AE International – Asia

Atmospheric Environment 38 (2004) 1535–1545

ATMOSPHERIC ENVIRONMENT

www.elsevier.com/locate/atmosenv

Comparison of particulate matter characteristics before, during, and after Asian dust events in Incheon and Ulsan, Korea

Byeong-Kyu Lee[a,*], Na-Young Jun[a], Haengah Kim Lee[b]

[a] *Department of Civil and Environmental Engineering, University of Ulsan, Ulsan 680-749, South Korea*
[b] *Environmental Studies Ph.D. Program, University of Massachusetts, Lowell, MA 01854, USA*

Received 26 August 2003; accepted 24 December 2003

Abstract

This study compares characteristics of particulate matter measured in Ulsan and Incheon, Korea, before, during, and after March and April Asian dust (AD) events in the year 2002. The concentrations of PM_{10} just after the AD periods in Ulsan were much higher than those just before the event, during normal spring days. In Incheon, the average PM_{10} concentrations during the first peak period of the AD event showed a significant correlation for 24 h average concentrations just before the first peak period. However, a correlation between concentrations in Ulsan was much weaker than those found in Incheon. The ratio of $PM_{2.5}$ to PM_{10} concentrations in Ulsan during the AD event was much higher than those after the AD event. Even though there was a large increase in PM_{10} concentrations during the AD event compared to normal spring days, there were no large differences in concentrations of $PM_{2.5}$ between them. Concentrations of Mn, Fe, Ni, Cr, Al, Ca, and Mg extracted from the total suspended particulate (TSP) collected during the AD event were very high as compared to those after the event. However, the concentrations of Pb and Cu contained in the TSP decreased during the AD event. A comparison of ozone and PM_{10} concentrations during the AD events shows that extremely high dust concentrations combined with lower sunshine duration time may significantly reduce the ambient ozone concentrations.

Keywords: Asian dust; PM10 and PM2.5; Peak period; Metal; Ozone

1. Introduction

Many Asian people experience a nuisance called Asian dust (AD) or yellow sand almost every spring. Spring and April have been the most abundant occurrence season and month of AD events, respectively. Recently, the number of days with AD events and the concentrations of particulate matter during AD events have significantly increased (KME, 2002). AD is sometimes observed even in winter and fall (Kim and Park, 2001; Zhang et al., 2002). The rapid increase of soil loss and desertification by rapid industrialization, forest fires and reckless deforestation in China and Mongolia significantly contribute to the recent increase of AD events (Singer, 1988; Gomes and Gillete, 1993; Rost, 2001). In addition, expansion of arid zones and loessial belts by local meteorological pattern change or geological change due to global warming may substantially increase the occurrence of AD events (Heslop et al., 1999; Zhang et al., 1999; Zhang et al., 2002).

The ADs have severely increased local particulate concentrations in downwind areas or countries in the AD transport paths e.g., China, Korea, and Japan (Hashimoto et al., 1984; Chung and Yoon, 1996). Also,

*Corresponding author. Tel.: +82-52-259-2864; fax: +82-52-259-2629.
E-mail address: bklee@mail.ulsan.ac.kr (B.-K. Lee).

1352-2310/$ - see front matter
doi:10.1016/j.atmosenv.2003.12.021

long-range transport of the ADs may have a profound effect on the budget of soil or particulate elements in the Hawaiian Islands and even California in the USA (Kurtz et al., 2001; Braaten and Cahill, 1986; Husar et al., 2001; Pettke et al., 2000; Uno et al., 2001; Lin, 2001; Jaffe et al., 2003). The ADs produce severe visibility reduction, respiratory symptoms, eye trouble to human beings as well as damage to animals, plants and industry activities (Takayama and Takashima, 1986; KEI, 2002; Kim et al., 2002). In particular, some ADs reaching Korea may carry various hazardous air pollutants (HAPs) entrained in passing through highly industrialized zones in China (In and Park, 2002). In fact, many Koreans, Chinese, and Japanese are fearful of exposure to ADs (Zhou et al., 1996; Kwon et al., 2002). In particular, citizens who live in the highest industrialized Korean cities, such as Ulsan and Incheon, worry about exposure to ADs and HAPs and their potential negative health effects.

This study focuses on the analysis of the spatial and temporal variations of PM_{10} concentrations and the relationships between PM_{10} and ozone before, during, and after recent AD events in Ulsan and Incheon, Korea. Also, we present the analysis of correlations between PM_{10} concentrations on the first peak period and just before the AD events, concentrations of metallic components extracted from total suspended particulates (TSPs), and ratio characteristics of PM_{10} and $PM_{2.5}$ measured during and after recent AD events.

2. Methods

This study analyzes the PM_{10} concentrations observed at 21 air pollution monitoring sites in Incheon and Ulsan, the mid-western and the southeastern part of Korea (Fig. 1), respectively, before, during and after March and April AD events in 2002. The air monitoring sites were mostly located at a height of approximately 10–15 m from ground level and a distance of at least 40–50 m away from roads. Even though there was a difference in the models of β-ray attenuation mass monitor (e.g., Met One BAM-1020 or Thermo Anderson FH 62 C14 Series) used for PM_{10} measurement among the monitoring sites, all the measurements were carried out using the β-ray attenuation methods, which satisfy the US EPA automated equivalent PM_{10} method, EQPM-1102-150. Ambient particulate matter is drawn into a 10 micron (μm) size selective inlet, which discriminates against particles with an aerodynamic diameter above 10 μm, with a flow rate of $16.67\,l\,min^{-1}\,(1\,m^3\,h^{-1})$ and deposited onto the continuous glass fiber filter tape. At the beginning of the sampling period, β-ray transmission using small ^{14}C β source (60–100 μCi) and proportional detector is measured across a clean section of filter tape. At the completion of each 1 h sampling interval, the mass of ambient particles deposited on the fibrous filter tape is detected by re-measuring a β-ray transmission after the filter tape is returned to its original location. An hourly precision of the β-ray attenuation mass monitor is usually less than $\pm$4–5 $\mu g\,m^{-3}$ under concentrations less than 80 $\mu g\,m^{-3}$. However, it is about $\pm$7% for concentrations greater than 80 $\mu g\,m^{-3}$. Also, the filter paper has a humidity effect, in particle concentration, of $\pm 2\,\mu g\,m^{-3}$ per 10% of relative humidity change. Only a few β-ray attenuation mass monitors used in this study have a heating system to reduce positive artifact measurement that can potentially occur as a result of condensation on the filter tape. However, the temperature difference between the maximum and the minimum under the peak periods of the AD studied was not that significant. The relative humidity was less than 60% which might be affected by a formation of the positive artifact. The β-ray attenuators at the monitoring sites were well cleaned, calibrated and checked according to the preventative maintenance schedule of the manufacturers.

The terms compared in this study are categorized as the term "before" (periods of 24 h just before the ADs reached the compared cities), the term "during" (peak periods of the AD events in Korea) and the term "after" (periods of 24 h just after finishing the AD events). The correlations between the PM_{10} concentrations on the period of 24 h just before the first peak periods and those on the first peak periods of the AD events (27–30 h in March and 15–20 h in April) in Ulsan and Incheon were analyzed (Table 1). This study also analyzed the ratios of $PM_{2.5}$ to PM_{10} concentrations, measured by β-ray attenuators (DASIBI 7001 model), during the April AD event periods and normal days in a typical residential area of Ulsan. Concentrations of the metallic components extracted from the TSP samples collected at 2 sites (a city central area and a residential area near an industrial complex) in Ulsan and 1 site (a residential

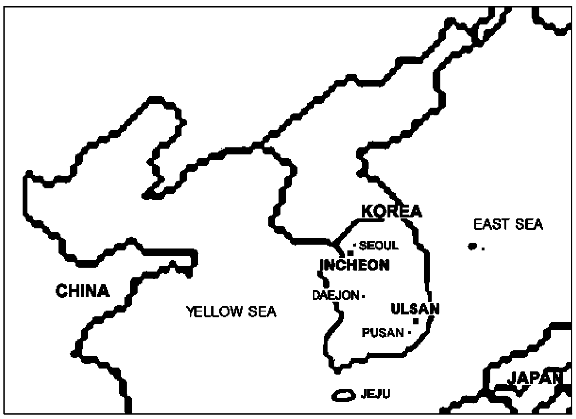


Fig. 1. Geographical position of Incheon and Ulsan in Korea.

Table 1
Duration time of peak periods during March and April 2002 AD events

	March AD peak period duration		April AD peak period duration		
	1st peak	2nd peak	1st peak	2nd peak	3rd peak
Incheon	3/21:07 – 3/22:10 (27 h)	3/22:10 – 3/22:23 (13 h)	4/7:23 – 4/8:13 (15 h)	4/8:16 – 4/9:20 (28 $\pm$ 1 h)	4/10:04 – 4/10:19 (15 h)
Ulsan	3/21:11 – 3/22:17 (30 h)	3/22:21 – 3/23/03 (6 h)	4/8:09 – 4/9:02 (20 h)	4/9:02 – 4/10:01 (23 $\pm$ 1 h)	4:10:02 – 4:11:04 (26 $\pm$1 h)

area) in Incheon during and after the April AD event were identified by atomic absorption spectroscopy (AAS) and inductively coupled plasma-mass spectroscopy (ICP-MS). Each sample was analyzed at least three times repeatedly by AAS or ICP-MS and most concentrations of the analyzed metallic components showed a consistency within a standard deviation of $\pm$1.28%. In addition, this study identified a relationship between the average concentrations of ozone and PM_{10}, based on 1-h measurements, at 21 air monitoring sites in Ulsan and Incheon before, during, and after March and April 2002 AD events.

3. Results and discussion

3.1. Weather patterns

Fig. 2 shows the weather maps on the surface and 850 hPa, respectively, at 00UTC March 21, 2002 when the March AD event began in Korea. A continental high-pressure region, having its center between 45–52°N and 86–96°E, was located in the northwestern direction from the Korean peninsula and a low-pressure region was located in the northern and northeastern parts of the Korean peninsula. Thus, a strong pressure gradient was formed at the Inner Mongolia Plateau (45–55°N, 110–120°E) and then resulted in the strong western or northwestern winds that can move AD, originating from the Plateau, to the Korean peninsula. The strong wind conditions observed on March 19 were maintained until March 21. Thus, a very large amount of particulate matter would be suspended in the air from the plateau surfaces (Chun et al., 2003) and resulted in the March AD in China and the Korean peninsula. The weather patterns during the April AD event were similar to those during the March AD event and thus the April AD event in the Korean peninsula was not significantly different from the March AD event.

3.2. Peak PM_{10} concentrations

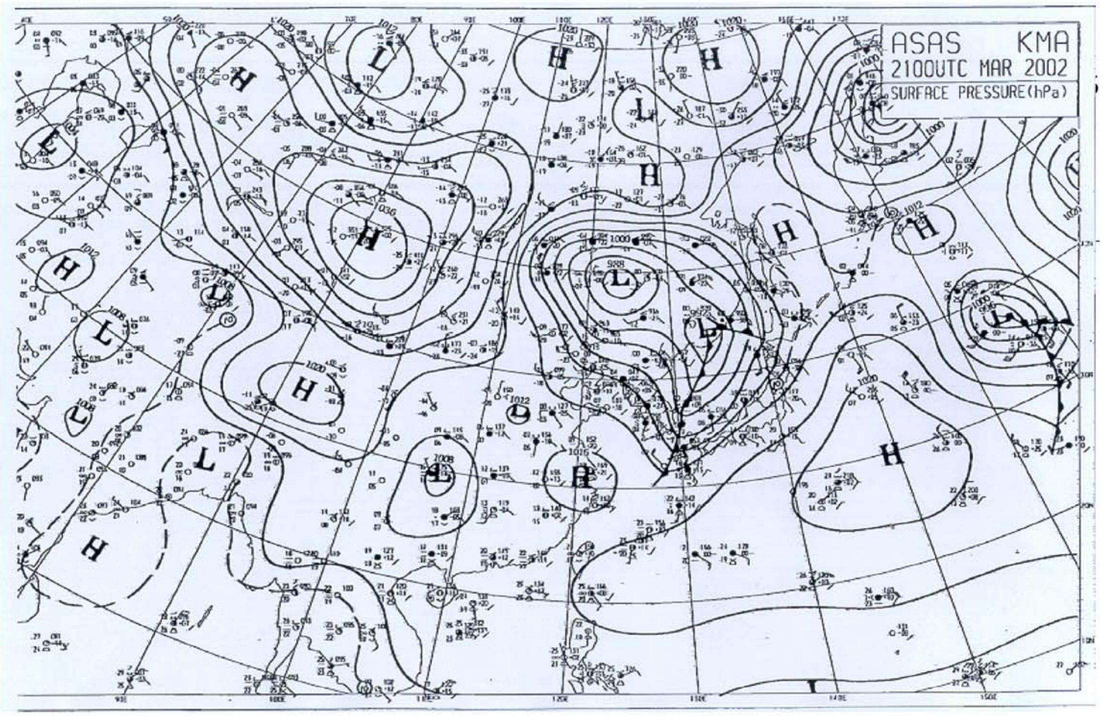
Table 1 shows the duration time of the peak periods, having unusually high-particulate concentrations, observed in Incheon and Ulsan during the AD events in March and April, 2002. There was a difference in peak duration time between the two cities located about 500 km from each other. In particular, there was a significant difference between Incheon and Ulsan in the duration time of the third peak period of April dust events. Fig. 3 represents the average of the total 1-h PM_{10} concentrations measured at 10 sites in Incheon and at 11 sites in Ulsan during the April AD events in the year 2002. Maximum 1-h PM_{10} concentrations at many air monitoring sites in both cities during the first peak periods of the March and April AD events exceeded 1000 $\mu g\,m^{-3}$. The average of the 24-h PM_{10} concentrations monitored at Kuwoldong, in Incheon, and at Hwasanri, in Ulsan, during the highest peak period of the March AD events exceeded 856 and 905 $\mu g\,m^{-3}$, respectively. These values are 5.7–6.0 times higher than the ambient air quality standard of 150 $\mu g\,m^{-3}$ for 24-h PM_{10} concentration in Korea.

3.3. Spatial and temporal variations

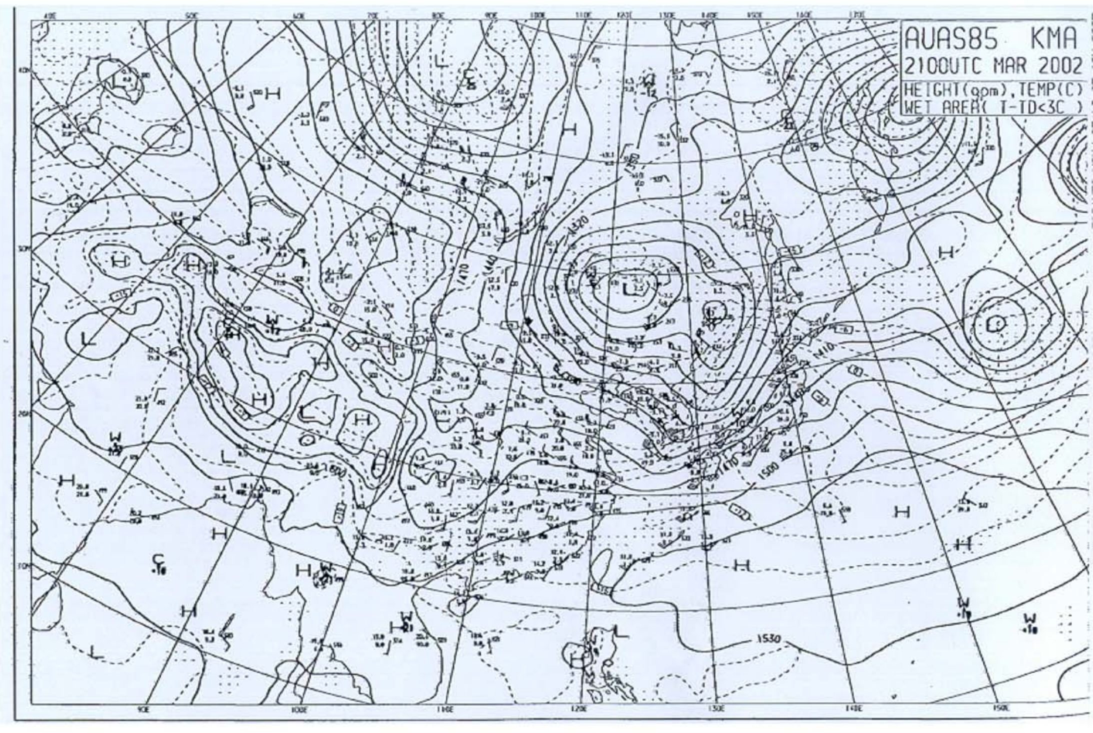
Fig. 4 compares the averaged PM_{10} concentrations measured at 10 sites in Incheon and at 11 sites in Ulsan before, during and after March and April AD events, respectively. Average PM_{10} concentrations in Ulsan before the March and April AD events were higher than in Ulsan. This might be related to the higher industrial emissions in Ulsan which has the largest industrial complex or zones in Korea. Higher PM_{10} concentrations were observed in March, which has a lower humidity, stronger wind speeds and higher energy usage, than in April.

There was a slight difference in average PM_{10} concentration of the peak periods between Incheon and Ulsan. Also, the average peak concentrations decreased with further progress of the AD events, even though there is a possibility that particles could have remained from the previous peak periods. These facts mean that dust particle distributions inside AD clouds between two cities, having different locations, peak times and progress time, are not uniform. However, the significant difference between Incheon and Ulsan in the average PM_{10} concentrations of the third peak periods is probably due to the large difference in peak duration between the two cities.

Fig. 5 shows spatial and temporal variations of the average PM_{10} concentrations measured at air



(a)



(b)

Fig. 2. Weather maps on the surface (a) and on 850hPa (b) at 00UTC March 21, 2002.

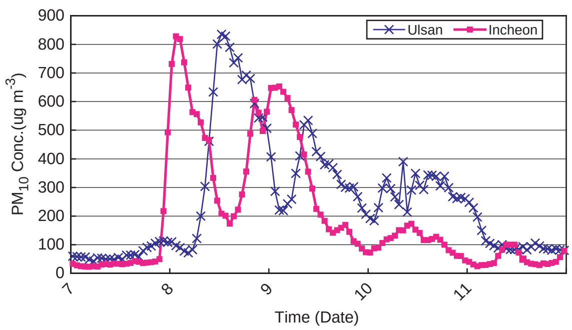


Fig. 3. Averaged 1-h PM_{10} concentrations in Incheon and Ulsan during AD event in 2002.

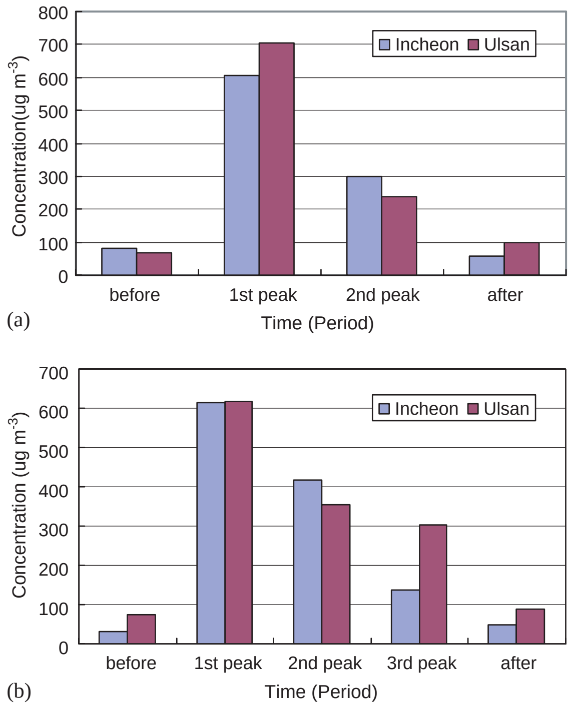


Fig. 4. Comparisons of the averaged PM_{10} concentrations in Incheon and Ulsan before, during and after March (a) and April (b) AD events in 2002.

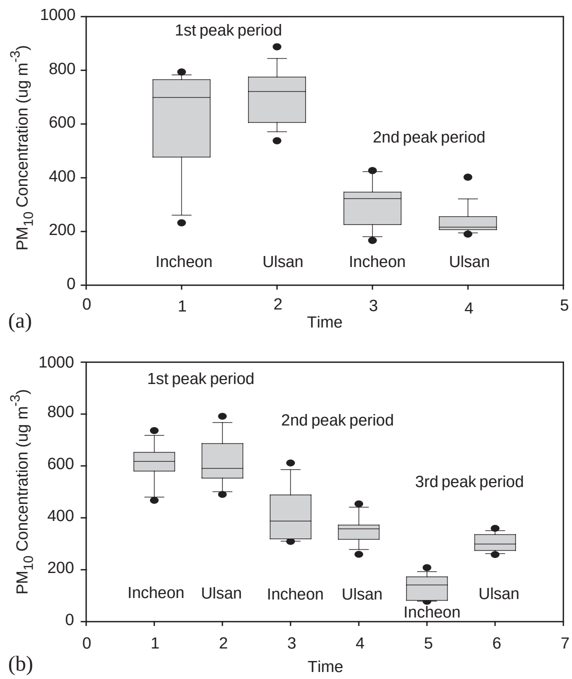


Fig. 5. Temporal and spatial variations of PM_{10} concentrations between Incheon and Ulsan during the March (a) and April (b) AD events in 2002.

monitoring sites in Incheon and Ulsan during the peak periods of the March and April AD events. There is a significant spatial variation among PM_{10} concentrations observed even within the same city during the same peak period. For example, the average 24 h PM_{10} concentrations just before the first peak period of the April AD events in Incheon only ranged from 122 to 32 $\mu g\,m^{-3}$. However, the average PM_{10} concentrations of the first peak period ranged from 793 to 232 $\mu g\,m^{-3}$. A range of spatial variation or a maximum concentration of PM_{10} concentrations during the peak periods was decreased with further progress of the AD events. If we compare the average PM_{10} concentrations between the second and the third peak periods of the April AD events, Ulsan and Incheon show the significantly different features. There is a large difference of 67.3% in Incheon, however, a slight difference of 14.8% appears in Ulsan. This implies that Incheon was almost at a terminal stage of the AD events during the third peak period on April 10, 2002. However, Ulsan was still in the middle of the significant AD events during the third peak period on that same day. This may be the evidence associated with a time lag effect of PM_{10} concentrations between Incheon and Ulsan due to differences in the passing time of the Asian dust streams through each city. This difference might also be associated with different activity levels of the AD events between the two cities.

Table 2 and Fig. 4 also represent that the average PM_{10} concentrations just after the peak periods of the Asian dusts are usually higher than those just before the April dust events. This result indicates that PM_{10} components even after an AD event are not entirely removed from the atmosphere. Remaining PM_{10} components from an AD event can still increase PM_{10} concentrations in the atmosphere for the subsequent non-Asian dust (NAD) periods even after a severe AD event is over.

Table 2
A comparison of average PM_{10} concentrations ($\mu g\,m^{-3}$) in Incheon and Ulsan before, during and after AD events in 2002

	March event concentration		April event concentration	
City	Incheon	Ulsan	Incheon	Ulsan
24 h average before 1st AD peak	82.1±30.7	67.6±20.7	32.2±12.2	75.6±20.7
2 peak period average during AD	453.5±221.3	471.9±252.7	516.0±138.8	485.4±156.4
24 h average after last AD peak	58.1±22.2	98.9±26.4	49.8±17.4	88.8±20.5
Concentration ratio of after to before AD event	0.71	1.46	1.55	1.17

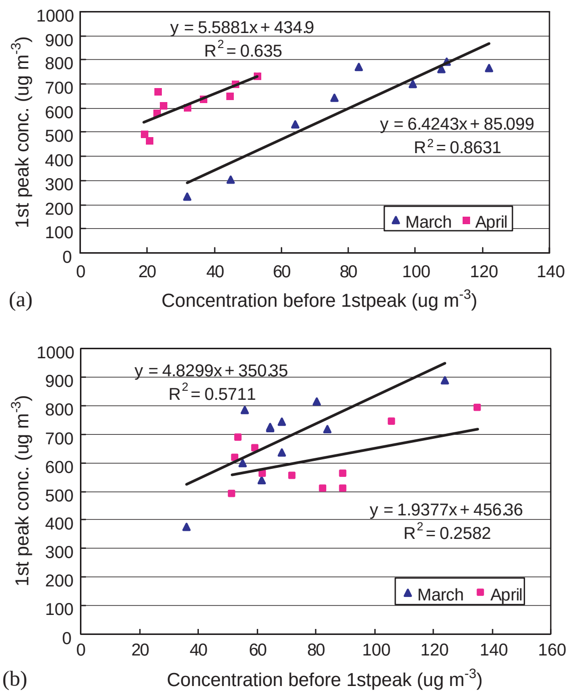


Fig. 6. Relationships between the average PM_{10} concentrations just before and during the first peak period of March and April 2002 AD events in (a) Incheon and (b) in Ulsan.

3.4. Relationship between just before and the first peak period of the AD events

Fig. 6 shows the analysis of a relationship between average PM_{10} concentrations just before and during the first peak period of the March and April AD events in Incheon and Ulsan, respectively. In Incheon, the average PM_{10} concentrations during the first peak periods of the AD events were significantly proportional to 24 h average concentrations just before the first peak periods (Fig. 6(a)). This means that PM_{10} components or concentrations just before an AD event starts can greatly affect the PM_{10} concentrations during the first peak periods of the AD events in Incheon. The linear relationship of the March AD event was greater than that of the April event. However, the relationship between them in Ulsan was much weaker than in Incheon in the case of both the March and April AD events. This difference between Incheon and Ulsan might have been affected by the differences in local source patterns of PM_{10} and in the transport distance from the AD origins. That is, the main local sources of PM_{10} in Incheon originated from vehicle traffic during normal days, however, local PM_{10} components in Ulsan mostly originated from industrial activities and fleet vehicles. Also, the ADs observed in Incheon located in the mid-western part of Korea spent a relatively short time inland, while the ADs observed in Ulsan located in the southeastern part of Korea had a relatively long transport range and more time spent inland. Thus, the AD transported to the Ulsan area might have more chances to be affected by complex local sources or situations after the AD reached the Korean peninsula. At this moment, however, the exact cause of the relationship difference between Incheon and Ulsan or between March and April ADs has not been identified. The different characteristics in terms of dust particle distribution, origin and transport path, duration time inland, meteorology, local source pattern, etc. between the ADs in March and April might affect the difference.

3.5. Ratio of $PM_{2.5}$ to PM_{10}

Fig. 7 compares averaged 1-h $PM_{2.5}$ and PM_{10} concentrations as a function of the time during the April AD event period and the NAD period after the AD event in a residential area of Ulsan. There was no major difference in the $PM_{2.5}$ concentrations between the AD event and NAD periods. However, the ratios of $PM_{2.5}$ to PM_{10} concentrations during the AD event period were very much reduced when compared to the NAD period. That is, the average ratio during the AD event period was only 0.1, however, the average ratio during the NAD period was 0.46. This large difference is due to a severe increase in PM_{10} concentrations during the AD event period as compared to an increase in $PM_{2.5}$ concentrations. Fine particles were a very important fraction in the PM_{10} mass measured during the NAD period. However, fine particles only occupied a small fraction of the PM_{10} mass measured during the AD event period. This means that most of the PM_{10} components collected in the residential area of Ulsan during the AD event period consisted of a coarse particle fraction rather than a fine particle fraction.

3.6. Analysis of metallic components

Table 3 and Fig. 8 represent the concentration characteristics of metallic components extracted from the TSPs collected at two sites in Ulsan and one site in Incheon during and after the April AD event period. There was a severe increase in the concentrations of aluminum (Al), magnesium (Mg), iron (Fe), manganese (Mn), calcium (Ca), nickel (Ni) and chromium (Cr) in the TSPs of Ulsan during the AD event period as compared to those during the NAD period after the event. This result or trend corresponds with previous study results of AD (Zhang and Iwasaka, 1999; Kim et al., 2003). The increase in ratios of the concentrations of metallic components during the AD event period to the NAD period were the highest on the first peak period and gradually decreased with a further progress

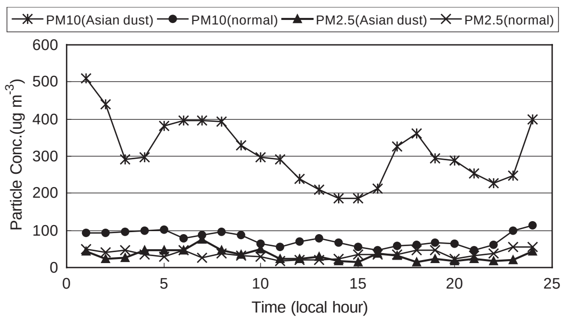


Fig. 7. PM_{10} and $PM_{2.5}$ concentrations in Ulsan during and after April 2002 AD event.

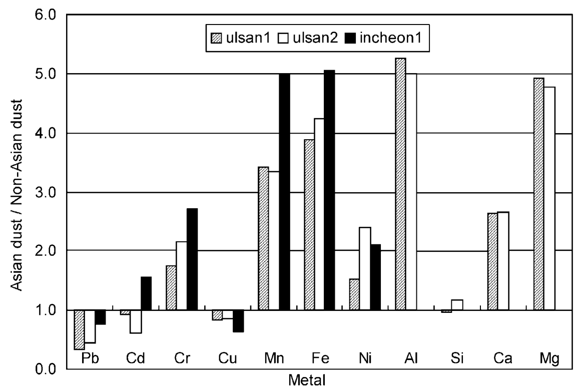


Fig. 8. A comparison of concentration ratios of the metallic components extracted from TSP collected at residential areas in Incheon and Ulsan during and after April 2002 AD event.

Table 3
Concentrations (ppm) and ratios of the metallic components extracted from TSPs collected in Ulsan and Incheon during and after the AD event

City	Term		Pb	Cd	Cu	Cr	Ni	Mn	Fe	Al	Mg	Ca	Si
Ulsan (Site 1)	Asian Dust (AD)	Day1	0.0126	0.0758	0.0287	0.0148	0.0027	0.6092	15.599	7.7927	16.767	66.307	2.3557
		Day2	0.0088	0.0546	0.0203	0.0081	0.0015	0.3287	8.6966	3.6031	7.5878	28.324	2.1521
		Day3	0.0084	0.0840	0.0434	0.0075	0.0041	0.2049	6.3652	2.2389	4.1684	27.656	2.2345
		AVG	0.0099	0.0715	0.0308	0.0101	0.0028	0.3809	10.220	4.5449	9.5076	40.762	2.2474
	NAD	AVG	0.0057	0.0852	0.0899	0.0067	0.0030	0.1117	2.6360	0.9223	3.6138	7.7425	2.3080
	(AD/NAD) Day1		0.3	0.9	0.9	2.2	2.2	5.5	5.9	8.6	8.4	4.6	1.0
	(AD/NAD) AVG		0.3	0.9	0.8	1.7	1.5	3.4	3.9	5.3	4.9	2.6	1.0
Ulsan (Site 2)	Asian Dust (AD)	Day1	0.0191	0.3797	0.0553	0.0206	0.0030	0.6865	17.166	8.2055	19.310	79.429	3.4068
		Day2	0.0129	0.2038	0.0475	0.0112	0.0017	0.3144	10.207	4.1077	6.8329	17.900	2.9092
		Day3	0.0105	0.1933	0.0515	0.0081	0.0020	0.2427	7.7265	2.6552	4.6810	35.632	2.8763
		AVG	0.0142	0.2589	0.0514	0.0133	0.0022	0.4145	11.700	4.9895	10.275	44.320	3.0641
	NAD	AVG	0.0066	0.3039	0.1178	0.0056	0.0036	0.1240	2.7649	1.0470	3.8591	8.8578	2.6032
	(AD/NAD) Day1		0.5	0.8	1.2	2.9	3.7	5.5	6.2	9.3	7.8	5.0	1.3
	(AD/NAD) AVG		0.4	0.6	0.9	2.1	2.4	3.3	4.2	5.0	4.8	2.7	1.2
Incheon (Site 1)	AD	AVG	0.0290	0.1390	0.0980	0.0299	0.0097	0.4878	12.597				
	NAD	AVG	0.0107	0.2184	0.1290	0.0143	0.0062	0.0981	2.4918				
	(AD/NAD) AVG		0.8	1.6	0.6	2.7	2.1	5.0	5.1				

Note: AD stands for Asian Dust, NAD stands for Non-Asian Dust, and AVG stands for average. All AVG values represent average concentrations based on 2 or 3 times measurements.

of the event. The highly increased concentrations of the metallic components might have originated from the soils of the AD origin areas.

However, the concentrations of lead (Pb), cadmium (Cd) and copper (Cu) in Ulsan decreased with a fluctuation during the AD event period when compared to the average of the NAD period after the AD event. Even though there is a slight difference in the concentrations of the metallic components in the TSPs between the two residential sites in Ulsan, there was no big difference in the increase and decrease ratios between the two sites during and after the AD event period. In addition, except for Cd, the increase and decrease ratios in the average concentrations of heavy metals extracted from the TSPs collected at 1 site in Incheon during and after the AD event period had a similar pattern to the ratios in Ulsan. The Cd concentrations of the TSPs in Ulsan slightly decreased during the AD event period as compared to the NAD period, while those in Incheon increased.

Traffic density and speed were much reduced during the AD event in Incheon and Ulsan because of severe visibility reduction and driving avoidance due to potential exposure to severe AD concentrations. Pb concentrations in TSPs during the NAD period were greatly affected by high traffic density (Harrison et al., 2003). The reduction of traffic exhaust or re-suspended road dust including high amounts of Pb might have caused a relatively low concentration of Pb in the TSPs during the AD event. According to recent studies of AD event (Zhang and Iwasaka, 1999; Kim et al., 2003), Cu concentrations in the AD were slightly higher when compared to the NAD. In this study, however, the Cu concentrations of the TSPs collected during the AD event period in Incheon and Ulsan were lower than during the NAD period. This might be explained by a severely reduced traffic volume, which could significantly reduce air emissions of Cu derived from brake linings in urban areas, during the AD event period. From these results, it is inferred that the April AD did not increase local concentrations of Pb, Cd and Cu in the TSPs but local sources of those metals may have greatly contributed to the concentrations. The increase ratios in concentrations of Fe, Mn, and Cr in Incheon during the AD event were greater than those in Ulsan. This is could be because Incheon is located a relatively short distance from the AD origin having, soil dust characteristics as compared to Ulsan.

3.7. Relationship between PM_{10} and ozone

Table 4 shows ozone reduction during the peak periods of the March and April AD events and a summary of the meteorological conditions before, during and after the peak periods. There were significant reductions in the afternoon ozone concentrations during the peak periods. The cause of the ozone reduction might be due to a cold front formation or precipitation just before the AD reached Incheon and Ulsan, reduction in sunshine duration time and increase in cloud fraction covering the sky during the peak periods, and large increases in particulate concentrations during the peak periods.

Fig. 9 also shows changes in average concentrations of ozone and PM_{10} measured every hour at 10 air monitoring sites in Incheon and at 11 air monitoring sites in Ulsan, respectively, before, during and after the peak periods of the March AD events. There was significant precipitation (rain fall) just before the ADs reached Incheon and Ulsan. The precipitation can scavenge the sources of ozone formation and thus lead to reduction in the surface ozone concentration. The atmosphere near the cold front line formed before the precipitation occurs is vertically unstable, therefore there is a possibility that the clean air-masses descend from the upper troposphere to near the surface. In addition, the stratospheric origin air-masses can sometimes come down. Thus the scavenge effect, meteorological condition and air mass movement associated with the precipitation could reduce the surface ozone reduction.

The higher coverage of the sky by cloud and the lower sunshine duration time can also reduce the surface ozone reduction. The low ozone concentrations on 21 March in Incheon and 22 March and 8 April in Ulsan are good examples associated with the increased cloud coverage and reduced sunshine duration (Table 4). When the morning ozone concentrations are compared to the afternoon ozone concentrations, in general, the latter are much higher than the former. However, the ozone concentrations during the morning were higher than those during the afternoon, which shows extremely high average PM_{10} concentrations of equivalent to or higher than 700 $\mu g\,m^{-3}$, during the first peak periods of March AD events. The very high particulate concentrations during the AD peak periods could facilitate higher cloud coverage and lower sunshine duration time conditions than the normal days or NAD periods, and thus the radiation of the sunlight available for ozone formation at the surface might be significantly reduced compared to normal conditions.

There is a significant difference in the reduction efficiency of the afternoon ozone concentrations between 21 and 22 March in Ulsan. It could also be due to the difference in the sunshine duration time between them. Also, it could be due to the difference in concentrations of ozone precursors like nitrogen oxide (NO_x), volatile organic compounds (VOCs), and radicals. As the extremely high concentrations of particulate were observed in the afternoon of 21 March in Ulsan, the traffic volume on that day was similar to normal days. However, the traffic volume on 22 March was

Table 4
Ozone reduction during March and April 2002 Asian dust peak periods and meteorological conditions

	March						April								
Period	N[a]	1st peak		2nd peak		N[a]	N[a]	N[a]	1st peak		2nd peak		3rd peak		N[a]
Date	20	21	21	22	22	23	6	7	8	8	9	9	10	10	11
Time[b]	PM	AM	PM	AM	PM	PM	PM	PM	AM	PM	AM	PM	AM	PM	PM
Incheon															
Precipitation (mm)	2.0	11.0		—			19.5	0.0	—		—		—		—
Avg. rel. humidity (%)	70	71		54		44	92	91	59		59		69		59
Avg. cloud fraction (%)	45	74		63		24	100	100	29		11		26		43
Sunshine duration (h)	5.2	0.0		4.6		9.6	0.0	0.0	7.2		9.3		10.6		7.4
PM_{10} conc. ($\mu g\,m^{-3}$)	114	464	693	209	337	50	34	36	435	214	381	166	154	123	43
Ozone conc. (ppb)	34.0	17.0	15.5	18.8	27.2	44.5	20.7	34.8	19.5	32.2	23.3	32.5	23.5	44.0	38.5
Ozone reduction (%)[c]			54.4		20.0					7.5		6.6		—	
Ulsan															
Precipitation (mm)	—	14.5		0.0		—	17.0	—	0.0		—		—		—
Avg. rel. humidity (%)	56	45		34		22	89	83	49		30		32		34
Avg. cloud fraction (%)	19	94		85		16	89	38	63		5		61		58
Sunshine duration (h)	9.4	5.1		0.2		10.1	0.0	5.9	1.9		9.4		7.9		5.5
PM_{10} conc. ($\mu g\,m^{-3}$)	110	73	785	617	498	87	52	70	539	746	464	348	299	327	78
Ozone conc. (ppb)	39.1	34.0	30.0	18.9	22.0	38.2	21.0	30.9	17.5	23.6	27.4	26.1	24.7	29.3	40.8
Ozone reduction (%)[c]			23.3		43.7					23.6		15.5		5.2	

[a] N stands for a normal day which does not have the AD events.
[b] AM stands for 06:00–12:00 and PM stands for 12:00–18:00.
[c] Ozone reduction efficiency was based on the average ozone concentration in the afternoon (12:00–18:00) of the normal day just before the 1st peak period of the AD events.

significantly reduced, about 20–25%, as compared to normal days. People in Ulsan had experienced the extremely high particulate concentrations and visibility reduction through the afternoon on 21 March. In addition, the warning reports of the AD levels expected on 22 March were delivered through the nighttime news hours. Thus uncomfortability or potential risk to be exposed to high dust concentrations dissuaded many people from driving their mobile vehicles throughout the entire day. Therefore, the significant amounts of vehicle emissions, including NO_x and VOCs, were reduced. The very short duration time of the sunshine might have significantly reduced the production of (hydroxyl) radicals or photochemical oxidants which can play an important role in surface ozone formation. These facts can also be applied to the afternoon ozone reduction on 8 April. However, there is a difference in ozone reduction efficiency between on 22 March and 8 April. The relatively low ozone reduction efficiency on 8 April, as compared to 22 March, might be related to its longer sunshine duration time. Through a comparison of ozone reduction efficiency and PM_{10} concentration among on 8–10 March, it is inferred that the higher particulate concentrations, in particular, in both morning and afternoon of AD events, can more substantially contribute to the reduction of the afternoon ozone concentrations than the lower ones.

4. Summary and conclusion

Through a comparison study of particulate matter characteristics in Incheon and Ulsan of Korea before, during and after March and April AD events 2002, we found the following:

(1) There were significant spatial and temporal variations in average PM_{10} concentrations during the peak periods of the AD events between Incheon and Ulsan, located 500 km from each other. The highest variation was usually observed during the first peak period of the events and this variation gradually decreased with further progress of the events. There was a time-lag effect of the PM_{10} concentrations during the peak periods between Incheon and Ulsan. This effect

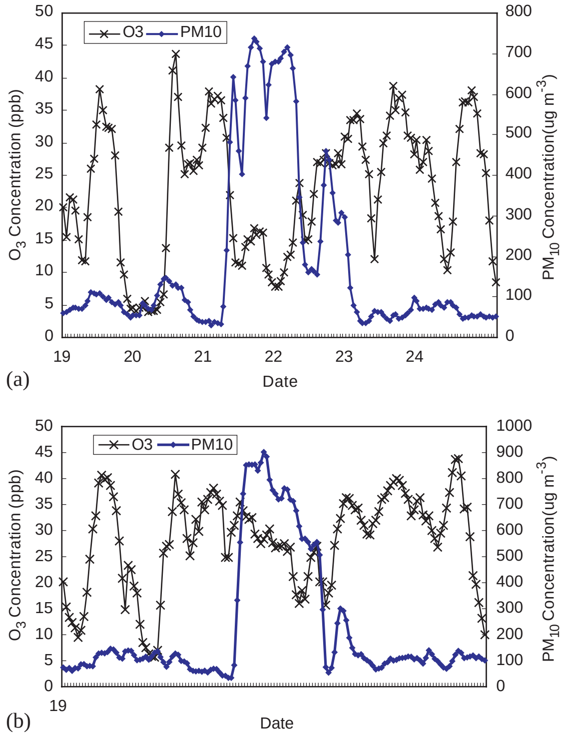


Fig. 9. Average concentrations of PM_{10} and ozone in Incheon (a) and in Ulsan (b) before, during and after March AD event in 2002.

might be due to the differences in the passing time of the AD streams through each city.

(2) The average PM_{10} concentrations after the AD events in Ulsan were significantly higher than those just before the AD events. This indicates that some PM_{10} components, even after the AD events, might not be effectively removed in the atmosphere but might affect local PM_{10} concentrations on the subsequent day.

(3) In Incheon, the average PM_{10} concentrations during the first peak period of the AD event were significantly proportional to those just before the first peak period. In Ulsan, however, the linear relationship between them was weaker than in Incheon.

(4) In Ulsan, there was no big difference in the average $PM_{2.5}$ concentrations between the April AD event period and the NAD period after the event. However, the average ratio of $PM_{2.5}$ to PM_{10} concentrations during the AD event period was much lower than that during the NAD period.

(5) The concentrations of Al, Mg, Fe, Mn, Ca, Ni and Cr in the TSPs collected during the April AD event period significantly increased as compared to those during the NAD period. The increased ratios of the metals were the highest value during the first peak period of the AD event and gradually decreased with further progress of the event. Most of these metals probably originated from soil dust in the desert areas. However, the concentrations of Pb and Cu in the TSPs during the AD period decreased when compared to those during the NAD period.

(6) Extremely high PM_{10} concentrations combined with lower sunshine duration time during the peak periods of the AD events may significantly reduce the ambient ozone concentrations in the afternoon of those peak periods or days.

Acknowledgements

The authors wish to acknowledge the excellent assistance provided by the Korea Environment Institute and the Ulsan Health and Environment Institute. This work was also supported by the University of Ulsan, Korea.

References

Braaten, D.A, Cahill, T.A., 1986. Size and composition of Asian dust transported to Hawaii. Atmospheric Environment Part A 20, 1105–1109.

Chung, Y.-S., Yoon, M.-B., 1996. On the occurrence of yellow sand and atmospheric loadings. Atmospheric Environment 30, 2387–2397.

Chun, Y.-S., Lim, J.-Y., Choi, B.-Y., 2003. The features of aerosol in Seoul by Asian dust and haze during Springtime from 1988 to 2002. Journal of Korean Meteorology 39, 459–474.

Gomes, L., Gillete, D.A., 1993. A comparison of characteristics of aerosol from dust storms in central Asia with soil-derived dust from other regions. Atmospheric Environment Part A 27, 2539–2544.

Harrison, R.M., Tilling, R., Romero, M.S.C., Harrad, S., Jarvis, K., 2003. A study of trace metals and polycyclic aromatic hydrocarbons in the roadside environment. Atmospheric Environment 37, 2391–2402.

Hashimoto, Y., Tanaka, S., Winchester, J.W., 1984. Detection of an Asian dust storm event in Japan during April 1980. Atmospheric Environment Part A 3, 526–528.

Heslop, D., Shaw, J., Bloemendal, J., Chen, F., Wang, J., Parker, E., 1999. Sub-millennial scale variations in east Asian monsoon systems recorded by dust deposits from the north-western Chinese Loess plateau. Physics and Chemistry of the Earth(A) 24, 785–792.

Husar, R.B., Tratt, D.M., Schichtel, B.A., Falke, S.R., Li, F., Jaffe, D., Gasso, S., Gill, T., Laulainen, N.S., Lu, F., Reheis, M.C., Chun, Y., Westphal, D., Holben, B.N., Guymard, C., Mckendry, I., Kuring, N., Feldman, G.C., McClain, C., Frouin, R.J., Merrill, J., DuBois, D., Vignola, F., Murayama, T., Nickovic, S., Wilson, W.E., Sassen, K., Sugimoto, N., Malm, W.C., 2001. Asian dust events of April 1998. Journal of Geological Research 106, 18137–18330.

In, H.-J., Park, S.-U., 2002. A simulation of long-range transport of Yellow Sand observed in April 1998 in Korea. Atmospheric Environment 36, 4173–4187.

Jaffe, D., McKendry, I., Anderson, T., Price, H., 2003. Six 'new' episodes of trans-Pacific transport of air pollutants. Atmospheric Environment 37, 391–404.

Kim, B.G., Park, S.U., 2001. Transport and evolution of a winter-time Yellow sand observed in Korea. Atmospheric Environment 35, 3191–3201.

Kim, K.W., Kim, Y.J., Oh, S.J., 2002. Visibility impairment during Yellow Sand periods in the urban atmosphere of Kwangju, Korea. Atmospheric Environment 35, 5157–5167.

Kim, K.H., Choi, G.-H., Kang, C.-H., Lee, J.-H., Kim, J.Y., Yoon, Y.H., Lee, S.R., 2003. The chemical composition of fine and coarse particles in relation with the Asian Dust events. Atmospheric Environment 37, 753–765.

Korea Environment Institute (KEI), 2002. Social damage costs by air pollution, 1–4 April.

Korea Ministry of Environment (KME), 2002. Effects and measures of yellow dust, 1–9.

Kurtz, A.C., Derry, L.A., Chadwick, O.L., 2001. Accretion of Asian dust to Hawaiian soils: isotopic, elemental, and mineral mass balance. Geochimica et Consmochimica Acta 65 (12), 1971–1983.

Kwon, H.-J., Cho, S.-H., Chun, Y., Lagarde, F., Pershgen, G., 2002. Effects of the Asian dust events on daily mortality in Seoul, Korea. Environmental Research Section A 90, 1–5.

Lin, T.S., 2001. Long-range transport of yellow sand to Taiwan in Spring 2000: observed evidence and simulation. Atmospheric Environment 35, 5873–5882.

Pettke, T., Halliday, A.N., Hall, C.M., Rea, D.K., 2000. Dust production and deposition in Asia and the north Pacific Ocean over the past 12 Myr. Earth and Planetary Science Letter 178, 397–413.

Rost, K.T., 2001. Late Holocene losses deposits and dust accumulation in the alpine meadow belt of the Wutai Shan. China. Quaternary International 76/77, 85–92.

Singer, A., 1988. Illite in aridic soils, desert dusts and desert loses. Sedimentary Geology 59, 251–259.

Takayama, Y., Takashima, T., 1986. Aerosol optical thickness yellow sand over the yellow sea derived from NOAA satellite data. Atmospheric Environment 20, 631–638.

Uno, I., Amano, H., Emori, S., Kinoshita, S., Matsui, I., Sugimoto, N., 2001. Trans-pacific Yellow Sand transport observed in April 1988. Journal of Geophysical Research 106, 18331–18344.

Zhang, D., Iwasaka, Y., 1999. Nitrate and sulfate in individual Asian dust-storm particles in Beijing, China in spring of 1995 and 1996. Atmospheric Environment 33, 3213–3223.

Zhang, X.Y., Arimoto, R., An, Z.S., 1999. Glacial and interglacial patterns for Asian dust transport. Asian dust linked to global change. Quaternary Science Review 18, 811–819.

Zhang, X.Y., Lu, H.Y., Arimoto, R., Gong, S.L., 2002. Atmospheric dust loadings and their relationship to rapid oscillations of Asian winter monsoon climate: two 250-kyr loses records. Earth and Planetary Science Letters 202, 637–643.

Zhou, M., Okada, K., Qian, F., Wu, P.M., Su, L., Casareto, B.E., Shimohara, T., 1996. Characteristics of dust-storm particles and their long-range transport from China to Japan-case studies in April 1993. Atmospheric Research 40, 19–31.