



Impact of Dust Storms on the Organic Composition in the Ambient Aerosol

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ABSTRACT

To better understand the impact of dust storm (DS) events on the ambient aerosol organic composition in Seoul, samples of solvent-extractable organic compounds in the atmospheric particulate matter with an aerodynamic diameter of less than or equal to a nominal 10 μm (PM_{10}) were collected for 3 months (March–May) in 2007 and characterized. The results of the statistical analysis suggested that during the DS events the ambient PM_{10} concentration increased, the *n*-alkanes concentrations decreased, and the PAH concentrations show no trend, although they increased slightly. The distributions of *n*-alkanes and PAH species showed that among *n*-alkanes only C_{25} and C_{27} species in the non-DS samples increased compared to in the DS samples. Since C_{25} and C_{27} species are mainly emitted from plants, this suggests that the impact of biogenic emissions of *n*-alkanes was reduced during the DS periods. Among PAHs, only the concentration of Fluoranthene increased in a statistically significant manner during the DS period, and only the 1,3,5-Triphenylbenzene level was higher during the non-DS period. The backward trajectory analysis results showed that the air parcels over Seoul did not show much difference between DS and non-DS days. The average level of *n*-alkanes per unit mass of PM_{10} was statistically lower in the DS samples, while those of the PAHs showed no statistically significant differences between the DS and non-DS samples.

Keywords: Dust storm event; Organic aerosols; *n*-alkanes; PAHs; Air mass backward trajectory analysis.

INTRODUCTION

Dust storm (DS) becomes a major socio-environmental issue in East Asia (Arimoto *et al.*, 2006). Dust particles emitted from the deserts and loess areas of North and Northwest China, South Mongolia, and Kazakhstan are carried eastward along with the prevailing seasonal westerlies and southwesterlies and passed over downwind areas including East China, North and South Korea, and Japan. If meteorological conditions are favorable, relatively fine airborne dust particles can be carried much further across the Pacific Ocean which might affect the air quality in the west coast of North America (Duce *et al.*, 1980).

Dust particles can affect both regional and global environment such as visibility reduction, change of radiative forcing, and detrimental effects on human health. Since intensified desertification in China has increased the frequency of DS occurrence along with its intensity and duration, it is expected that the impact of DS will persist

for a foreseeable future (Kim, 2008).

Although DS mainly consists of ambient mineral particles, these particles can act as a long-range transporter of various ambient trace species such as secondary inorganic ions, Persistent Organic Pollutants (POPs), and trace elements including heavy metals (Ghim, 2011). There are several previous studies on DS which demonstrated that DS events have brought a large amount of dust particles along with increased concentrations of anthropogenic species such as sulfate, nitrate, black carbon (BC), gaseous pollutants (e.g., CO, SO_2 , and O_3), and even bioaerosols (Choi *et al.*, 2001; Kim *et al.*, 2009; Chang *et al.*, 2010; Jeon *et al.*, 2011).

According to Choi *et al.* (2001), at Seoul, the concentrations of the earth crustal elements like Mg^{2+} , Ca^{2+} , Na, Mg, Al, Ca, Fe, and Mn in total suspended particles (TSP) and PM_{10} increased in accordance with the intensity of DS, while those of secondary inorganic ions like sulfate (SO_4^{2-}), nitrate (NO_3^-), and ammonium (NH_4^+) salts and harmful heavy metals including Ni, Cu, Zn, Cd and Pb were lower during heavy DS periods than non-DS periods. Back trajectory results showed that the concentrations of anthropogenic pollutants were largely dependent on the transport pathways of DS.

Kim *et al.* (2009) carried out a statistical analysis on the aerosol composition change between DS and non-DS periods

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in spring from March 1992 to May 2006 for the TSP data measured at Gosan, a background area in Korea. Among eight inorganic ions and twelve elements analyzed, the concentrations of all species except NH_4^+ were statistically significantly higher during the DS period. This result was in contrast with another study using the same data base but shorter period; between 1992 and 1999 (Park *et al.*, 2003). Park *et al.* (2003) found that among the anthropogenic species, the concentrations of Pb, non-sea salt (nss)- SO_4^{2-} , and NO_3^- were higher during the DS period. Kim *et al.* (2009) suggested that the drastic increase of primary energy consumption in Northeast Asia during the 2000s might affect the aerosol composition significantly.

Jeon *et al.* (2011) collected 85 TSP samples from May 2008 to March 2010 at Seoul and applied various biological techniques to identify and quantify bacteria. They found that the concentration of culturable bacteria was significantly increased and the bacterial community structure was abruptly changed during the DS events. These might affect human health significantly during a DS event.

Likewise, dust particles may also absorb and convey diverse organic compounds such as polycyclic aromatic hydrocarbons (PAHs) (Kim *et al.*, 2012). Even though organic compounds frequently make up the most significant fraction of aerosols, especially fine particles mass concentration (Jacobson *et al.*, 2000; Seinfeld and Pankow, 2003), complete characterization of the organic fraction of ambient aerosol is difficult due to the complexity of their physical and chemical properties like solubility and reactivity (Jacobson *et al.*, 2000). As a result, relatively few studies have been reported on the organic compositions of aerosols during DS.

Normal alkanes (*n*-alkanes) are an important class of organic compounds in the ambient aerosols, and their homologue distribution may indicate different pollution sources as some of alkane species have been successfully used as molecular tracers in source apportionment of atmospheric particulate pollution (Li *et al.*, 2010). *n*-Alkanes also do have negative impacts on human health. For example, the *n*-alkanes with more than 16-carbon number are known to have a detrimental effect on the skin and even engender skin cancer (Li *et al.*, 2010).

PAHs are one of the most widespread atmospheric organic pollutants mainly derived from incomplete combustion processes of carbon-containing fuels like biomass, wood, coal and oils. Therefore, PAH emission concentrations and patterns are strongly correlated with combustion sources and conditions (Schnelle-Kreis *et al.*, 2007). PAHs are released into the atmosphere in both gaseous and aerosol phases. Approximately 90% of PAH emissions in urban and industrial atmospheres are estimated to be anthropogenic in origin (Fang *et al.*, 2010). Some of PAHs and their derivatives which mainly exist in the particle phase in the atmosphere are of concern because they have been identified as strong human carcinogens (Lee and Kim, 2007). Therefore, long-range transport of PAHs over hundreds to thousands of kilometers has also been of interest in various locations in the world.

There have been a few studies investigating the relationship

between DS events and the concentration of PAHs. At various locations in East Asia, increased concentrations of particle-associated PAHs were observed during DS events (Guo *et al.*, 2003; Fang *et al.*, 2005; Tamamura *et al.*, 2007). Guo *et al.* (2003) measured TSP from June, 2001 to May, 2002 at Qingdao, China and found out that PAHs level was high during DS compared to other seasons except winter when the increase of the use of fossil fuels could result in high PAHs concentration. The results from Fang *et al.* (2005) suggested that the concentration level of PAHs in coarse particles ($\text{PM}_{2.5-10}$) was elevated during March–April because of DS. According to Choi *et al.* (2012), the average concentrations of particulate PAHs during the DS periods at Gosan were statistically higher (t-test, $p < 0.05$) than those during the non-DS periods in TSP and similar air trajectories were observed during the polluted and DS periods.

In order to estimate adverse effects on the environment and human health, a study of organic aerosols in PM_{10} during DS events should be conducted since long-range transported dust particles are typically in the coarse particle size range with aerodynamic diameters of 1–10 μm (Ghim, 2011; KMA, 2011; Stone *et al.*, 2011). According to Chun *et al.* (2001), the particles in the range of 1.35–10 μm in diameter were increased significantly both at Seoul and Anmyon island during a heavy DS in spring, 1998. The PM_{10} which prevailed in the Seoul samples showed highly diurnal variation regardless of DS events and thus, were thought to be mainly resulted from local emission.

Seoul, the capital of the Republic of Korea, is one of the largest cities in East Asia with a population of approximately 10 million and an area of 605.33 km^2 . It is located in the mid-western part of Korean Peninsula and has a long history of early spring time dust storm blown mainly from the Taklimakan Desert, the Gobi desert and the Loess Plateau of China (Ghim, 2011).

The purposes of this research are; (1) to analyze and compare organic compositions and concentrations (18 *n*-alkanes and 16 PAHs) in PM_{10} between the DS and non-DS period at Seoul, Korea from March to May, 2007, (2) to identify the effect of DS on the levels and patterns of ambient *n*-alkanes and PAHs, and (3) to discuss on the possibility of the role of dust particle as a long range transporter.

MATERIALS AND METHODS

Aerosol Sampling

Atmospheric aerosol samples were collected on the roof of the School of Public Health building at the Seoul National University (127°001'E, 37°51'N; 17 m above ground level) between March and May, 2007. Total of 15 samples was obtained and six DS events were observed during sampling period. We collected 24-h PM_{10} samples on pre-baked quartz fiber filters (Whatman Quartz Microfibre Filter, QM-A, $20.3 \times 25.4 \text{ cm}^2$) using a high-volume air sampler (Kimoto, model 121 series) equipped with PM_{10} size-selective inlets in a flow rate at 700 L/min. Quartz fiber filters were pre-baked in an oven at 450°C for 8 hr. Each sampling began at about 9:00 am local time each day.

GC/MSD Analysis

Detailed methods for extraction and analysis are described elsewhere (Lee *et al.* (2011b) for *n*-alkanes and Lee *et al.* (2006, 2011a) for PAHs). In brief, a half of filters were ultrasonicated two times for 30 min each with a mixture of dichloromethane and methanol (3:1; v/v). Before extraction, two deuterated *n*-alkanes and three deuterated PAHs standards were added to each sample as a surrogated internal standard. Total extracts were filtered using a syringe (Whatman PVDF, ID 25 mm, pore size 0.45 μm) and then blown down to 500 mL using a concentrator (ZymarkTurboVap 500) under a pure nitrogen stream at 40°C.

The chemical compositions were identified and quantified by a Hewlett Packard 7890A gas chromatograph equipped with a 5975 mass selective detector (GC-MSD, Agilent Technologies) in the synchronous selected ion monitoring (SIM)/Scan mode. The names of used internal standards and their target compounds are given in Table 1.

The GC-MSD operating conditions were as follows; temperature hold at 60°C for 1 min, increase from 60°C to 310°C at a rate of 6 °C/min with final isothermal hold at 310°C for 15 min. Helium was used as a carrier gas. The sample was injected on a splitless mode at an injector temperature of 300°C. The mass spectrometer was operated on electron impact (EI) mode at 70 eV and scanned from 50 to 650 Da. Data was acquired and processed with the Chemstation software. Individual compounds were identified by comparison of mass spectra with literature and library data, comparison with authentic standards, and interpretation of mass spectrometric fragmentation patterns. The data reported here were corrected for the recoveries. Three field blanks were analyzed and there were no detection of PAHs in the field blanks except Fluoranthene and Pyrene. Fluoranthene and Pyrene were detected in only one field blank and the amount of these compounds in the blank was minor (under 0.1% compared to the amounts in the samples). For *n*-alkanes, the compounds from C22 to C29 were detected in the three field blanks, however, the amounts were under 1% of the amounts in the samples. Therefore, no correction of field blank was applied in the reported data.

Statistical Analysis

To assess the concentration differences between DS and non-DS aerosol samples, ‘independent samples (or two samples) t-test’ was performed for the data. Theoretically, when small samples ($n < 30$) are used in the hypothesis testing, certain assumptions should be met if the test is to

work properly and yield reliable results (Scheffler, 1988). One of them is that the variances between two groups should be homogeneous.

In this study, the f-test was carried out to decide whether or not the variances between two groups are homogeneous so that the above assumption can be satisfied. For most cases, the variances between two sets were homogeneous except the PM₁₀ mass concentrations and some of alkane species. However, according to Boneau (1960), even relatively severe departures from homogeneity of variances did not have serious consequences. Thus, we still carried out the t-test for those species.

In present study, the f-test and t-test are conducted at the 90% ($p < 0.1$) and 95% ($p < 0.05$) confidence level.

Air Mass Backward Trajectory Analysis

In order to track the transport pathways of dust clouds emitted from source regions, backward trajectories were calculated by the NOAA Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT4) model (Draxler and Rolph, 2003) with starting height at 1500 m considering the main transport routes of DS.

The location of the backward trajectory start point was the School of Public Health building at the Seoul National University (127°1'E, 37°51'N). The run time of every trajectory was 72 h (3 days), with 6-h time resolution. The Final Run (FNL) meteorological data, which was six hourly archive data from NCEP's GDAS (Global Data Assimilation System), were used for the trajectory calculation.

RESULTS AND DISCUSSION

General Characteristics

The daily average PM₁₀ concentrations for the 15 samples are summarized in Table 2 with the meteorological conditions and shown in Fig. 1(a). According to the Korean Meteorological Administration (KMA), 6 days of DS storm events were observed at Seoul during the sampling days as indicated in Table 2. The PM₁₀ mass concentrations during the DS events ranged from 34.5–1004.2 (average: 308.6 ± 360.75) $\mu\text{g}/\text{m}^3$, while that during the non-DS events were 36.3–95.2 (average: 61.8 ± 21.69) $\mu\text{g}/\text{m}^3$. Though it was reported as a DS day on April 2, 2007 (D4 in Table 2), the DS was rather weak and the PM₁₀ concentration was low as will be discussed later in this section. During the DS events, the concentrations of PM₁₀ were higher than the non-DS events significantly ($p < 0.05$, one-tailed t-test) when

Table 1. Internal standards used in this study and their target compounds.

Internal Standards	M.W.	Target Compounds
<i>n</i> -Alkanes		
C24-d50	388	Heptadecane (C ₁₇ H ₃₆) to Tetracosane (C ₂₄ H ₅₀)
C30-d62	484	Pentacosane (C ₂₅ H ₅₂) to Hexatriacontane (C ₃₆ H ₇₄)
PAHs		
Phenanthrene-d10	188	Phenanthrene
Chrysene-d12	240	Pyrene, Fluoranthene, Benz(a)anthracene, Chrysene, Retene, and 1,3,5-Triphenylbenzene
Perylene-d12	264	Benzo(b)fluoranthene, Benzo(k)fluoranthene, Benzo(e)pyrene, Benzo(a)pyrene, Perylene, Indeno(1,2,3-cd)pyrene, Benzo(g,h,i)perylene, and Dibenz(a,h)anthracene

Table 2. Summary on the sampling conditions and mass concentrations.

Sample	Date	PM ₁₀ ($\mu\text{g}/\text{m}^3$)	Mean temperature ($^{\circ}\text{C}$)	Mean wind speed (m/s)	Mean humidity (%)	Remarks
N ^a 1	March 15	50.20	9.16	1.9	35.71	Haze and Mist
N2	March 17	36.27	6.77	2.1	43.75	
N3	March 22	87.66	7.88	3.1	76.46	Haze
N4	April 8	95.17	9.53	2.6	64.42	Haze
N5	April 17	47.01	10.19	2.2	57.08	Haze and Mist
N6	April 26	49.76	14.56	2.4	47.63	Haze
N7	May 13	65.80	16.39	3.5	54.83	
N8	May 22	42.07	19.53	2.0	47.50	
N9	May 29	82.43	18.46	2.8	74.38	Shower and Haze
D ^b 1	March 6	90.87	-4.99	4.1	39.42	Snow
D2	March 31	353.61	8.98	2.7	84.00	Shower and Haze
D3	April 1	1004.25	9.19	2.6	55.83	Haze
D4	April 2	34.47	5.66	3.3	47.13	
D5	May 8	109.19	19.41	3.5	56.29	Haze
D6	May 25	259.44	19.71	3.2	72.88	Rain with the fog and Haze

^a N: Non-dust storm day sample, ^b D: Dust storm day sample.

equal variances are assumed. F-test results, however, showed that the variances in two groups are not significantly similar for the PM₁₀ concentration ($p < 0.1$). As mentioned in section 2.3, when the number of samples (n value) is less than 30, the variances in the two groups should be similar for the t-test results to be statistically meaningful. Still, based on the finding by Boneau (1960), we carried out the t-test for the PM₁₀ concentrations. When 'unequal variances assumed t-test' was applied, the PM₁₀ concentrations were higher during the DS events only at $p < 0.1$ level (one-tailed t-test).

Previous studies have reported that PM₁₀ concentration can be significantly increased during a DS event. Han *et al.* (2005) found that the mean concentration of ambient PM₁₀ was about eight times higher during the DS periods in spring 2001 at Gosan. In this study, it is thought that the average PM₁₀ concentration during non-DS were rather high due to stable atmospheric condition resulted from frequent haze and mist events, while that of DS might be low due to rain and snow events during the DS events (Table 2). Statistical data from the Ministry of Environment (ME), Republic of Korea shows that the average concentration of PM₁₀ at Seoul during the spring season including DS periods (from March to May) in 2007 was about $77.7 \mu\text{g}/\text{m}^3$.

During the DS events, the maximum hourly values of PM₁₀ particles ranged 63–249 (average: 192.3 ± 66.79) $\mu\text{g}/\text{m}^3$ were recorded by National Institute of Environmental Research (NIER), Republic of Korea. An unusual daily average concentration of PM₁₀ which exceeded the Korea's 24-h ambient air quality standard of $150 \mu\text{g}/\text{m}^3$ was observed three times during the DS events on March 31 (D2), April 1 (D3) and May 25 (D6), 2007. On April 1, in particular, Seoul site was covered with extremely high level of aerosol concentrations (daily average concentration of PM₁₀ exceeding $1000 \mu\text{g}/\text{m}^3$). This severe dust storm event originated from North and Northwestern China. However, on April 2, the level of PM₁₀ moved down to the lowest of

all samples within a day. It seems like it was because April 2 was the last day of three-day dust storm event (March 31–April 2). D1 is regarded as a relatively weak dust storm event which originated from the forest regions in Siberia/northeast China.

As shown in Table 3, 18 species of *n*-alkanes (C17–C34) were determined. The alkane data on N8 sample is not reported due to the low recoveries of internal standards which might be resulted from experimental errors. Also, total *n*-alkanes concentrations for each sampling days were shown in Fig. 1(b). The average total concentration of the *n*-alkanes was $66.87 \text{ ng}/\text{m}^3$. The average total concentrations of *n*-alkanes for the DS samples was $54.13 \pm 24.78 \text{ ng}/\text{m}^3$ with the range of 15.28 – $84.23 \text{ ng}/\text{m}^3$, while that for the non-DS samples was $76.42 \pm 25.94 \text{ ng}/\text{m}^3$ with the range of 44.49 – $122.73 \text{ ng}/\text{m}^3$. F-test results demonstrated the homogeneous variances between two groups and thus, equal variances assumed t-test was performed. The average concentration of *n*-alkanes during DS was even lower statistically than that of non-DS at $p < 0.1$.

Sixteen species of PAHs and their abbreviation forms are provided in Table 4 along with the concentration data. PAHs species of low molecular weight with 2 or 3 rings (e.g., Nap, Ace, Acy, and Flu) were not analyzed here as they exist predominantly in the gas phase in the normal atmospheric conditions because of their high volatility.

The average total concentration of the ambient particulate PAHs in our Seoul samples was $11.88 \pm 5.55 \text{ ng}/\text{m}^3$. The average concentration of the sum of 16 individual PAHs at Seoul between August, 2002 and December, 2003 was $26.6 \pm 28.4 \text{ ng}/\text{m}^3$ and it showed winter maxima and summer minimum mainly due to the increased fuel consumption in winter both at Seoul and Northeast Asia (Lee *et al.*, 2011a). The average total particulate PAHs concentration for the DS samples ($13.44 \pm 6.03 \text{ ng}/\text{m}^3$) was slightly higher than those for the non-DS samples ($10.84 \pm 5.31 \text{ ng}/\text{m}^3$) (Fig. 1(c)). The average concentrations of each PAH species in

Table 3. Mass concentrations (ng/m³) of *n*-alkanes analyzed in 6 dust storm samples and 9 non-dust storm aerosol samples.

Compound	Formula	M.W.	Non-dust storm aerosol									Average ± standard deviation
			N1	N2	N3	N4	N5	N6	N7	N8	N9	
n-Alkanes												
Heptadecane	C ₁₇ H ₃₆	240	n.d. ^a	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	-	n.d.	0 ± 0
Octadecane	C ₁₈ H ₃₈	254	n.d.	n.d.	n.d.	0.07	0.01	n.d.	n.d.	-	n.d.	0.04 ± 0.04
Nonadecane	C ₁₉ H ₄₀	268	0.37	0.41	0.23	0.53	0.36	0.32	0.16	-	0.39	0.35 ± 0.11
Eicosane	C ₂₀ H ₄₂	282	0.75	0.77	0.34	0.84	0.50	0.23	0.12	-	n.d.	0.51 ± 0.29
Heneicosane	C ₂₁ H ₄₄	296	2.09	1.90	1.18	1.89	2.01	1.48	0.43	-	0.55	1.44 ± 0.66
Docosane	C ₂₂ H ₄₆	310	3.71	3.80	2.71	3.80	2.72	2.17	0.89	-	1.45	2.66 ± 1.10
Tricosane	C ₂₃ H ₄₈	324	5.29	5.37	3.94	6.02	5.15	4.67	1.90	-	2.83	4.40 ± 1.41
Tetracosane	C ₂₄ H ₅₀	338	6.34	6.00	4.51	6.53	6.56	5.20	2.25	-	3.85	5.16 ± 1.54
Pentacosane	C ₂₅ H ₅₂	352	9.44	10.87	4.69	36.23	12.06	13.19	2.70	-	5.43	11.83 ± 10.55
Hexacosane	C ₂₆ H ₅₄	366	2.91	3.62	2.48	22.36	4.89	4.80	1.42	-	3.59	5.76 ± 6.81
Heptacosane	C ₂₇ H ₅₆	380	10.53	13.28	4.67	25.30	11.24	14.28	5.11	-	10.84	11.91 ± 6.42
Octacosane	C ₂₈ H ₅₈	394	3.32	4.75	2.32	7.46	3.96	4.36	2.03	-	4.37	4.07 ± 1.69
Nonacosane	C ₂₉ H ₆₀	408	7.26	9.00	3.93	7.43	6.13	7.24	5.74	-	8.20	6.87 ± 1.58
Triacontane	C ₃₀ H ₆₂	422	3.82	5.12	2.54	2.19	3.50	3.63	2.49	-	4.18	3.43 ± 0.99
Hentriacontane	C ₃₁ H ₆₄	436	10.14	12.89	5.06	2.08	7.23	8.58	6.74	-	9.21	7.74 ± 3.29
Dotriacontane	C ₃₂ H ₆₆	450	3.71	5.39	2.80	n.d.	3.17	3.55	2.99	-	4.06	3.67 ± 0.88
Trtriacontane	C ₃₃ H ₆₈	464	7.50	9.63	4.77	n.d.	5.63	5.64	5.90	-	5.53	6.37 ± 1.66
Tetracontane	C ₃₄ H ₇₀	478	4.16	4.87	n.d.	n.d.	n.d.	n.d.	3.61	-	n.d.	4.21 ± 0.63
Total			81.33	97.69	46.16	122.73	75.12	79.33	44.49	-	64.48	76.42 ± 25.94

^a n.d.: Not detected.

Compound	Formula	M.W.	Dust storm						Average ± standard deviation
			D1	D2	D3	D4	D5	D6	
n-Alkanes									
Heptadecane	C ₁₇ H ₃₆	240	0.17	n.d.	n.d.	n.d.	n.d.	n.d.	0.17 ± 0.00
Octadecane	C ₁₈ H ₃₈	254	0.35	0.04	n.d.	n.d.	n.d.	n.d.	0.20 ± 0.22
Nonadecane	C ₁₉ H ₄₀	268	0.54	0.58	0.20	0.25	0.26	0.63	0.41 ± 0.19
Eicosane	C ₂₀ H ₄₂	282	0.87	0.32	0.41	0.68	0.21	0.29	0.46 ± 0.26
Heneicosane	C ₂₁ H ₄₄	296	1.57	1.00	0.64	1.91	1.07	1.15	1.22 ± 0.45
Docosane	C ₂₂ H ₄₆	310	2.01	2.35	0.85	3.13	1.94	2.13	2.07 ± 0.74
Tricosane	C ₂₃ H ₄₈	324	2.55	4.23	1.13	3.98	4.07	4.42	3.40 ± 1.30
Tetracosane	C ₂₄ H ₅₀	338	2.49	6.07	1.43	3.90	4.33	5.33	3.93 ± 1.73
Pentacosane	C ₂₅ H ₅₂	352	2.13	9.34	0.68	2.69	11.21	3.98	5.01 ± 4.26
Hexacosane	C ₂₆ H ₅₄	366	1.16	5.03	0.60	2.04	3.82	1.96	2.44 ± 1.67
Heptacosane	C ₂₇ H ₅₆	380	3.64	9.50	1.50	3.48	12.60	6.83	6.26 ± 4.20
Octacosane	C ₂₈ H ₅₈	394	1.93	4.43	1.14	2.20	4.42	3.48	2.93 ± 1.38
Nonacosane	C ₂₉ H ₆₀	408	4.83	6.60	2.31	4.46	10.19	6.26	5.78 ± 2.65
Triacontane	C ₃₀ H ₆₂	422	2.92	4.08	1.46	2.16	4.34	4.52	3.25 ± 1.26
Hentriacontane	C ₃₁ H ₆₄	436	6.50	9.43	2.90	5.22	10.77	9.67	7.42 ± 3.05
Dotriacontane	C ₃₂ H ₆₆	450	3.50	3.64	n.d.	2.02	4.09	5.37	3.72 ± 1.20
Trtriacontane	C ₃₃ H ₆₈	464	5.61	5.61	n.d.	3.43	6.76	8.76	6.03 ± 1.94
Tetracontane	C ₃₄ H ₇₀	478	3.93	n.d.	n.d.	n.d.	4.14	n.d.	4.04 ± 0.15
Total			46.72	72.25	15.28	41.54	84.23	64.78	54.13 ± 24.78

most DS samples (except one) were also slightly higher than those of non-DS samples (Table 4). However, t-test result showed that these differences are statistically not meaningful ($p < 0.05$).

Comparison of *n*-alkanes/PAHs Distribution Pattern

The above results revealed that the concentration of

PM₁₀ tends to be increased by DS but the trend of the concentrations of organic classes during the sampling period varied differently. Generally, the average concentration of *n*-alkanes decreased during dust storm period ($p < 0.1$) and that of PAHs seemed to increase a little, though that increase was not statistically meaningful at $p < 0.05$.

To further understand the behavior of *n*-alkanes and

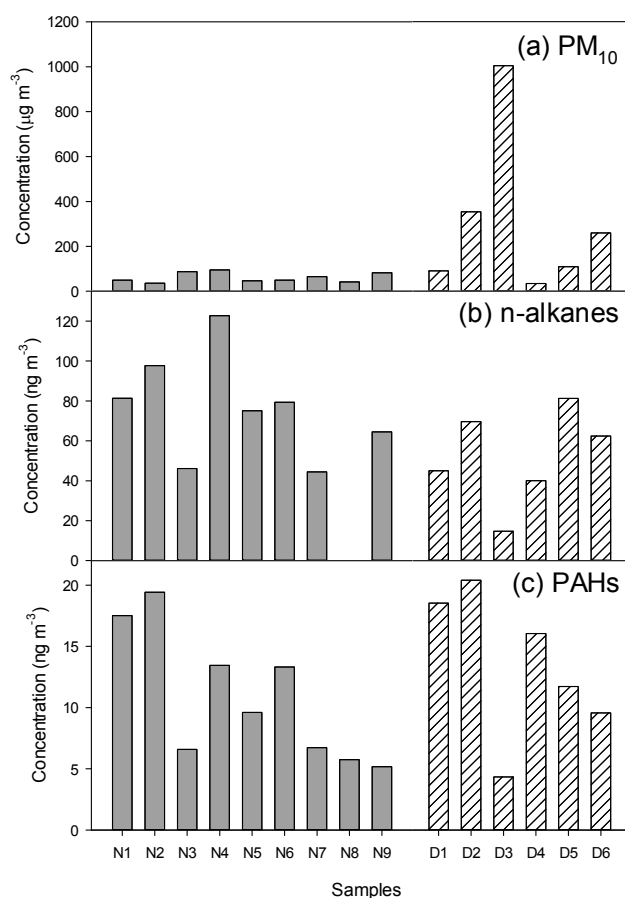


Fig. 1. Trend of (a) PM₁₀, (b) total *n*-alkanes, and (c) total PAHs levels during the sampling days.

PAHs, their compositional distribution pattern between the DS and non-DS samples are studied. Since some organic species are considered as organic molecular markers (or tracers) as they are emitted preferentially by some unique sources, several studies have used these organic compounds for source apportionment (Schnelle-Kreis *et al.*, 2007; Li *et al.*, 2010). Therefore, different concentration trends for *n*-alkanes and PAHs might give a clue to their emission and transport patterns during DS.

The distribution patterns for the each species of *n*-alkanes and PAHs between DS and non-DS samples are shown in Fig. 2. The distribution of *n*-alkanes, expressed as the relative abundance of each homologue in total alkanes can help identifying the likely emission sources (Schnelle-Kreis *et al.*, 2007; Li *et al.*, 2010). The high concentrations of biogenic hydrocarbons (C_{27} , C_{29} , C_{31} and C_{33}) when accompanied with low concentrations of the intervening even carbon number *n*-alkanes as shown in Fig. 2 suggest high plant wax release into the atmosphere (Cass, 1998; Li *et al.*, 2010). The high average concentrations of C_{25} , C_{26} and C_{27} in the non-DS samples seem to be mostly resulted from those of the most alkane-polluted day, N4 (Table 3). Statistically, the concentrations of C_{25} and C_{27} species in the non-DS samples were higher than those from the DS samples (at $p < 0.1$ for C_{25} ; at $p < 0.05$ for C_{27}). However, in case of C_{26} , there was no statistical change between the DS and non-DS samples.

Among the PAHs analyzed, only the concentration of Fluoranthene increased statistically during the DS period ($p < 0.1$) and those of 1,3,5-Triphenylbenzene alone was higher during the non-DS period ($p < 0.05$). 1,3,5-Triphenylbenzene is a useful urban tracer since it has been detected in particles from solid waste incinerators and from burning of plastics (Simoneit *et al.*, 2004). Excluding these two, there was no statistically significant concentration change during the DS events. When we compare the concentrations of each species, *f*-tests were carried out beforehand and most species showed homogeneous variances but four species showed non-homogeneous variances (C_{17} , C_{18} , C_{25} and C_{26} alkane species at $p < 0.05$). For these species, as explained before, we carried out unequal variance assumed *t*-test.

Apart from the DS event, transport from outside of Korea, especially from China, is one of the major sources of air pollutants in Korea during spring (Park *et al.*, 2003, 2004). According to the three-days of backward trajectory analysis, almost all air parcel trajectories for the samples were from Russia, North and Northeast China and Inner Mongolia region regardless of DS which means the sources of long-range transported organic pollutants would be quite similar between DS and non-DS event. These trajectories confirmed that Korea is influenced mostly by the westerly during spring (Park *et al.*, 2004). In some cases, two samples with similar trajectories but different levels and distribution patterns of *n*-alkanes and PAHs were found.

Similar result was observed for the particulate ionic species at Gosan (Kim, *et al.*, 2008). This variation may reflect additional local input or intervention of other complex environmental factors. Based on the previous studies, other factors, e.g., source types, transport pathways and mechanisms, meteorological conditions, local emission and atmospheric chemical compositions are also expected to affect the level and distribution of ambient organic species significantly in combination (Park *et al.*, 2004; Lee *et al.*, 2011a).

Role of the DS Particles as a Long Range Transport Carrier

Our initial assumption was that coarse crustal DS particles may absorb and convey various organic compounds, and therefore cause high organic aerosol concentration during a DS due to the increased PM₁₀ concentration. However, as summarized in section 3.2, a large number of coarse particles in DS might not be an important carrier of organic substances considering that the levels of *n*-alkanes and PAHs were not increased as much as those of PM₁₀ during the DS period. More precisely, in this study, the absolute concentration of *n*-alkanes even decreased during DS and no statistical difference was found in PAHs level between the DS and non-DS periods.

A similar conclusion was made by Choi *et al.* (2012). Choi *et al.* (2012) measured PAHs in both gaseous and particulate phases at Gosan for 15 days (March 29–April 12, 2002) and found out that (1) the levels of particulate PAHs during the DS period were close to or lower than those during the non-DS period and (2) they showed even higher value when PM₁₀ was substantially low, concluding

Table 4. Mass concentrations (ng/m³) of 16 quantified PAH compounds analyzed in 6 dust storm samples and 9 non-dust storm aerosol samples.

Compound	Abbrev.	Non-dust storm aerosol									Average ± standard deviation
		N1	N2	N3	N4	N5	N6	N7	N8	N9	
PAHs											
Phenanthrene	Phen	1.26	1.59	0.26	1.34	0.68	0.94	0.45	0.21	0.53	0.81 ± 0.50
Antracene	Anthr	0.11	0.19	0.03	0.06	0.05	0.08	0.02	0.02	0.05	0.07 ± 0.05
Fluoranthene	Flt	2.13	2.11	0.72	1.54	1.04	1.48	0.99	0.49	0.36	1.21 ± 0.65
Pyrene	Pyr	1.63	1.87	0.61	1.24	0.90	1.32	0.77	0.43	0.36	1.01 ± 0.53
Banz(a)anthracene	BaA	0.90	1.28	0.51	0.81	0.68	0.87	0.46	0.47	0.41	0.71 ± 0.28
Retene	Ret	0.45	1.10	0.12	0.31	0.17	0.20	0.03	0.04	0.06	0.28 ± 0.34
Benzo(b)fluoranthene	BbF	1.84	1.79	0.79	1.47	1.15	1.48	0.81	0.72	0.54	1.18 ± 0.49
Benzo(k)fluoranthene	BkF	1.36	1.53	0.59	1.08	0.86	1.21	0.58	0.58	0.50	0.92 ± 0.39
Benzo(e)pyrene	BeP	1.18	1.18	0.52	0.92	0.74	0.99	0.56	0.51	0.43	0.78 ± 0.30
Benzo(a)pyrene	BaP	1.22	1.52	0.47	0.88	0.67	1.04	0.41	0.38	0.33	0.77 ± 0.42
Indeno(1,2,3-cd)pyrene	I(1,2,3-cd)P	1.87	1.76	0.67	1.07	0.78	1.09	0.58	0.56	0.47	0.98 ± 0.52
Indeno(1,2,3-cd)fluoranthene	I(1,2,3-cd)F	0.43	0.43	0.15	0.36	0.24	0.34	0.12	0.14	0.09	0.26 ± 0.14
Benzo(g,h,i)perylene	BghiP	1.38	1.34	0.56	0.84	0.65	0.84	0.51	0.49	0.40	0.78 ± 0.36
Dibenz(a,h)anthracene	DahA	0.47	0.48	0.16	0.38	0.22	0.38	0.10	0.13	0.10	0.27 ± 0.16
1,3,5-Triphenylbenzene	135 tpbz	0.40	0.55	0.19	0.57	0.43	0.52	0.13	0.37	0.39	0.39 ± 0.15
Coronene	COR	0.89	0.70	0.24	0.57	0.34	0.53	0.21	0.20	0.16	0.43 ± 0.26
Total		17.52	19.42	6.59	13.44	9.60	13.31	6.73	5.74	5.18	10.84 ± 5.31
Dust storm											
Compound	Abbrev.	D1	D2	D3	D4	D5	D6	Average ± standard deviation			
PAHs											
Phenanthrene	Phen	2.44	1.12	0.22	2.08	0.87	0.37	1.18 ± 0.90			
Antracene	Anthr	0.23	0.13	0.01	0.16	0.05	0.01	0.10 ± 0.09			
Fluoranthene	Flt	2.78	2.34	0.54	2.13	1.67	1.29	1.79 ± 0.80			
Pyrene	Pyr	2.03	1.89	0.43	1.68	1.37	1.04	1.41 ± 0.60			
Banz(a)anthracene	BaA	0.98	1.19	0.41	0.87	0.69	0.79	0.82 ± 0.26			
Retene	Ret	1.31	0.41	0.09	0.61	0.04	0.05	0.42 ± 0.49			
Benzo(b)fluoranthene	BbF	1.41	2.51	0.54	1.49	1.40	1.26	1.44 ± 0.63			
Benzo(k)fluoranthene	BkF	1.16	1.79	0.43	1.21	1.10	0.88	1.10 ± 0.44			
Benzo(e)pyrene	BeP	0.93	1.70	0.35	0.94	0.92	0.87	0.95 ± 0.43			
Benzo(a)pyrene	BaP	1.00	1.64	0.35	1.06	0.77	0.67	0.92 ± 0.44			
Indeno(1,2,3-cd)pyrene	I(1,2,3-cd)P	1.43	2.05	0.40	1.27	0.89	0.94	1.16 ± 0.56			
Indeno(1,2,3-cd)fluoranthene	I(1,2,3-cd)F	0.39	0.44	0.07	0.38	0.27	0.15	0.28 ± 0.15			
Benzo(g,h,i)perylene	BghiP	1.07	1.55	0.28	0.93	0.72	0.62	0.86 ± 0.43			
Dibenz(a,h)anthracene	DahA	0.47	0.52	0.07	0.42	0.25	0.14	0.31 ± 0.19			
1,3,5-Triphenylbenzene	135 tpbz	0.11	0.37	0.06	0.22	0.24	0.15	0.19 ± 0.11			
Coronene	COR	0.80	0.75	0.09	0.59	0.47	0.34	0.51 ± 0.27			
Total		18.54	20.40	4.34	16.04	11.72	9.57	13.44 ± 6.03			

the influence of coarse particles of DS on the levels of PAHs was probably not significant.

The levels of *n*-alkanes and PAHs per unit mass of PM₁₀, or the enrichment factor (Kim *et al.*, 2009) were shown in Fig. 2. It seems that, in general, relative importance of organic species per unit mass of PM₁₀ during DS event would be not high. The average level of *n*-alkanes per unit mass of PM₁₀ was statistically lower in the DS samples than that in the non-DS samples, while that of PAHs per unit mass of PM₁₀ showed no statistical difference between

the DS and non-DS periods ($p < 0.05$). *N*-alkanes/PM₁₀ concentration ratio followed a similar pattern to that of PAHs/PM₁₀ with the correlation coefficient of 0.71 ($n = 14$) when excluding the N8 sample. Considering the absolute concentration of *n*-alkanes also showed decreasing tendency during the DS period ($p < 0.1$), it can be estimated that PM₁₀ in the non-DS samples contained more *n*-alkanes, especially C₂₅–C₂₇ species, than in the DS samples.

The tendency of PAHs/PM₁₀ ratios during sampling period was different to *n*-alkanes/PM₁₀ ratios (Fig. 3). The

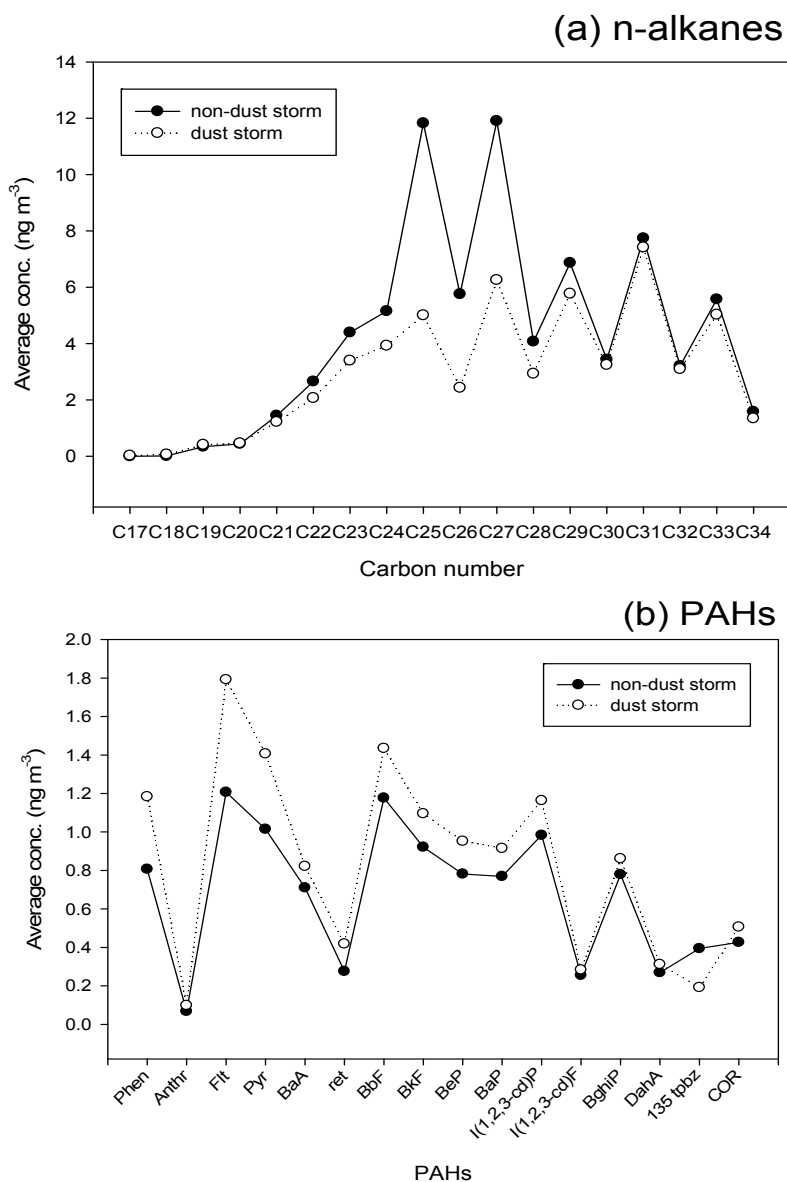


Fig. 2. Component distribution pattern of (a) *n*-alkanes and (b) PAHs for non-dust storm aerosol and dust storm aerosol samples.

variation of PAHs/PM₁₀ ratios was small during sampling period, while, the ratios of *n*-alkanes/PM₁₀ were fluctuate widely. PAHs and *n*-alkanes have different emission sources and strength. Thus, different emission sources and chemical types of these compounds might give influence to the different distribution in the dust particles. Furthermore, it is possible that the two organic classes have different interactions with dust particles. However, at this stage, it is hard to conclude that DS event give different influence to PAHs and *n*-alkanes.

As shown in Fig. 2, the average concentrations of *n*-alkanes species were higher during the non-DS period, while those of PAHs were higher during the DS period. It can be explained with the above suggestions: Since PM₁₀ in dust particles contain less amount of *n*-alkanes than non dust particles, the overall concentration of *n*-alkane species went down during DS even with the increased PM₁₀ concentration

of the DS period. However, the concentration of PAHs species increased during DS (even though it was not statistically meaningful) due to the increase of dust particles (PM₁₀) which contain as much PAHs as normal aerosols do.

SUMMARY

Dust particles may absorb and convey diverse organic compounds. Though organic carbon (OC) compounds are a major fraction of ambient aerosols, complete characterization of the organic fraction of ambient aerosol is difficult, especially, for dust particles. As a result, relatively few studies have been reported on the organic compositions of aerosols during dust storm (DS).

To better understand the impact of the DS event on the ambient aerosol organic composition at Seoul, the solvent-extractable organic compounds in the PM₁₀ samples

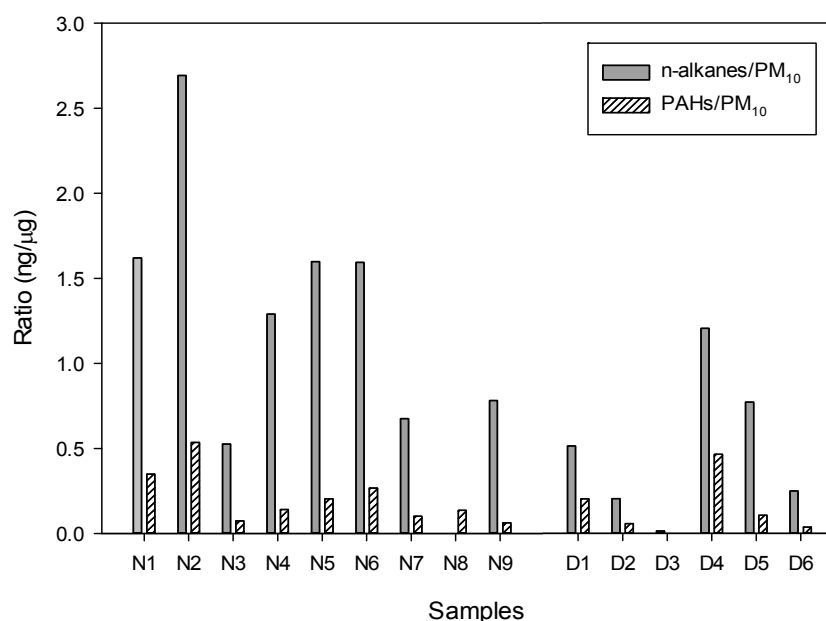


Fig. 3. Levels of *n*-alkanes and PAHs per unit mass of dust particles (PM₁₀).

between March and May in 2007 were characterized by a GC-MS. 18 species of *n*-alkanes (C₁₇–C₃₄) and 16 species of PAHs were identified and quantified.

The results revealed that the concentration of PM₁₀ tends to be increased by DS event while the absolute concentrations of *n*-alkanes showed decreasing tendency ($p < 0.1$) and those of PAHs were not changed statistically significantly ($p < 0.05$).

The distributions of *n*-alkanes and PAHs species showed that among *n*-alkanes, only C₂₅ and C₂₇ species in the non-DS samples increased in their level compared to those in the DS samples (at $p < 0.1$ for C₂₅; at $p < 0.05$ for C₂₇). Since C₂₅ and C₂₇ species are mainly emitted from plant, it suggested that the impact of biogenic emissions of *n*-alkanes was reduced during the DS periods. Among PAHs, only the concentration of Fluoranthene increased statistically during the DS period ($p < 0.1$) and only 1,3,5-Triphenylbenzene level was higher during the non-DS period ($p < 0.05$).

The average levels of *n*-alkanes per unit mass of PM₁₀ was statistically lower in the DS samples, while those of PAHs showed no statistical difference between the DS and non-DS samples suggesting; (1) non-DS particles carried more *n*-alkanes than DS particles and (2) comparable amount of PAHs was involved in the DS and non-DS particles.

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