

The Elemental Contents and Fractal Dimensions of PM_{2.5} in Taipei City

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Five sites (i.e., Sung-Shan, Wen-Lin, Gu-Ting, Wan-Hwa, and Yen-Ping) located in Taipei City were selected for simultaneously collecting PM_{2.5} using honeycomb denuders (Koutrakis, et al., 1993). The collected filters were subsequently analyzed with a Computer Controlled Scanning Electron Microscope (CCSEM) (RJ Lee Group, Inc., PA, USA) to obtain aerosol elemental compositions. Multivariate statistics such as Cluster Analysis and Principal Component Analysis (PCA) were applied to the resolved elemental compositions for source apportionment. Additionally, aerosol morphology from selected aerosols was quantitatively analyzed using fractal geometry to reveal differences among source types. The measurement results display that predominant particles are either pure carbon or contain a high proportion of carbon. For particles associated with a high percentage of carbon, 63.7% of 9,592 particles were found for the first season (fall), 71.3% of 5,987 for the second season (winter), and an even higher 82.9% of 9,000 for the third season (spring). Cluster analysis for the total amount of aerosols collected reveals 27 source types. Among the resolved source types, 73.3% of 24,579 particles were from motor vehicles, 12.4% were from soil dusts, and the remainders were from industrial process, secondary reactions, and sea spraying. In contrast, only 9 source categories were resolved using PCA method, compared to the 27 identified from cluster analysis. Although the apportioned source types of aerosols identified using the cluster method can be lumped together for comparison with PCA, cluster analysis indicates a higher resolution in the source apportionment procedure. A discriminant function is formulated from the resolved aerosol source types of the first two seasons to verify the source apportionment using the cluster procedure. The discriminant function analysis demonstrated that 123 out of 1,535 particles were misjudged (excluding high percentage carbon particles). The calculation of fractal dimension on the morphology of 15 selected particles illustrates that particles are differentiated from each other based on kinky periphery and compact surface.

Keywords: source apportionment, single particles, statistical methods, CCSEM, fractal dimension of aerosols

1. Introduction

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Urban aerosols frequently degrade air quality in Taiwan's cities. Consequently, reducing aerosol emission sources is a high priority for local pollution control authorities. Effectively reducing the emission sources heavily depends on source apportionment of urban aerosols. Aerosols were

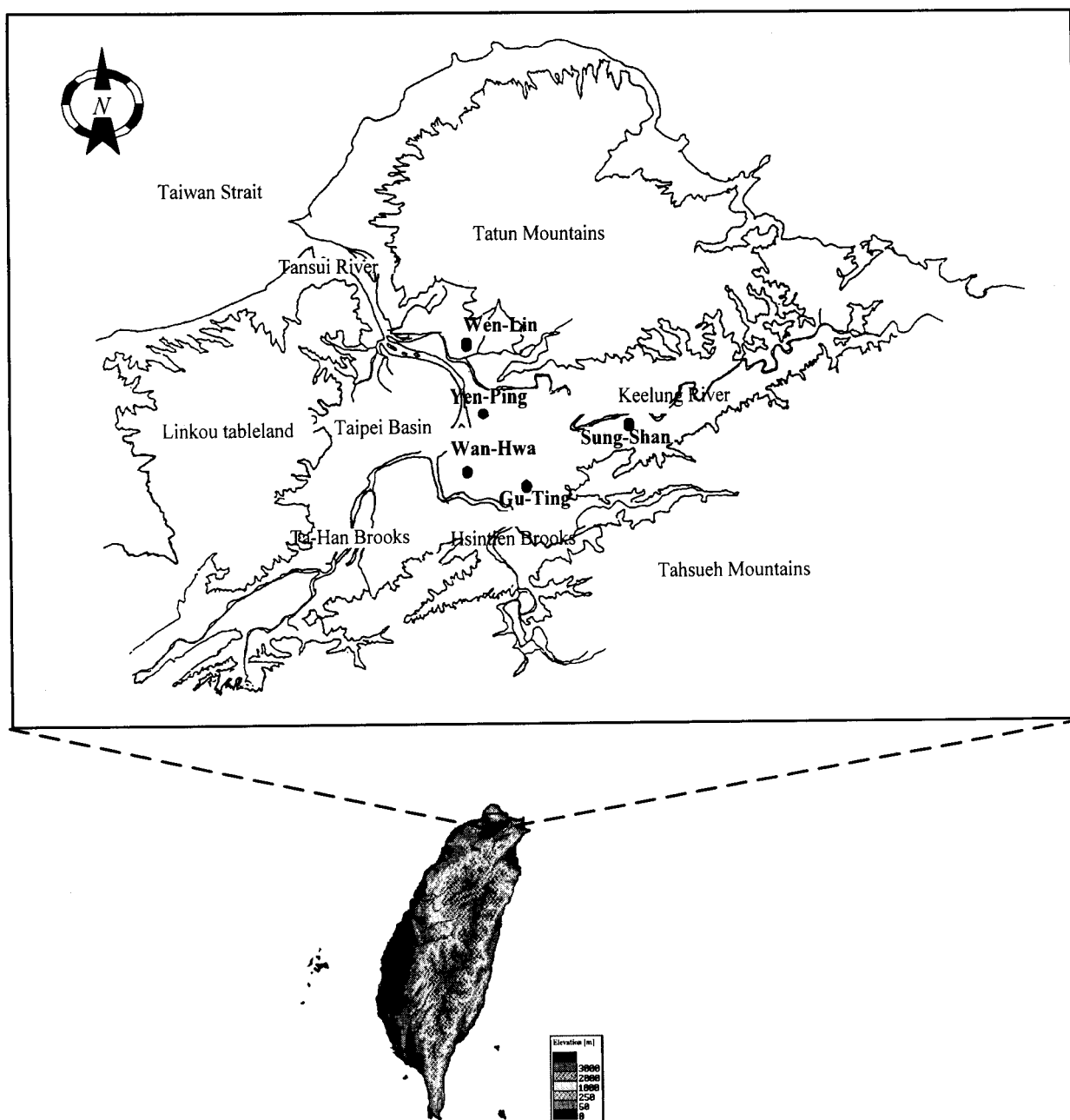


Figure 1. The geographical locations of the five sampling sites, and the position of Taipei City in northern Taiwan.

normally collected on filters and then analyzed in the laboratory. The analyzed results were reported in terms of aerosol bulk properties, and a source apportionment technique, for example, chemical element balance (Miller et al., 1972), was then applied to resolve the analyzed aerosol compositions. However, a comprehensive aerosol property should also consider elemental compositions from individual particles. As elemental distribution tends to be averaged out in bulk

analysis, a minor element might be a prominent part of the composition of some particles.

The chemical contents and morphology of a particle with regard to its origin are generally self-explanatory. For example, while both soil dusts and fly ash particles contain aluminosilicate, soil particles have a more irregular shape and rougher surface than the round and smooth fly-ash particle (Mamane et al., 1986). This difference between soil and fly ash particles is difficult to resolve using

bulk chemical analysis.

Five sites in Taipei City were selected herein for collecting PM_{2.5}, with the sampling period being in 1997-98. The collected filters were analyzed using a Computer Controlled Scanning Electron Microscope (CCSEM) (RJ Lee Group, Inc., PA, USA) to obtain aerosol elemental compositions. Multivariate statistics were then applied to apportion source contributions to the resolved aerosols. Finally, particle morphology is characterized using fractal geometry based on particle boundary, projected area, and surface texture.

2. Methods

The ambient aerosols were collected, resolved, statistically analyzed, and morphologically characterized herein.

2.1 Site Description

Figure 1 displays the locations of the Sung-Shan, Gu-Ting, Wan-Hwa, Yen-Ping, and Wen-Lin sampling sites in Taipei City. At each site, ambient aerosols were collected from the roof of a building that was around 13 m high. The surrounding environment and possible pollution sources at each site are described as follows.

Sung-Shan site

The site is situated in the eastern area of Taipei City. To the northwest of the site, a prosperous temple and a night market attract people to the neighborhood. The site is very close to a local railway station, which lies about 200 m away.

Gu-Ting site

Situated in the south of Taipei City, the site is very close to a high traffic bridge, meaning vehicle emissions exert a strong influence.

Wan-Hwa site

The Wan-Hwa site is situated in the west of the City, and is near the junction of two major roads. Besides vehicle emissions, no specific sources observed during the sampling period.

Yen-Pin site

The site is situated in central Taipei. Small factories were seen in the vicinity of the site, as well as an express highway and a major road.

Wen-Lin site

Surrounded by rice paddy, the Wen-Lin site is situated in a less developed northern part of Taipei City. However, heavy traffic roads connecting Taipei City with the satellite cities lie within 1 km to the site. Therefore, besides agricultural activity, the contribution from vehicle emissions is significant.

2.2 Sampling and Analysis

A honeycomb denuder sampler (Koutrakis *et al.*, 1993) was installed at each site for collecting PM_{2.5} simultaneously. The leading honeycomb denuders in the sampler were coated with appropriate chemicals for removing gaseous precursors to eliminate the interference with the deposited particles during collection. Meanwhile, a 47 mm polycarbonate filter with 0.2 μm pore size (Costar Scientific, Inc., U.S.A.) was installed in the filter package for PM_{2.5} collection. Fall sampling was conducted on September 10, 11, and 17, of 1997, and the winter run was carried out on January 20 and 21, of 1998. Meanwhile, aerosol collection in the spring season was performed on March 23, 25, and 26 in 1998. On each sampling day, aerosols were collected from 8 a.m. to 4 p.m. for 4 minutes per hour. The rationale for this sampling scheme is to avoid overloading the filter and masking particle detections. Sampling was also thought to spread over as many hours as possible. Although sampling was limited during the daytime, the aerosol was

collected on randomly selected dates.

The collected aerosols were scanned and analyzed using a CCSEM equipped with an Energy Dispersive X-ray Spectrometer (EDS) (RJ Lee Group, Inc., PA, U.S.A.). The measured results were reported in terms of the signal intensity of the following nineteen elements: C, O, Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn and Pb. Normally a ZAF (representing atomic number, absorption, and fluorescence) correction is applied to convert elemental intensity into weight fraction (Goldstein, 1981). However, this approach is not adopted herein for two reasons. First, x-rays were only collected for a short period (< 10 seconds) during CCSEM analysis. ZAF is usually obtained from spectra collected over extended periods (several minutes). Second, the ZAF software does not permit ZAF correction of light elements such as carbon and oxygen.

2.3 Statistical Analysis

Data were analyzed herein using statistical methods from SAS (Statistical Analysis System, SAS Institute, Cary, NC, USA) package.

2.4 Cluster Analysis

As the resolved particles accumulated, a statistical treatment may become necessary for extracting the desired information. To classify particles with similar chemical contents into a group, the Euclidean distance of the resolved elements between any pair of particles was initially calculated. Later, the Ward's minimum variance method was adopted for clustering each particle (Ward, 1963). This method minimizes the sum of the squares of any two clusters formed at each step. The coefficient of determination (R^2) explaining the total variance was employed for determining the final number of clusters. The similarity is generally decreased during the formation of a new cluster because of the increase of total within-group error sum of the squares. The breakpoint of R^2 versus the

cluster number indicates that a critical point of similarity exists among groups. However, a subjective judgement is sometimes necessary to determine the final number of clusters.

2.5 Principal Components Analysis (PCA)

PCA aims to reduce the number of variables in explaining data variations. PCA can be used to group several highly correlated elements into a component (a factor) and becomes a source type of aerosols. The first principal component is the weighted linear combination of the elements that explains the largest total variation in the data. The second principal component is not correlated with the first one, but accounts for the maximum amount of remaining total variation not explained by the first one and *vice versa*. The number of principal components is determined by retaining those with eigenvalues exceeding 1. Next, a Varimax rotation of initial components was conducted to enhance interpretability. The aim of rotation is to obtain a simple structure, such that the original elements relate closely to just one component.

2.6 Discriminant Function Analysis

Discriminant function analysis basically attempts to determine whether pre-determined groups differ with regard to the mean of a variable, and then to use that variable to predict group membership. The minimum Mahalanobis distance is adopted to classify a sample as belonging to the cluster to which it is closest. The Mahalanobis distance calculated the distance between the evaluated sample and the centroid of a cluster. Finally, the classification matrix indicates the number of cases that were correctly classified and the number that were misclassified.

2.7 Aerosol Morphology Analysis

Aerosol morphology is an important parameter in particle identification. However, morphology

characterization of particles is difficult to achieve because of irregular particle shapes. Fractal geometry has been applied to quantify particle morphology based on particle boundary, projected area, and surface roughness (Lee and Chou, 1994). A coordinate system is constructed using the 3 calculated fractal dimensions to display particle distribution in the system.

3. Results and Discussion

3.1 The apportioned source types from cluster analysis

Table 1 lists the results from cluster analysis based on the resolved particle elemental contents. Vehicle emissions clearly dominate identified particles, with 18,022 out of 24,579 particles being vehicle emission related. Notably, the percentage of carbon dominated particles ranged from 64 to 83% depending on the season.

The second major source was soil dusts, composed of particles dominated by aluminum, silicon, calcium, manganese, and iron. These particles ranged from 13 to 23% of the total depending on the season, with an average value of 18%. This soil dusts may come from construction work and dust stirred up by motor vehicles. Meanwhile, industrial processes represent the third largest source category but only reach an average of 3% of total amount of particles. This source is a relatively minor contributor to total pollutant levels because of the lack of major factories in Taipei City. Following industrial processes come secondary reactions, sea spraying and agricultural burning.

Although mobile sources were expected to make a high contribution to aerosols in Taipei City, the predominance of carbon in the aerosols is surprising. Overestimation caused by the detection of extraneous X-rays from the carbon substrate media is possible, as the theoretical X-ray spot size in EDS is approximately 1-5 μ m in diameter.

Nonetheless, a carbon-stripping factor had been applied to correct this overestimation.

Particulate carbon is generally classified into organic and elemental carbon. Elemental carbon is mainly produced by emissions from the incomplete combustion of fossil and biomass fuels. Elemental carbon is rather inert, and is thus unlikely to be transformed by atmospheric chemical reaction. In contrast, sources of organic carbon are numerous, with general burning processes, atmospheric photochemical reactions, vehicle emissions, cooking, and tire wear all generating aerosols that contain organic carbon (Wang, 1997).

To confirm the significance of carbon in the collected aerosols, bulk chemical analyses for carbon content were conducted on aerosol samples in the third season. PM_{2.5} was collected for all five sites, with a sampling time of eight hours for each. Since the carbon from EDS analysis can not differentiate elemental or organic carbon from total carbon, total particulate carbon in the aerosol samples was analyzed. Table 2 presents the resolved carbonaceous contents from this study and other studies. The carbonaceous fraction in PM_{2.5} for four of the five sites ranged from 9 to 26%, a fraction as high as 52% was obtained at the Gu-Ting site. A source apportionment for aerosols previously collected at Yen-Pin site had shown that transportation activities contributed about 50% of aerosol mass (Lee and Hsu, 1996). Meanwhile, other investigations revealed that the fraction of total carbon ranged from 18 to 67% in Taipei and other major cities in Taiwan, comparing to a range of 17 to 40% for other cities worldwide. Based on the above, the determination of particulate carbon differs for single particle and bulk chemical analyses. This difference might be due to the carbonaceous nature of filter substrate or the representative problem associated with the particles selected by the CCSEM technique. Besides, as a

Table 1. Apportioned source types of aerosols from cluster analysis for different seasons.

Sample batches		Overall	First season (Fall, 1997)	Second season (Winter, 1997)	Third season (Spring, 1998)
Number of identified particles		24,579	9,592	5,987	9,000
Number of source types		27	23	18	18
Source category	Source types				
Motor vehicles		18,022(73.32)	6,136(63.97)	4407(73.61)	7479(83.1)
	Carbon dominated	17,845(72.60)	6,108(63.68)	4,272 (71.35)	7,465(82.94)
	Lead, sulfur	177(0.72)	28(0.29)	135(2.25)	14(0.16)
Soil Dusts		4,465(18.17)	2,253(23.49)	1,011(16.89)	1201(13.34)
	Aluminum, silicon	258(1.05)	102(1.06)	70(1.17)	86(0.96)
	Calcium dominated	61(0.25)	41(0.43)	8(0.13)	12(0.13)
	Silicon, sulfur, aluminum	49(0.20)	35(0.36)	14(0.23)	N.D.
	Silicon dominated	591(2.40)	215(2.24)	167(2.79)	209(2.32)
	Manganese, silicon	43(0.17)	43(0.45)	N.D.	N.D.
	Aluminum dominated	3,294(13.40)	1,755(18.30)	707(11.81)	832(9.24)
	Iron, silicon	169(0.69)	62(0.65)	45(0.75)	62(0.69)
Industrial process		761(3.10)	416(4.34)	190(3.17)	155(1.72)
	Zinc, iron	6(0.02)	3(0.03)	3(0.05)	N.D.
	Aluminum manufacture (Al, S)	159(0.65)	147(1.53)	N.D.	12(0.13)
	Fibrous	127(0.52)	74(0.77)	45(0.75)	8(0.09)
	Iron foundry (Fe)	205(0.83)	N.D.	114(1.90)	91(1.01)
	Sulfur, calcium	52(0.21)	25(0.26)	13(0.22)	14(0.16)
	Steel manufacture (Mn)	29(0.12)	23(0.24)	3(0.05)	3(0.03)
	Cement (Al, Ca)	27(0.11)	27(0.28)		
	Fertilizer (P)	82(0.33)	57(0.59)	9(0.15)	16(0.18)
	Pigment (Ti, Al)	42(0.17)	28(0.29)	3(0.22)	11(0.12)
Cosmetics (Al, Cl)	32(0.17)	32(0.33)	N.D.	N.D.	
Secondary reaction	Sulfur dominated	691(2.81)	420(4.38)	146(2.44)	125(1.39)
Sea-spraying		281(1.14)	50(0.52)	221(3.69)	10(0.11)
	Chlorine, sodium	215(0.87)	N.D.	215(3.59)	N.D.
	Long range transport (Na, S)	66(0.27)	50(0.52)	6(0.10)	10(0.11)
Agricultural burning	Potassium, sulfur	215(0.87)	200(2.09)	12(0.20)	3(0.03)
Unknowns		144(0.59)	117(1.22)	N.D.	27(0.30)
	Copper, chlorine	8(0.03)	5(0.05)	N.D.	N.D.
	Magnesium dominated	38(0.15)	38(0.40)	N.D.	N.D.
	Aluminum, iron	13(0.05)	N.D.	N.D.	17(0.19)
	Aluminum, potassium	78(0.32)	74(0.77)	N.D.	10(0.11)

(): denotes percentage of the number of particles in a certain source type to the total number of particles in the corresponding season or overall sampling period.
N.D.: denotes no detection.

ZAF correction was not applied to convert elemental intensity to weight fraction, a difference in sensitivity of this conversion might change the determination of elemental weight. The apportioned source types are fairly uniform across all sites, as listed in Table 3. This uniformity reveals that differences among sites are insignificant, and aerosols collected from a central site (for example, the Yen-Pin site) may well represent ambient aerosols in Taipei City.

3.2 Source types resolved through principal component analysis

To avoid the masking effect from particles with high percentage carbon and oxygen, these particles were excluded during this stage of the analysis. In the PCA, a factor is extracted when its eigenvalue exceeds 1. Table 4 lists the factors (source types) resolved from PCA. For data pooled from 3 seasons, nine factors explained 68% of total variance. The elements listed with a source type denote the high factor loadings of that factor. The

Table 2. Aerosol mass (PM_{2.5}) and carbonaceous content from this work and other studies.

Site	date	Mass		EC		OC		TC		OC/EC
		conc. ($\mu\text{g}/\text{m}^3$)	conc. ($\mu\text{g}/\text{m}^3$)	Ratio (%)	conc. ($\mu\text{g}/\text{m}^3$)	Ratio (%)	conc. ($\mu\text{g}/\text{m}^3$)	Ratio (%)		
Taipei, Sung-Shan(this work)	3/23/1998	44						8	18	
Taipei, Wan-Hwa(this work)	3/23/1998	47						12	26	
Taipei, Wen-Lin(this work)	3/23/1998	44						4	9	
Taipei, Yen-Pin(this work)	3/25/1998	35						9	26	
Taipei, Gu-Ting(this work)	3/26/1998	31						16	52	
Taipei, Ta-Tung ¹	6/2000	42.8							67.0	1.1
Taipei, Chung-Shan ¹	4/1999-4/2000	24.4							54.0	1.3
Taipei, Chung-Shan ²	12/1996-5/1997			11-20		7-32				
Taichung ³	12/1996-5/1997			17.1		10.6			27.7	0.6
Kaohsiung ⁴	11/1998-7/1999	66.6	4.1	6.2	10.5	15.8	14.5	21.8	2.6	
Kaohsiung, Shan-Ming ⁵	1/1998-5/1998	67.0								1.9
Kaohsiung, Chung-Cheng (street dust) ⁶	2/1999-3/1999			14.5		3.2		17.7	4.5	
Kaohsiung, (car) ⁶	2/1999-3/1999			22.8		15.8		38.6	1.4	
Kaohsiung, (motorcycle) ⁶	2/1999-3/1999			28.1		26		54.1	1.1	
Seoul, Korea ⁷	6/1994			7.6		10.0		17.5	1.3	
Brisbane, Australia ⁸	9/1993-11/1995	7.3	1.8	24.8						
Burbank, USA ⁹	6/1987-9/1987	42.6	2.2	5.2	9.1	21.4	11.3	26.6	4.1	
	11/1987-12/1987	78.3	6.3	8.1	19.6	25.0	25.9	33.0	3.1	
Los Angeles, USA ⁹	6/1987-9/1987	41.1	2.4	5.8	8.3	20.1	10.6	25.9	3.5	
	11/1987-12/1987	90.2	7.3	8.1	18.5	20.5	25.7	28.5	2.5	
Long Beach, USA ⁹	6/1987-9/1987	25.4	1.0	3.9	3.4	13.2	4.3	17.1	3.4	
	11/1987-12/1987	72.7	6.0	8.3	17.8	24.5	23.8	32.8	3.0	
Anaheim, USA ⁹	6/1987-9/1987	26.8	1.2	4.5	4.7	17.6	5.9	22.1	3.9	
	11/1987-12/1987	83.5	5.5	6.5	13.9	16.6	19.3	23.1	2.5	
Los Angeles, USA ¹⁰	Winter			12-32		1-13				3.7
	Summer			7-46		0-10				8.5-10.3
Los Angeles, USA ¹¹								40.0		

¹Lee et al. (2000); ²Yang et al. (1997); ³Tsai and Cheng (1998); ⁴Lin et al. (1999); ⁵Yuan et al. (1998); ⁶Chen et al. (1999); ⁷Kim et al. (1999);

⁸Chan et al. (1999); ⁹Chow et al. (1994); ¹⁰Daniel (1984); ¹¹Gray et al. (1986)

resolved source types are generally similar to those listed in Table 1 from cluster analysis. Although a quantitative result cannot be obtained using PCA, the result of cluster analysis is confirmed.

3.3 Confirmation through discriminant function analysis

The particles from the three seasons were classified herein according to cluster analysis, and discriminant functions were then derived based on the clusters constructed for the first two seasons. Particles collected in the third season were used to confirm the results from cluster analysis during the

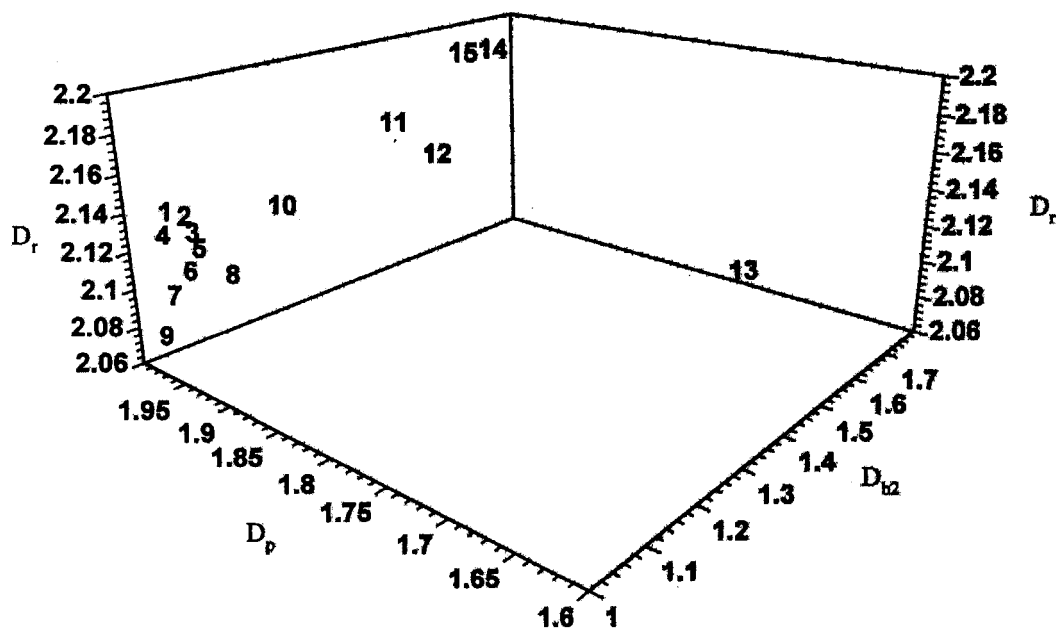
previous two seasons. Analytical results reveal that 123 out of 1,535 particles are misclassified in the third season. Meanwhile, among 27 source types resolved in Table 1, only aluminum silicon, aluminum dominated, and iron foundry have a correctness of classification less than 75%. For all other source types, the success rate of classification exceeded 90%.

3.4 Aerosol morphology from typical particles

Table 5 lists the selected 15 typical particles and the calculated fractal dimensions for the particle

Table 3. The apportioned source types in percentage of particle numbers for different sites from cluster analysis

	Sung-Shan	Wan-Hwa	Wen-Lin	Yen-Pin	Gu-Ting
Analyzed particle numbers	5,197	4,795	4,996	4,795	4,796
Motor vehicles, %	69	76	77	73	71
Soil Dusts, %	19	17	17	19	17
Industrial process, %	5	3	3	3	4
Secondary reaction, %	4	3	3	3	2
Sea-spraying, %	1	0	0	0	5
Agricultural burning, %	1	1	0	1	1
Unknowns, %	1	0	0	1	0

**Figure 2.** Aerosol fractal dimensions from particle boundary (D_{b2}), projected area (D_p), and surface texture (D_r) distributed in a coordinate system.

boundary, projected area, and surface texture. The calculated fractal dimensions are further identified in the coordinate system illustrated in Fig. 2. A high fractal dimension value based on the particle boundary implies a kinky periphery, while a more compact particle exhibits a value closed to 2 in fractal dimension based on projected area. The third fractal dimension, based on particle surface structure, deviates more from 2 as it goes further from the smooth surface. Based on the calculated fractal dimension, particles 1 to 9 all feature a less kinky periphery, a compact structure, and a rugged surface. Meanwhile, beginning from number 10, particle boundaries tend to be kinkier and have a value much higher than 1. The fractal dimension

based on projected area is similar for most particles; however, particle number 13 is less compact, thus resulting in a value of 1.64. Further data analysis is needed to resolve source types using fractal geometry on aerosol morphology.

4. Conclusions

PM_{2.5} were collected from five sites in Taipei City from 1997 to 1998 and single particles were analyzed using a CCSEM technique. For particles whose elemental composition was identified, 17,845 out of 24,579 particles (about 70%) had a high fraction of carbon. Cluster analysis for the

Table 4. Potential source types resolved from principal component analysis.

Overall	First season (Fall, 1997)	Second season (Winter, 1997)	Third season (Spring, 1998)
6,734*	3,484*	1,715*	1,535*
Soil dusts (Mg, Al, Si)	Soil dusts (Mg, Si)	Soil dusts (Mg, Mn, Si)	Soil dusts (Mg, Si)
Industrial process (Cu, Mn)	Industrial process (Cu, Mn)	Steel manufacture (Fe, Cr)	
Alloy industry (Fe, Zn)	Alloy industry (Fe, Zn)	Copper smelter (Cu)	Copper smelter (Cu)
Motor vehicles & Secondary sulfate (S, Pb)	Motor vehicles & Secondary sulfate (S, Pb)	Motor vehicles & Secondary sulfate (S, Pb)	Motor vehicles & Secondary sulfate (S, Pb)
Fertilizer (P, Ca)	Fertilizer (P, Ca)	Fertilizer & Dusts(P, Ca, Mg)	Fertilizer (P) & Iron foundry (F)
Agricultural burning (K) & Secondary sulfate (S)	Agricultural burning (K) & Secondary sulfate (S)	Agricultural burning (K) & Secondary sulfate (S)	Agricultural burning (K)
Incinerator (Cr, Ni)	Incinerator (Cr, Ni)		Incinerator (Cr, Ni)
Sea-spraying (Na, Cl)	-	Sea-spraying (Na, Cl)	
Pigment (Ti)	Pigment (Ti)	Pigment (Ti)	Pigment (Ti)
68.3%**	60.8%**	70.4%**	71.5%**

* : number of particles classified from the season listed in this table.

** : total variance explained from the listed factors.

total amount of particles collected reveals 27 source types. Among the resolved source types, 73.3% of 24,579 particles were from motor vehicles. This source constitutes the largest source category. The fraction of soil dusts ranged from 13 to 23% in different seasons, and had an average value of 18%. Industrial processes were the third largest aerosol source category, but only accounted for an average of 3% of total particle number. Meanwhile, the apportioned source types were relatively uniform across all 5 sites in Taipei city. PCA analysis demonstrated that the source types were similar to those from cluster analysis. Most source types from among 27 source types resolved using cluster analysis were classified correctly based on the discriminant function analysis. Meanwhile, analytical results from 3 statistical analyses successfully validate each other. The fractal dimensions of the selected 15 particles exhibit a contrast in kinky periphery and surface compactness.

Acknowledgements


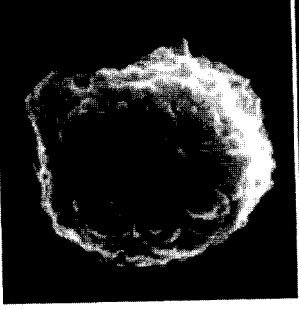
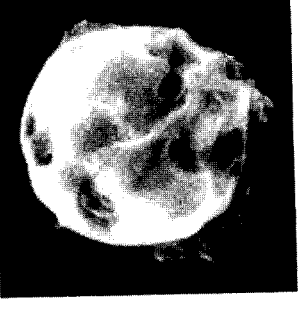

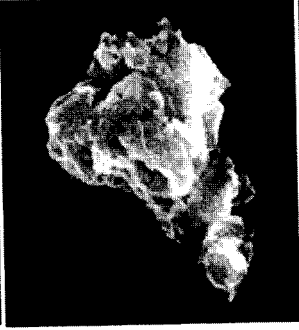
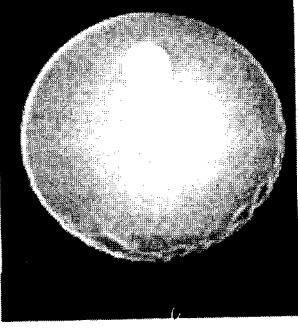
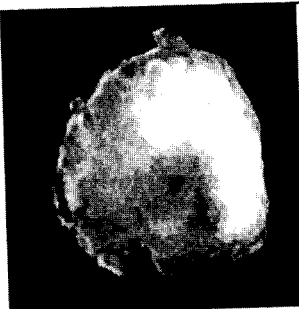
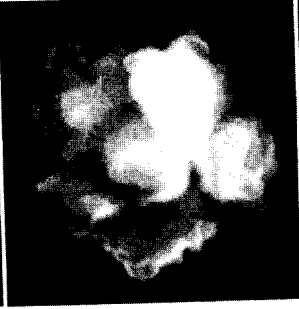
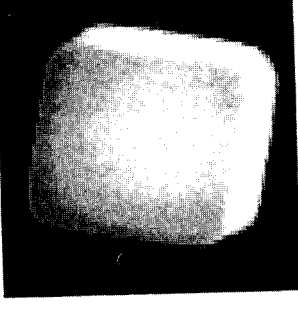
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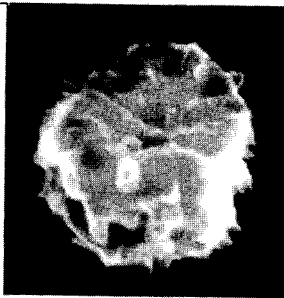
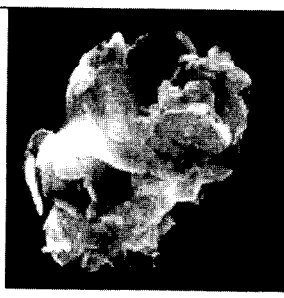

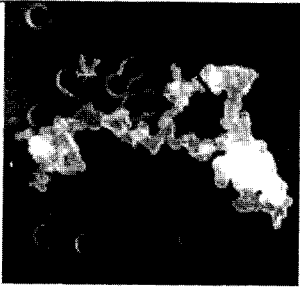
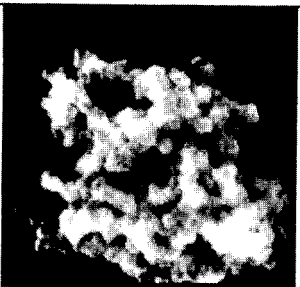
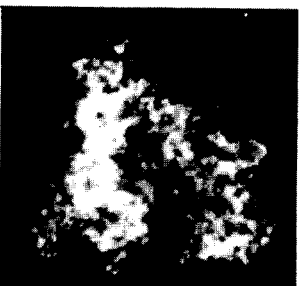
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Table 5 Fractal dimensions on aerosol morphology from selected 15 typical particles.

			
Number	1	2	3
Morphology	Irregular shape particle with amorphous layers of formation	Spherical particle with rugged surface	Hollow sphere
Coordinate*	(1.06, 1.97, 2.14)	(1.09, 2.00, 2.13)	(1.10, 2.00, 2.12)
			
Number	4	5	6
Morphology	Square with rugged surface	Irregular shape particle with amorphous layers of formation	Sphere with round and smooth surface
Coordinate	(1.09, 2.00, 2.12)	(1.07, 1.97, 2.12)	(1.09, 2.00, 2.10)
			
Number	7	8	9
Morphology	Bulky particle with smooth surface	Irregular cubic agglomerates	Cubic crystal
Coordinate	(1.06, 2.00, 2.09)	(1.16, 2.00, 2.09)	(1.04, 2.00, 2.07)

* The numbers in the parenthesis of coordinate are fractal dimensions based on particle boundary, projected area, and surface texture, respectively.

Table 5 (continued) Fractal dimensions on aerosol morphology from selected 15 typical particles.

			
Number	10	11	12
Morphology	Round particle with rugged protuberance	Irregular shape with flaky layers of formation	Hollow sphere
Coordinate	(1.26, 2.00, 2.12)	(1.5, 2.00, 2.15)	(1.48, 1.94, 2.14)
			
Number	13	14	15
Morphology	Chain agglomerates	Compact spherical agglomerates	Compact spherical agglomerates
Coordinate	(1.42, 1.64, 2.13)	(1.75, 2, 2.18)	(1.59, 1.96, 2.19)

* The numbers in the parenthesis of coordinate are fractal dimensions based on particle boundary, projected area, and surface texture, respectively.

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