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Some Guidelines to Improve Air Quality Management in Santiago, Chile: From Commune to Basin Level

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1. Introduction

1.1 General considerations

Particulate matter is natural or manmade and comes from different sources that determine the variety of its chemical, physical and thermodynamic characteristics.

Particulate matter may be formed by rupture of material and/or by agglomeration of small fragments, including molecules (Prospero and Charlson, 1983; Ondov and Wexler, 1998) and is classified according to its primary or secondary source. Primary particulate matter is emitted directly by sources and secondary particulate matter is formed in the atmosphere by chemical reactions. Primary particulate matter has different sizes, whereas secondary is usually very small (U.S. EPA, 2004). The most important primary natural sources are the dust raised by wind, sea spray, volcanic emissions, forest fires and brush fires. Natural sources include secondary sulphates, nitrates and organic compounds (U.S. EPA, 2004).

Since the mid 60's the city of Santiago de Chile has experienced high levels of air pollution by particulate matter, especially during the autumn-winter period; during the so-called "episodes", which may last even for a few days, the Chilean standards for PM₁₀ air quality (particulate matter <10µm), are overcome, reaching levels considered dangerous to human health, especially to children and the elderly (WHO, 2005).

High levels of air pollution in Santiago are due to a combination of factors: a) geographical and meteorological conditions in the Metropolitan Region, particularly unfavourable for proper dispersion of pollutants, b) the growing economy of the city, c) the large size and functional segregation of the city; d) a progressive increase in transport distances, all the above in spite of technological progress (CONAMA, 1997; CONAMA, 2008).

Particulate matter has a very heterogeneous and changing chemical composition with organic and inorganic components. The studies on the subject were initiated in the mid 70's (Préndez et al, 1984; Trier, 1984, Trier and Silva, 1987; De la Vega et al., 1987, Rojas et al., 1990; Préndez et al. 1991). In 1985, a study conducted by the University of Chile found that diesel vehicles contributed 71% of ambient concentrations of particulate matter, although they represented only 19% of total PM₁₀ emissions. On the contrary, natural dust, the main source of PM₁₀ with 49% of the tons emitted, provided only 15%, and gas industries and vehicles, 6% each.

More recently other studies have confirmed the early ones, giving a different distribution of source contributions (Ortiz et al. 1993; Artaxo et al., 1999; Sienra et al., 2005; Gramsch et al., 2006). The lack of databases of chemical composition of emissions makes the contribution of sources and changes in time difficult to learn. Only some sources have been studied by Préndez et al., (2007). In order to overcome the problem, the Chilean studies use the USEPA database. The last emissions inventory identifies industrial processes, boilers, motor vehicles, recycled dust from the floor, home fireplaces using wood and agricultural burning as the main sources of particulate matter (DICTUC, 2007). There is also a significant fraction of secondary particulate matter (Morata et al., 2007).

The PM₁₀ particle size is harmful to human health when entering the airways. The fine fraction of PM₁₀ (diameter <2.5 µm, PM_{2.5}) is most dangerous because it is 100% breathable, entering and staying longer in the lungs; in addition, its chemical composition is generally more toxic (Préndez, 1993; U.S. EPA, 2004).

Several authors have reported the main effects of particulate matter from Santiago on the population health (Oyanguren, 1972; Ostro et al., 1996; Ostro et al., 1999; Ilabaca et al., 1999; Cifuentes et al., 2000). Pino et al. (2004) established a 5% increases for each increment of 10 µg/m³ of PM_{2.5}; Cakmak et al. (2007) established a 4.53% probability of death for 85 µg/m³ of PM₁₀ in adults under age 65 and 9.47% over 65 years.

Other proven effects of particulate matter pollution include reduction of visibility, soiling of building facades and clothes, potential problems of dust deposition and acid rain (Préndez et al., 1991; Préndez, 1993; USEPA, 2004).

Since 1997, a Plan of Prevention and Decontamination of Atmospheric Pollution (PPDA) has been implemented in the Metropolitan Region, which includes a series of measures to reduce concentrations of particulate and gaseous pollutants (CONAMA, 1997; CONAMA, 2001; CONAMA 2008). However, in the period 1997-2008, there were 370 days in which concentrations were above the maximum daily alert level ($\geq 195 \mu\text{g}/\text{m}^3\text{N}$ daily concentrations) or pre-emergency level ($240 \mu\text{g}/\text{m}^3\text{N}$ daily concentrations). In most of those days (68%) the monitoring station located in Pudahuel (NW of the city) reached the highest concentration, defining the condition for the adoption of emission control measures and restrictions on the operation of stationary and mobile sources.

The main objective of this study was to identify the causes of high levels of PM₁₀ pollution in Pudahuel in order to contribute to improve the management of air quality in the city of Santiago.

1.2 Environmental management of the Metropolitan Region

The Metropolitan Region (33.5 ° S, 70.8 ° W) is a closed basin between the Andes to the east and the Coast Range to the west, the Chacabuco mountain range to the north, and the Cantillana mountain range to the south. Thus, the central valley is surrounded by mountains (altitudes between 1000 and 5000 m) and this fact makes the wind flow and air exchange difficult within the basin, where the city of Santiago is located (Fig. 1).

The first systematic measurements of the levels of air pollution in Santiago were performed in 1964 as recommended by the Pan American Health Organization; in 1976, a network consisting of 5 monitoring stations located in concentric rings around the center of the city was set up (Ulriksen, 1993). Later, (in 1987) the Automatic Monitoring Network of Air Pollutants (MACAM network) was set up, with 4 stations located in the downtown area of the city: Independencia (IS), Plaza Gotuzzo (PGS), Providencia (PS) and Parque O'Higgins

(POS)) and a mobile station, finally located in Las Condes (LCS). In 1997, four stations were added in the external area of the city: Pudahuel (PudS), El Bosque (EBS), La Florida (LFS) and Cerrillos (CES) and two stations PGS and PS were removed. Thus, the present network, called MACAM2 (ASRM, 2008) is formed by seven stations equipped with PM10-TEOM continuous monitors that can provide hourly concentrations of PM10 and continuous monitoring of gases CO, SO₂, NO₂, O₃ and total hydrocarbons (Fig. 1).

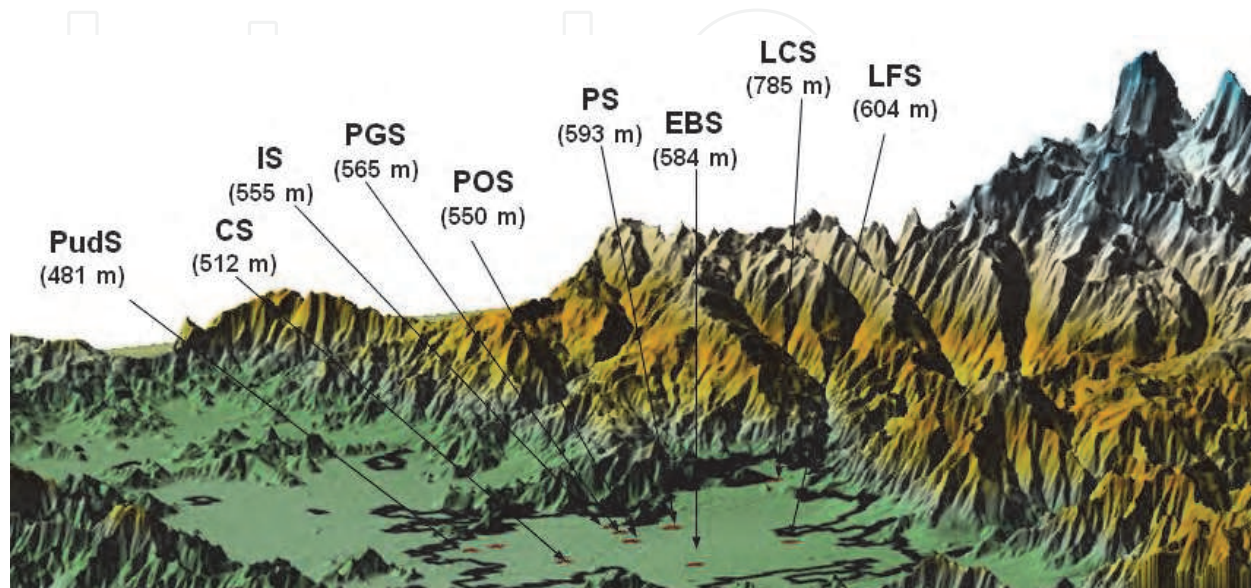


Fig. 1. Air quality stations of MACAM and MACAM2 networks of the Metropolitan Region

In 1988, the Particle Air Quality Index (ICAP) was established in terms of PM10 concentrations for 24h. ICAP was set at 0-149 $\mu\text{g}/\text{m}^3\text{N}$ = ICAP 100 (good); 150-194 $\mu\text{g}/\text{m}^3\text{N}$ = ICAP 200 (regular) and 285-330 $\mu\text{g}/\text{m}^3\text{N}$ = ICAP 500 (dangerous), varying linearly between ranges (ASRM, 2008).

In 1990 the register of sources and the isokinetic testing mandatory for estimating emissions from smokestacks were established and in 1992 emission standards for particulate matter from point sources were set to a gradual reduction of emissions from 112 $\text{mg}/\text{m}^3\text{N}$ to 32 $\text{mg}/\text{m}^3\text{N}$ as of January 1st, 2005.

In 1996 the Metropolitan Region was declared a saturated area by PM10, TSP, CO and O₃ and latently saturated by NO₂ and ICAP calculation was corresponded to the highest 24-hour mobile concentration of PM10 recorded during the day at one of the network stations MACAM2.

In 1998, PPDA was established, which sets targets for emissions of pollutants in the short, medium and long terms to comply with all air quality standards as of 2012, with regular revisions and updates; in the primary standard it was also established that the 98 percentile of daily concentrations of PM10 during a calendar year must not exceed 150 $\mu\text{g}/\text{m}^3\text{N}$; in 2001, the maximum allowable annual averages of three consecutive years was set at 50 $\mu\text{g}/\text{m}^3\text{N}$. Furthermore, in 2000, the use of the methodology of air quality forecast for PM10 in the Metropolitan Region was approved.

1.3 Meteorological characteristics of the Metropolitan Region

During the autumn-winter period, topoclimatic characteristics of the Santiago basin are unfavourable to the dispersion of pollutants (Rutland 1973; Ulriksen 1980; Rutland and

Salinas 1983). Due to the predominance of anticyclonic conditions in the region, forcing the airflow through the large-scale weather systems a weak ventilation of the basin is produced mainly by a system of winds generated locally by the radiative heating of the surface. Therefore, from April to August (austral autumn-winter), the flow of air into the basin is much weaker than in summer (Ulriksen, 1993).

Two configurations of weather conditions have been established associated with days of high concentrations of PM10, called A and BPF types episodes. The A type corresponds to the development of a low pressure area from the Andes to the ocean, accompanied by wind from the east in the lower troposphere and a decrease in the height of the inversion layer of subsidence. The BPF type episode corresponds to a prefrontal condition, with overcast skies and weak ventilation from the NW in the Santiago basin (Rutland and Garreaud, 1995, Rutland and Garreaud, 2004).

During the A type episodes the PudS station usually shows higher concentrations of PM10 than other monitoring stations in the city. During the BPF type episodes however, the maximum concentrations are usually seen in the SW sector of the city. The number of episodes associated to A and BPF configurations that occurred in the Metropolitan Area between 1997 and 2008 are shown in fig. 2. Muñoz et al. (2003), classified the episodes occurring between 2001 and 2003 as "early episodes", with high concentrations of PM10 between 21 and 22h and "late episodes" occurring during the early hours of the next day with a lower peak.

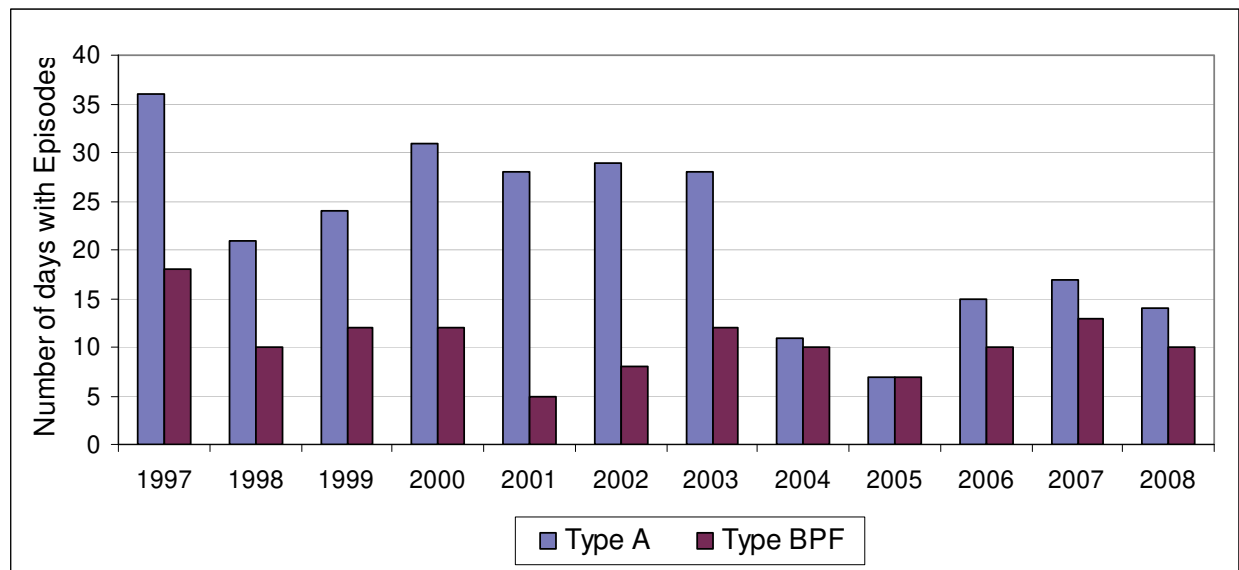


Fig. 2. Number of episodes associated to A and BPF configurations in the Metropolitan Area between 1997 and 2008

2. Materials and method

The study was divided into two stages, the first one corresponding to the identification and study of the causes of high concentrations of PM10 in the area of Pudahuel on days of pollution episodes in Santiago; the second one corresponding to the proposed management actions to reduce the occurrence of high concentrations of PM10, thus improving air quality in Pudahuel and in the city of Santiago.

2.1 Collection and critical study of the information

- a. Collection of information of PM₁₀ and meteorology to develop a diagnosis of Pudahuel air quality, considering the official historical information of PM₁₀ (Network of Metropolitan Health Authority, ASRM, and the National Environment Commission, Metropolitan Region, CONAMA RM) and from the National Centre for the Environment (CENMA), with emphasis on the period from 2000 to 2008, including environmental emergencies, Santiago basin weather (average hourly temperature, relative humidity, speed and direction wind, rainy days) and reports of episode forecasting system.

The information of PM₁₀ and meteorological data used correspond to percentages above 75% of valid data for analysis periods (daily, monthly, yearly). A principal component analysis (PCA) was performed (SPSS version 8.0) and Airviro and Excel software was applied to relate information between PM₁₀ and meteorological data in Pudahuel.

- b. Analysis of primary data from two campaigns of measurements of particulate matter by CENMA in 1999 and 2003 (unpublished data) to determine the geographic extent of the area of high concentrations in the area of Pudahuel. The first season held hourly concentrations of PM₁₀ with a continuous monitor (TEOM) between August and September 1999, a period corresponding to the final stage of the management of episodes of PM₁₀ pollution in 1999. Measurements were made at two distant sites: one located within the area of population representativeness (radius of 2 km), 1 km SE (MunPS) and in a suburban area about 6 km SW (LAFS).

The second campaign was conducted in the winter of 2003 in the area near PudS at the hours of maximum daily PM₁₀ concentrations, 20h to 02h. The study area covers about 6 × 6 km approximately, including the PudS. Days of episodes were privileged. No measurements were made at nights with rain or with fog coming from the coast. A continuous monitor PM₁₀ type nephelometer (TOPAS) was used programmed to record minute PM₁₀ concentrations, installed on the roof of a vehicle. Measurements were carried out at 17 nights between July 10th and September 1st, 2003.

To calculate hourly averages, early episodes were separated from the later episodes (Muñoz et al., 2003). PM concentrations under study were integrated in geographic maps in a GIS environment processed with SURFER 8.0 software to generate maps of isolines of concentrations for A and BPF type episodes.

- c. The chemical and physical characterization of particulate emissions was made using industrial and natural sources taken from the 2005 emissions inventory (DICTUC, 2007) and the emissions data for the year 2008 (CENMA, 2008b); the annual emissions were calculated by multiplying the daily broadcast on operating the emission sources and dividing the daily broadcasting time by the number of hours of operation of the sources. Information is grouped by categories of sources and interpreted by comparison with the behaviour of the PM₁₀.
- d. The following factors were analyzed: 1) PM measurements of the two CENMA's campaigns; 2) behaviour of wind during episodes in Pudahuel; 3) behaviour of the system winds in the area of Pudahuel; 4) emissions inventory for Pudahuel area; 5) results of speciation analysis of physical and chemical PM₁₀ emission sources and environmental samples from literature.

A comparison was made between the average hourly wind speed in Pudahuel and the speeds measured at the other stations using different statistical tests to a confidence

level of at least 95%, including Wilconxon/Mann, Whitney, Kruskal-Wallis and Chi-square using eViews software. The tests were performed separately for A and BPF type episodes registered between 2004 and 2007 using both the original data series and the data series smoothed using moving averages of order 24. Days of episodes were selected with daily concentrations greater than or equal to the value of the standard between 2004 and 2007 and compared with the behaviour of PM10, wind speed and direction using scatter plots, and daily cycles of wind roses.

To identify differences of the contribution of pollutant sources during episodes and no-episodes days the re-analysis of samples published by Artaxo (1999) for the fine and coarse fractions of PM10 in PudS was performed using absolute principal component analysis (SPSS V.8.0). These results were compared with information for the winter of 2005 published by Gramsch (2006).

2.2 Analysis of management actions to reduce PM10 concentrations in Pudahuel

Based on the data of weather, topographic conditions and emission sources the authors built a scenario in the Pudahuel area to promote actions to reduce particulate matter pollution at local level. This approach is supported by the policy of authorities, the pollution of Pudahuel station values taken as key to daily actions for the whole Metropolitan Region.

3. Results and discussion

3.1 Environmental concentrations of particulate matter in Santiago

Fig. 3 shows annual mean concentrations of PM10 for the period 1997-2008 at MACAM2 network stations. In general PudS presents the highest values, except for 2008. There is a general decline of PM10 concentrations towards 2005 and a further increase, except for LCS.

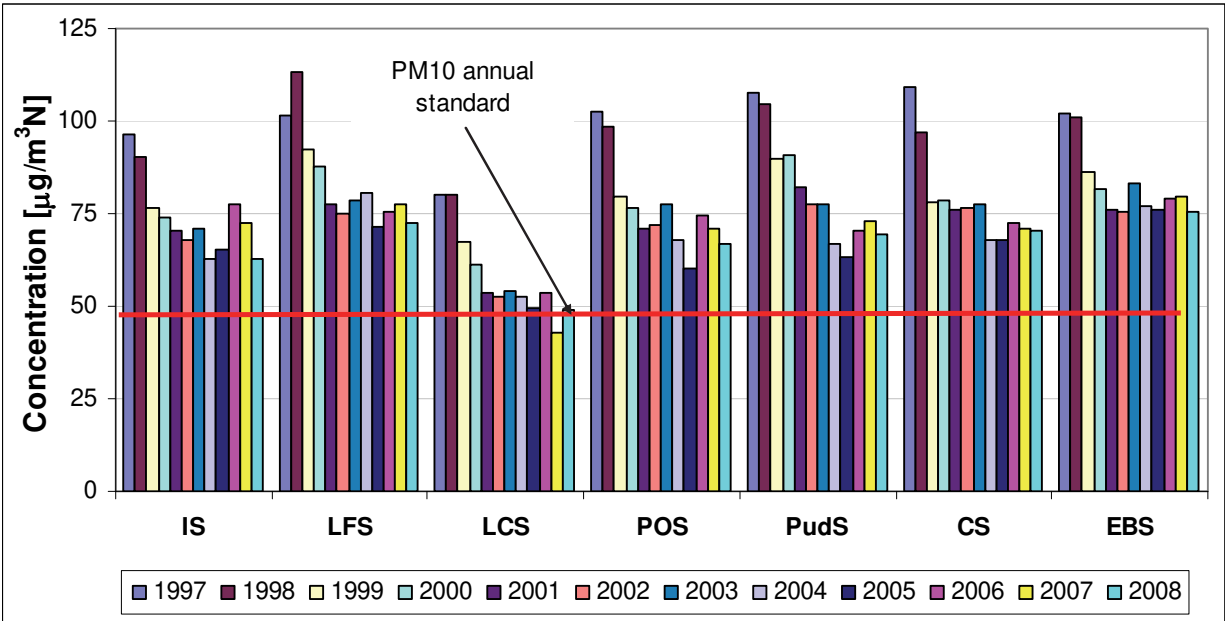


Fig. 3. Annual mean concentrations of PM10 collected with TEOM monitors of MACAM2 network (1997-2008).

This increase is primarily associated with the energy crisis that forced the industries using natural gas to return to diesel oil; however, in 2008 the number of episodes decreases in relation to 2007.

At PudS an exceedance of 26% of the daily standard and 42% of the annual standard has been observed. LCS is the only one always under the current standard. Moreover, in monitoring stations with high levels of PM10 concentration such as Puds, CS, EBS and LFIS, there was a decrease of days under environmental contingency during the period 1997 to 2005 (from 38 to 9 alert; 37 to 2 pre-emergencies, and disappearance of emergencies) as a result of the implementation of measures of PPDA.

Fig. 4 shows that in general, the highest value for daily maximum of 24h rolling averages concentrations, especially on days of high concentrations, corresponds to PudS. The peaks in 1997 were around $380 \mu\text{g}/\text{m}^3$ and in 2008 close to $260 \mu\text{g}/\text{m}^3$.

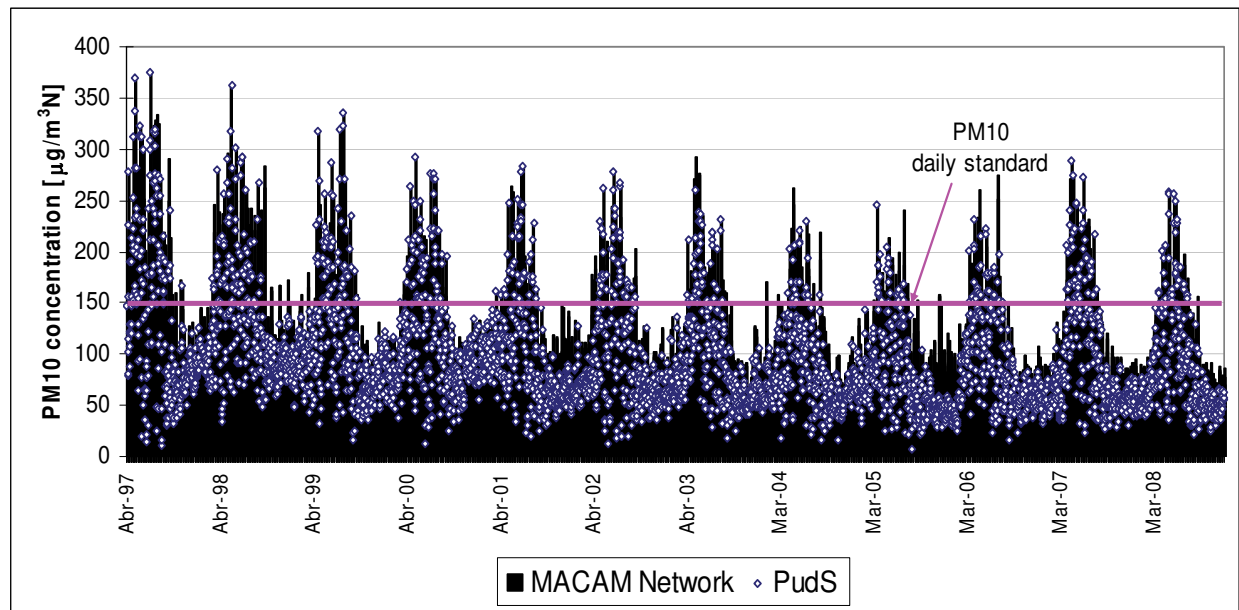


Fig. 4. Highest values for daily maximum of 24h rolling averages concentrations of PM10 in MACAM2 and PudS, 1997 to 2008.

During the period there were 371 days with PM10 alert level, 130 of them exceeding the pre-emergence level, 68% of the highest concentrations corresponding to PudS, most coinciding with A type episodes; in other cases, usually BPF type episodes, the highest concentrations were found at EBS, CS and LFIS stations (CENMA, 2005).

Figs. 5 a) and b) (autumn-winter) and c) and d) (spring-summer) show for most stations two peaks, one at the beginning of the activity of the city (07-09h) and the other associated with the increase in vehicular traffic and atmospheric stability (19-21h); the valleys (12-17h) are associated with an increase in the ventilation of the city. The exact shape of the curves and maximum values depend on each station, but in general, concentrations have declined in the decade under review. For PudS, mean concentrations during autumn and winter had decreased about 22% in the morning peak and about 25% in the afternoon peak. In spring and summer, the concentrations showed a decrease of about 25% in the morning peak and approximately 40% in late afternoon with a not sharply defined maximum.

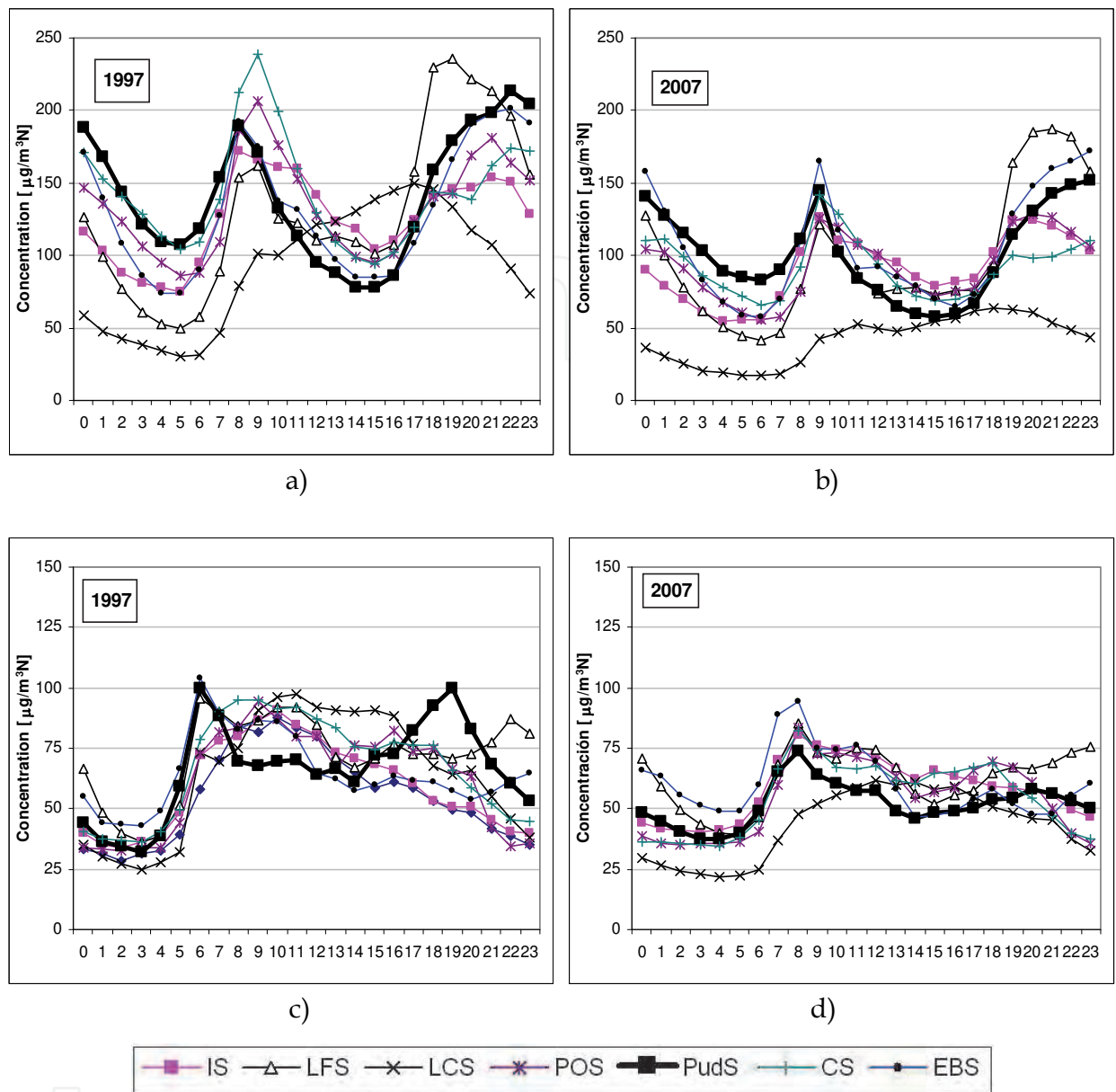


Fig. 5. Mean daily cycles of PM10 for MACAM2 network stations, fall-winter period: a) 1997; b) 2007; spring-summer period: c) 1997, d) 2007.

3.2 PM concentrations in Pudahuel

Fig. 6 shows that the mean concentrations of PM10 for the autumn-winter period are almost twice the mean concentrations during spring-summer. Between 2006 and 2008, the average from April to August of PM10 has been close to 95 $\mu\text{g}/\text{m}^3\text{N}$, slightly higher than for the years 2004 and 2005 ($\sim 82 \mu\text{g}/\text{m}^3\text{N}$) and clearly lower than those for the years 1997 and 1998 ($> 125 \mu\text{g}/\text{m}^3\text{N}$).

Analysis of the concentrations of fine ($<2.5 \mu\text{m}$) and coarse ($> 2.6 - <10 \mu\text{m}$) fractions of PM10, showed similar values except for the years 2004 and 2008 when the fine fraction exceeded the coarse fraction for more than 10 $\mu\text{g}/\text{m}^3\text{N}$. Averages of the spring-summer period have remained above 50 $\mu\text{g}/\text{m}^3\text{N}$, the value established as a limit on the annual standard for PM10.

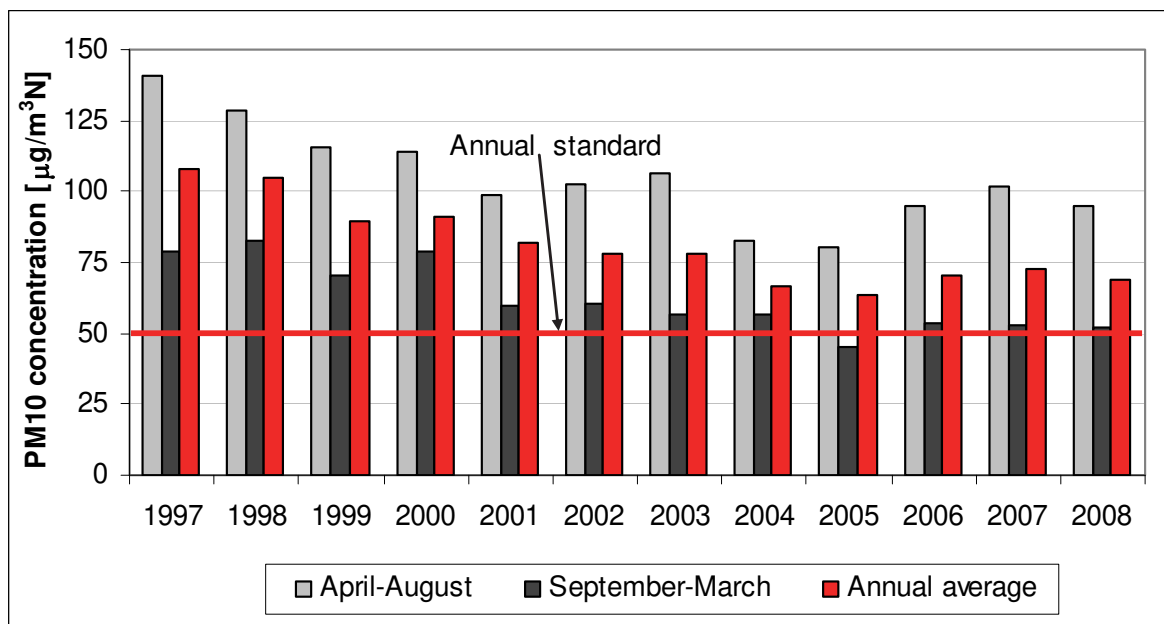


Fig. 6. Mean concentrations of PM10 for April-August and September-March periods and for the mean annual concentrations for the years 1997 to 2008.

Analysis of the annual cycles for monthly mean concentrations of PM10 and PM2.5 at PudS between 1997 and 2008 identifies the mean maximum between May and July for the autumn-winter concentrations and the mean minimum between October and November for spring-summer. For the 1997 to 2003 period the maximum monthly mean concentrations of PM10 and PM2.5 are close to 150 µg/m³N and 75 µg/m³N, respectively. In 2004, the lowest mean monthly maximum of PM10 was 100 µg/m³N, the historically lowest value for Pudahuel; the lowest mean monthly maximum for PM2.5 occurred in 2005, with 50 µg/m³N. Since 2006 concentrations have increased again, with recorded monthly mean maxima of PM10 and PM2.5 of 132 µg/m³N and 60 µg/m³N, respectively.

Between 2004 and 2007, 50 A type and 38 BPF type episodes occurred in Santiago, (CENMA, 2008). PudS showed, 56% of the time, the highest concentrations during A type episodes and only 11% during BPF type. Table 1 shows the concentrations for the 11 largest PM10 episodes at PudS, for that period.

Date	13-06-04	11-07-04	16-04-05	30-04-06	14-06-06	09-05-07	12-05-07	24-05-07	28-05-07	03-06-07	29-06-07	11-07-04
PM10 conc. (µg/m³N)	221	231	246	232	223	226	289	274	223	246	273	221
Episode Type	A	A	A	A	B	A	B	A	B	A	A	A

Table 1. Characteristics of the 11 major episodes of PM10 concentrations at Pudahuel station for the years 2004 to 2007.

Fig. 7 a) and b) show a clear difference between the concentrations of the daily cycles of PM10 and PM2.5 during the 11 days of the major episodes and the mean concentrations for the autumn-winter period for the years 2004 to 2007. The morning peak during the episodes

days show an increase of almost 85% for PM10 and 67% for PM2.5 in relation to the mean for the autumn-winter period; during the afternoon of the episode days PM concentrations fall and then about 17h they begin to increase again, reaching, from 21 to 23h, 2.9 and 3.8 higher levels for PM10 and PM2.5 respectively, compared with the mean for the autumn-winter period.

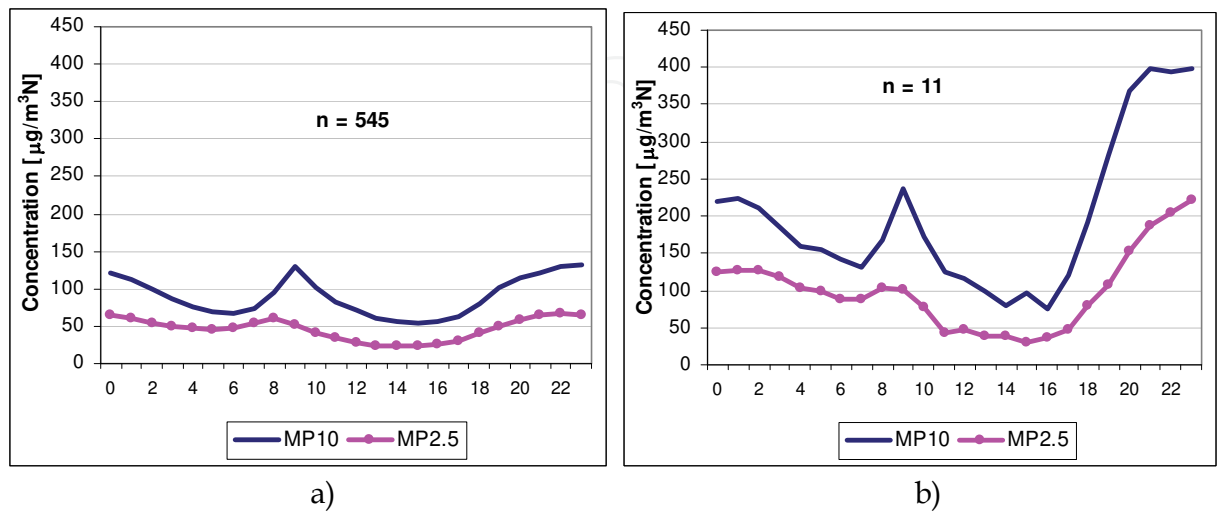


Fig. 7. Mean daily cycles of PM10 and PM2.5 at Puds for the years 2004 to 2007: a) April-August period; b) the 11 episodes. Numbers of data included.

Considering the concentrations of fine and coarse fractions for 48 h for the 11 days of the major episodes, it can be seen that the maxima do not coincide exactly at the same times, as shown in Fig. 8. The maxima are separated by 2-3 hours. In the morning both fractions decrease their concentrations, but the fine fraction maintains higher values, reaching 127 $\mu\text{g}/\text{m}^3\text{N}$ at 07h while the coarse fraction goes to 68 $\mu\text{g}/\text{m}^3\text{N}$ at 06h. The increase in city activities and vehicle emissions also increases the concentrations of the fine (140 $\mu\text{g}/\text{m}^3\text{N}$ at 07h) and coarse (170 $\mu\text{g}/\text{m}^3\text{N}$ at 08h) fractions. After the morning peak, concentrations decrease to minimum values in the afternoon, around 30 $\mu\text{g}/\text{m}^3\text{N}$ for the fine fraction and around 50 $\mu\text{g}/\text{m}^3\text{N}$ for the coarse fraction.

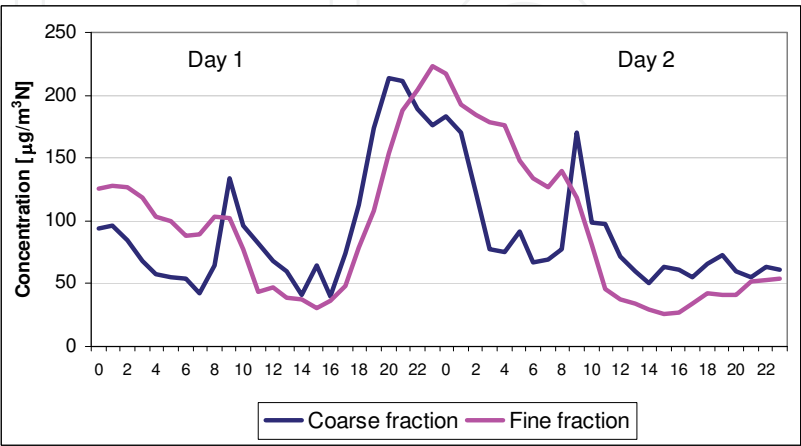


Fig. 8. 24 h PM10 mean concentrations profile for fine and coarse fractions for the 11 major events between 2004 and 2007.

The decrease in concentrations and the end of episodes occurs with increase in ventilation, height of the atmospheric boundary layer and moist coastal air intake. The profile of PM₁₀ mean daily cycle for working days (Monday to Friday) and weekends (Saturday and Sunday) do not show significant differences, except for maximum concentration values in the morning and evening. Every Sunday morning shows concentrations 30% lower than the rest of the week. Conversely, the maximum night is 10 to 30% higher on Sunday and Saturday than on weekdays. However, results show that this increase is not related to the episodes. The mean daily cycle of temperature and wind speed, do not show significant variation during the different days of the week.

3.3 Extent of the geographical area of elevated concentrations during episodes of air pollution in Pudahuel

3.3.1 Pudahuel 1999 campaign

Fig. 9 shows similarities of the daily PM₁₀ concentrations between MunPS (1km SE of PudS) and PudS stations and their great differences compared with LaFS (6km SW of PudS) for most days, except on August 8, 14, 25 and 28 when PudS concentrations were higher than at MunPS; LaFS concentrations were approximately 50% less than the PudS value.

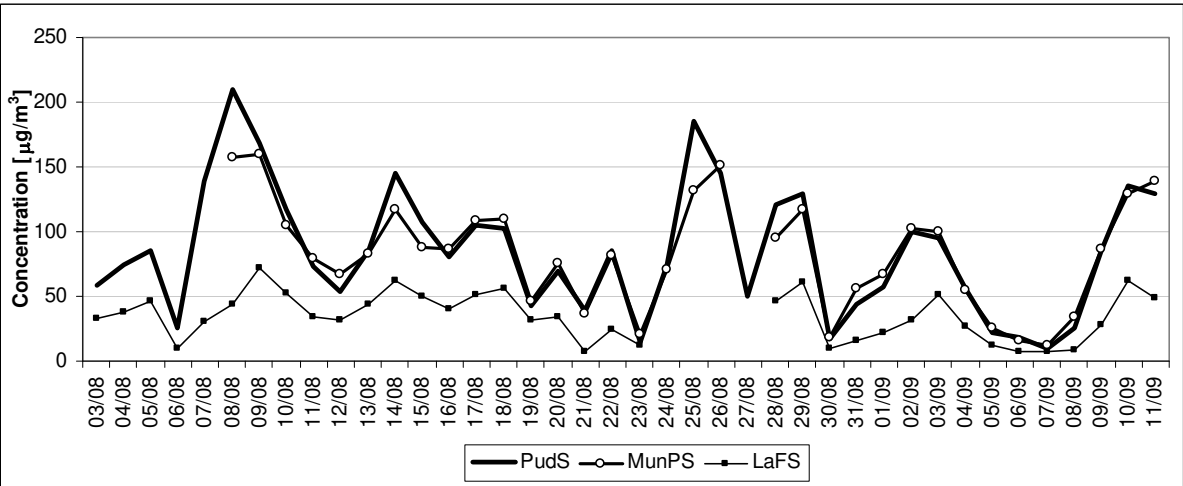


Fig. 9. PM₁₀ daily concentrations at different stations in Pudahuel during August-September 1999

The daily cycle analysis confirmed the similarity of behaviour between PudS, and MunPS and their differences with LaFS, noting that the maxima at PudS are about 21% higher than at LaFS. During the afternoon, the concentrations at MunPS are higher than at PudS, probably due to the increased activity within the Municipality premise, where the MunPS is located. The above results show that spatial variability of concentrations in the Pudahuel area, during episode days, even within the area of population representativeness (radius of 2 km), does not depend on the weather, but on local conditions of the sites under study. During the days exceeding the PM₁₀ daily standard at PudS, PM₁₀ concentrations at MunPS as well as at LaFS are within the standard.

3.3.2 Pudahuel 2003 campaign

Results of the measured concentrations, including 7 days of episodes (5 of A type and two BFP type) show higher values between 20h and 23 h (early episodes) than between 23h and

02 h the next day (later episodes). The highest concentrations of PM10 may be associated with local illegal burning, home heating and dust rising from bad roads by vehicle traffic. These measurements confirmed the results of the 1999 campaign showing lower concentrations at MunS than at PudS during the night. The analysis of georeferencing mean PM10 concentrations showed that between 20 and 23h on the days of early A type episodes values increase towards the north of PudS, reaching mean concentrations of 700 $\mu\text{g}/\text{m}^3\text{N}$ (Fig. 10); in this area, illegal burning and dust rising from the streets by vehicular traffic were visually identified. In other sectors, mean concentrations were much smaller and in general PM10 concentrations tended to decrease towards the south of the Commune. On the other hand, the mean PM10 concentrations between 23h and 02h during late A type episode days show a decrease in concentrations throughout the area under study compared with the period 20h to 23h, with maxima in the north of 450 $\mu\text{g}/\text{m}^3\text{N}$; in other sectors concentrations are only slightly lower.

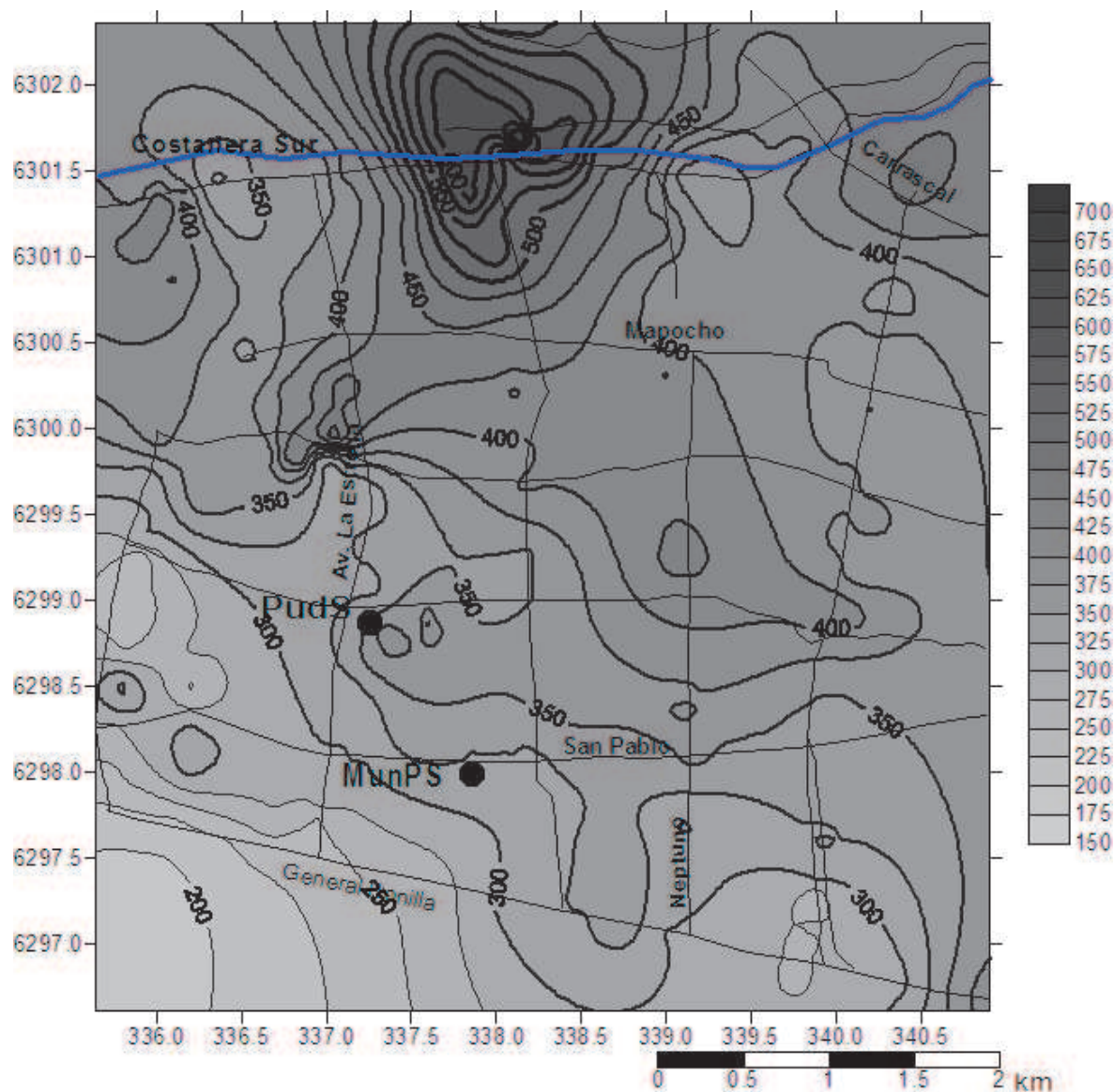


Fig. 10. Spatial distributions of mean PM10 concentrations between 20 and 23 hours, on the days of early A type episodes. July 25th to September 1st, 2003.

The mean hourly PM10 concentrations during early episode days (20 to 23 h) for BPF type episodes are lower than those during A type episodes. On the days of BPF type episodes, PM10 peaks between 20 and 23h are located in the NW area of Pudahuel, reaching maximum concentrations about 550 $\mu\text{g}/\text{m}^3\text{N}$; about 2 km from PudS, the hourly mean concentrations are approximately 300 $\mu\text{g}/\text{m}^3\text{N}$ decreasing towards areas located southwest of the station, reaching approximately 225 $\mu\text{g}/\text{m}^3\text{N}$ in the area of MunPS. In addition, lower concentration islands appear in areas of high concentrations, which could be attributed in part to differences in the ground level and to local conditions. The mean hourly concentrations between 23 and 02h during late BPF type episodes are lower than those recorded between 20 and 23h, and similar to levels in A type episodes.

3.4 Meteorological variables in the urban area of Santiago during episode days

Temperature and relative humidity measured in days of A type episodes show similarities between the values recorded at PudS and the other stations, except for LCS, for relative humidity, whereas there are differences for wind speed and direction recorded at PudS as shown in Fig. 11 for daily cycles and prevailing directions at hours of highest concentration (18 to 23h).

The correlation coefficients for wind speed with a confidence level of 95% for 1200 observations at each of the stations show a value of -0.25 between PudS and LCS and values between 0.43 and 0.69 between PudS and the rest of the network stations, for wind direction; the correlation coefficients between PudS and the rest of the stations are below 0.4.

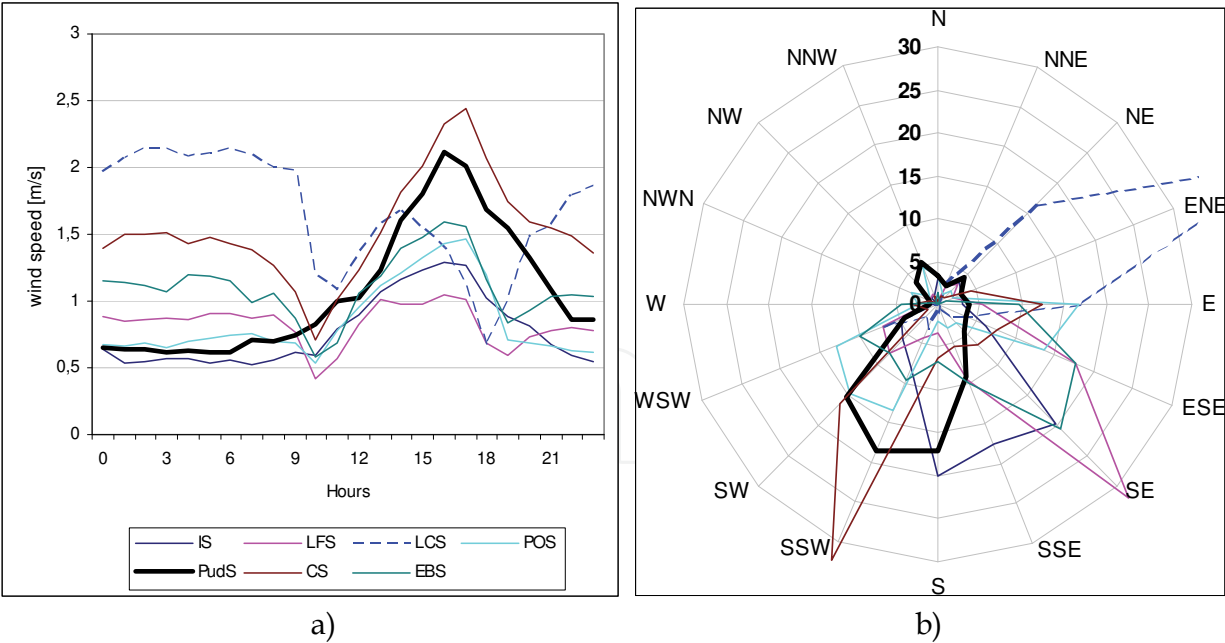


Fig. 11. a) Daily cycles of wind speed; b) directions prevailing during hours of high concentrations (18 to 23h) for 50 days of A type episodes between 2004 and 2007 at MACAM2 network stations

Fig. 12 shows an inverse correlation between daily PM10 concentrations and wind speed recorded at PudS. Nevertheless, the site showed the highest and also the lowest daily PM10

concentration at the lowest wind velocity. For temperature, relative humidity and wind direction, no definite relationship was found.

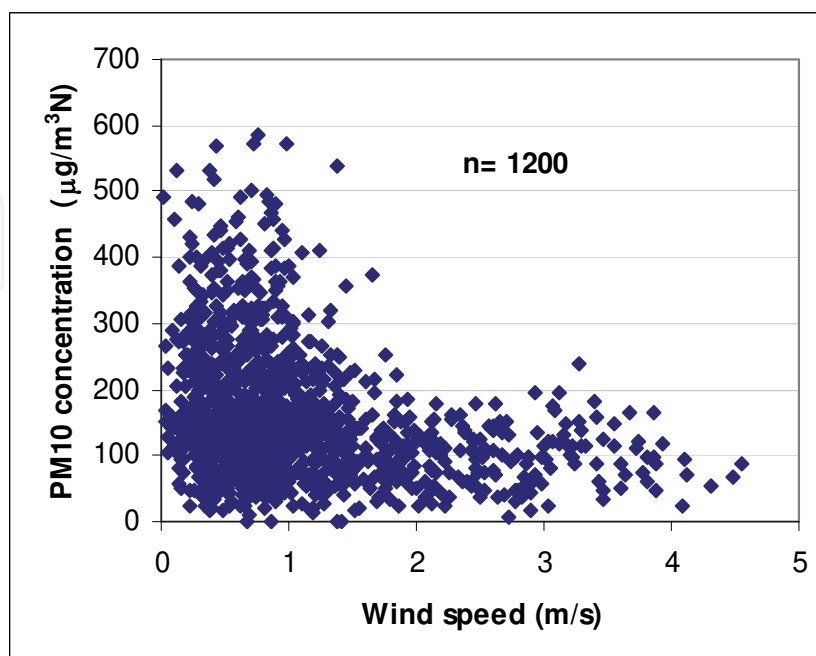


Fig. 12. Daily concentrations of PM10 as a function of wind speed at Pudahuel station, years 2004 to 2007.

The results of different statistical tests show, with a confidence level of 95% or 99%, that the wind speed measured at PudS is different from the rest of the stations, including days of A and BPF type episodes for the years 2004 to 2007. This result is consistent with that obtained by Gramsch et al. (2006) who classified the MACAM2 network stations for PM10 in 5 groups, leaving PudS alone in one of them.

Fig. 13 shows that wind direction from different areas of the city goes to the PudS area at the hours of highest PM10 concentration (18 to 23h) for days of A type episodes. At PudS, the predominant component is SW with wind speeds close to 0.8 m/s. During days of BPF type episodes, wind direction at LFS and LCS is also towards the Pudahuel area, but with less intensity. At other stations there is great variability in wind direction from the SE, S and SW sectors with no component from the North.

Differences between the daily cycle of wind speed at stations in the eastern (LFS and LCS), central-south (EBS), and western (PudS) sectors of the city for days of A and BPF type episodes during which the daily concentrations of PM10 at PudS are higher than the standard limit value are shown in Fig.14. At LFS and LCS the daily cycle is affected by a mountain-valley breeze effect that produces changes in wind direction and intensity about 10 AM and 18PM, being more pronounced at LCS where higher speeds are reached during the morning and night. On the contrary, the minimum speed is recorded during the night and early morning at PudS and EBS, and the maximum speed is reached in the afternoon, an hour before the minimum intensity at LCS.

At PudS, in the afternoons the wind speeds are higher during the A type episodes than during BPF type episodes. A similar situation occurs at LCS and EBS.

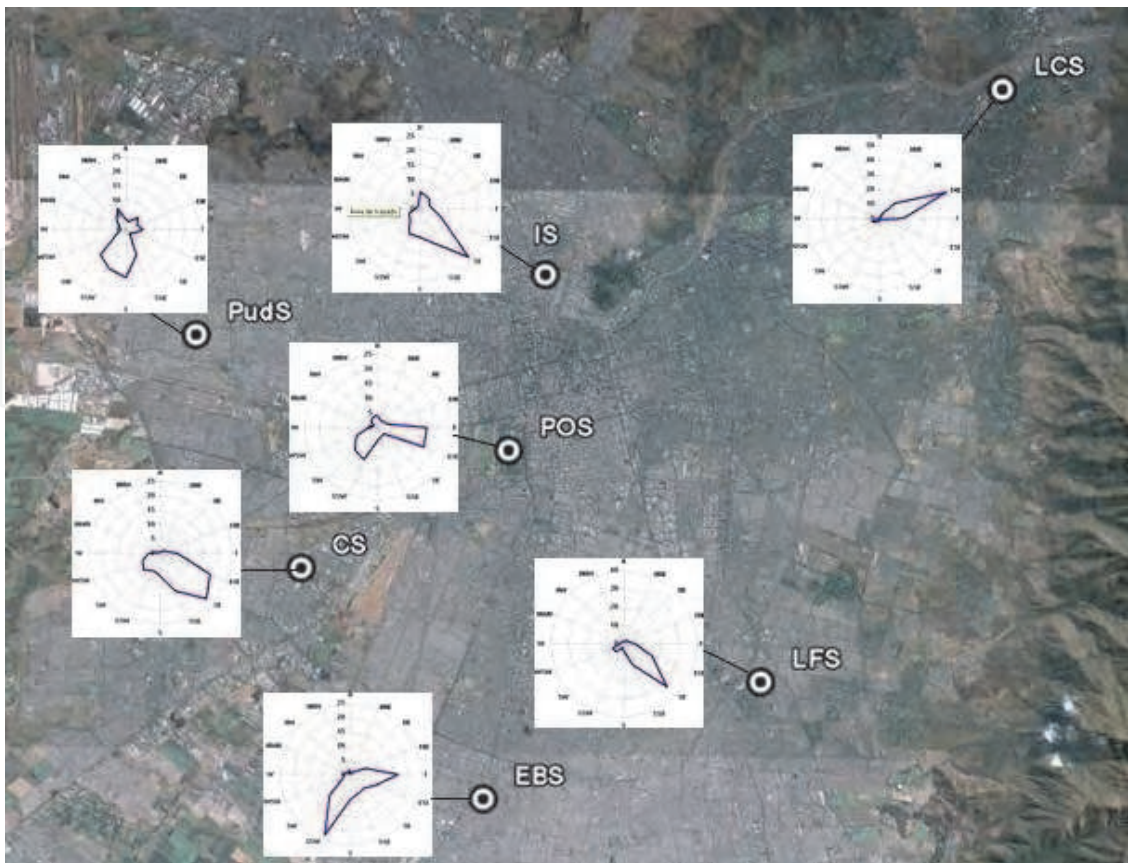


Fig. 13. Prevailing wind directions for days of A type episodes, at the hours of highest concentration of PM10 (18 to 23h) at MACAM2 network stations, years 2004 to 2007

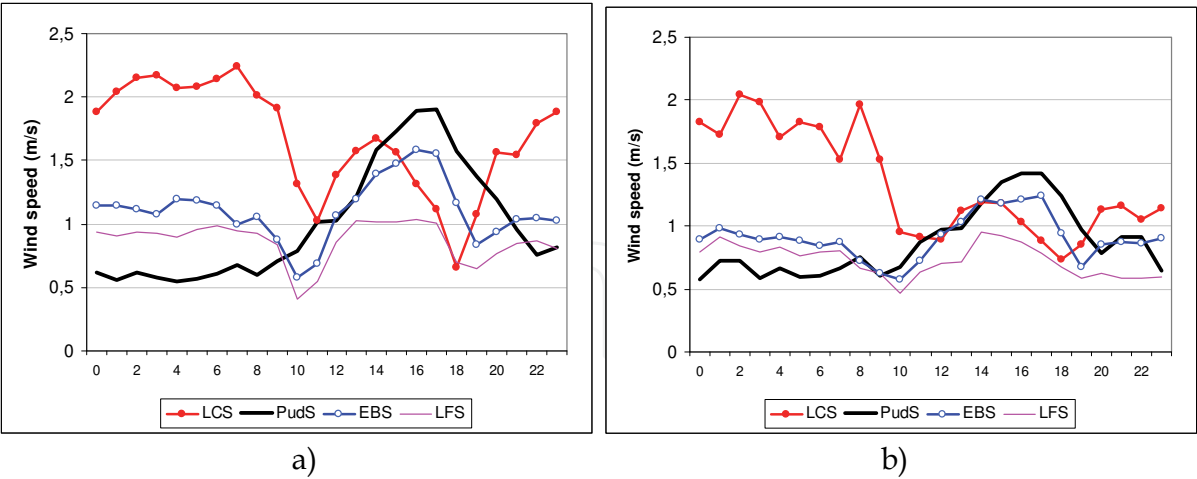


Fig. 14. Mean daily wind speed at LCS, LFS, EBS and PudS for A type (a) and BPF type (b) episodes during years 2004 to 2007.

3.4.1 Behaviour of hourly PM10 concentrations of local wind at Pudahuel station
Figs. 15 a) and b) show a negative correlation between hourly and daily PM10 concentrations and wind speed, respectively, recorded at PudS. The highest hourly concentrations ($> 400 \mu\text{g}/\text{m}^3\text{N}$) occurred with wind speeds between 0.5 and 1.5 m/s. Some high concentrations, with

speeds higher than 3 m/s, occurred in the afternoon during April, 2005. With wind speeds of 5 m/s the PM10 concentrations are lower than 100 $\mu\text{g}/\text{m}^3\text{N}$. Most days that exceed the value of the daily standard for PM10 have wind speeds averaging less than 1.5 m/s. In addition, there is no correlation between concentrations of PM10 and a predominant wind direction, particularly for very low wind speeds, unlike high speeds, for which a predominant direction remains for several hours. These results are broadly consistent with those reported by Muñoz et al. (2003).

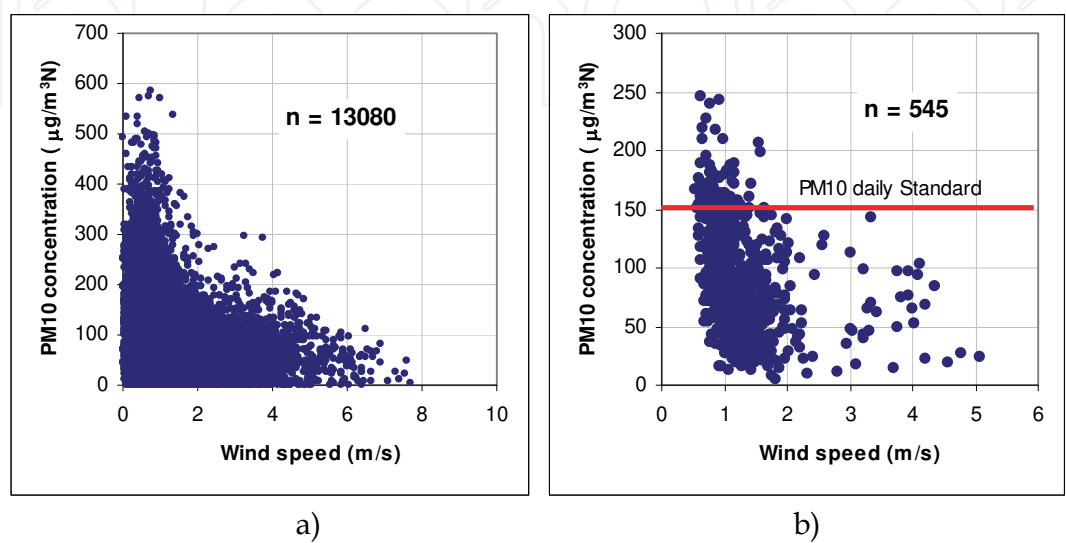


Fig. 15. Correlation between PM10 concentrations and wind speed at Pudahuel station. Period April to August, years 2004 to 2007; a) hourly values, b) daily values.

Fig. 16 shows the mentioned inverse correlation between mean concentrations of PM10 and wind speed. From 19h wind speed is less than 1.5 m/s and PM10 concentrations reach values close to 260 $\mu\text{g}/\text{m}^3\text{N}$ around 23h, coinciding with declining wind speed values to under 1 m/s, which suggests an impact of local emission sources more than the impact of distant sources that require wind to be transported.

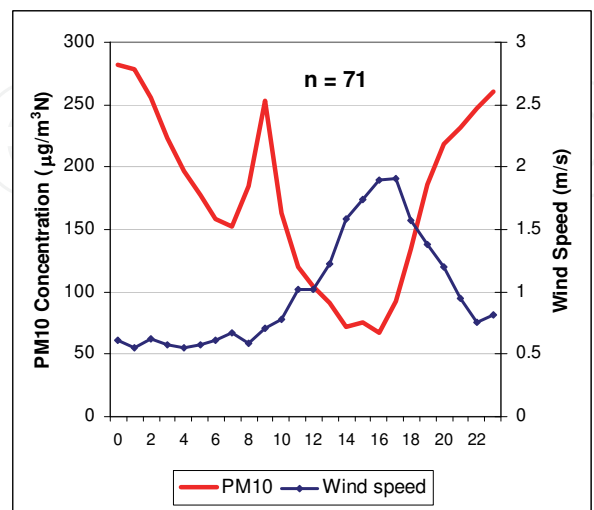


Fig. 16. Daily cycle of mean hourly concentrations of PM10 and wind speed, on days with PM10 concentrations above the standard. April-August period of 2004 to 2007 at Pudahuel station.

Fig. 17 shows the effect of the wind on episode days (35 days of A type, 19 days of BPF type) and 491 days under daily PM10 standard. It is again clear an inverse relationship between PM10 concentrations and wind speed including producing concentrations below the standard. This condition is more intense, from 18h, during days of A type episode than during days of BPF type episodes. At early morning the wind strength for the days of A and BPF type episodes remains close to 0.6 m/s. During days of episodes PM10 concentrations have at PudS a sharp increase around 08h associated with the begin of the city activity and vehicular traffic; during the afternoon, hours of more ventilation, occurs minimum concentrations.

Days of A type episodes show a different cycle of wind speed at LCS compared with Pudahuel, which means that during the night and early morning wind speed is greater (2 - 2.5 m/s). Along the day the wind intensity decreases and there is a change of direction from WSW to ENE at 10h, with a minimum of 1 m/s and from ENE to WSW at 18h, with a minimum of about 0.7 m/s. Days of BPF type episodes, show similar behaviour with lower intensity of the wind, especially at peak concentration hours at PudS (between 18 and 23h).

Consequently, the daily cycle of PM10 concentrations at LCS during episode days, is smaller than that at Pudahuel, even on occasions where PM10 concentrations at PudS have levels of alert or pre-emergency. The situation is similar during days of A and BPF type episodes, but the latter reach lower concentrations and higher wind speeds.

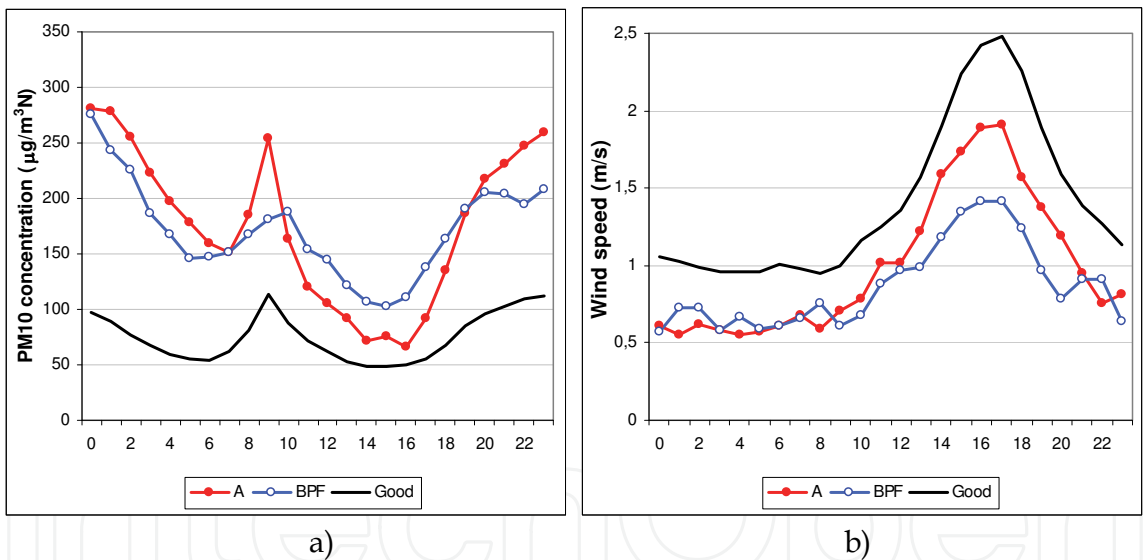


Fig. 17. Daily cycle a) mean hourly concentrations of PM10 and b) wind speed for days of A and BPF type episodes and days below the standard. April-August period of 2004 to 2007 at Pudahuel station.

3.5 Contribution of PM10 emission sources to PM10 environmental concentrations in Pudahuel

In the Pudahuel Commune, DICTUC (2007) has identified 147 stationary sources, mainly backup generators, bakery ovens and industrial boilers (CENMA, 2008b). Major stationary sources close to PudS are bakeries, bus terminals, and industrial boilers. The emissions of PM10 of Pudahuel Commune correspond to 1.5% of total emissions of industrial and mobile sources of the Metropolitan Region, as shown in Table 2.

	Light vehicles	Heavy trucks	Clean buses	Other buses	Industry	Total
Pudahuel	2,0	26,8	2,2	3,1	6,6	45,1
MR	514,0	763,0	221,0	94,0	1266,9	3017,2
% Pudahuel	0,4	3,5	1,0	3,3	0,5	1,5

Source: CENMA, 2008b and CONAMA, 2009

Table 2. PM10 emissions from mobile sources and industry to Pudahuel and Metropolitan Region, expressed as tons per year.

Table 3 shows the importance of estimating not only annual but also hourly emissions for major categories of industrial Pudahuel sources especially from 18h until the early hours of the next day, hours during which the PM10 environmental concentrations increase. For instance, backup power generator industries work just a few hours (79% of the hourly emissions), usually at night, during winter days in order to not exceed the limits of electricity consumption and pay fines to the electricity distribution companies.

Source category	Number of sources	Emission	
		Annual t/year	Hourly kg/h
Power Generators	36	1,0	6,2
Industrial Boilers	22	2,9	0,5
Heating Boilers	30	1,1	0,3
Bakery Ovens	39	0,4	0,4
Other Ovens	6	0,5	0,2
Others	14	0,7	0,3
TOTAL	147	6.6	7.9

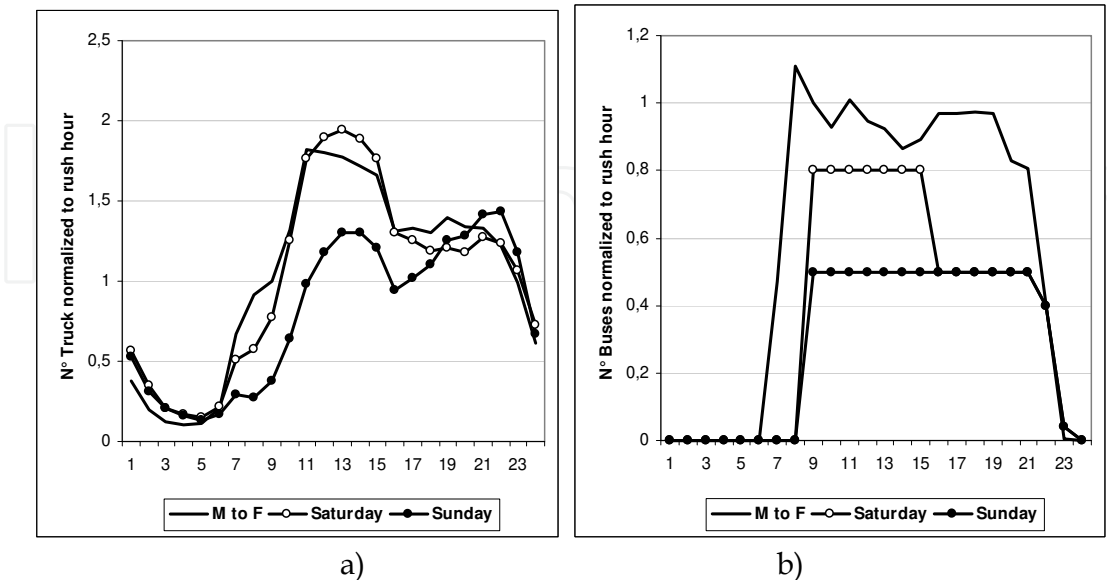
Source: CENMA, 2008b and CONAMA, 2009

Table 3. PM10 emissions from categories of industrial sources of Pudahuel

Figs. 18 a) and b) show that heavy trucks and buses are the major emission mobile sources in the area that includes the Pudahuel and other nearby Communes (DIMEC, 2007; DIMEC, 2007a). The flow is normalized to peak flow (09h) for working days (Monday to Friday) and weekends (Saturday and Sunday). The flow of heavy trucks has a similar behaviour every day, with a maximum between 10h and 13h. During the evening the flow decreases by 30% compared with the morning. On Sunday, the morning flow decreases by 30% in relation to the week maxima, but it has the highest values at night, between 21h and 22h. Buses (diesel) show differences in the flow of working days and weekends. During the week, there is an increase before the peak, which may be associated with the departure of buses from the large number of bus terminal stations in the area. Between 10h and 22h the flow remains between 90%-100%, of the rush hour, but between 23h and 06h the movement is virtually null. On Saturday morning circulation is equivalent to about 80% and during Sunday afternoon, about 50% of working days.

Mobile and industrial sources show lower emissions on weekends, which do not explain the increased concentrations of PM10 during weekend nights, so that increased concentrations

should be associated with untested local sources, including all kinds of home heating fuels and the dust recycled from streets and roads, by a greater flow of private vehicles.



Source: DIMEC, 2007 and DIMEC, 2007a

Fig. 18. Daily cycle flow normalized to peak in sector 5 for: a) heavy trucks, b) buses

According to Artaxo (1999) the chemical analysis of the fine and coarse fractions of PM₁₀ in PudS during the winter of 1998 shows 3 major sources: soil dust, transport and copper smelting (S + As + Cu). In the coarse fraction, 88% (73 $\mu\text{g}/\text{m}^3$) was attributed to soil dust, 9% to sources emitting S + As + Cu, and 3% to transport. For the fine fraction, the main source was associated to copper smelting with 48% (15 $\mu\text{g}/\text{m}^3$), 32% to transport and 20% to soil dust. Reanalysis of that information done for this study, separating the episode days (alerts and pre-emergency) from the good days (concentrations $<100 \mu\text{g}/\text{m}^3$) maintains the 3 sources but shows an increase in the concentrations in both fractions on the episode days. In addition, there is a change in the relative contribution of the sources of fine and coarse fractions. The largest increase is for element concentrations associated with the smelting of Cu (6 to 22 $\mu\text{g}/\text{m}^3$) followed by soil dust (5 to 11 $\mu\text{g}/\text{m}^3$); for the coarse fraction, the major increase corresponds to soil dust (60 to 135 $\mu\text{g}/\text{m}^3$), smelting of Cu (44 $\mu\text{g}/\text{m}^3$) and transport (20 $\mu\text{g}/\text{m}^3$). These results indicate that despite the measures taken by the government (CONAMA, 1997) to reduce emissions from factories and transportation for episode days, an increase in PM₁₀ concentrations is occurring, associated with the 3 sources, especially the coarse fraction. Similar results, but for smaller PM₁₀ concentrations, were obtained by Gramsch (2006), in a campaign conducted in 2005. It is interesting to note that this study assigns 50% of PM_{2.5} to carbon (39% to organic C and 11% to inorganic C).

3.6 Guidelines to improve the management of air quality of Pudahuel and Santiago basin

The first version of PPDA for the Metropolitan Region (CONAMA, 1997) considered 139 measures to improve air quality throughout the city of Santiago, including 104 actions to direct and permanently reduce emissions of major pollution sources; 26 management actions for pollution episodes (PGEC), including events of alert, pre-emergency, and

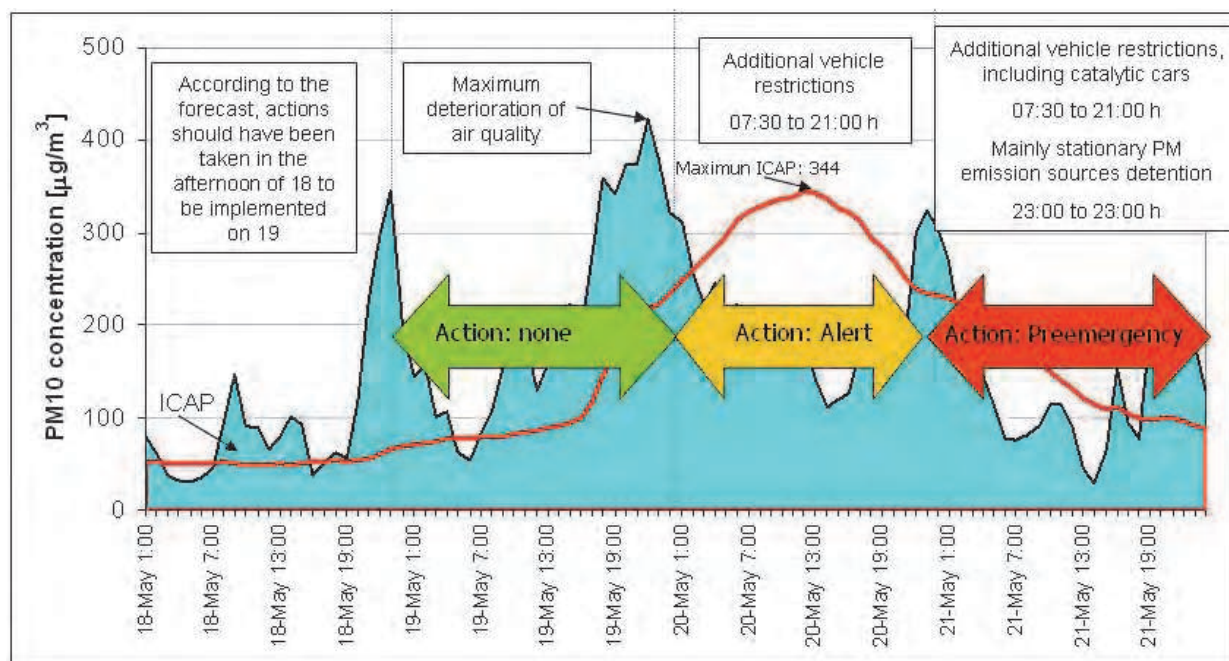
emergency: 9 actions for indirect reduction of emissions, i.e., public participation and education.

The PPDA considered a revision and update twice to meet in force the primary standard for the year 2012. Initially, structural measures were considered with a strong impact on reducing industrial emissions of particulate matter and gases, namely modernization of public transport, use of cleaner fuels and accomplishment of goals for reducing industrial emissions. Later, the revision and update of the plan (CONAMA, 2009), strengthened and deepened structural measures to reduce the fine fraction of PM₁₀ by controlling and reducing NO_x emissions, some VOCs, SO_x and NH₃.

In the case of Pudahuel, those measures are of weak impact considering that the industrial sources of the commune represent only 1.5% (147 sources) of the total annual emissions in the Metropolitan Region. However, the backup power generator groups correspond to 79% of hourly night emissions.

The PGEC of the PPDA has three components: 1) Forecast of air quality for PM₁₀, 2) permanent control of emission sources during critical events and 3) public communication of air quality, recommendations and actions. For the period April 1st to August 31th it also establishes permanent actions including restriction of circulation for vehicles without catalytic converters, prohibition of agricultural burning in the entire Metropolitan Area and sweeping of streets according to budget availability. During episodes some of these restrictions are increased depending on the quality of the episode (alert, pre-emergency or emergency).

The forecasting system for PM₁₀ episodes established in 2000 has a preventive nature, recommending actions depending on the probable 24h rolling averages maximum for the next day. The announcement is made about 21h on television and on the CONAMA website. Results show that for short episodes (1 day) actions are taken when the problem has already occurred. Fig.19 illustrates the case on May 21, 2006.



Source: CENMA, 2007

Fig. 19. Episode of May 21, 2006

To improve the management of air quality we suggest that the recommendation proposed by CENMA (2008) be taken into account by changing the present forecasting procedure to considering the use of the mean value from 06h to 05h of the previous day and move the announcement of the action to 18h, warning when high concentrations are detected at night time, especially at PudS. In addition, it was recommended that forecasting point models for the periods of high concentrations be developed, usually between 18h and 23h.

PPDA measurements are applied to the entire Metropolitan Area, with no specific proposals for individual Communes. For Pudahuel the results show an increase in both fractions of PM₁₀ (fine and coarse) in recent years. Regarding the coarse fraction, there are many diffuse sources of recycled dust, which involves implementing specific actions to reduce these emissions, including an important increase in green area surfaces. For the fine fraction there should be greater control and an educational campaign to prevent the wrong environmental practices detected. Other specific actions for the Pudahuel area might include:

i) development of programs to improve the conditions of streets and roads, access to terminals bus stations and street sweeping program to meet for example, the standard of the State of California (USA); ii) improvement in the control of industries, households, small size sources using firewood, particularly on episode days; iii) development of incentive programs for the setting up of mitigation and control systems to decrease emission sources; iv) development of programs to improve thermal insulation and housing subsidies for the purchase of clean-fuel heating equipment operating on clean fuels; v) creation of media mechanisms (Internet, radio or community television, neighbourhood associations and others) to prevent exposure and physical activity of the population during periods of high concentrations of PM₁₀.

4. Conclusions

The results of this study support the existence of spatial heterogeneity of air quality for the population of the city of Santiago. Pudahuel commune has its own characteristics, due to both meteorological conditions and to emissions sources of particulate matter that determine the concentrations of this pollutant observed in some days of the autumn-winter period. Consequently, the concentrations observed are not necessarily representative of the Metropolitan Area. As a result, management of episodes can not be based only on PM₁₀ concentrations observed at Pudahuel station.

It is clear that a very specific campaign must be implemented to decontaminate Pudahuel. But it is also clear that there is a necessity to implement an environmental policy to manage air quality as a support to health and quality of life of people living or working in specific communes. These actions should be subsidized by the State or should be included in measures funded by private companies for instance as part of corporate social responsibility activities.

Since the environmental policy began to be implemented in Chile, the authority has used the "prevention principle" to determine PPDA actions, which may have certain advantages when the State has some level of basic information on air quality. This idea has led the authorities to consider PudS as key to determining environmental alerts. This study shows that, given the spatial heterogeneity of air pollution, a more detailed knowledge of pollution in Santiago would focus on more effective measures at local level which could be managed from the same municipalities in coordination with the metropolitan government.

5. Acknowledgment

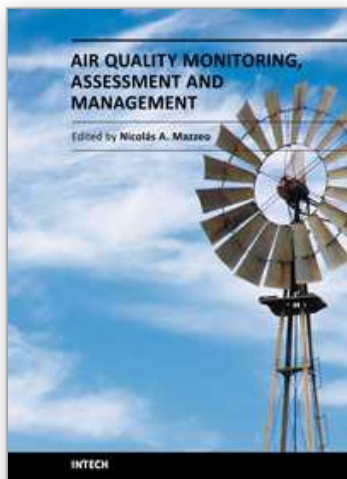
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Human beings need to breathe oxygen diluted in certain quantity of inert gas for living. In the atmosphere, there is a gas mixture of, mainly, oxygen and nitrogen, in appropriate proportions. However, the air also contains other gases, vapours and aerosols that humans incorporate when breathing and whose composition and concentration vary spatially. Some of these are physiologically inert. Air pollution has become a problem of major concern in the last few decades as it has caused negative effects on human health, nature and properties. This book presents the results of research studies carried out by international researchers in seventeen chapters which can be grouped into two main sections: a) air quality monitoring and b) air quality assessment and management, and serves as a source of material for all those involved in the field, whether as a student, scientific researcher, industrialist, consultant, or government agency with responsibility in this area.

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