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Examination of pollution trends in Santiago de Chile with cluster analysis of PM_{10} and Ozone data

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Abstract

Because of the high levels of pollution that Santiago de Chile experiences every year in winter, the government has set up an air quality monitoring network. Information from this network is employed to alert people about the quality of air and to enforce several control strategies in order to limit pollution levels. The monitoring network has 8 stations that measure PM_{10}, carbon monoxide (CO), sulphur dioxide (SO_2), ozone (O_3) and meteorological parameters. Some stations also measure nitrogen mono- and dioxide (NO_x), fine particles ($PM_{2.5}$) and carbon. In this study we have examined the PM_{10} and O_3 data generated by this network in the year 2000 in order to determine the seasonal trends and spatial distribution of these pollutants over a year's period. The results show that concentration levels vary with the season, with PM_{10} being higher in winter and O_3 in summer. All but one station, show a peak in PM_{10} at 8:00 indicating that during the rush hour there is a strong influence from traffic, however, this influence is not seen during the rest of the day. In winter, the PM_{10} maximum occurs at 24:00 h in all stations but Las Condes. This maximum is related to decreased wind speed and lower altitude of the inversion layer. The fact that Las Condes station is at a higher altitude than the others and it does not show the PM_{10} increase at night, suggest that the height of the inversion layer occurs at lower altitude. Cluster analysis was applied to the PM10 and O_3 data, and the results indicate that the city has four large sectors with similar pollution behavior. The fact that both pollutants have similar distribution is a strong indication that the concentration levels are primarily determined by the topographical and meteorological characteristics of the area and that pollution generated over the city is redistributed in four large areas that have similar meteorological and topographical conditions.

Keywords: Particulate matter; Ozone; Cluster analysis

1. Introduction

The high levels of pollution that are observed in many large cities of the world have well documented consequences for human health (Lee et al., 2000; Dockery et al., 1997). Santiago has high levels of

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pollution throughout most of the year, with high PM_{10} levels in winter, and high O_3 levels in summer. It is common to observe an increase in the number of children's hospitalizations due to respiratory diseases following a pollution event in winter to (Ostro et al., 1999; Sanhueza et al., 1999), even an increase in daily mortality was observed (Cifuentes et al., 2000; Ilabaca et al., 1999). Particle mass concentration (PM_{10}) averages near $300\,\mu g\,m^{-3}$ are frequent in the western part of Santiago (Pudahuel, Cerrillos). Some isolated events of $500\,\mu m\,m^{-3}$ or more occur several times during winter (Jorquera et al., 1998; Perez et al., 2000; Artaxo et al., 1999). Another effect that contributes to the high particle levels observed in winter is the temperature inversion. The height of the inversion layer during winter could be as low as 300 m at night and early morning (Gramsch et al., 2000), in summer, it reaches 2000–3000 m (Rutland and Garreaud, 1995). Ozone is a secondary pollutant and its concentration depends on the concentration of primary pollutants (NO_x, VOC) and the intensity of solar UV radiation, thus ozone concentration is high during summer. Ozone hourly maxima reach concentrations levels between 100 and $150\,\mu g\,m^{-3}$ with some isolated events as high as $320\,\mu g\,m^{-3}$ in the eastern part of the city (Las Condes) which is located downwind from the center of the city. The Chilean norm for ozone is $160\,\mu g\,m^{-3}$ hourly maximum; however this norm is exceeded more than 140 days per year.

Because of the potential health effects associated with elevated levels of PM_{10} and Ozone, the government developed a number of control strategies to help reduce pollution. In 1994, the "Environmental-Base Law" (Conama, 1994) was passed and directed the National Commission for the Environment (Conama) to develop a pollution-control plan for Santiago and its surroundings. This plan,—which was completed on July 1, 1997—, provided the framework for the decontamination effort in Santiago. The Plan established specific emission reduction targets for the most common pollutants such as particulate matter with aerodynamic diameter $<10\,\mu m$ (PM_{10}), ozone (O_3), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and carbon monoxide (CO). The Plan also provides the legal framework to enforce the control strategies needed for the pollution reduction efforts in Santiago (Conama, 1997). The first strategies implemented in the early 1990 were directed towards removing fixed sources like diesel electric generators, waste burning, and large wood and coal heaters. Afterwards, the quality of the public transportation buses was improved, all new cars were required to have catalytic converter, and many streets were paved. Currently, the efforts are directed towards improving the public transportation and reducing the number of private cars used in the city. However, nothing has been done to reduce pollution from kerosene and wood burning for house heating.

An important part of the plan was to set up a network of eight monitoring stations (Macam network) distributed around the city and operated by the Ministry of Health. In 1995, five monitoring stations were located near the center of the city. Later it was determined that this arrangement did not cover areas with high pollutant levels and most contamination events (days with high average PM_{10} levels) were not detected. In 1997, new stations were added and some were closed. The new configuration has eight stations distributed across the city that measure PM_{10}, O_3 and CO on an hourly basis.

Table 1
Years of operation, pollutants measured and altitude over sea level for the monitoring stations of the Macam network

Station	Las Condes	Providencia	La Paz	Parque O'Higgins	La Florida	Pudahuel	El Bosque	Cerrillos
First year of operation	1988	1988	1988	1988	1997	1997	1997	1997
CO	X	X	X	X	X	X	X	X
SO_2	X	X	X	X	X	X	X	X
O_3	X	X	X	X	X	X	X	X
NO_X/NO_2	X	Until 1996	—	Until 1996	—	X	—	X
PM10	X	X	X	X	X	X	X	X
PM2.5	X	—	—	X	X	X	—	—
Height (m)	700	550	530	500	500	480	470	470

X, contaminant being measured, —, not measured.

In addition, there are several stations that also monitor organic and elemental carbon, $PM_{2.5}$, NO_x and nitrate. Information on the years of operation and pollutants measured for all the stations of the Macam network is shown in Table 1.

Although the stations are better distributed across the city (Schmitz, 2004; Silva and Quiroz, 2003), the new monitoring network is still not optimized. It is for example not known whether all sectors with high pollution levels are monitored or if there are too many stations covering a sector with similar concentrations levels.

The objective of this study was to perform an analysis of the data generated by the Macam network to determine the pollution trends in the city and to determine which areas of the city have similar pollution behavior and may be covered by too many stations of the network.

2. Methods

2.1. Experimental

PM_{10} was measured with a Tapered Element Oscillating Microbalance (TEOM 1400) monitors from Rupprecht & Patachnick, Albany, New York. The instrument uses an oscillating hollow tube with the free end attached to a filter element. Due to accumulation of particles, the filter mass changes and the oscillating frequency changes, providing a measurement of the mass. The tapered tube, filter, and sampled air are kept at 50 °C. The sampling interval was set to 15 min.

Ozone was measured with 400 E UV absorption analyzers from Teledyne Instruments, Los Angeles, CA. A 254 nm UV light signal is passed through the sample cell where it is absorbed in proportion to the amount of ozone present. Using the Lambert–Beer law, it is possible to obtain the ozone concentration with a lower detectable limit is of 0.6 ppb. Meteorological parameters (wind speed and direction, temperature, humidity and pressure) are measured at all stations of the Macam network with standard equipment with 5 min time intervals at 3 m height.

Every day, PM_{10} and O_3 data were obtained in the year 2000 at all eight stations of the Macam network. Monthly and hourly averages were calculated for both pollutants. The hourly average is obtained by selecting all the data collected at a specific hour, and averaging over all days of the month.

2.2. Sampling sites

The study was performed in Santiago de Chile, a city with a population of almost 6 million. Santiago is located in a relatively flat valley at an altitude of 500 m. There are two hills inside the city, San Cristobal, with an altitude of 800 m above sea level and Cerro Renca of 700 m height. The Andes mountain range is located to the east, with hills up to 5500 m. A smaller coastal mountain range is located in the west, with hills up to 2000 m. The map in Fig. 1 shows the locations of the Macam network monitoring stations and the topography of the city.

The station of the Macam network that measures the quality of air in downtown Santiago is Parque O'Higgins. It is placed in a large park about 2 km south of the city center and 1 km west of a major highway with a traffic of about 60 000 vehicles per day. The area has a mixture of houses, retail and light industries (machine shops, auto repair shops, furniture manufacturing shops, etc.). This station monitors PM_{10}, $PM_{2.5}$, O_3, CO, SO_2, elemental and organic carbon and meteorological parameters. A list of the monitors and the height above sea level for all stations is given in Table 1. Two other stations are near downtown, Providencia and La Paz.

Providencia is a station located about 3 km east of the city center, about 30 m north of Providencia street with a traffic of 40 000 vehicles per day. This site has some commercial activity, and many office buildings. The station is located in a park near the Mapocho river and it is surrounded by trees. La Paz is located in the northern part of Santiago, in between two large roads with about 25 000 vehicles per day that run in the north–south direction. These roads have a lot of commercial activity with many small retail stores, some light industries, and a large hospital nearby.

The stations that are located in the western part of the city are Pudahuel and Cerrillos, primarily in residential areas. Pudahuel station is located in the western part of Santiago; it is placed in a small park, near a medical clinic. Two major roads are in this area: one towards the south with traffic of about 20 000 vehicles per day and one in the west with about 15 000 vehicles per day. These roads show a lot of commercial activity with many small retail stores. The rest of the area is mainly residential. Cerrillos is also located in the western part of Santiago near a street with 30 000 vehicles per day. The area has some of commercial activity with

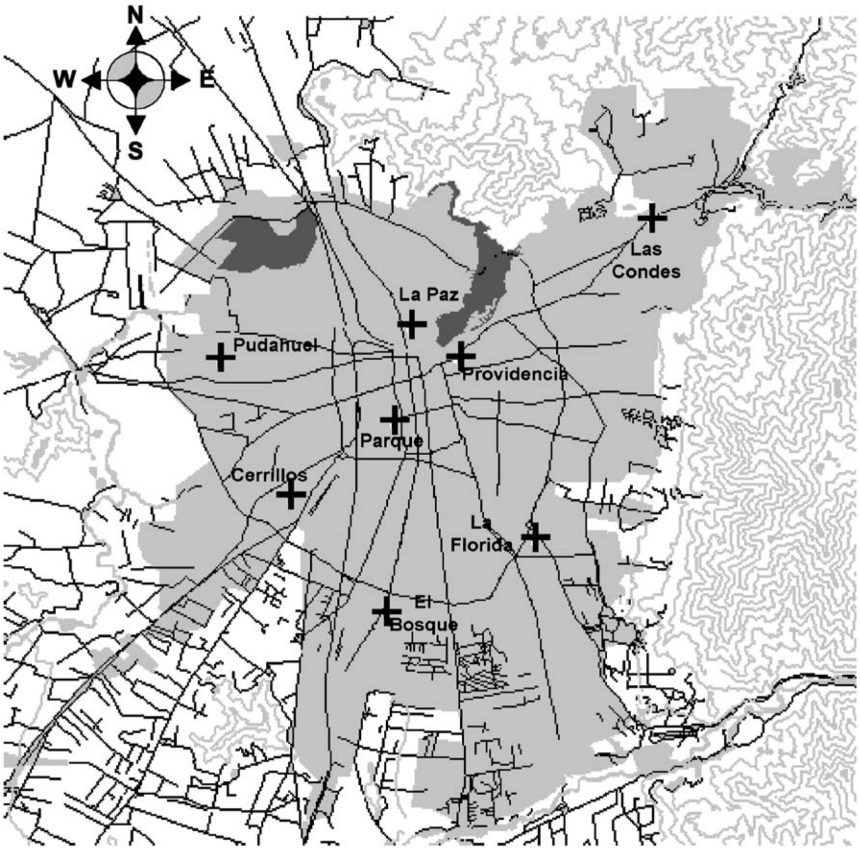

Fig. 1. City of Santiago de Chile showing the location of the monitoring stations.

many light industries around. An airport is located towards the south of the station.

Las Condes is located in the eastern part of Santiago at an altitude of 700 m above sea level. It is placed in a park, south of a street with about 15 000 vehicles per day. The area is primarily residential, with some retail stores located around the larger streets.

La Florida and El Bosque are located in the southern part of Santiago. Both stations are located close to large streets, in an area with growth in real estate. La Florida station is located about 500 m north of a road with a traffic 30 000 vehicles per day, east of another road with 55 000 vehicles and west of a third road with about 35 000 vehicles per day. The area has a lot of commercial activity, heavy traffic, several residential buildings and a residential area with one story houses. El Bosque is a station located in the south-west part of Santiago, near a highway with about 60 000 vehicles per day. The area has some commercial activity with light industry but mainly contains residential buildings and one story houses.

2.3. *Traffic information*

The flux of vehicles per day was obtained from the ''Demand Equilibrium Model for Multimodal Urban Transportation Networks with Multiple User Classes'' (ESTRAUS). This model simulates the operation of a city's urban transportation system and it is used by the Ministry of Transportation to evaluate the impacts on the urban transportation system of implementing different road infrastructure projects (highways, metro lines, bus corridors, etc.) as well as transport policies (road pricing, transit integrated pricing systems, street reversibility, increase in gasoline taxes, etc.).

2.4. *Statistical methods*

The study was performed using cluster analysis with the Statistical Analysis System, SAS program V.6.12 (SAS Institute Inc.) to classify the stations according to the distance between them. The distance between two stations was defined with the

Pearson correlation function. When the correlation approaches one, it indicates that the temporal behavior of the data is similar. For example, if two stations show an increase in PM_{10} at rush hour and a decrease in the afternoon, the correlation will be close to one, independent of the concentration level. Hence, it is possible to have stations with different average pollution levels and similar temporal behavior that have close correlation.

The cluster analysis procedure is realized by requiring that the intra-variance within a group of stations be less than a certain number, R_i. This number is the sum of the intra-variance of the groups divided by the total variance. Because of a normalization procedure for the data, the total variance of the groups is 8, because there are eight stations. This number (R_i) determines how close the elements of a group are to each other. The variances are defined by

$$\text{Total variance} = \frac{\sum_{i=1}^{n}(x_i - X)^2}{N}$$

$$\text{Intravariance} = \frac{\sum_{i=1}^{N_h}(x_i - x_h)^2}{N},$$

where x_i is the hourly average for the station, x_h is the average inside the group h, X is average of all stations, and N is the total number of elements.

A study of the data from Santiago's monitoring network was done using an index of multivariate effectiveness (Silva and Quiroz, 2003), based on Shannon information index. They found that data (CO, PM_{10}, O_3 and SO_2) from one of the stations (Parque O'Higgins) could be reproduced by using information from the other stations.

3. Results

3.1. Seasonal variation of PM_{10} data

Concentrations of particulate material (PM_{10} and $PM_{2.5}$) show a seasonal trend, with the highest concentrations during winter and the lowest concentrations during summer in the whole city. The average monthly PM_{10} concentration can be seen in Fig. 2, showing higher concentration in March through August. For clarity, only four stations are shown in Fig. 2: some are located in the eastern part of the city (Las Condes), south (La Florida), one in the center (Parque O'Higgins) and western part of the city (Pudahuel).

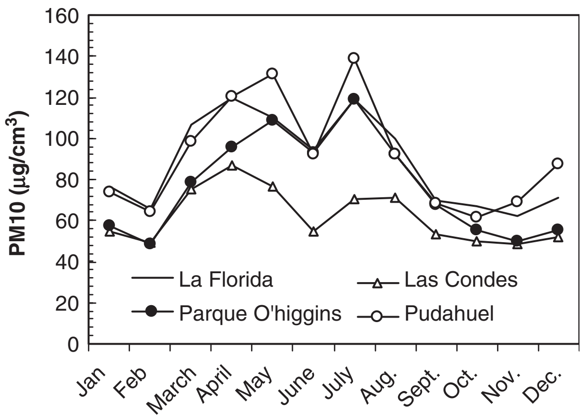

Fig. 2. PM_{10} monthly average in four stations in Santiago in the year 2000.

The station that has the highest PM_{10} concentrations throughout the whole year is Pudahuel (slightly higher than La Florida). In the first part of the year (January–May) and in November and December, Pudahuel has higher concentrations than Parque O'Higgins and Las Condes. In August through October, Pudahuel and Parque have similar PM_{10} concentration. PM_{10} during June was lower because it was a rainy month (334.2 mm compared to 10.4 mm in May and 40.8 mm in July), indicating that when the ground is wet less large particles are re-suspended and PM_{10} is washed out from the atmosphere by rain. In Santiago, the winter months (May–August) are cold with moderate rain and low wind speeds. Summer is hot and dry and the average wind speed is higher than the other months. An analysis of the wind pattern can help explain the PM_{10} trends.

The wind pattern in Santiago is complicated because of the complex topography. The city is surrounded by two mountain ranges with several isolated hills in between. In the afternoon, in the eastern part of the city the wind is from west to east, from the valley towards the mountains and, at night, the direction reverses to an east to west direction (from the mountains towards the valley). However, the wind speed and direction vary a lot, and is dependant on the location of the sampling site. In June (Fig. 3) the stations located in the western part of Santiago (Pudahuel, Cerrillos) have higher wind speeds in the afternoon. Because the wind comes from the west, it brings clean air into this part of the city. However, at night the wind that comes from the mountain (east) does not reach Pudahuel or Cerrillos and there is very high

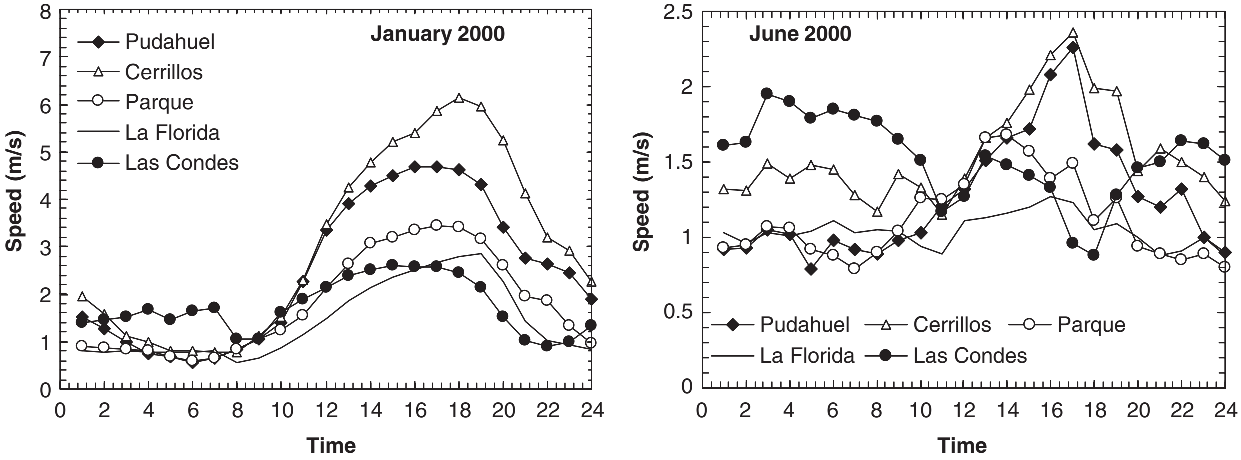

Fig. 3. Hourly average wind speed in January (summer) and June (winter) for several stations of the Macam network.

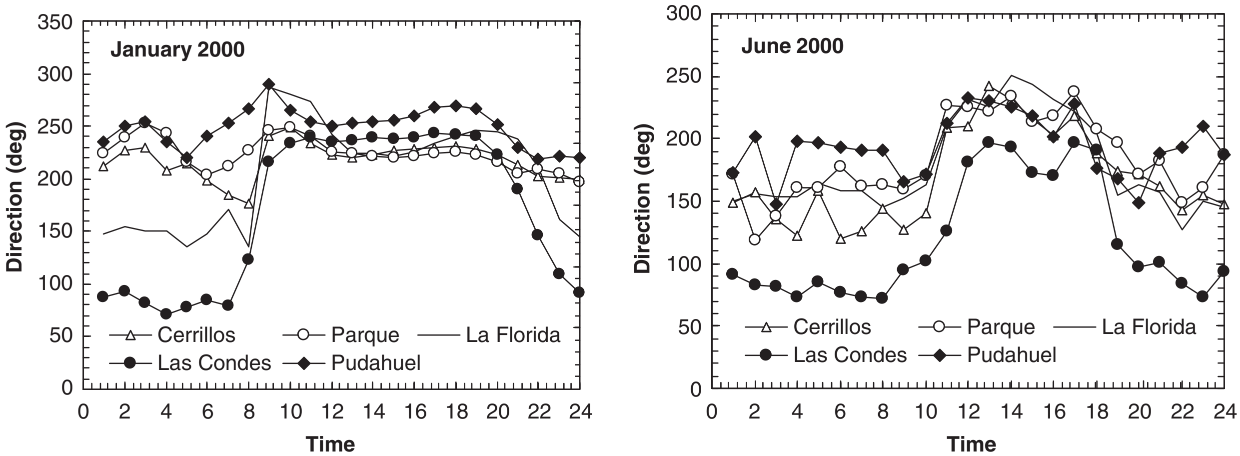

Fig. 4. Hourly average wind direction in January (summer) and June (winter) for several station of the Macam network.

atmospheric stability in this part of the city. This effect can be seen in Fig. 3, the stations located in the western part of the city (Pudahuel and Cerrillos) have high wind speeds between 14:00 and 19:00, but very low speed between 20:00 and 6:00. During the afternoon the wind comes from the south-west, which corresponds to a direction between 200 and 240°, as can be seen in Fig. 4. At night the wind comes from the south–east (150–200°). Wind characteristics during the other winter months are similar to the observations presented for June.

Throughout summer (December–March), the sites located in the western part of the city (Pudahuel, Cerrillos) have higher PM_{10} because the stations are located at the edge of the city, close to undeveloped land. In this area wind blown dust, increases the PM_{10}. As seen in Fig. 3, the wind speed in summer is much higher in Pudahuel and Cerrillos, up to $6\,m\,s^{-1}$ than the stations at the central or eastern part of the city, Parque or Las Condes, $3.5\,m\,s^{-1}$. This difference can explain the higher average PM_{10} that is measured in Pudahuel or Cerrillos. It is important to note that the high PM_{10} concentration that is seen in Pudahuel during summer is probably not harmful because most of it is natural dust: Ca, Al, Si, Ti, Fe and Sr (Artaxo et al., 1999). In summer, PM_{10} levels in Las Condes and Parque O'Higgins are lower than the other stations (as seen in Fig. 2) because in these sectors of the city most streets are paved and the wind speed is less. Thus, re-suspended dust from the west does not reach Parque O'Higgins or Las Condes stations.

To illustrate the correlation of particle matter with traffic and wind speed, the PM_{10} hourly average for several months has been calculated for two stations, Pudahuel and Las Condes, respectively (Figs. 5 and 6). PM_{10} for the Pudahuel station (Fig. 5) is shown for several months of the year 2000. January, March and November correspond to warmer months, June and July corresponds to the colder months of the year. This plot shows several interesting trends in the PM_{10}. For all months it is possible to discern a peak at 8:00 which is most likely due to vehicular emissions during the morning rush hour. In the warmer months (January, March and November) there is a peak in PM_{10} occurring at 20:00 h, decreasing at 24:00 h, showing the influence of the evening rush hour. In the colder months (June, July) the maximum is shifted towards later hours, peaking at 23:00–24:00 h. This increase is caused by a reduction of atmospheric turbulence that also reduces dispersion of pollutants and it is not related to traffic. As shown in Fig. 3, the wind speed at night decreases to 1–1.5 m s^{-1}. In addition, during winter large temperature differences can occur between day and night (up to 25 °C). Cooling of the surface's earth at night generates a temperature inversion that reduces the air turbulence. This effect leads to a well-known accumulation of pollution in this area of Santiago (Rutland and Garreaud, 1995; Gramsch et al., 2000). Results for the other winter months and for most other stations are similar showing the same pattern.

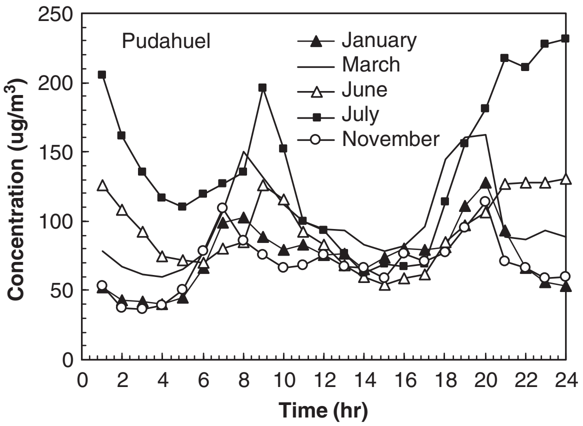

Fig. 5. PM_{10} hourly average in Pudahuel station in the year 2000.

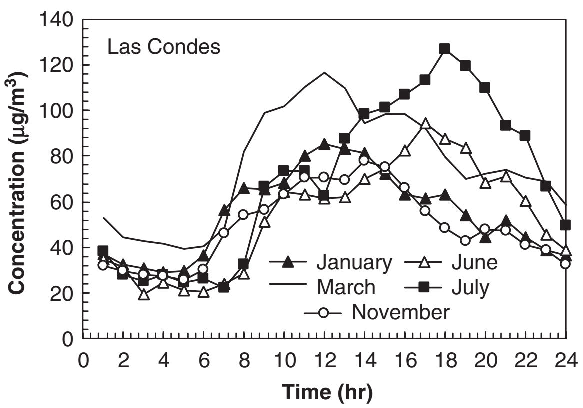

Fig. 6. Hourly average of PM_{10} at Las Condes station in the year 2000.

The data for Pudahuel indicate that vehicular emissions have a clear influence on PM_{10} only in the morning. In the evening a clear influence from the rush hour traffic on the PM_{10} is seen only in summer (November, January and March). During the other hours PM_{10} seems to be influenced by the wind and temperature inversion.

In the afternoon (12:00–18:00 h) there is a decrease in PM_{10} in Pudahuel which is due to an increase in the wind speed and clean air coming from the west. The wind speed and direction shown in Figs. 3 and 4, confirm this fact. It has to be noted that PM_{10} decreases in the afternoon in spite of the fact that emissions from vehicles remain approximately constant (because the flux of vehicles does not decrease much).

The only station in which PM_{10} has a different pattern is Las Condes. Fig. 6, shows the PM_{10} hourly average. The peak in the morning or evening cannot be seen, indicating that there is little influence from traffic. Instead, a wide peak in the afternoon is observed, which is most likely due to transport of pollution from downtown. The wind pattern shown in Figs. 3 and 4 indicates that in Parque O'Higgins in the afternoon the wind direction is 230–250°, i.e. directed towards Las Condes with a speed of 2–2.5 m s^{-1}. This wind can carry pollution from downtown towards Las Condes site. Another feature of the data in Fig. 6 is that the PM_{10} peak at night due to the temperature inversion cannot be seen for any month in Las Condes station, while in Pudahuel it is very clear in June and July. The altitude of the Las Condes site is about 250 m higher than Pudahuel, probably located near or above the inversion layer. This could also explain the lower concentrations seen at this station.

At night and early morning, the wind coming from the north-east cleans the eastern part of Santiago (Las Condes), but it takes the pollution from downtown towards the west, therefore increasing PM_{10} levels in Pudahuel, Cerrillos and El Bosque. As seen in Fig. 3, at night the wind decreases in magnitude as it reaches the central and western part of Santiago, thus it is not strong enough to clean the area.

3.2. Ozone data

Ozone is a secondary pollutant that is generated through reactions of NO_2 and NO with O_2 in the atmosphere with intervention from UV radiation. Thus, ozone is generated primarily in summer and during the hours when the UV radiation is a maximum. In Fig. 7, hourly average of ozone concentrations are shown for several months in 2000 for the Las Condes site. The correlation between ozone concentration and UV radiation is clearly seen because the shape of the UV radiation curve is very similar to the concentration curve. Although not shown, results for the other months of the year show a similar shape. The data for the stations in the east part of the city (La Florida, Providencia and La Paz) are also similar, and peak with UV radiation. However, in the stations located in the west part of the city (Pudahuel, Cerrillos, El Bosque), the O_3 concentration shape is different than the UV radiation shape (Fig. 8), remaining high into the evening. In this area of the city, the average ozone levels are lower, and the peak is not as pronounced because the station is located upwind from the center of Santiago. Therefore, the NO and NO_2 generated in downtown do not reach these stations and only local pollutants are responsible for the generation of ozone.

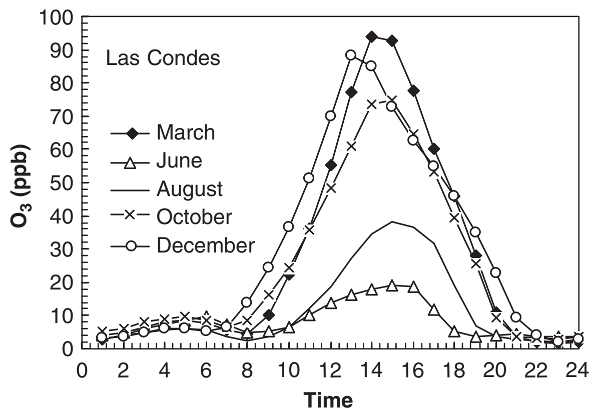

Fig. 7. Average O_3 concentration at Las Condes station in the year 2000.

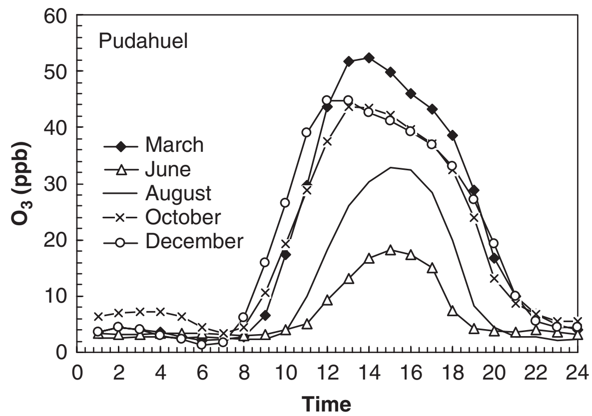

Fig. 8. Average O_3 concentration at Pudahuel station in the year 2000.

3.3. Cluster analysis

The geographical distribution of the stations in the Macam network in Santiago was not the result of a study of pollution levels, but the stations were placed in sites thought to be representative of large sectors of the city. One of the aims of this study is to determine if there is redundancy of the stations, and whether there are sectors of the city that have similar concentration levels and pollution patterns. The cluster analysis outlined in Section 2.4 was applied to the PM_{10} and O_3 data for the year 2000. The results of the process for PM_{10} are shown in Table 2. When $R_i = 0.724$, the stations are separated into two groups, with each group having the smaller possible intra-variance. The groups correspond to stations located in the west-central part of the city (Pudahuel, Parque and Cerrillos) or the eastern part (Providencia, La Paz, La Florida, El Bosque, Las Condes). If a higher R_i is imposed, i.e. that the members of the group are more related to each other, more groups start to appear. Las Condes station breaks away and forms a separate group, indicating that the behavior of the station is different than all of the others. This can also be seen in Figs. 5 and 6, which show that the temporal behavior of PM_{10} in Las Condes is very different than Pudahuel (or the other stations). There is an increase in PM_{10} in Las Condes in the afternoon (12–16 h), and Pudahuel has a decrease in PM_{10}. If R_i is set to 0.855, four groups of stations are obtained, in which it is possible to see a topographical trend. The stations in the central-west part of the city are grouped together; the stations in the south (El Bosque and La Florida) and the stations in the north (Providencia and La Paz) are also

Table 2
Results of the cluster analysis of PM_{10} data

Iteration	Cluster no	Group members	Intra-variance	Ratio of intra to total variance, R_i
1	1	All	4.990	0.624
2	1	Parque Pudahuel Cerrillos	2.341	
	2	Providencia La Paz La Florida El Bosque Las Condes	3.453	0.724
3	1	Parque Pudahuel Cerrillos	2.341	
	2	Providencia La Paz La Florida El Bosque	3.057	0.799
	3	Las Condes	1.000	
4	1	Parque Pudahuel Cerrillos	2.341	
	2	La Florida El Bosque	1.744	0.855
	3	Las Condes	1.000	
	4	Prov. La Paz	1.756	
5	1	Parque Cerrillos	1.696	0.899
	2	La Florida El Bosque	1.744	
	3	Las Condes	1.000	
	4	Prov. La Paz	1.756	
	5	Pudahuel	1.000	

grouped. Las Condes station remains isolated. A diagram of the groups that are formed is shown in Fig. 9.

The same type of analysis can be carried out with the O_3 data and the results of the calculation are shown in Table 3. In this case, if $R_i = 0.909$ two groups are obtained: one located in the east and north (La Paz, Providencia, Las Condes), and one located in the west and south (Pudahuel, Parque, Cerrillos, El Bosque and La Florida). As with PM_{10}, the groups are related to the geographical location of the stations. If we set R_i to a higher value, more groups start to appear. If $R_i = 0.956$, the same groups as with PM_{10} are obtained. Las Condes station breaks away and forms a separate group, the stations in the central-west part of the city are grouped together; the stations in the south (El Bosque and La Florida) and the stations in the north (Providencia and La Paz) are also grouped. Again, the geographical location of the station determines how the stations are clustered.

It should be noted that the configuration of the groups for O_3 is the same as for PM_{10}, in spite of the fact that these pollutants have very different sources and have maximum concentrations in different season of the year. O_3 is a secondary pollutant generated during the day, when the UV radiation has a maximum and PM_{10} is a primary pollutant that has many different sources. The fact that both pollutants have very similar distribution is a strong indication that the concentration levels are primarily determined by the topographical and meteorological characteristics of the area. These results also indicate that the pollution generated over the

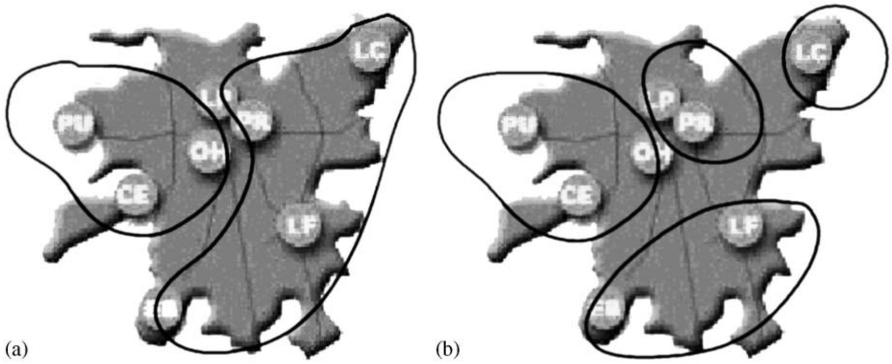

Fig. 9. (a) Clustering of the city into two groups when $R_i = 0.72$ and (b) clustering into four groups when $R_i = 0.86$. The analysis was performed with PM_{10} data.

Table 3
Results of the cluster analysis of O_3 data

Iteration	Cluster no	Group members	Intra-variance	Ratio of intra to total variance
1	1	All	6.895	0.862
2	1	Parque Pudahuel Cerrillos La Florida El Bosque	4.54	0.909
	2	Prov La Paz Las Condes	2.73	
3	1	Parque Pudahuel Cerrillos	2.81	
	2	Prov La Paz Las Condes	2.73	0.932
	3	La Florida El Bosque	1.9	
4	1	Parque Pudahuel Cerrillos	2.82	
	2	La Florida El Bosque	1.907	0.956
	3	Las Condes	1.000	
	4	Prov La Paz	1.93	
5	1	Parque	1.00	
	2	La Florida El Bosque	1.91	
	3	Las Condes	1.000	
	4	Prov La Paz	1.93	0.967
	5	Pudahuel Cerrillos	1.92	

city is redistributed in four large areas according to the meteorological and topographical conditions of the area. Three of these areas have two or more monitoring sites. The findings of this study indicate that in cities like Santiago, the actions required to reduce pollution have to be directed towards the whole city. The local sources may have a minor effect on the local concentration levels.

4. Discussion

Information from Santiago's monitoring network was used to study the seasonal and geographical trends of PM_{10} and O_3 in the year 2000. The pollutant concentrations from two stations are found to have very different behavior. Pudahuel station has the highest PM_{10} levels in winter and it is located in the lowest part of the city (480 m above sea level). Las Condes is a station located in the eastern part of the city, close to the Andes mountain range, about 220 m higher than Pudahuel. It shows the lowest average PM_{10} levels in winter, but in summer it has the highest ozone levels. These differences seem to be related to the meteorological and topographical diversity of the sites.

The PM_{10} data from the monitoring stations of the Metropolitan Air Quality Monitoring Network show a pronounced dependence with the season of the year. PM_{10} in summer is 50% lower than winter, as seen in Fig. 2, and this difference is most likely due to the higher winds prevalent in summer and the higher vertical dispersion due to higher temperatures (Gramsch et al., 2000). The wind speed in summer can be as high up to $6\,m\,s^{-1}$ compared to $2.5\,m\,s^{-1}$ in winter (Fig. 3). All stations but one, show a peak in PM_{10} at 8:00 indicating that during the rush hour there is a strong influence from traffic. However, this influence is not seen during the rest of the day. The data in Fig. 2 show that in the afternoon, there is a decrease in PM_{10} although the traffic remains approximately constant. The decrease is due to stronger winds in the afternoon (Fig. 3). The increase in PM_{10} from traffic in the evening rush hour (18:00–22:00 h) is only seen in summer (January, March and November in Fig. 5). In winter, the increase in PM_{10} occurs between 21:00 and 24:00 h, which is partly related to an increase in traffic, but primarily it is related to a decrease in wind speed (Fig. 3) and temperature inversion (Gramsch et al., 2000).

The PM_{10} pattern in Las Condes station is also related to meteorological and topographical conditions, because in the afternoon the downtown wind (Fig. 4) is directed towards Las Condes and can carry pollution from downtown. A similar effect, but with opposite direction, occurs with the wind at night and early morning. In the eastern part of Santiago (from 20 to 6 h) the wind speed (Fig. 3) close to the mountains is higher than in the western side of the city. The wind speed for Las Condes is clearly higher than the other stations and the direction (between 70 and 100°) corresponds to wind coming from the east. The wind brings clean air from the mountains, reducing the PM_{10} levels at night in this part of the city.

Cluster analysis of the data indicates that the PM_{10} and O_3 pollution generated over the city is redistributed in four large areas. It is interesting to note that the grouping depends on the location of the stations, which probably is due to the topographical characteristics of the site where the station is located. Pudahuel is the sector of the city with the lowest altitude (450 m above sea level), with lower temperatures and higher humidity in winter. There is a hill towards the north (Renca hill) that may prevent good ventilation. The south part of the city (El Bosque and La Florida) is very flat, with no hills nearby. Providencia and La Paz are located close to several hills, in a sector of Santiago slightly higher than the rest of the city. Three of these areas have two or more monitoring sites. The results indicate that in cities like Santiago, reduction of pollution has to be directed towards the whole city because local pollution levels are not solely determined by local sources. For example, pollution from kerosene and wood burning used for house heating may drift to the lowest part of the city (Pudahuel) generating the large PM_{10} levels observed in winter.

There are other cities with complex topographical and meteorological conditions, like Beijing, Bogota, Mexico City or Athens (Molina et al., 2004) in which the distribution of pollution is influenced by the topography of the site. In these situations, the methods and results of this study may be used to suggest pollution-control guidelines.

5. Conclusions

The results show a pronounced dependence of the concentration levels with the season of the year, with PM_{10} being higher in winter and O_3 in summer. In winter, the PM_{10} maximum occurs during the night, which is an indication that the meteorological conditions are responsible for the high levels. The higher sector of the city does not show the PM_{10} increase at night, suggesting that the height of the temperature inversion occurs at lower altitude. Cluster analysis of the data indicates that PM_{10} and O_3 generated over the city is redistributed in four large areas. The areas are the same for O_3 and PM_{10}, in spite of the fact that these pollutants have very different sources and have their maximums on different season of the year. The fact that both pollutants have similar distribution is a strong indication that the concentration levels are primarily determined by the topographical and meteorological characteristics of the area. These results indicate that in cities like Santiago, reduction of pollution has to be directed towards the whole city because local pollution levels are not solely determined by local sources.

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References

Artaxo, P., Oyola, P., Martinez, R., 1999. Aerosol composition and source apportionment in Santiago de Chile. Nuclear Instruments & Methods in Physics Research Section B—Beam Interactions with Materials and Atoms 150 (1–4), 409–416.

Cifuentes, L.A., Vega, J., Kopfer, K., Lava, L.B., 2000. Effect of the fine fraction of particulate matter versus the coarse mass and other pollutants on daily mortality in Santiago, Chile. Journal of the Air and Waste Management Association 50 (8), 1287–1298.

Conama, 1994. Environmental Base Law. March 9, 1994, Chilean Government, Santiago, Chile. http://www.conama.cl/rm/568/article-931.html.

Conama, 1997. Metropolitan Region Prevention and Decontamination Plan. July 1, 1997, Edited by "Comisión Nacional del Medio Ambiente", Conama RM, Santiago, Chile. http://www.conama.cl/rm/568/article-932.html.

Dockery, C.A., Pope III, C.A., Xu, X., Spengler, D.J., Ware, J.H., Fay, M.E., Ferris, B.G., Speitzer, F.E., 1997. An association between air pollution and mortality in six U.S. cities. New England Journal of Medicine 329, 1753–3744.

Estraus, A description of the program can be found in http://www.sectra.cl/contenido/modelos/transporte_urbano/Estraus_ingles.htm.

Gramsch, E., Catalán, L., Ormeño, I., Palma, G., 2000. Traffic and seasonal dependence of the light absorption coefficient in Santiago de Chile'. Applied Optics 39 (27), 4895–4901.

Ilabaca, M., Olaeta, I., Campos, E., Villaire, J., Tellez-Rojo, M.M., Romieu, I., 1999. Association between levels of fine particulate and emergency visits for pneumonia and other respiratory illnesses among children in Santiago, Chile. Journal of the Air and Waste Management Association 49, 154–163.

Jorquera, H., Perez, R., Cipriano, A., Espejo, A., Letelier, M.V., Acuna, G., 1998. Forecasting daily maximum levels at Santiago, Chile. Atmospheric Environment 32 (20), 3415–3424.

Lee, S.A., Hastie, T., Mancilla, P.F., Astudillo, P.O., Kuschner, W.G., 2000. Fine particulate air pollution ($PM_{2.5}$) and medical visits for lower respiratory tract illnesses among children in Santiago, Chile. Journal of Investigative Medicine 48 (1), 524.

Molina, L.T., Molina, M.J., Slott, R.S., Kolb, C.E., Gbor, P.K., Meng, F., Singh, R.B., Galvez, O., Sloan, J.J., Anderson, W.P., Tang, X., Hu, M., Xie, S., Shao, M., Zhu, T., Zhang, Y.H., Gurjar, B.R., Artaxo, P.E., Oyola, P., Gramsch, E., Hidalgo, D., Gertler, A.W., 2004. Air quality in selected megacities, critical review online version. Journal of the Air & Waste Management Association 55.

Ostro, B.D., Eskeland, G.S., Sanchez, J.M., Feyzioglu, T., 1999. Air pollution and health effects: A study of medical visits among children in Santiago, Chile. Environmental Health Perspectives 107 (1), 69–73.

Perez, P., Trier, A., Reyes, J., 2000. Prediction of PM2.5 concentrations several hours in advance using neural networks in Santiago, Chile. Atmospheric Environment 34 (8), 1196–1198.

Rutland, J., Garreaud, R., 1995. Meteorological air-pollution potential for Santiago, Chile—towards an objective episode forecasting. Environmental Monitoring and Assesment 34 (3), 223–244.

Sanhueza, P., Vargas, C., Jimenez, J., 1999. Daily mortality in Santiago and its relationship with air pollution. Revista Medica de Chile 127 (2), 235–242.

SAS Institute Inc., http://www.sas.com.

Schmitz, R., 2004. Modeling of air pollution dispersion in Santiago de Chile. Atmospheric Environment, in print.

Silva, C., Quiroz, A., 2003. Optimization of the atmospheric pollution monitoring network at Santiago de Chile. Atmospheric Environment 37 (17), 2337–2345.