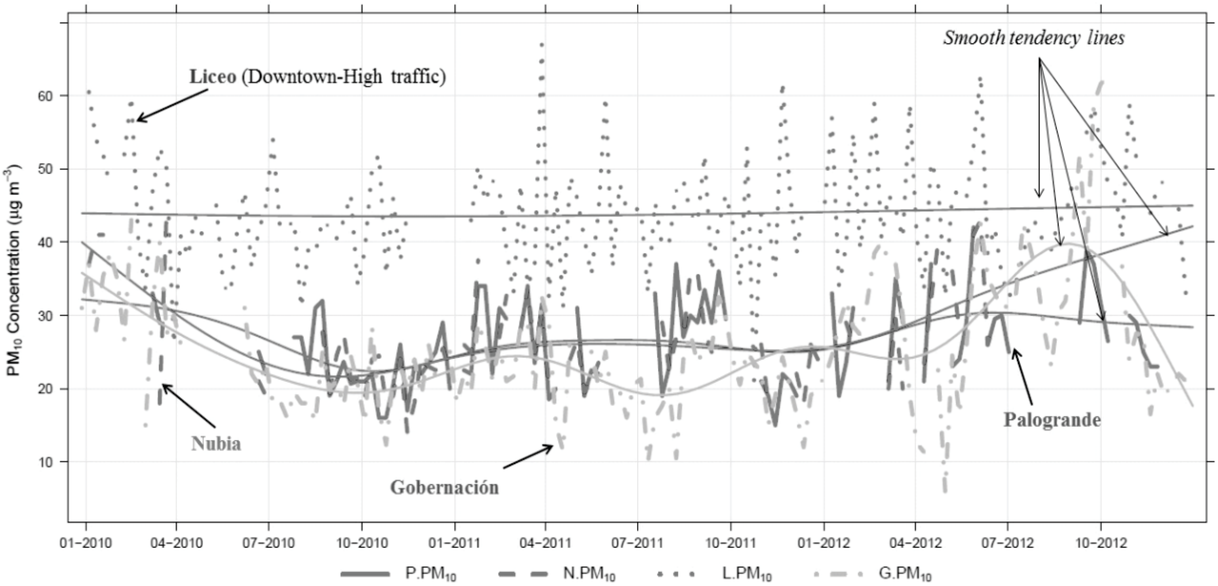


Figure 2 Seasonal distribution of PM_{10} in Manizales city

Other cities in Colombia have reported high PM_{10} concentrations associated with the density and extent of traffic and the relatively high sulfur content of fuels. For example, [14] reported values of PM_{10} in Medellín, Colombia -located at center of the country with 2250000 inhabitants-ranged from 31 µg m^{-3} to 65 µg m^{-3}. Downtown Liceo exhibited similar patterns of Medellín, indicating that pollution exhibited at this zone of the city were comparable to big cities of Colombia. However, mean PM_{10} concentration obtained in downtown Liceo never reached the mean concentration of PM_{10} reported by [24] in Bogotá, Colombia (7400000 inhabitants), with a value of 55 µg m^{-3}. On the other hand, residentially located Palogrande, industrially influenced Nubia, and downtown Gobernación exhibited similar patterns to those reported by [1], in Vienna, Austria, with average values of PM_{10} in a range of 26 - 31 µg m^{-3}, and higher levels than those reported by [25] in Birmingham, UK, with mean PM_{10} concentrations in a range of 15 - 20 µg m^{-3}. Even though these values corresponded to urban sites, PM_{10} concentrations were not in the range of larger metropolitan areas in Colombia such as Bogotá and Medellín.

Comparison of ion concentrations in PM_{10} may help to understand principal sources of suspended particulates. Values of principal ion concentrations in PM_{10} were compared with other cites of the world (Table 2). Sulfate was the predominant ion in PM_{10} over widely ranging sized urban areas, with differences in climate, geography and altitude. A previous study reported by [23] showed a predominance of sulfate in mid-sized Manizales, Colombia. This pattern was reported in larger urban cities with dry temperate coastal climate like Thessaloniki, Greece -one of the most populated cities in Greece with 1200000 inhabitants and 75 km^2 [3, 26]- and the Metropolitan area of Barcelona, Spain, with 3 million inhabitants and 604 km^2 [27].

Table 2 PM_{10} ionic content (ηmol m^{-3}) in Manizales and other sites of the world

	Manizales, Colombia [23]		***Thessaloniki, Greece*** [3]		***Barcelona, Spain*** [27]	
	Mean	Range	**Mean**	**Range**	**Mean**	**Range**
PM_{10}[a]	31	14 - 57	83	25 - 210	50	19 – 119
SO_4^{-2}	28.5 (56%)	1.7 – 65.2	66.6 (36%)	11.5 – 427.3	70.3 (28%)	14.6 – 143.7
NO_3^-	9.9	3.9 –22.1	54.8	14.0 – 209.2	91.9	16.1 – 427.4
Ca^{+2}	9.7	3.3 – 19.5	32.2	1.7 – 168.9	56.1	10.0 – 159.7
Cl^-	2.7	1.3 – 4.6	30.7	2.8 – 108.3	31.0	1.4 – 118.5
Mean annual rainfall (mm)	2000[b]		425[c]		628[d]	

[a]Values in µg m^{-3}
[b][29] [c][26] [d][30]

In Manizales molar concentration of sulfate (mean 28.5 ηmol m^{-3}) was three times higher than the next most concentrated ion nitrate [23]. The predominant ion sulfate was followed by nitrate, calcium and chloride for the ions analyzed over six-month period. According to [28], SO_2 is one of the main contributors to the formation of sulfate aerosols in the atmosphere; hence, high percentage of sulfate in PM_{10} of Manizales suggests predominance of SO_2 emissions coming from three principal sources: vehicular emissions due to Colombian fuels with high sulfur content, industrial emissions at southeast of the city, and sulfur gas emissions from a nearby active volcano [23].

PM_{10} levels related with meteorological variables

The sampling period was characterized by high precipitation (Ppt) with higher values at Liceo (Total Ppt = 1470 mm / mean Ppt = 8 mm) followed by Palogrande (Total Ppt = 934 mm / mean Ppt = 7 mm) and Nubia (Total Ppt = 516 mm / mean Ppt = 4 mm). Differences in precipitation showed spatial variability of meteorology in spite of the relatively small urban area (54 km^2), and this is consistent with earlier studies of climate zone variability throughout the city [29].

The study area of Manizales was found to have slightly unstable atmospheric conditions. General information of meteorological variables collected for the downtown, connecting ridge, and industrially influenced areas (Liceo, Palogrande, and Nubia) are shown in table 3. Atmospheric stability was defined for Manizales using information of solar radiation and wind velocity. Turner's stability categories were used to define stability classes in the city [18]. This stability classification is based on Pasquill stability classes and it relates the incoming radiation index, with surface wind speed [18]. Manizales exhibited solar radiation index equal to 1 in Liceo, Palogrande and Nubia (Incoming radiation ≤ 350 W m^{-2}). With these indexes and values of wind velocity, which not exceed 1.7 m s^{-1}, Manizales exhibited stability class C (slightly unstable) at three stations. Lower value of solar radiation in Liceo (Table 3) with respect to other stations could be another factor to explain higher levels of PM_{10} around this zone, due to higher vertical atmospheric stability and reduced vertical dispersion of pollutants. Differences in solar radiation could be explained taking into account the marked climate variability and differences in topography throughout the city, in spite of relatively small distances between sampling sites. According to [29], Manizales exhibits different zones with different rainfall patterns. Climate characteristics of Manizales proposed by [29] indicated that each monitoring station in this study was located in zones with dissimilar meteorological behavior, such as precipitation, thus resulting in differences in solar radiation.

Table 3 Meteorological variables at three monitoring stations

Station		Air Temperature (°C)	Wind velocity ($m\ s^{-1}$)	Atmospheric pressure (mm Hg)	Relative humidity (%)	Total precipitation (mm)	Solar radiation ($W\ m^{-2}$)
Liceo (n=184)	Mean	17	1.1	587	83	8 – 1470*	294
	Min	14	0.3	584	57	0	98
	Max	21	1.7	589	99	84	617
Palogrande (n=131)	Mean	17	0.8	593	90	7 – 934*	338
	Min	14	0.2	590	64	0	102
	Max	20	1.5	597	100	52	591
Nubia (n=120)	Mean	16	0.6	601	89	4 – 516*	343
	Min	14	0.0	599	72	0	106
	Max	18	1.1	603	100	29	609

*Sum of total precipitation

Both, precipitation and relative humidity exhibited relatively negative associations with PM_{10} levels, while temperature was positively associated with PM_{10} (Table 4). The significant negative correlation between relative humidity and PM_{10} at all stations (Nubia: r = -0.63; Liceo: r = -0.40 and Palogrande: r = -0.39), suggests that high humidity enables PM_{10} removal, perhaps by the increment of precipitation occurrence accompanied by in-cloud scavenging, which results in low concentrations of aerosols in air [31]. Correlations observed between precipitation and PM_{10} at Palogrande (r = -0.44), Nubia (r = -0.38) and Liceo (r = -0.33) suggest a reduction in PM_{10} concentrations due to scavenging effects that can remove pollutants from the atmosphere [7]. On the other hand, positive correlations between temperature and PM_{10} at Nubia (0.47), Palogrande (0.37) and Liceo (0.36), suggest high PM_{10} concentrations during warm days, possibly related with the enhanced photochemical activity in days with high solar intensity, and the possible formation of secondary particulate matter [32].

Table 4 Pearson correlation coefficients obtained for PM_{10} and meteorological variables

	Liceo	Palogrande	Nubia	Overall value
Total precipitation (mm)	-0.33**	-0.44**	-0.38**	-0.38
Relative humidity (%)	-0.40**	-0.39**	-0.63**	-0.47
Air Temperature (°C)	0.36**	0.37**	0.47**	0.40
Atmospheric pressure (mm Hg)	-0.25**	0.19*	-0.17	-0.10
Wind velocity ($m\ s^{-1}$)	0.07	0.21*	0.24**	0.17
Solar radiation ($W\ m^{-2}$)	0.18*	0.03	0.38**	0.19

*Values statistically significant at P<0.05
** Values statistically significant at P<0.01

Scavenging processes of PM_{10} by rainfall were observed in a comparison of PM_{10} concentrations during dry periods (little to no rain, < 1 mm per day) versus wet 24 hour periods (rains > 2.5 mm per day). There was a significant difference at each station between the two mean values with a confidence level of 95%. - calculated with LSD Fisher test. Higher mean value of PM_{10} for dry periods at all stations with respect to mean value in wet periods (Figure 3), confirmed the high negative association obtained for rain and PM_{10} and the presence of scavenging process by rain in Manizales. Differences between dry and wet periods were evident with a higher reduction of PM_{10} levels during wet periods at industrially influence Nubia station (25%), compare with residential Palogrande (23%) and downtown Liceo (17%).

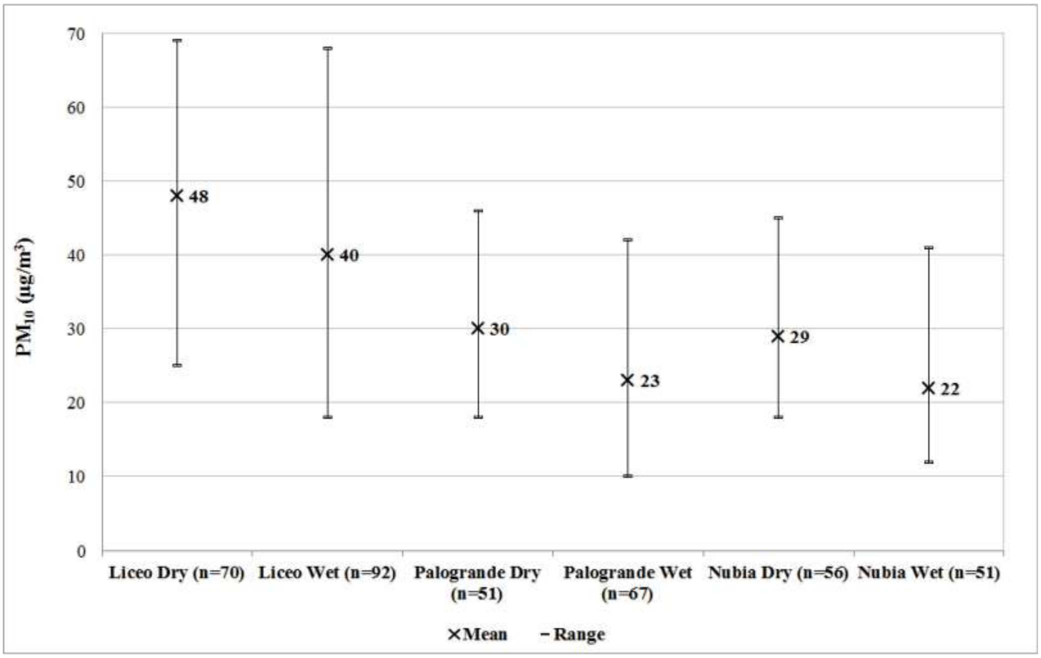
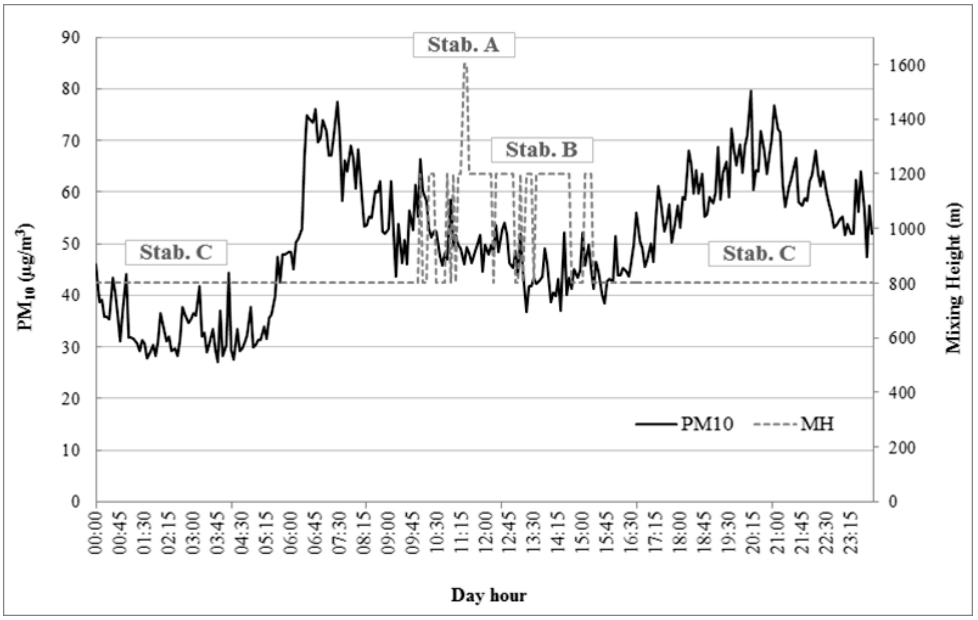


Figure 3 Comparison of average PM_{10} during dry and wet periods

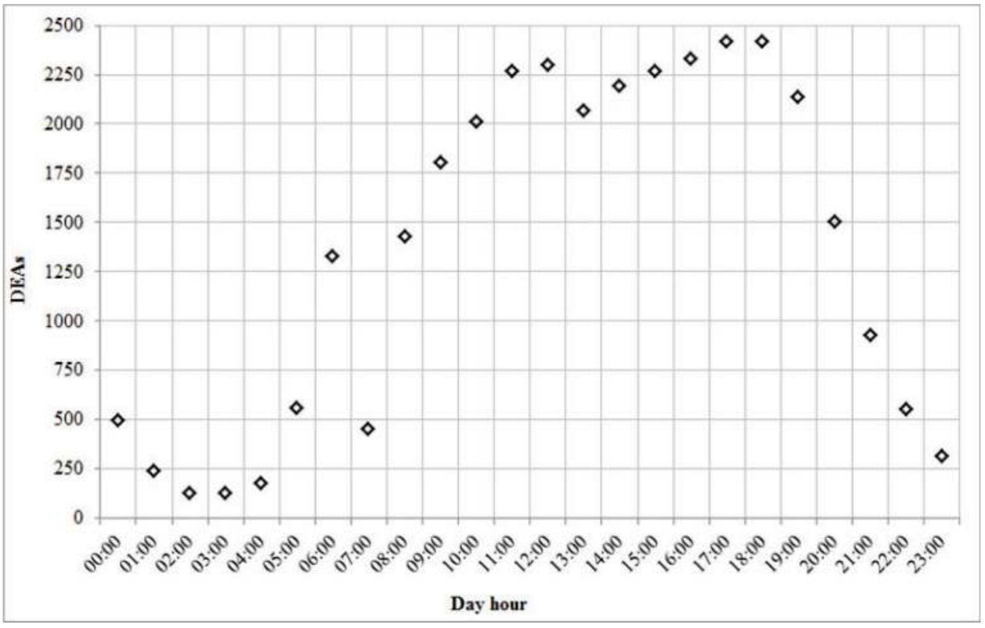
Real-time PM_{10} analysis

Two diurnal critical periods of PM_{10} pollution were characteristic in downtown Agustinos station: early morning and early evening; in spite of the high periods of midday vehicular traffic in terms of daily equivalent automobiles (DEAs) and their associated emissions. DEAs were calculated taking into account conversion factors for different vehicular categories and were reported by [33], during the vehicular mobility study developed for Manizales city. Mixing height values during this time were also higher reaching 1200 m and 1600 m in comparison with 900 m obtained for the other periods of the day, helping to explain the reduction of PM_{10} concentrations. Figure 4a shows the variation of mixing height (MH) in Agustinos. Height values were calculated using a simplified methodology reported by [34], which uses the atmospheric stability classes and wind velocity to define an approximated value of MH.

Three peak hours (PH) of PM_{10} pollution were defined with respect to higher pollution episodes (Figure 4a) and higher levels of traffic around the downtown zone (Figure 4b). PH1 from 6:30 a.m. to 8:30 a.m.; PH2 from 11:45 am to 12:45 a.m. and from 1:30 p.m. to 2:30 p.m.; and PH3 from 5:45 p.m. to 7:45 p.m. PH1 and PH3 were characterized by higher mean levels of PM_{10} (69 µg m^{-3} and 61 µg m^{-3} respectively) with respect to PH2 (46 µg m^{-3}). As well as, daily average PM_{10} concentration of 50 µg m^{-3} was obtained, suggesting important levels of PM_{10} at this station located near downtown Liceo (Figure 1), and with direct influence of vehicular and public transportation emissions.



(a)



(b)

Figure 4 Variation of PM_{10} concentration and vehicular traffic around Agustinos station: (a) Average PM_{10} concentration and MH at different hours of the day. (b) Variation of daily equivalent automobiles (DEAs)

Conclusions

Higher levels of PM_{10} were observed in downtown (Liceo station) with values ranging from 18 µg m^{-3} to 69 µg m^{-3} and a mean concentration of 44 µg m^{-3}. The influence of public transportation and automobiles, which use diesel and gasoline as principal fuels, respectively, were the main sources of particulate matter emissions. Other zones of the city with lower influence of mobile sources showed a reduction of daily mean values of PM_{10} compared with levels of downtown Liceo. All stations showed mean PM_{10} levels under annual Colombian limit of 50 µg m^{-3}; nevertheless, annual WHO limit (20 µg m^{-3}) was exceeded by all stations, in particular Liceo (44 µg m^{-3}), suggesting the benefits of new PM_{10} reduction limits in order to diminish health risk of population.

Precipitation, temperature and relative humidity exerted the highest influence over concentration levels of PM_{10}. Precipitation and relative humidity showed an inverse relationship, hence a PM_{10} reduction effect, while temperature showed a positive association with PM_{10} concentrations. The comparison of PM_{10} mean values during dry and wet periods suggested the removal of PM_{10} during scavenging processes by rain.

Two diurnal critical periods of PM_{10} concentration were found over downtown: early morning and early evening. Higher mixing height values during midday were associated with low PM_{10} concentrations, in spite of higher levels of vehicular traffic during midday, suggesting a process of vertical pollution dispersion. Mean value obtained at this zone of downtown (50 µg m^{-3}) is indicative of the need to establish a PM_{10} monitoring station with Hi-Vol. samplers in this zone of the city, which can complement the air quality network of Manizales.

Additional studies that analyze other types of particles ($PM_{2.5}$) and compare their composition, could develop a better understanding of the sources and fates of particulate matter pollution, characterizing organic and elemental carbon, ions and metals in particulate matter. Results obtained in this study identify essential mechanisms for modeling PM_{10} in tropical mountain climates.

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