A RECEPTOR MODEL FOR ATMOSPHERIC AEROSOLS FROM A SOUTHWESTERN SITE IN MEXICO CITY

J. MIRANDA, E. ANDRADE, A. LÓPEZ-SUÁREZ and R. LEDESMA

Instituto de Física, Universidad Nacional Autónoma de México, Apartado Postal 20-364, México, D.F. 01000, Mexico

and

T. A. CAHILL and P. H. WAKABAYASHI

Crocker Nuclear Laboratory, University of California, Davis, CA 95616-8569, U.S.A.

Abstract—Samples of atmospheric aerosols were taken in a southwestern site in Mexico City, during the Fall of 1993, using a Stacked Filter Unit (SFU). This allowed separation of particles with sizes between 2.5 and 15 μm (coarse, deposited on Nuclepore filters), and smaller than 2.5 μm (fine, deposited on Teflon filters). The samples were analyzed using Proton Induced X-ray Emission (PIXE) for elements with atomic numbers between 13 and 26 (Al to Fe), Proton Elastic Scattering (PESA) for hydrogen in the fine fraction, and X-ray Fluorescence (XRF) for elements heavier than Fe. A receptor model is presented using Principal Components Analysis (PCA) in order to find possible sources of the pollutants. Cluster Analysis for each of the fractions was also performed, to assist PCA in the source identification. The multivariate analyses permitted to identify four major sources in each fraction, with soil as the major contributor in both cases. Copyright © 1996 Elsevier Science Ltd

Key word index: Atmospheric aerosols, Mexico City, PIXE, XRF, cluster analysis, principal components analysis.

INTRODUCTION

The atmospheric pollution issue in the Metropolitan Area of Mexico City (MAMC) has raised interest in the scientific community, because of the peculiarities in its geographical characteristics and the constantly growing population, around 16 million of inhabitants in 1990. One of the specific questions is the atmospheric aerosol's composition, sources, and behavior. Several studies have been presented in the past regarding this problem (Aldape *et al.*, 1991a; Miranda *et al.*, 1992, 1994), although the information hitherto obtained is still very limited, both in the temporal and geographical aspects. Thus, a continuous effort is necessary to achieve a better understanding of the aerosols in this urban area.

One of the zones of interest in the MAMC is the Southwest, as it is claimed that the winds tend to concentrate there the pollutants (Bravo *et al.*, 1990), a fact already observed for ozone. It is in the Southwest that the highest ozone concentrations have been measured (Cicero-Fernandez *et al.*, 1994). However, little knowledge exists about the composition of aerosols in this part of the urban area, while data exist only for Total Suspended Particles (TSP) (Bravo *et al.*,

1989) and total mass of particles with dimensions below 10 μm, also known as PM10 (Cicero-Fernandez *et al.*, 1993). As a consequence, a study was conducted during the Fall of 1993, to investigate the composition of aerosols with particle sizes between 15 and 2.5 μm, and smaller than 2.5 μm, using Proton Induced X-ray Emission (PIXE), Proton Elastic Scattering Analysis (PESA), and X-ray Fluorescence (XRF). The resulting data were then subjected to Principal Components Analysis (PCA) and Cluster Analysis (CA), to identify possible sources of the aerosols present in this particular geographical area.

EXPERIMENTAL

The sampling site was located at the Instituto de Física facilities, in the U.N.A.M. main campus (Fig. 1). This campus is located in the middle of a residential area. Industrial activities and traffic are less intense than in zones like Downtown or the Northwestern area. Thus, the main nearby pollution sources are local soil, light traffic, and isolated small industries. The aerosol samples were collected with a Stacking Filter Unit (SFU) of the Davis design (Cahill *et al.*, 1990). With this unit, based on a two-step sequential filtering of the aerosols, it was possible to separate particles
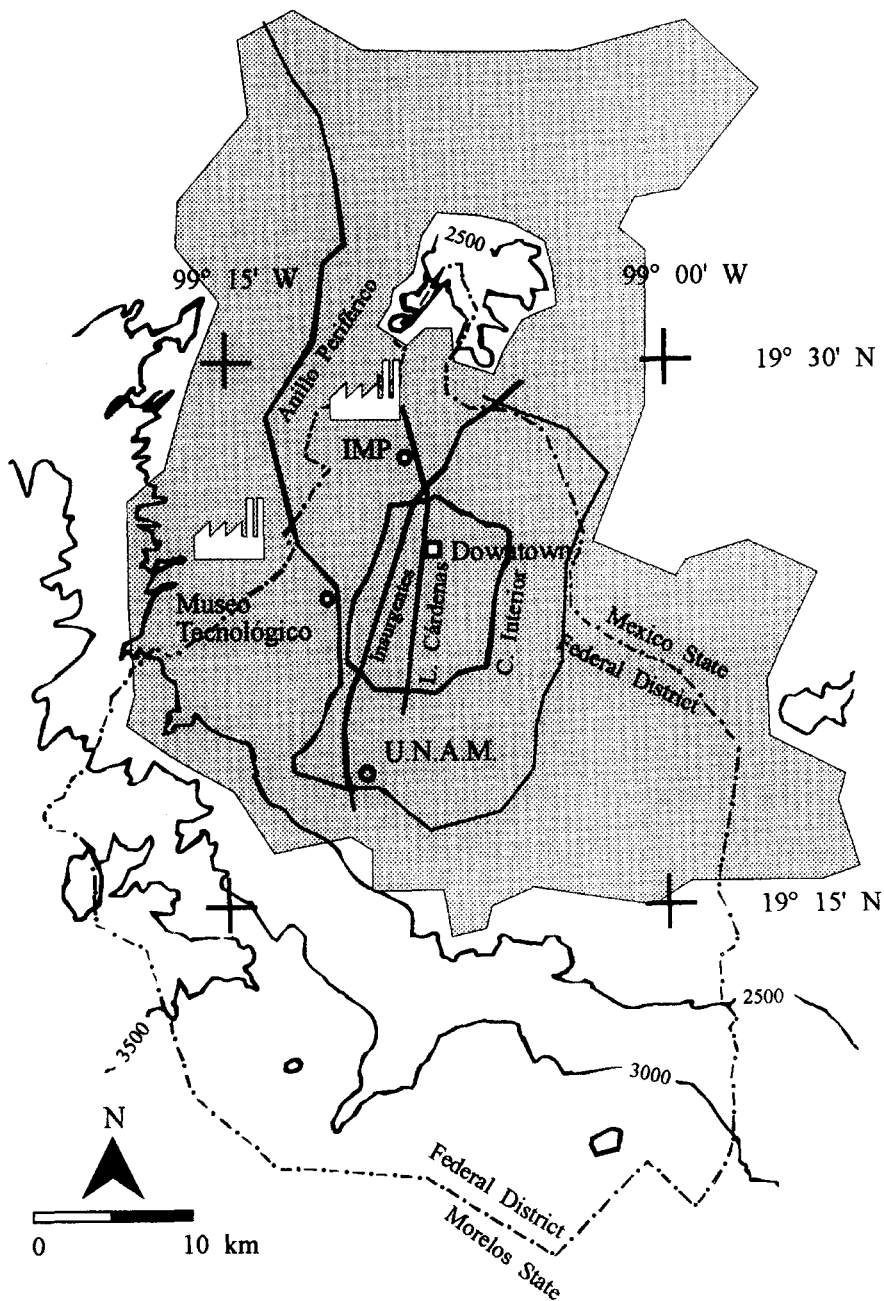
Fig. 1. Map of the metropolitan area of Mexico City (shaded area), showing the main avenues, elevations (in m), and the location of the sampling sites mentioned in this work. In this map, it is possible to estimate the lower traffic density in the U.N.A.M. main campus, due to the number of avenues; the weaker direct influence of industry, and to understand why the pollutants may accumulate in the Southwestern zone, due to the high nearby elevations and the predominant North-to-South wind direction.

with sizes between 2.5 and 15 μm on 8 μm pore size Nuclepore filters (coarse fraction), and particles between 0 and 2.5 μm on Teflon filters (fine fraction). The sampling periods were between 8:00 and 14:00 h, daily from 16 October to 10 December, 1993. The hours were selected because it has been shown that they present the highest aerosol concentrations during the day in the MAMC (Aldape et al., 1991b).

The filters were pre- and post-weighed to determine gravimetric mass of the aerosols, with an Ohaus GA200D electrobalance. Proton Elastic Scattering Analysis (PESA)

was used to determine H content on the Teflon filters; a 2.2 MeV proton beam and a surface barrier detector located at 30° from the beam incident direction were used for this technique; Proton Induced X-ray Emission (PIXE) was performed with 2.2 MeV protons, and a Si(Li) detector with a resolution of 180 eV at 5.9 keV, located at 90° from the beam direction. The beam impinges on the filters at an angle of 45° with the normal to their surface. An Ortec 672 amplifier and an Ortec ACE® multichannel analyzer card were used to obtain the spectra. PIXE gave information on all

elements heavier than Na. Both for PESA and PIXE, the Instituto de Física, U.N.A.M. 5.5 MV Van de Graaff accelerator was employed. The Si(Li) detector sensitivity curve was determined with thin film MicroMatter® standards. Typical beam currents were 5 nA. X-ray Fluorescence analysis (XRF) was applied to the filters to determine the concentrations of elements heavier than Fe. XRF was carried out with the Crocker Nuclear Laboratory, University of California, Davis, XRF system. It uses the Mo K lines as exciting radiation, and a Si(Li) detector (resolution 174 eV at 5.9 keV) is located at 90° from the primary X-rays direction. This primary radiation reaches the samples with an angle of 45° with their normal. A set of 25 aerosol samples previously analyzed using both XRF and PIXE were used to obtain accurate calibrations of the XRF system, and a quality assurance of the overall analysis. Moreover, blank filters were analyzed with all the techniques, and the concentrations of the elements that can be measured with them were always below the minimum detection limits.

RESULTS AND DISCUSSION

The resulting PIXE spectra were analyzed with the *Axil*® computer code (Maenhut and Vandenhaute, 1986), while the XRF ones were deconvoluted with the *Race* code (Harrison and Eldred, 1974). The concentrations obtained for elements detected with both PIXE and XRF (such as Fe and Zn) presented differences of less than 6%. Typical uncertainties for abundant elements, such as Si, Ca and Fe, were around 5%, while those of scarce and light elements (like Al or Cu) could be up to 20%. Nineteen elements were found in the fine fraction using the three techniques, while 17 were observed in the coarse fraction. The resulting average concentrations are given in Table 1 (fine fraction) and Table 2 (coarse fraction), together with the average mass concentrations. These averages are compared with previous results from other sampling periods (September 1990 and February 1991) and areas in the MAMC (Miranda *et al.*, 1994). The uncertainties quoted in Tables 1 and 2 correspond to a 0.05 confidence level.

The data displayed in Tables 1 and 2 show that the characteristics of the aerosols in the Southwestern site are different from those previously measured. The columns denoted by Sep. 90 correspond to data obtained in the Museo Tecnológico site, West of the MAMC, as seen in Fig. 1, while the columns identified by Feb. 91 give data from the IMP site, in the North-Central part of the MAMC. The Museo Tecnológico is close to one of the largest industrial areas in Mexico, adjacent to avenues with very heavy traffic, while IMP is in the middle of another important industrial area, with somewhat lower traffic density. Sampling and analytical procedures were very similar in all these studies. The effect of traffic (identified by Pb and Br) is much lower in the Southwest than in the North and Downtown (1990–1991). It may be due either to the lower traffic density in the zone, or to the use of unleaded gasoline in the MAMC since 1991. In spite of the different sampling methods and sites, the works by Aldape and co-workers (1991a, b) showed

Table 1. Concentrations of the elements (in μg m^{-3}) in the fine fraction and comparison with other measurements (Miranda *et al.*, 1994)

Element	Mean	Error	Sep. 1990	Feb. 1991
Mass	50	7	42	39
H	1.79	0.20	1.76	1.43
Al	1.25	0.08	0.179	0.155
Si	1.94	0.11	0.378	0.461
P	0.568	0.033	NO	NO[a]
S	3.77	0.35	3.79	1.99
Cl	0.180	0.011	NO	0.652
K	0.159	0.010	0.158	0.309
Ca	0.220	0.013	0.274	0.310
Ti	0.020	0.002	0.032	0.013
V	0.021	0.004	0.082	0.060
Cr	0.005	0.001	0.013	NO
Mn	0.009	0.001	0.030	0.036
Fe	0.198	0.014	0.208	0.273
Ni	0.004	0.001	0.008	0.007
Cu	0.014	0.001	0.050	0.056
Zn	0.096	0.008	0.412	0.625
Se	0.005	0.001	0.051	0.050
Br	0.014	0.001	0.007	NO
Pb	0.081	0.006	0.934	0.425

[a]NO = Not observed.

Table 2. Concentrations of the elements (in μg m^{-3}) in the coarse fraction and comparison with other measurements (Miranda *et al.*, 1994)

Element	Mean	Error	Sep. 90	Feb. 91
Mass	56.4	0.004	39	174
Al	4.14	0.43	0.880	5.12
Si	16.3	1.5	2.88	13.3
P	0.785	0.102	0.125	NO[a]
S	1.14	0.13	1.06	2.87
Cl	0.228	0.019	NO	1.55
K	0.530	0.087	0.433	1.66
Ca	3.16	0.33	2.03	6.40
Ti	0.204	0.021	0.123	0.369
V	0.027	0.003	0.056	0.088
Cr	0.074	0.006	0.056	0.062
Mn	0.051	0.005	0.040	0.075
Fe	1.95	0.25	0.918	3.45
Ni	0.007	0.002	0.010	NO
Cu	0.004	0.002	0.034	0.165
Zn	0.081	0.008	0.266	1.74
Br	NO	NO	0.044	0.080
Sr	0.004	0.001	0.019	0.085
Pb	0.020	0.003	0.257	0.805

[a]NO = Not observed.

that during Fall the elemental concentrations were not much lower than those of Winter, and thus the difference in Br and Pb contents is not probably due to a seasonal variation. The explanation must be found with other studies in different areas of the MAMC, already under progress. However, S contents in both fractions are very similar to the observations in September 1990. A reason for this may be some transport towards the Southwest, although correlations with wind directions and velocities could not be examined. Concentrations of Cu, Zn, V, Cr, and Ni, normally with an industrial origin, are much lower in

the U.N.A.M. campus, a fact explained because the other two zones lie very close to or in the middle of large industrial areas, while the campus is surrounded mainly by residential zones. Finally, elements like Al, Si, K, Ca, Ti and Fe, normally associated with soil, present high concentrations, but below those measured in February 1991. This is not surprising, as Fall is the beginning of the dry season, and for Winter usually there have already been several months of drought. This would obviously produce more airborne soil particles. On the other hand, during September there is still some rain, giving lower soil concentrations. The total mass concentrations for the fine fractions are similar in all the cases, while those of the coarse fraction are much lower than those measured in February 1991. Again, the explanation must come from the different climatic conditions.

Another point to be stressed is the similitude between the mass concentrations of the fine and coarse fractions (shown in Tables 1 and 2), as opposed to results in the February 1991 study (Miranda et al., 1994), while keeping a resemblance with the September 1990 results. The attempt to calculate the reconstructed mass from elemental concentrations, following the procedure explained by Miranda et al. (1994), is impossible in this study, as elemental carbon data were not obtained.

At this point, a comparison with other urban areas is useful. However, it must be kept in mind that the differences in sampling and analytical protocols limit this kind of associations. A good example is the work presented by Andrade et al. (1994) in the São Paulo Metropolitan Area, Brazil. These authors employed also a Stacking Filter Unit for sampling, with the same particle size separation, and used PIXE for the analysis. The main difference is the sampling hours, as they took samples along the whole day, dividing it in three periods (morning, 8–14 h; afternoon, 14–20 h; and night, 20–8 h). Although the morning period coincides with the one presented in this work, data were presented as averages of the whole period. Additionally, both urban areas have populations above 15 million inhabitants, supporting the suitabilty of the comparison. Table 3 shows the comparison between

Mexico City and São Paulo average elemental concentrations for a few representative elements. From the figures in Table 3, several remarks can be made. First, in an overall view, there is a similarity between the elemental contents in both urban areas. While the concentrations of some pollutants are higher in Mexico City (such as Si, S, Ca and V), others are higher in São Paulo (K, fine Fe, Zn, coarse Pb). Special consideration can be paid to Si, because the values in the ZMCM are very high. The explanation must be the dry weather in Mexico City during the sampling period, while the São Paulo study had some rainfall. This would let more soil dust free to be incorporated into the airborne particles. This may also affect Ca. Also, the differences in K should arise from combustion and probably sea salt, which is not found in Mexico City. The distinction in the remaining elements is not too strong to determine the origin of these differences. It must be kept in mind, however, that the present study refers to sampling during the most polluted hours of the day. Thus, the average daily concentrations, as taken in the São Paulo study, must certainly decrease, in an amount still to be determined with further investigations.

Using the present data set, Cluster Analysis (CA) was applied to obtain a first approach to learn about the emitting sources of the different elements found in the samples. Some elements, like H and Se, were not considered for this analyisis, due to a low number of measurements. Resulting dendograms (obtained through Ward's method of amalgamation and the 1-Pearson's rule for linkage measures), are observed in Figs 2 and 3, for the fine and coarse fractions, respectively, as obtained using the computer code *Statistica/W* (Statsoft, 1994). In the fine fraction, there is a clear grouping of the elements K, Ti, Fe, Ca and Si, which are commonly associated to soil. Moreover, the elements Cl, P, and Al also form a group, undetermined, but suggesting also a soil origin, because it is related to the first one. On the other hand, a cluster typically identified as fuel oil is formed by Cr, Ni, V and S. High correlations are found between Zn, Cu, and Mn, too. These elements are either associated to industry or traffic, although Andrade et al. (1994)

Table 3. Comparison of concentrations (in $\mu g\, m^{-3}$) between Mexico City (1993) and São Paulo (1989) for selected elements

Element	Fine fraction		Coarse fraction	
	Mexico City	São Paulo	Mexico City	São Paulo
Mass	50.0	37.5	56.4	60.8
Si	1.94	0.288	16.3	2.87
S	3.77	2.01	1.14	0.885
K	0.159	0.433	0.530	0.567
Ca	0.220	0.110	3.16	1.56
V	0.021	0.016	0.027	0.015
Fe	0.198	0.277	1.95	1.68
Zn	0.096	0.111	0.081	0.126
Pb	0.081	0.058	0.020	0.042

Fine Fraction

Fig. 2. Dendogram for the fine fraction.
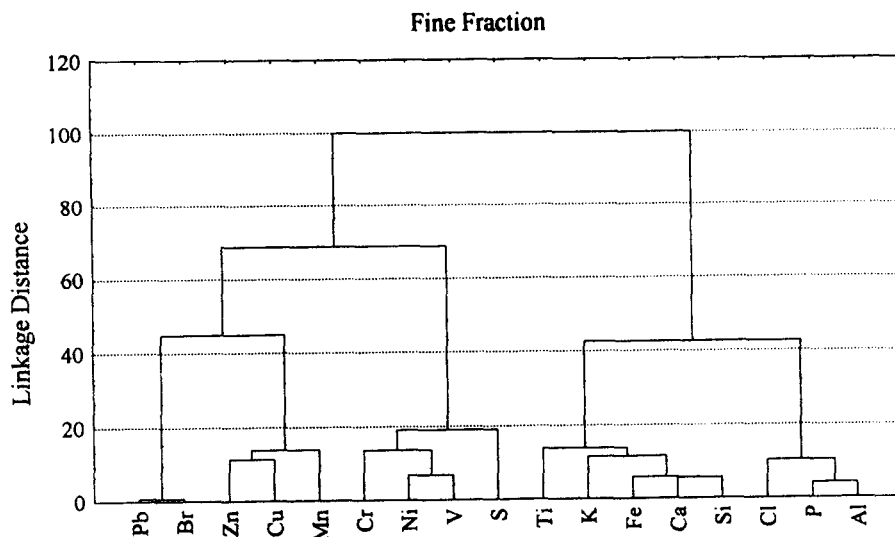
Coarse Fraction
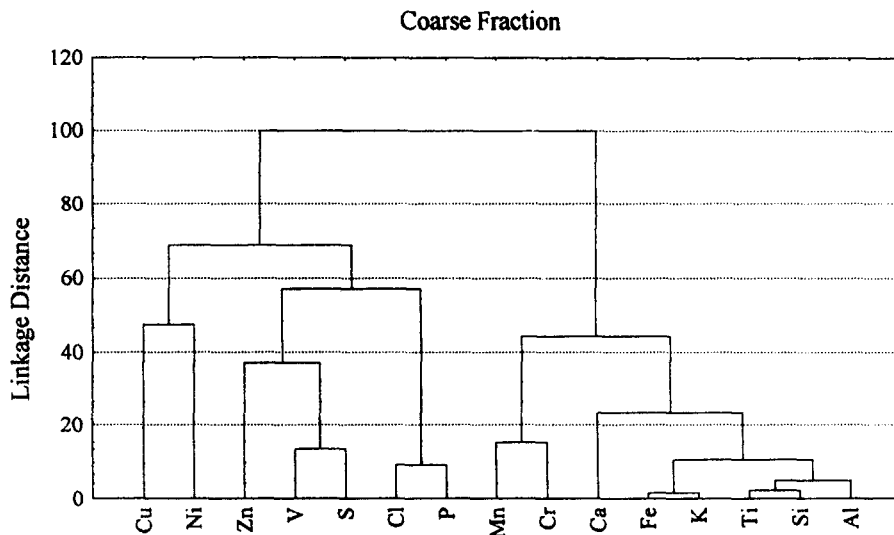

Fig. 3. Dendogram for the coarse fraction.

found similar correlations in São Paulo, connecting these elements to industry. A final group, easily identified with traffic, is based on Pb and Br. In short, there is a structure in this dendogram, where the soil elements are clearly separated from the industrial–traffic (anthropogenic) elements. The coarse fraction dendogram presents a different structure, strongly dominated by soil elements, such as Ca, Fe, K, Mn, Ti, Si and Al. To a lesser extent, Mn and Cr are also correlated with this group. The very low number of appearances of Sr and Pb in this fraction does not allow them to be included in this multivariate analysis. However, a cluster formed by Cu, Ni, Zn, V, S, Cl and P should have an industrial source. Nevertheless, it must be noted that the latter elements do not show high correlations. In all these cases, correlations due

to transport originated from wind should not be discarded, even though the elements do not have the same origin. Unfortunately, wind data are not available for the full sampling period, because of a malfunction in the measuring devices, thus making it difficult to establish if the grouping is indeed caused by transport. Moreover, a simple study of correlations among the few available wind velocities and elemental concentrations did not show any significant correlation.

The next step is the application of Principal Components Analysis (PCA) (Thurston and Spengler, 1985; Maenhut and Cafmeyer, 1987). With this technique, it is possible to identify sources of pollutants, as well as the different contributions of those sources to the total contents in the aerosols. The application of this method to the current data set is valid, following

Table 4. Factor loadings after a VARIMAX rotation, communalities, and standard deviations of the loadings, fine fraction

Element	Factor 1 Soil 1	Factor 2 Soil 2	Factor 3 Fuel oil	Factor 4 Traffic	Commun.	Deviation
Al	0.924	0.201	0.014	0.085	0.900	0.038
Si	0.723	0.623	0.036	0.057	0.972	0.011
P	0.905	0.131	0.178	0.161	0.946	0.021
S	0.508	0.193	0.683	0.253	0.902	0.037
Cl	0.877	− 0.093	− 0.173	0.103	0.858	0.054
K	0.735	0.415	0.125	0.079	0.822	0.067
Ca	0.506	0.781	0.069	0.007	0.920	0.031
Ti	0.610	0.564	0.030	− 0.077	0.737	0.097
V	0.088	0.190	0.942	0.047	0.906	0.036
Cr	− 0.042	0.588	0.734	0.033	0.868	0.050
Mn	0.062	0.882	0.113	0.182	0.839	0.061
Fe	0.370	0.826	0.135	0.271	0.961	0.015
Ni	− 0.115	− 0.039	0.913	0.050	0.820	0.068
Cu	0.095	0.599	0.233	0.381	0.686	0.115
Zn	0.082	0.665	0.209	0.444	0.814	0.070
Br	0.155	0.211	0.074	0.925	0.975	0.010
Pb	0.084	0.196	0.057	0.948	0.975	0.010

the criteria explained by Henry et al. (1984). Table 4 displays the factor loadings for the fine fraction, after a VARIMAX (maximization of variance) rotation, obtained with the computer code Statistica/W (Statsoft, 1994), together with the communalities and standard deviations of the loadings. In this case, four factors were obtained, and the eigeinvalues after the VARIMAX rotation were 4.5, 4.2, 3.0 and 2.4, summing 83% of the total variance. The first factor presents high loadings for Al, Si, P, Cl and K, and can be identified as soil. The second factor, with important loadings for Ca, Mn and Fe must correspond to another soil component, although from a different nature than the first factor. This statement is supported by the dendogram in Fig. 2, where the clustering of all these elements was already noticed. Possible explanations for two different soil components may be a local source, and another one through transport from a remote source. Further studies in several sites must clarify this point. It must be noted, nevertheless, that the grouping in the dendogram in Fig. 2 is different from that obtained with PCA. The origin of this difference is the VARIMAX rotation, which maximizes the variance. If a PCA analysis is performed without any rotation, the soil component is very similar to the whole soil group resulting from CA. In other words, the VARIMAX rotation helps to separate a second soil constituent of the aerosols. The third factor includes S, V, Cr, and Ni, elements that are connected to fuel oil. Finally, the last factor is easily related to traffic, because it has high loadings for Br and Pb. Table 5 shows the source profiles obtained following this model. The relative concentrations (in arbitrary units) were normalized to obtain a value of 100 for a representative element in each factor. The uncertainties presented there were calculated with the standard deviations of the loadings in Table 4. Values of the source profiles that are smaller than three times

the uncertainty are not displayed. The relative contents of the elements present in the first source, as given in Table 5, presumably soil, are evaluated through enrichment factors (EF), using Si as a reference, and the earth crust average composition (CRC, 1993). The EF for Al, K, Ca and Ti are 4.7, 0.7, 0.8 and 2.45, respectively. These values, close to unity, are in good agreement with those expected for an average soil. Moreover, if the EF with respect to Si are calculated for Ca, Mn, and Fe in the second factor, the results are 1.45, 4.54, and 0.92, respectively. As these EF are again close to unity, they strongly support the statement that this factor corresponds to a different kind of soil. In the third source, fuel oil, the V/Ni ratio is around 5, in full agreement with other reported values (Maenhut and Cafmeyer, 1987). Moreover, the Br/Pb ratio is 0.17, slightly below the observations in other urban areas (Maenhut and Cafmeyer, 1987; Ferrer and Perez, 1990; Andrade et al., 1994).

Regarding the PCA in the coarse fraction (Table 6), the first four eigenvalues after the VARIMAX rotation are 6.44, 2.72, 1.74 and 1.30, contributing 82% to the total variance. It must be noted that the communalities for Cr, Ni and Cu are very low, due to the low concentrations of these elements measured in the samples. The strongest component in this case corresponds to soil, with almost half of the total variance registered. The second factor presents strong components for P and Cl, and a less important one for S. The origin of this factor remains undetermined, because Cl is a typical representative of marine aerosols, absent in the MAMC atmosphere. The third factor, with loadings on S, Ni, Zn and possibly V, is related to fuel oil, while the last factor was very probably originated from some kind of industry, with a high loading on Cu. Table 7 presents the source profiles for the coarse fraction, in a similar fashion to those of the fine fraction. Again, the EF relative to Si for the elements

Table 5. Source profiles, fine fraction, in arbitrary units with the relative concentrations normalized to obtain a value of 100 for a representative element in each factor

Element	Factor 1 Soil 1	Factor 2 Soil 2	Factor 3 Fuel oil	Factor 4 Traffic
Al	94.01 ± 3.88	145.66 ± 27.68		
Si	100.00 ± 1.50	614.35 ± 10.67		113.37 ± 21.46
P	37.39 ± 0.86	38.53 ± 6.13	2.46 ± 0.29	95.32 ± 12.33
S	222.54 ± 16.37	602.58 ± 116.66	100.00 ± 5.48	1585.73 ± 234.58
Cl	12.19 ± 0.75			
K	9.16 ± 0.83	36.84 ± 5.94		
Ca	8.31 ± 0.51	91.46 ± 3.62		
Ti	1.27 ± 0.20	8.34 ± 1.44		
V		6.80 ± 1.29	1.58 ± 0.06	
Cr		4.32 ± 0.37	0.25 ± 0.02	
Mn		8.31 ± 0.57		
Fe	6.29 ± 0.25	100.00 ± 1.81	0.77 ± 0.09	65.90 ± 3.65
Ni			0.33 ± 0.02	
Cu		7.91 ± 1.52	0.14 ± 0.07	10.11 ± 3.05
Zn		48.89 ± 5.15		65.59 ± 10.36
Br	0.18 ± 0.01	1.78 ± 0.08		15.74 ± 0.17
Pb	0.62 ± 0.07	10.26 ± 0.50	0.14 ± 0.02	100.00 ± 1.01

Table 6. Factor loadings after a VARIMAX rotation, communalities, and standard deviations of the loadings, coarse fraction

Element	Factor 1 Soil	Factor 2 Undetermined	Factor 3 Fuel oil	Factor 4 Industry	Commun.	Deviation
Al	− 0.852	0.372	− 0.003	0.17 1	0.893	0.041
Si	0.929	0.290	0.098	0.100	0.967	0.013
P	− 0.003	0.941	− 0.050	− 0.154	0.912	0.034
S	0.247	0.612	0.584	− 0.205	0.819	0.068
Cl	0.273	0.860	0.014	0.043	0.816	0.069
K	0.876	− 0.057	− 0.046	0.386	0.922	0.030
Ca	0.810	0.139	0.199	− 0.269	0.787	0.080
Ti	0.943	0.176	0.078	0.113	0.939	0.024
V	0.469	0.462	0.550	0.156	0.760	0.089
Cr	0.316	0.479	0.100	0.465	0.556	0.158
Mn	0.711	0.275	0.077	0.457	0.796	0.077
Fe	0.945	0.063	0.007	0.260	0.965	0.014
Ni	− 0.279	− 0.004	0.728	0.272	0.682	0.116
Cu	0.212	− 0.185	0.058	0.764	0.665	0.122
Zn	0.500	− 0.203	0.614	− 0.223	0.718	0.104

Table 7. Source profiles, coarse fraction, in arbitrary units, where the relative concentrations were normalized to obtain a value of 100 for a representative element in each factor

| Element	Factor 1 Soil	Factor 2 Undetermined	Factor 3 Fuel oil	Factor 4 Industry
Al	26.32 ± 1.26	167.26 ± 18.31		4997.27 ± 27.47
Si	100.00 ± 1.38	453.71 ± 20.11	190.82 ± 24.92	10,230.12 ± 30.16
P		100.00 ± 3.60		− 1066.23 ± 5.40
S	2.35 ± 0.65	84.50 ± 9.43	100.00 ± 11.68	− 1850.15 ± 14.14
Cl	0.37 ± 0.09	16.76 ± 1.35		55.00 ± 2.03
K	5.44 ± 0.19			2273.91 ± 4.08
Ca	19.15 ± 1.88			− 6033.05 ± 41.04
Ti	1.43 ± 0.04	3.89 ± 0.52	2.14 ± 0.65	162.31 ± 0.78
V		1.53 ± 0.30	2.26 ± 0.37	33.80 ± 0.44
Cr				204.43 ± 1.60
Mn	0.27 ± 0.03	1.55 ± 0.43		167.68 ± 0.65
Fe	16.65 ± 0.24	16.27 ± 3.48		4346.93 ± 5.22
Ni			1.41 ± 0.23	27.79 ± 0.27
Cu				100.00 ± 0.37
Zn	0.29 ± 0.06		6.52 ± 1.10	− 124.71 ± 1.33
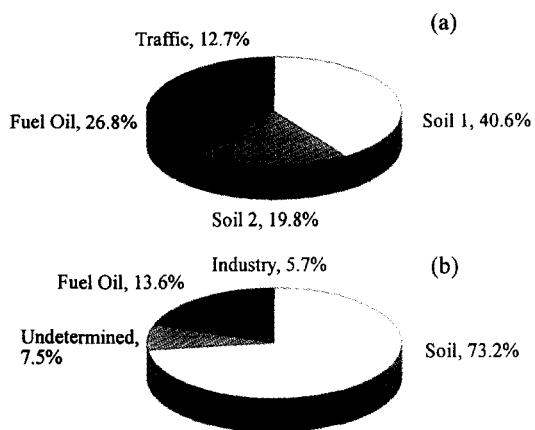
Fig. 4. Relative contributions of each component to the total measured mass for (a) the fine fraction, and (b) the coarse fraction.

Al, K, Ca, Ti, Mn, and Fe in the first source are 1.32, 0.42, 1.86, 2.78, 0.92, and 0.95, respectively. These values, close to 1, undoubtedly correspond to a soil composition, although a little impoverished in K. In the third factor, the ratio V/Ni is now much lower than in the fine fraction, although the low concentrations do not permit a solid conclusion in this regard.

There are differences between the fine and coarse fraction. Although in both cases the most important contribution to total variance comes from the soil, it is slightly higher in the fine fraction, when the two fine soil components are taken into account. The traffic component is almost absent in the coarse fraction, which represents a strong difference to the other two studied sites in the MAMC (Miranda et al., 1994). The industrial contributions, though, are still present in both fractions, but there is no clear indication of a predominance of one size or the other in these pollutants.

Finally, a calculation of the relative contributions of each component to the total measured mass can be carried out following the procedure suggested by Thurston and Spengler (1985). The results are displayed in Fig. 4, which demonstrates the statements made above based on the total variance explained by each component, i.e. the most important contributor is soil, in both fractions. Also, the traffic component in the fine fraction contributes the least to the total mass, while in the coarse fraction the industrial constituent is not as important as the fuel oil source.

CONCLUSIONS

The results given in this work represent the first effort to apply multivariate techniques to the atmospheric aerosols problem in the MAMC. It has been shown how CA can assist PCA for the identification of pollutant sources, as is the case of the second fine soil component. The elemental concentrations found

in this site are in many cases lower than those found in other areas of the MAMC in the past, although higher in some instances than the results from other urban areas. Based on the contribution to total variance from the PCA analysis, as well as on the mass apportionment shown in Fig. 4, soil was found to be the most important contributor to the aerosol composition, both in the fine and coarse fractions. Although in a more limited way, the results reported previously for 1990 and 1991 (Miranda et al., 1994) stated that the soil component was more important only in the coarse fraction, while in the present work soil is more important also in the fine fraction. The traffic contribution is present only in the fine fraction, representing a higher health risk. Also, the contents of elements with an industrial origin are lower in this site. The results determine a different regime for the Southwest, in agreement with what was expected from the nearby emitting sources. However, the lack of meteorological data in the area for the full sampling period did not allow a more complete understanding of the possible transport of pollutants. The scarce meteorological data did not offer significant information regarding correlations with the elemental concentrations. As mentioned before, the explanation should be found in the future with further studies, carried out simultaneously in different zones of the MAMC. These investigations are already under way.

REFERENCES

Aldape F., Flores-M. J., Díaz R. V., Morales J. R., Cahill T. A. and Saravia L. (1991a) Seasonal study of the composition of atmospheric aerosols in Mexico City. Int. J. PIXE 1, 355–371.
Aldape F., Flores-M. J., Díaz R. V., Miranda J., Cahill T. A. and Morales J. R. (1991b) Two year study of elemental composition of atmospheric aerosols in Mexico City. Int. J. PIXE 1, 373.
Andrade F., Orsini C. and Maenhut W. (1994) Relation between aerosol sources and meteorological parameters for inhalable atmospheric particles in Sao Paulo City, Brazil. Atmospheric Environment 28, 2307–2316.
Bravo A. H., Camacho R., Saavedra M. I., Sosa R. and Torres R. (1989) Concentrations of nitrates and sulfates in total suspended and respirable particles as a result of air pollution control strategies in Mexico City. In Proc. 82nd Ann. Meet. AWMA, Anaheim, 25–30 June 1989, pp. 89–155. AWMA, PA.
Bravo A. H., Perrin G. F., Sosa E. R. and Torres J. R. (1990) Efecto del cambio en la formulación de la gasolina sobre los niveles en la atmósfera de plomo y ozono en la Ciudad de México. In Problemas de la Cuenca de Mexico (edited by Kumate J. and Mazari M.), p. 315. El Colegio Nacional, Mexico.
Cahill T. A., Eldred R. A., Feeney P. J. Beveridge P. J. and Wilkinson L. K. (1990) The stacking filter unit revisited. Trans. AWMA 213–222.

Cicero-Fernández P., Thistlewaite W. A., Falcón Y. I. and Guzmán I. M. (1993) TSP, PM10 and PM10/TSP ratios in the Mexico City metropolitan area: a temporal and spatial approach. *J. Exposure Anal. environ. Epidem.* **3**, Suppl. 1, 1–14.

Cicero-Fernández P., Sánchez-Martínez S. and Moucheron-Hemmer M. C. (1994) Seasonal, spatial, and day-of-the-week analysis of ozone and meteorology in Mexico City. In Proc. 82nd Ann. Meet. of the AWMA, Cincinnati, Ohio, 19–24 June 1994, pp. 94-TP47.01. AWMA, PA.

CRC (1993) *Handbook of Chemistry and Physics*, 73rd ed., pp. 14–17. CRC Press, Boca Raton, Florida.

Ferrer N. and Pérez J. J. (1990) Determination of sources of atmospheric aerosol in the neighborhood of Barcelona based on receptor models. *Atmospheric Environment* **24B**, 181–184.

Harrison J. F. and Eldred R. A. (1974) Automatic data acquisition and reduction for elemental analysis of aerosol samples. *Adv. X-ray Anal.* **17**, 560–583.

Henry R. C., Lewis C. W., Hopke P. K. and Williamson H. J. (1984) Review of receptor model fundamentals. *Atmospheric Environment* **18**, 1507–1515.

Maenhut W. and Vandenhaute J. (1986) Accurate analytic fitting of PIXE spectra. *Bull. Soc. Chim. Belg.* **95**, 407–418.

Maenhut W. and Cafmeyer J. (1987) Particle induced X-ray emission analysis and multivariate techniques: an application to the study of the sources of respirable atmospheric particles in Gent, Belgium. *J. Trace Microprobe Techn.* **5**, 135–158.

Miranda J., Morales J. R., Cahill T. A., Aldape F. and Flores-M. J. (1992) A study of elemental contents in atmospheric aerosols in Mexico City. *Atmósfera* **5**, 95–108.

Miranda J., Cahill T. A., Morales J. R., Aldape F., Flores M. J. and Díaz R. V. (1994) Determination of elemental concentrations in atmospheric aerosols in Mexico City using proton induced X-ray emission, proton elastic scattering, and laser absorption. *Atmospheric Environment* **28**, 2299–2306.

StatSoft (1994) *Statistica/W* (StatSoft Inc., Tulsa, Oklahoma).

Thurston G. D. and Spengler J. D. (1985) A quantitative assessment of source contributions to inhalable particulate matter pollution in metropolitan Boston. *Atmospheric Environment* **19**, 9–25.