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Distribution and temporal behavior of particulate matter over the urban area of Buenos Aires

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ABSTRACT

This paper contributes for the first time in Buenos Aires city to the temporal and horizontal distribution of the $PM_{2.5}$ and PM_{10} concentrations. Their variations and relationships with relevant variables that characterize the air pollution potential of the urban air shed are also given. The measurements were carried out for one year from May 2006 to May 2007. During this period, particulate matter (PM) was continuously measured at one reference station and alternatively for shorter time periods at six different sites. The values and temporal variations on a daily and seasonal basis were consistent with the ventilation potential of the atmosphere. The cold season, which had the lowest values of the ventilation coefficient, indicated higher probabilities of poor air quality and this was confirmed by the higher concentrations of PM_{10} and $PM_{2.5}$ measured. At the reference station, the daily EU limit value for PM_{10} was exceeded 36 times during one year while the Buenos Aires limit value was exceeded only once. The PM_{10} annual mean value was almost 70% of the Buenos Aires annual limit. The $PM_{2.5}$ annual mean value (15 $\mu g\ m^{-3}$) was same as the regulated one (15 $\mu g\ m^{-3}$). The correlation between PM_{10} and $PM_{2.5}$ concentrations and frequencies of wind directions showed that the highest concentrations were observed when the wind was from the city (land wind) and lowest concentrations when the wind was from Rio de La Plata (fluvial wind). The concentrations during land wind events exceeded the Buenos Aires $PM_{2.5}$ annual limit value. The ratio of $PM_{2.5}$ to PM_{10} was 0.44, which indicates the coarse particles (>2.5 μm) originated from road dust, soil re-suspension and abrasion processes are the dominated fractions of PM. Results of random PM measurements at 60 sites showed that $PM_{2.5}$ was more homogeneously distributed over the city than PM_{10}.

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1. Introduction

The worldwide evidence on airborne particulate matter and its public health impact consistently shows adverse effects to exposures that are currently experienced by urban populations in both developed and developing countries. The epidemiological evidence shows impacts following both short-term and long-term exposures (Wilson and Suh, 1997). The range of health effects is broad but predominantly relates to the respiratory and cardiovascular systems. The entire population is affected, but susceptibility to pollution may vary with health or age (WHO, 2006). Air pollution in Buenos Aires, like in most of the mega-cities in the world, is of major concern (Gurjar et al., 2008). The high population density and urbanization are key factors as regards the effects of poor air quality conditions on health. Buenos Aires city, the capital of Argentina, is located at the right edge of the Rio de la Plata (Figure 1). The city is part of Buenos Aires Metropolitan Area (BAMA), the third biggest metropolis in Latin America with a population of 11.5 million inhabitants. Buenos Aires city has approximately 2.77 million inhabitants and an area of 203 km^2, which represents a density of 13.7 inhabitants per km^2 (INDEC, 2001). Good ventilation and dilution of the pollutants have been frequently associated with the terrain flatness of the city, its coastal location and moderate mean surface winds coming from Rio de La Plata. That is the reason of its name, which means "good air". However, knowledge about the actual air quality situation and the influences of meteorological parameters on the dispersion of the pollutants over the city is lacking. The sources of air pollution in Buenos Aires, in order of importance, are the traffic and three power plants located at the coast. No large industries are situated within the city but an industrial complex is nearby the city, at the southeast. Smichowski et al. (2004) have stated that vehicular emissions are the main source of particulate matter (PM). Due to the high degree of commercial activities and services within the city, 3 million persons travel everyday and there is a flow of approximately one million vehicles per day (CoPUA, 2006) in the main access and exit routes to the city. However, there is an estimate of more than 1.5 millions of vehicles (mainly motorcars and buses) for the city, which generally are not equipped with catalyzers. Some air quality measurements were performed in the city within the framework of short experimental campaigns (Bogo et al., 1999; Bogo et al., 2003; Gomez et al., 2005; Reich et al., 2006). The most important air pollutants with an increasing trend are volatile organic compounds (VOC), nitrogen oxides (NO_X), and PM (Ortiz, 2000).

Upon their release, the pollutants' fate and dilution are controlled by the atmospheric transport, dispersion, and removal mechanisms. The results of studies of air pollution potential in Buenos Aires can be found elsewhere (Ulke and Mazzeo, 1998;

Ulke, 2000; Ulke, 2004). The hourly daytime mean mixing heights range between 261–592 m in winter and 547–1 170 m in summer. The most commonly occurring mixing heights for a given time of the day are lower than the corresponding mean values and they occur in the range of 205–349 m in winter and 333–833 m in summer. There is a frequency of 99% of daytime mixing heights below 1 500 m in winter and 85% in summer. The most frequent daytime stability conditions are the near neutral and the slightly unstable (Ulke and Mazzeo, 1998). The frequencies of reduced ventilation in Buenos Aires (ventilation factor below 6 000 $m^2 s^{-1}$) are 71% in winter, 63% in autumn, 47% in spring and 40% in summer. This indicates that the self cleansing ability of the atmosphere is reduced during the cold season. Although better ventilation conditions are more frequent during spring, it is important to remark that, nearly half of the daytime the ventilation factor is also indicative of a reduced self cleansing ability of the atmosphere. In Buenos Aires, the frequency of occurrence of wind directions from the Rio de La Plata towards the city, 58% during the warm period and 48% during the cold one. This means that climatologically, the possibility of having clean air flow over Buenos Aires is reduced in the cold season (Ulke, 2004).

As part of the project BARUCA (Buenos Aires Research on Urban Climate and Air Pollution) (BARUCA, 2007), this work focuses on the characterization of the air quality situation of Buenos Aires city in terms of PM. Moreover, the relationships with relevant meteorological variables and the dispersion ability of the atmosphere are analyzed. The paper contributes with detailed information on the concentrations, the temporal behavior (on diurnal and seasonal basis) and the spatial distribution of PM obtained by an extended measurement campaign on several places within the city. The work provides a unique and firm basis to document the effects of reduced assimilation capacity of the Buenos Aires air shed.

2. Materials and Methods

Continuous ground level measurements of PM were performed using two Grimm light scattering photometers GRIMM 1.108 (Grimm Aerosol Technik GmbH, 2005). One Grimm device was permanently installed at a reference measurement station (site P1), from May 2006 to May 2007. The second device was relocated every four to six weeks in order to measure continuously at each of six selected sites over shorter periods. In Figure 1 the location and description of the sites are given. P1 to P7 represent the PM sampling sites and M the meteorological stations from the National Meteorological Service of Argentina (Servicio Meteorológico Nacional, SMN). The sites were selected in order to obtain a realistic diagnosis of the temporal variation and spatial distribution of PM in city. Most of the PM monitoring sites were mainly influenced by traffic emissions and located close to busy roads and street canyons. The exception was site P6, which had a coastal location and was less influenced by vehicular emissions. The measurements at sites P3, P4 and P5 were performed at a height of 15 m at the roof of buildings as it was not possible to place the instrument at ground level (2 m above ground).

The Grimm light scattering photometers permit the determination of particulate matter concentrations ($\mu g\ m^{-3}$) in 16 different size diameters from 0.23 to >20 µm. The measurements were taken in a time resolution of 1 minute basis and hourly and daily averages were calculated. In this study, the concentration of $PM_{2.5}$ includes the concentrations of the particles found in the size range 0.23 to 2 µm and 50% of the concentrations of the particles in the size range of 2 to 3 µm. The latter can be divided since the particle size distribution curve is very flat between 2 and 3 µm (Wilson and Suh, 1997). In other studies (Maletto et al., 2003; McKendry et al., 2004; Thai et al. 2008) the total mass concentration of the particles in the size range of 2–3 µm was considered. However, from our point of view this leads to an overestimation of $PM_{2.5}$ concentrations. PM_{10} is the sum of the concentrations from the particles found in the size range from 0.23 to 10 µm.

As part of quality assurance measurements, the instruments were protected with weather housings equipped with temperature and humidity sensors to avoid moisture effects. If the relative humidity exceeded 85.5%, the air sample was diluted with dry air in order to reduce the moisture of the sampled air. Moreover, to assure the quality of the results and to reduce the measurement uncertainty, the data from the Grimm spectrometers were calibrated on the basis of simultaneous measurements between them. Additionally, the mass concentrations of the spectrometers were compared with gravimetric measurements using low volume samplers (MiniVS) (Sven Leckel, 2009). The deviation between these two measurement principles was determined between 1.4 and 2.7% for PM_{10} and $PM_{2.5}$ respectively.

A random measurement technique in many different sites was chosen to determine the spatial distribution of PM over the city. The total measuring area was 97 km^2 covering 48% of the total area of Buenos Aires city.

The random measurements were performed according to the German regulation (TA Luft, 1986). The investigation area was divided into grids of approximately 1.5 x 1.5 km^2 making a total of 43 grids and 60 measurement points (Figure 8). In addition, the random measurements were also performed at the seven sites shown in Figure 1. Measurements were taken with a third Grimm photometer fixed on the roof of a car. Within the measurement period (June 2006 to March 2007), 26 individual measurements of 30 minutes were performed at each point of every grid. The measurements were divided in a morning shift from 06:00 to 14:45 local time and an afternoon shift from 14:15 to 23:00 local time. For a qualitative control of the measurements at every shift a protocol was filled out. The protocol included details such as the time in which each measurement took place, traffic incidence during the measurement, current weather conditions or significant events (rain, wind, fog, etc.) and other relevant observations.

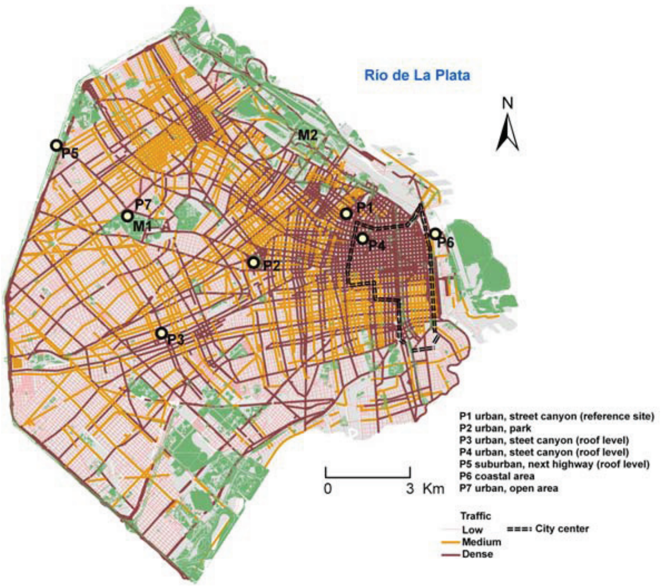

Figure 1. *Buenos Aires city and monitoring sites. (P indicates concentration measurement site, M indicates meteorological observation site).*

The individual 26 measurements at each point were equally distributed over the year (during different seasons), over the week (equal distribution between weekdays, Saturdays and Sundays), as well as over the time per day, in order to cover meteorological conditions and emission patterns as much as possible. A total of 1 742 measurements of particulate matter were obtained.

To determine a correlation between the measured concentrations and the features of the sites from the random PM measurements traffic categorization and land use (residential or commercial) maps were used. The corresponding maps were obtained from governmental institutions (Council of Urban Environmental Planning, CoPUA and Coordination Unit of Strategic Planning, CoPE).

The SMN operates two meteorological stations in Buenos Aires city: Observatorio Central Buenos Aires (34°35´S, 58°29´W) (site M1 and P7) and Aeroparque (34°35´S, 58°25´W) (site M2) (Figure 1). Upper air observations are made at 09:00 local time (1200 UTC) at Ezeiza Aero (34°49´S, 58°32´W), (located at about 50 km southwest of the city).

The surface wind speed and direction at M1 during the campaign were used to study the frequencies of occurrence of velocity ranges and to detect the prevalence of wind sectors. Pollution wind roses joining the particulate matter concentrations and wind conditions were obtained. The provided hourly surface information at M1 was used along with the sounding data at Ezeiza Aero to estimate the hourly daytime mixing height, the transport wind and the ventilation factor during the campaign as well as the stability conditions. The ventilation factor is defined as the product of the mixing height times the transport wind. Stability conditions are obtained using cloud cover data, wind speed and Turner's scheme. The methodology is detailed elsewhere (Ulke and Mazzeo, 1998; Ulke, 2000; Ulke, 2004). These parameters characterize the self-cleansing capability of the atmosphere. This information was related with the measured air pollutant concentrations and behavior in order to elucidate their possible relationships.

3. Results and Discussion

3.1. Temporal and spatial variability in PM

The temporal and spatial variability of PM measurements was analyzed aiming to present novel information about the detailed structure of the air quality situation in Buenos Aires city. The evolutions of daily averaged values of PM_{10} and $PM_{2.5}$ (in μg m^{-3}) at monitoring site P1 during the field campaign are shown respectively, in Figure 2.

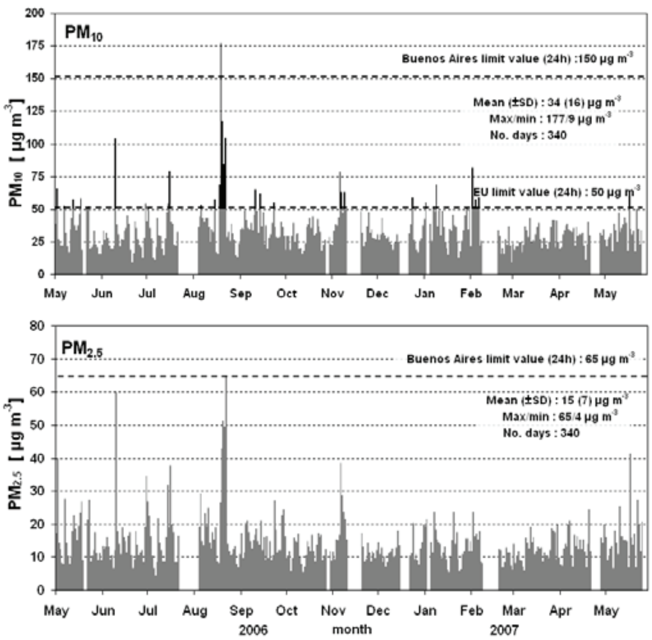

Figure 2. *Daily values of PM_{10} and $PM_{2.5}$ (μg m^{-3}) obtained at the permanent site P1 within May 2006–May 2007.*

In general, the measured values were higher from July to September. The highest concentrations of PM_{10} and $PM_{2.5}$ were obtained in August and the lowest in March. The Buenos Aires daily PM_{10} limit (150 μg m^{-3}) was exceeded only once, whereas the European Union (EU) daily limit (50 μg m^{-3}) was exceeded 36 times (Figure 2). The highest number of exceedances of the EU limit occurred during the winter months (June to August) and the lowest in autumn (March to May). Some exceedances occurred also during summer, which were not expected as the traffic (particularly in January) is considerably lower and the dispersion conditions are generally better in this season. The daily limit for $PM_{2.5}$ in Buenos Aires city (65 μg m^{-3}) was reached once on the same day that the highest value of PM_{10} (177 μg m^{-3}) was measured (Figure 2). North westerly winds with average 2.7 m s^{-1} speed in M2 and 1.9 m s^{-1} in M1 (see Figure 1) prevailed on this day.

The World Health Organization (WHO) guideline value for $PM_{2.5}$ (25 μg m^{-3}) was exceeded on 21 occasions. The main statistical measures for PM concentrations at P1 site are presented also in Figure 2. It is worthy to note that the PM_{10} annual average value of 34 μg m^{-3} was almost 70% of the Buenos Aires annual limit (50 μg m^{-3}). This means that the population of the city is, on an annual basis, exposed to relatively high particulate matter concentrations. As regards the $PM_{2.5}$ annual mean, the regulated value in Buenos Aires is 15 μg m^{-3}, and the average value at P1 was equal to this limit. In addition, the averages were above the WHO air quality guidelines (20 and 10 μg m^{-3} for PM_{10} and $PM_{2.5}$).

The mean ratio of $PM_{2.5}$ to PM_{10} at P1 was 0.44, which indicates that in Buenos Aires, coarse particles (>2.5 μm) originated from road dust soil re-suspension and abrasion processes are the dominating fraction in PM. This result is not in agreement with that reported in a previous study on particulate matter in Buenos Aires city (Bogo et al., 1999). It is important to remark that, in the present study, the measurements of $PM_{2.5}$ and PM_{10} were performed simultaneously and this was not the case in the previous study. However, the ratio is in agreement with the value found in Santiago de Chile (Jorquera et al., 2000).

Further to the permanent measurements at site P1, $PM_{2.5}$ and PM_{10} were measured rotationally for five to eleven weeks (27 to 69 days) at six sites (sites P2 to P7 in Figure 1). In Table 1 an overview of the statistical parameters such as the mean of daily average concentrations, standard deviations (SD), maximum and minimum values, ratio Px/P1 (where Px indicates sites (P2 to P7), and correlation coefficients (r) for $PM_{2.5}$ and PM_{10} are given. The values are compared to those obtained at P1 during the same measurement time.

The highest mean for both $PM_{2.5}$ and PM_{10} concentrations were obtained at sites P2 (20 and 45 μg m^{-3}, respectively) and P3 (19 and 44 μg m^{-3}, respectively). These results might be related to the fact that the measurements at P2 and P3 were carried out during winter and the early spring. Winter is, from the climatology of the air pollution perspective, the season with the lowest ventilation capability.

The lowest PM concentrations were obtained at the coastal site P6. PM concentrations at this site were, on the average, 30% less than at P1. The results might be due to both the coastal location of the site and the measurement period (summer).

For PM_{10}, the measured concentrations at P2, P3 and P7 were slightly higher (ratios Px/P1 1.2, 1.1, and 1.1 respectively) than those measured at the reference site P1. Opposite behavior is observed at sites P4, P5 and P6. However, since a part of the coarse particles (abrasion processes and re-suspension of road dust) tend to be deposited faster than fine particles, the absolute PM_{10} values between P3 (15 m height) and P1 (2 m height) are not directly comparable. This is also valid for sites P4 and P5, where

Table 1. *Mean of daily average $PM_{2.5}$ and PM_{10} concentrations at the six sites (P2 to P7), standard deviations (SD), maximum and minimum values, ratio Px/P1 (Px indicates sites (P2 to P7), and correlation coefficients (r)*

Period/Site	PM_{10} ($\mu g\ m^{-3}$)				$PM_{2.5}$ ($\mu g\ m^{-3}$)			
	Mean (±SD)	Max/min	Ratio Px/P1	Correlation (r)	Mean (±SD)	Max/min	Ratio Px/P1	Correlation (r)
winter (34 days)								
P2	45 (24)	146/15	1.20	0.94	20 (11)	51/7	1.20	0.93
P1	35 (15)	79/11			16 (7)	38/4		
spring[a] (42 days)								
P3 (15 m height)	44 (26)	155/13	1.10	0.87	19 (13)	66/6	1.10	0.97
P1	43 (29)	177/13			18 (12)	65/7		
spring[b] (34 days)								
P4 (15 m height)	31 (10)	69/14	0.89	0.86	12 (5)	31/5	0.85	0.87
P1	35 (13)	78/15			14 (6)	38/5		
summer[c] (27 days)								
P5 (15 m height)	27 (9)	52/13	0.79	0.44	11 (6)	32/8	0.86	0.79
P1	30 (7)	48/18			11 (2)	18/7		
summer[d] (69 days)								
P6	23 (11)	56/6	0.72	0.77	9 (4)	24/3	0.80	0.84
P1	33 (14)	81/9			13 (4)	24/5		
autumn (36 days)								
P7	31 (8)	48/9	1.10	0.66	12 (4)	25/5	0.86	0.79
P1	30 (7)	46/11			14 (4)	25/7		

[a] Measurement period August 23 – October 03, 2006
[b] Measurement period October 10– November 20, 2006
[c] Measurement period November 21 – December 26, 2006
[d] Measurement period December 27, 2006 – March 17, 2007

the measurements were taken at 15 m as well. In the case of $PM_{2.5}$, the concentrations at P2 and P3 are as well slightly higher (ratios Px/P1 1.2 and 1.1 respectively) than in P1. For the other sites, the concentrations at P1 are higher.

The correlations coefficients (r) were obtained from the comparison of the PM daily concentrations of the six sites (P2 to P7) with those of the reference station P1 for the same measurement periods. High correlation coefficients indicate that the concentrations at both sites have the same behavior which is mainly influenced by traffic and the temporal variation of the meteorological exchange conditions. $PM_{2.5}$ shows better correlation coefficients than PM_{10}. This quantitatively indicates that $PM_{2.5}$ is more spatially evenly distributed over the city air than PM_{10}. Thus, in the case of $PM_{2.5}$ the difference among sampling heights is negligible.

P2 and P3 have higher correlation coefficients than P4 even though P4 is closer to P1. That means that the source structure has much more influence on the comparability of the concentrations than the distance between two sites (Grivas et al., 2008). Sites P5 and P7 show the lowest correlation coefficients compared to the other sites, especially for PM_{10}. Similar results were found in other studies (Burton et al., 1996; Gehrig and Buchmann, 2003; Grivas et al., 2004).

In Figure 3 the comparison of daily $PM_{2.5}$ and PM_{10} variations for different sites are shown as an example. The variations at the traffic site P3 are compared to those at P1 for the same measurement period (August 23 – October 03, 2006). For sites P3 and P1, the daily $PM_{2.5}$ and PM_{10} variations are very well comparable. Both sites are influenced by vehicular emissions, but P3 is located in a road with high incidence of heavy traffic (trucks). They show that the concentrations are varying according to the traffic load that is nearly the same over the time. PM_{10} values at P3 are even slightly higher (1.1 times higher than P1) which shows that the total load at street level at P3 (15 m height) must be much higher than at P1. This is in accordance with personal observations and transit network that permits the circulation of heavy duty trucks at P3 whereas at P1 these vehicles are not allowed to circulate. The high concentrations observed for four consecutive days at P3 ($PM_{2.5}$ = 35–66 $\mu g\ m^{-3}$, PM_{10} = 99–115 $\mu g\ m^{-3}$) and P1 ($PM_{2.5}$ = 42–64 $\mu g\ m^{-3}$, PM_{10} = 64–177 $\mu g\ m^{-3}$) were caused by poor dispersion conditions during these days. Low wind speeds (2.3–2.7 m s^{-1}) were observed for the first two days with a prevailing NW direction. On the third day the wind speed remained low (2.3 m s^{-1}) with a shift of the wind direction to E-SE. On the fourth day, 20% of calms were observed on the early morning hours which caused the concentrations to remain high. During the day the wind speed increased to 6.5 m s^{-1} with a prevailing SE wind direction. As a result, the decreased concentrations on the fifth day were because of better dispersion conditions coupled with a lower traffic flow (weekend).

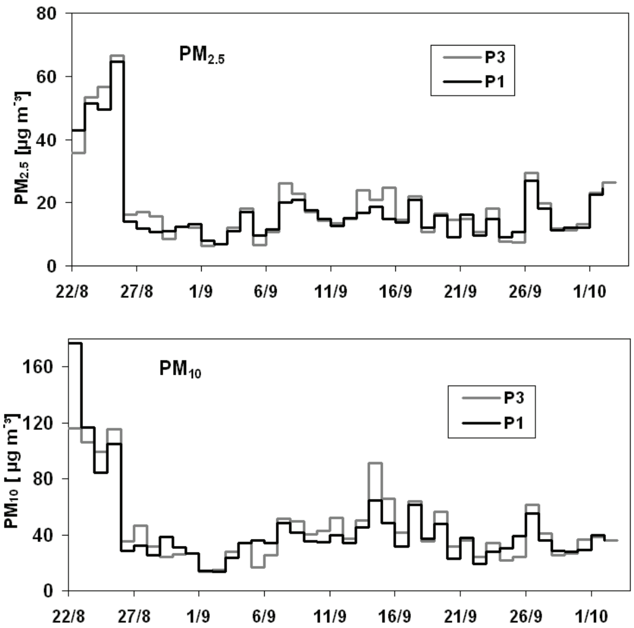

Figure 3. *Comparison of the daily variability of PM at sites P1 and P3.*

In Figure 4a the average diurnal patterns of PM_{10} and $PM_{2.5}$ at sites P3 and P1 are shown for the same measurement period as in Figure 3. The pattern of PM_{10} at site P3 shows two peaks in the concentrations. The morning peak occurs between 8 am and 12 pm, and the evening one between 8 and 11 pm. A similar pattern

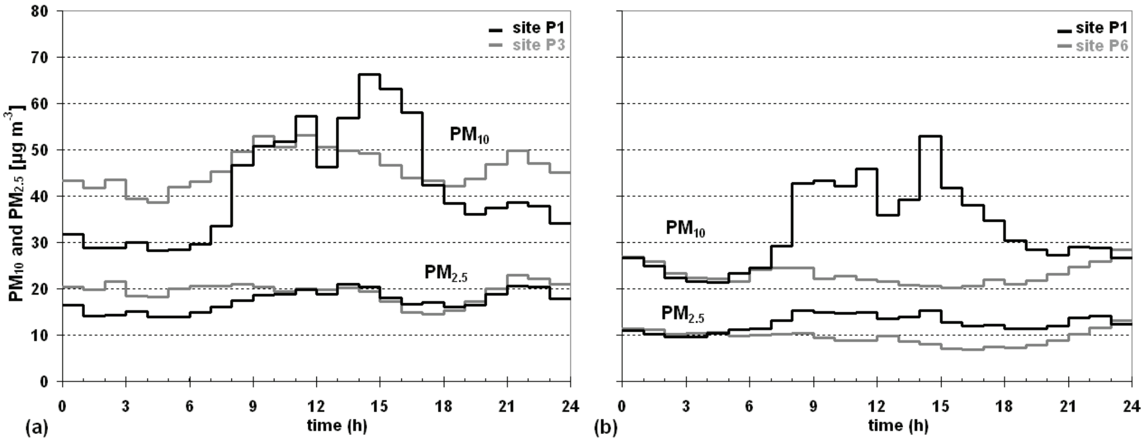

Figure 4. *Comparison of diurnal patterns of PM at sites P3 (a) and P6 (b) in comparison with site P1.*

can be observed for site P1; however the morning peak is followed by a higher peak between 1 and 5 pm. The concentrations during this period are much higher in P1 than in P3. This difference must be caused by the coarse particles which sink before reaching the sampling height of 15 m at P3. The decrease of the concentrations during the night is much lower in P3 than in P1, which again shows that the concentrations at street level in P3 must be higher than in P1.

For both sites, the lowest concentrations were observed during midnight and 6 am. Morning and evening peaks can also be observed for $PM_{2.5}$, but they are less pronounced, especially at site P3 where the concentrations in the early morning are slightly higher than in the day.

The PM diurnal patterns at both sites show the result of increased traffic emissions during the morning and evening.

Figure 4b shows the average diurnal pattern of PM_{10} and $PM_{2.5}$ at sites P6 and P1 from December 27, 2006 to March 17, 2007. At the traffic site P1, PM_{10} concentrations are much higher (30%) than those found at the coastal site P6. The pattern of PM_{10} concentrations at P1 is the same as in Figure 4a. However, some small differences are observed such as that the highest peak occurs between 2 and 4 pm and the evening peak between 9 and 11 pm. PM_{10} diurnal pattern at the coastal site P6 follows a different pattern with decreasing concentrations during daytime and increasing concentrations during night time. The $PM_{2.5}$ diurnal patterns at both sites show a similar behavior except that the morning peak is not appreciable at P6. Contrarily, the concentrations during these hours decrease at P6 instead of increasing as in P1. The low concentrations observed in P6, make difficult to appreciate a diurnal pattern of the PM concentrations.

3.2. Seasonal variability of PM and influences of meteorological parameters

To further identify the areas around Buenos Aires affecting the pollution at site P1, the frequencies of wind directions and speeds along with the associated pollution roses for the annual period were obtained (Figure 5). The most frequent wind direction was SE (30%). The lowest wind velocities (3.6 to 4 m s^{-1}) occurred in the NW-N sector and the highest (4.5 to 5 m s^{-1}) were measured for winds from the SW, E-SE and SE-S sectors. The highest concentrations of PM_{10} were observed when the wind was from the NW-W sector, which are light winds coming from the city (land wind), but this situation had a low frequency (13%). The smallest concentrations were obtained when the wind was coming from the NE-E and E-SE sector, from Rio de La Plata (fluvial wind) and stronger. Similar behavior was observed for $PM_{2.5}$. It is especially worthy of note that the concentrations associated with the NW-W sector exceeded the annual value for $PM_{2.5}$ in Buenos Aires.

Figure 6 shows the average diurnal pattern of PM_{10} and $PM_{2.5}$ at the reference site P1 for the four seasons. The pattern of $PM_{2.5}$ concentrations shows a clear seasonal influence. Higher concentrations can be observed during winter and lower concentrations during summer whereas in autumn and spring similar concentrations were found. The seasonal variability of $PM_{2.5}$ concentrations is influenced by the less traffic density observed during summer than in winter and by meteorological factors which are explained below.

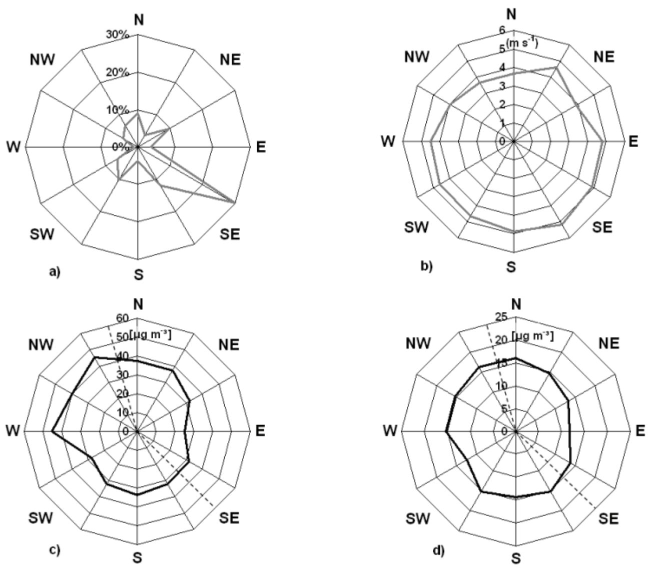

Figure 5. *Frequencies of occurrence of wind directions (a) and speeds (b) and pollution wind roses of PM_{10} (c) and $PM_{2.5}$ (d) at P1. The dotted lines in (c) and (d) separate the wind directions from the river (NNW to SE) and land sectors.*

The average diurnal pattern for PM_{10} is different than the observed for $PM_{2.5}$ especially the daily variation of PM_{10} is much higher than that of $PM_{2.5}$. This is due to the shorter residence times of PM_{10} leaving $PM_{2.5}$ suspended in the air. A clear seasonal variability for PM_{10} cannot be distinguished. However, as the coarser particles are the dominating fraction in PM_{10} ($PM_{2.5}/PM_{10}$ ratio = 0.44), the seasonal variability can be explained by the $PM_{2.5}/PM_{10}$ ratios obtained for the different seasons (refer to Table 1). Generally, the lower ratios were observed during spring and summer and higher ratios in autumn and winter. The higher ratios (0.46–0.47) obtained in the cold season where coupled with higher values of relative humidity (71–84%) and lower mean wind speeds (3.8–4.0). On the other hand, the lower values of relative humidity (58–75%) obtained in spring and summer with higher mean wind speeds (4.5–5.5) enhanced lower ratios (0.36–0.40) to occur during these seasons. These findings are in accordance with Vardoulakis and Kassomenos (2008) and Kukkonen et al. (2005) who indicated that the effect of re-suspension of road dust is enhanced during the warm and dry seasons.

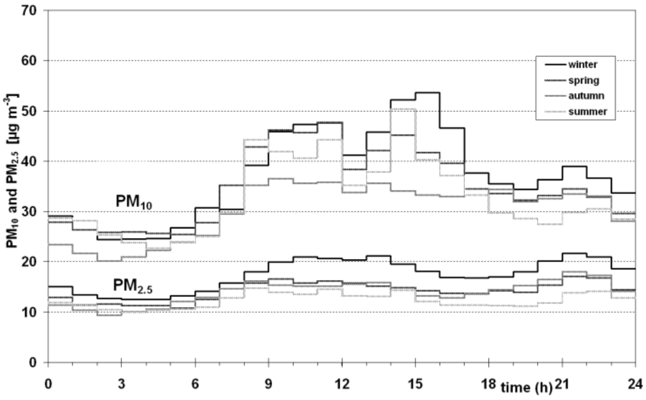

Figure 6. *Seasonal average diurnal patterns $PM_{2.5}$ and PM_{10} at the reference site P1.*

The average diurnal course of the mean daytime mixing height, transport wind and ventilation factor for each season are depicted in Figure 7. The estimated values are within the climatological ones (Ulke and Mazzeo, 1998; Ulke 2000; Ulke 2004) and their variability are related to the particular weather patterns during the experimental campaign. The lowest mean mixing heights occur during winter, whereas the highest values were obtained in summer. The mixing heights in spring were greater than that found in autumn (Figure 7a). It is worthy to notice that the smallest mean transport wind occurred in autumn and the greater in spring (Figure 7b). As the ventilation factor is obtained as the product of the mixing height and the transport wind, the best overall ventilation conditions occur during summer and the worst in winter (Figure 7c). The ventilation in spring was very similar to the summer one as a result of the increased transport wind. A feature of concern was that the dispersion potential of the atmosphere of Buenos Aires during the cold season and the morning hours that was seriously reduced. The ventilation factor was well below the critical value and this was in coincidence with the morning traffic maximum intensity and emissions. The daytime variation of the ventilation factor was governed by the pattern of the mixing height, which in turn results from the seasonal decrease of surface heating.

These features are very well correlated with the courses of the observed PM concentrations observed in Figure 7.

In summary, the average diurnal courses of PM and their seasonal behavior are in agreement with the expected ones as regards to the ventilation conditions. The higher concentrations of $PM_{2.5}$ observed in winter were enhanced by the lowest mean mixing heights and ventilation factors which occurred this season. In summer, $PM_{2.5}$ concentrations were lower as consequence of higher mixing heights and better ventilation conditions. The concentrations were also reduced due to low traffic density during this season.

In accordance with higher transport winds, stronger near surface winds and lower humidity, the reason for the lower $PM_{2.5}/PM_{10}$ ratios in the warm season is that the increased winds enhanced the mechanical turbulence and in consequence, the re-suspension processes near the surface.

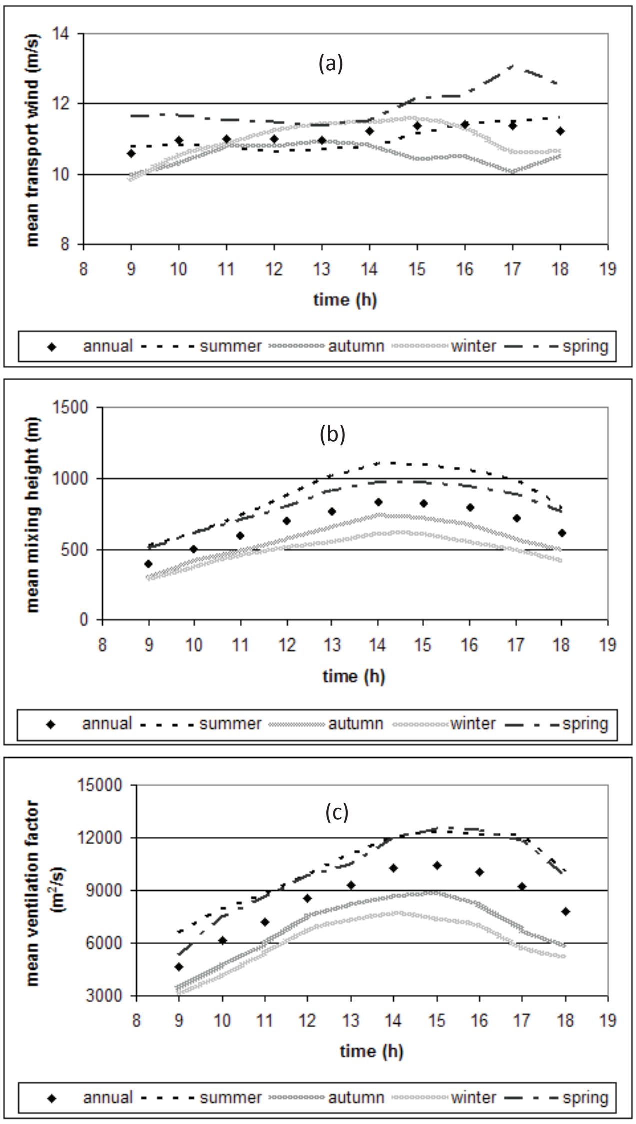

Figure 7. *Average diurnal cycle of mixing height, transport wind and ventilation factor for the four seasons during the measurement period.*

3.3. Spatial PM distribution obtained from random measurements

The results of the random measurements performed from June 2006 to March 2007 are shown in Figure 8 over the map of Buenos Aires city. In the map a total of 43 grids show the averages of $PM_{2.5}$ and PM_{10}. It can be seen that $PM_{2.5}$ (Figure 8) is more evenly distributed horizontally than PM_{10} (Figure 8). The mean values for $PM_{2.5}$ (23 µg m^{-3}) and PM_{10} (52 µg m^{-3}) (obtained in the grid where P1 is located) are 1.5 times higher than those obtained in P1 (15 and 34 µg m^{-3}, respectively). The reason for these differences is that the measurements were performed at street level next to the emission sources. The obtained values have suggested that $PM_{2.5}$ was above the annual limit of 15 µg m^{-3} and a great portion of the city experienced values that exceeded the annual PM_{10} limit (50 µg m^{-3}).

Table 2. *Relationship between average PM concentrations and traffic and residential use categories*

Mean concentration	Traffic			Residential use		
	Low	Medium	Dense	25-50%	75%	90%
$PM_{2.5}$ (µg gm^{-3})	20	20	23	24	23	21
PM_{10} (µg m^{-3})	50	51	55	56	54	52

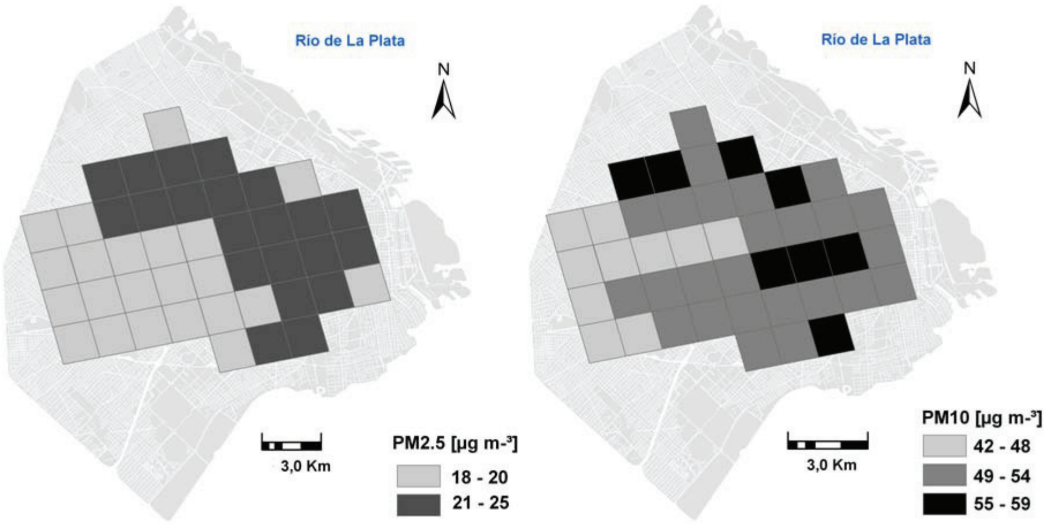

Figure 8. *Map of Buenos Aires city with the results of random measurements for PM_{10} and $PM_{2.5}$ (µg m^{-3}).*

Traffic is the main source of air pollution in the city, however the high population density and urbanization are also deteriorating the city's air quality. Therefore, it is important to determine if there is a correlation between the measured concentrations and the features of the sites from the random measurements. For this purpose, maps of traffic categorization and land use (residential or commercial) for the city were used. The major land use categories are residential, mixed residential/commercial, commercial, industrial, open spaces and recreational (green areas). The structure of the city is characterized by a relatively compact city centre located at the east of the city, with two other secondary centers (Figure 1), one located at north and the second one 6 km to the west from the main city centre. These areas have a high traffic density (Figure 1). The largest use of city land is mainly residential, found mostly in the western part of the city, as well as at south and northwestern part. These areas present a medium to low traffic density. From a qualitative point of view, it can be concluded that a more deteriorated air quality than in other parts is expected at the east and northeastern parts of the city. To ascertain this, the relationships between average $PM_{2.5}$ and PM_{10} concentrations of sites located within different traffic categories and residential uses are given in Table 2.

Sites that were located at areas with low and medium traffic density showed lower concentrations for PM_{10} and $PM_{2.5}$ than those with dense traffic. In relation with residential use, the sites with 25–50% residential use present the highest PM_{10} concentrations. However, for $PM_{2.5}$, 75% residential use and 25–50% show similar values. The lowest concentrations for PM_{10} and $PM_{2.5}$ are found for sites with a 90% of residential use.

4. Conclusions

The results of a field campaign that took place in Buenos Aires as part of an international project (BARUCA, 2007) are presented and analyzed. Simultaneous meteorological and particulate matter measurements (in the fine and coarse fractions) at several sites in the city were carried out during one-year period. The daily limit for PM_{10} was exceeded only once (177 µg m^{-3}), but the EU daily limit (50 µg m^{-3}), was exceeded on 36 occasions. The daily limit for $PM_{2.5}$ was reached on the same day. On an annual basis the average PM_{10} concentration (34 µg m^{-3}) was 70% of the regulated one (50 µg m^{-3}), which means a relatively high long-term exposure of the population. A striking and novel result was that for $PM_{2.5}$ the annual mean (15 µg m^{-3}), was the same as the limit (15 µg m^{-3}). As regards the spatial distribution, a consistent pattern among the sites was observed. The average $PM_{2.5}$/PM_{10} ratio was 0.44 indicating that coarse particles are the dominating fraction in PM. The association of PM_{10} and $PM_{2.5}$ concentrations and frequencies of wind directions showed that the highest concentrations were obtained when the wind was from the city (land wind) and smallest concentrations when the wind was from Rio de La Plata (fluvial wind). Average diurnal patterns of $PM_{2.5}$ show a clear seasonal variation. Concentrations in winter were in average 1.4 times higher than in summer. Lower values of the ventilation coefficient indicate less dispersion potential of pollutants in the atmosphere or greater probabilities of poor air quality and this was ascertained with the seasonal trends of the measured concentrations.

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