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Characteristics of particles sampled in southern Taiwan during the Asian dust storm periods in 2000 and 2001

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Abstract

Intensive field samplings followed by laboratory measurements were performed to characterize the particles collected at urban and rural sites in southern Taiwan during the Asian dust storm (ADS) periods in 2000 and 2001. These particles were size-resolvedly (cut sizes of eight-and ten-stages) sampled by two side-by-side micro-orifice uniform-deposited impactors (MOUDI). Results show that the concentrations of $PM_{2.5}$, $PM_{2.5-10}$ and PM_{10} increased during the ADS periods and these PM_{10} concentrations, $>150\,\mu g\,m^{-3}$, were roughly 2 to 3 times higher than the average PM_{10} concentrations measured in non-ADS periods. The concentrations of particle-bearing water-soluble ions including four crust-related species (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}), three secondary aerosol-associated species (SO_4^{2-}, NO_3^{-}, and NH_4^{+}), and one sea-connected species (Cl^{-}) increased and their size distributions changed during the ADS periods in comparison with those during non-ADS periods, implying that they were partially from foreign sources. This supports the increasing health concerns for ADS. The SO_4^{2-} had a major mode in fine size range (0.56–1.0 μm) while the Ca^{2+} obtained a major mode in coarse size (3.2–5.6 μm) at both sites.

Keywords: Asian dust storm; $PM_{2.5}$; $PM_{2.5-10}$; Size distribution

1. Introduction

Most of natural aerosol emissions (~90%) originate from desert/loess areas or marine (Pueschel, 1995). Similarly, Asian dust storm (ADS) particles are frequently emitted from the deserts of central Eurasia. For instance, an intense dust storm which lifted desert soil particles into the atmosphere was generated over the Badain Jaran Desert in China from 14 to 15 April 1998. The annual dust emission amount is some 43 million tons, and the dust emission in the spring season accounts for a half of this amount (Xuan, 1999). These particles can be carried east by prevailing winds at middle latitude and deposited in East Asia areas, i.e., Korea, Japan, and Taiwan. Strong dust storms usually contain diversified organic matter and nutrients that may cause adverse health effects and substantial economic damage. Some epidemiological studies have revealed that suspended particulate matter (PM) considerably influences respiratory health. Particularly, relationships between suspended PM and lung-function parameters, respiratory symptoms and mortality have been studied (Dockery et al., 1993). This brings the

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concerns of particle concentration and size distribution and particle-bearing species in ADS events.

Ma et al. (2001) investigated the characteristics of single particles sampled in Japan during the ADS period. Those particles were sampled in Kyoto, Japan from the middle of April to the end of July 1999. Their results revealed that the mass concentration in Asian dust events was roughly 3–5 times higher than that of the highest concentration measured in non-ADS seasons. Moreover, they indicated that the single particles were generally sharp-edged and irregular in shape and contained mostly crustal elements such as Si, Fe, Ca, and Al. Particles which have more than 40% Si content comprised nearly 50% of coarse single particles in ADS events. Main concentration range of Al in single ADS particles was 10–20%, and those of Ca and Fe were below 10% (Ma et al., 1999). Mori et al. (2002) reported that the concentration of Al in the desert soil source aerosol was $5.3 \times 10^3\,\mu g\,m^{-3}$ and the aerosol mass concentration was $9.0 \times 10^4\,\mu g\,m^{-3}$ on the basis of Al concentration in aerosol at the dust storm source.

More observations of aerosol concentrations were made during several ADS periods in a wide Asian region including the eastern part of China (Zhou et al., 1981; Wang et al., 1982; Zhang et al., 2003; Guo et al., 2004), Japan (Mizohata and Mamuro, 1978), Korea (Chun et al., 2001; In and Park, 2002), the North Pacific Ocean (Duce et al., 1980; Uematsu et al., 1983), Hawaiian Island (Shaw, 1980; Parrington et al., 1983), and source regions (Ren et al., 1993; Zaizen et al., 1995; Husar et al., 2001).

Nevertheless, more regional/global studies are necessary to picture the adverse effects resulting from ADS events but there are no data available yet about the characteristics of particles associated with ADS in southern Taiwan. In addition, the air quality of Pingtung County in southern Taiwan, in terms of PSI value, is one of the worst in Taiwan. The non-attainment days of PM_{10} in southern Taiwan show an increasing trend in the recent years, especially at Chaochou in Pingtung County (Kao, 2001). Thus, this study aims : (1) to investigate the characteristics of particle size distribution in Pingtung and Chaochou, (2) to analyze the particulate composition in different size ranges, and (3) to analyze water-soluble ions, associated with secondary aerosols and crustal sources, in particles during the ADS periods. Additionally, the results of this investigation were used to evaluate if partial southern Taiwan's high PM was imported from vicinal sources in the ADS events.

2. Experimental

2.1. Sampling

ADS events occurred within the two stages of our experimental periods. In this investigation, it is regarded that 19–23 March 2000 and 8–12 April 2001 were the "before ADS period" while 25–28 March 2000 and 14–18 April 2001 were the "after ADS period". Moreover, 24 March 2000 and 13 April 2001 were the "during ADS period", of which heavy-dust incidents were only observed in southern Taiwan from morning to afternoon on those two days.

Atmospheric suspended particles were sampled simultaneously in southern Taiwan at Chaochou (namely, CC) and Pingtung city (namely, PT). PT city is a metropolitan in southern Taiwan Plain with local sources of anthropogenic pollutants and others from Kaohsiung Area. On the other hand, CC represents the rural background air of an open plain with much less local pollutants in southern Taiwan Plain.

A dichotomous sampler and a micro-orifice uniform-deposited impactor (MOUDI) were used simultaneously to collect the PM at each sampling site. In general, particles $<10\,\mu m$ in aerodynamic diameter are called respiratory particulates or PM_{10}, whereas $PM_{2.5}$ denotes fine particles $<2.5\,\mu m$ in aerodynamic diameter (Ohlström et al., 2000). Applying a dichotomous sampler (Graseby Andersen G241), particle concentrations can be discussed in the three ranges, diameter $<2.5\,\mu m$, $2.5\,\mu m <$ diameter $<10\,\mu m$, and diameter $<10\,\mu m$. The dichotomous sampler was equipped with an inlet having a cut point of $10\,\mu m$. The PM_{10} particles were divided into two size fractions, a coarse fraction ($2.5\,\mu m <$ diameter $<10\,\mu m$, $PM_{2.5-10}$) and a fine fraction (diameter $<2.5\,\mu m$, $PM_{2.5}$) using a virtual impactor with a $2.5\,\mu m$ cut point when entering the sampler. The dichotomous sampler was operated at a total flow rate of $16.7\,l\,min^{-1}$ (1.67 and $15\,l\,min^{-1}$ for coarse and fine flows, respectively). In this sampler, particles were collected using 37-mm Teflon fiber filters supported by polyolefin rings.

For understanding the detail size distribution, one eight-stage (at PT site) and one ten-stage (at CC site) MOUDI were also used to measure the size distributions of particles and the chemical species in the ambient air. The principles and description about the MOUDI were mentioned in our previous study (Chen et al., 1996). The eight-stage MOUDI includes the cutoff points of 18, 10, 5.6, 3.2, 1.8, 1.0, 0.56, 0.32, 0.18, and $0.056\,\mu m$ while the ten-stages MOUDI includes cutoff points of 18, 10, 5.6, 3.2, 1.8, 1.0, 0.56, 0.32, 0.18, 0.1, and $0.056\,\mu m$. The flow rate of MOUDI was adjusted to $30\,l\,min^{-1}$ and each sample was extracted continuously per 12 h.

Hourly wind speed was recorded and the mean wind speed during each sampling period was calculated. At PT and CC sites, particles were collected on the rooftop of a single-story building. Before and after field sampling, the sampling filter papers (used in both the dichotomous sampler and MOUDI) were weighed on an electronic balance (AND HM202) with a reading precision of $10\,\mu g$ to determine the mass concentration after being conditioned at $25\,^{\circ}C$ and 40% relative

humidity for 24 h. The sample filters collected from the field were stored in a refrigerator at 4 °C before they were chemically analyzed to limit possible loss of volatile components.

2.2. Chemical analysis and quality control

After sampling, the filter was normally extracted within 24 h after weighing. Water-soluble inorganic species, Na^+, K^+, Mg^{2+}, Ca^{2+}, NH_4^+, Cl^-, NO_3^-, and SO_4^{2-} at each filter were extracted using 100 ml of ultra-pure water (specific resistance $\geqslant 18.3\,M\Omega\,cm$). All the extraction solutions were filtered using a cellulose acetate filter (ADVANTEC MFS, Inc. USA, cat no: CO20A025A, pore size: 0.2 μm, diameter: 25 mm) and stored in plastic vials in the refrigerator at 4 °C until they were chemically analyzed. The inorganic species were analyzed using ion chromatography (DIONEX 100) and an electrochemical detector (DIONEX CDM-1). The method detection limit (MDL) was estimated by repeatedly analyzing a predefined quality control solution. The detection limits are: $0.86\,ng\,m^{-3}$ for Na^+, $1.48\,ng\,m^{-3}$ for K^+, $1.6\,ng\,m^{-3}$ for Mg^{2+}, $1.29\,ng\,m^{-3}$ for Ca^{2+}, $2.21\,ng\,m^{-3}$ for NH_4^+, $5.7\,ng\,m^{-3}$ for Cl^-, $3.5\,ng\,m^{-3}$ for NO_3^-, and $7.56\,ng\,m^{-3}$ for SO_4^{2-}.

3. Results and discussion

3.1. Particles mass concentration

The variation of particle mass concentration is determined by mass conservation equation, and is influenced by advection, diffusion, wind erosion, and deposition processes. In general, it appears to be "during ADS" > "after ADS" > "before ADS" in PM_{10} concentration (Table 1). The trend of PM_{10} concentration variation measured at each site was consistent with the one obtained from the air pollutant monitoring station at the same site. The concentrations for $PM_{2.5}$, $PM_{2.5–10}$, and PM_{10} increased during the ADS periods. Exceeding the National Ambient Air Quality Standards in Taiwan ($125\,\mu g\,m^{-3}$), the range of mean mass concentration of PM_{10} was 156–260 $\mu g\,m^{-3}$ (Table 2), apparently higher than that (51.7–100.1 $\mu g\,m^{-3}$) collected in Kyoto, Japan by Ma et al. (2001) in 1999 ADS events.

3.2. $PM_{2.5}/PM_{10}$, $PM_{2.5–10}/PM_{2.5}$, and $PM_{2.5–10}/PM_{10}$

For both sites, the ratio of $PM_{2.5}$ to PM_{10} during the ADS periods in 2000 and 2001 were below 0.5 (ranged from 0.37 to 0.45). On the contrary, the ratio of $PM_{2.5}$ to PM_{10} in non-ADS periods in 2000 and 2001 all exceeded 0.5 (ranged from 0.58 to 0.74). In general, the percentages of $PM_{2.5}/PM_{10}$ were approximately 60–70% before and after the ADS periods, but this ratio decreased to <45% during the ADS periods, because the coarse particulate concentrations ($PM_{2.5–10}$) increased during the ADS periods. Moreover, Fig. 1(a) shows that the levels of $PM_{2.5–10}/PM_{2.5}$ in non-ADS period were below 0.46 and 0.45 in 2000 and 2001, respectively, at PT site. Similarly, Fig. 2(b) shows the ratios of $PM_{2.5–10}$ to $PM_{2.5}$ in non-ADS periods were below 0.45 and 0.46 in 2000 and 2001, respectively, at CC site.

3.3. Mass size distribution during ADS period

At PT site, the mass size distributions during the ADS periods in 2000 and 2001 were uni-modal and peaked

Table 1
Atmospheric PM_{10} concentrations ($\mu g\,m^{-3}$) at the sampling sites and air pollutant monitoring stations in southern Taiwan during the ADS and non-ADS periods

Sample period	*N*	Sample values		Air pollutant monitoring values	
		PT (urban)	CC (rural)	PT (urban)	CC (rural)
Case I: In 2000					
Before ADS period	5	101–147	59.4–147	86–119	121–168
(2000.3.19–2000.3.23)		(125 ± 17.2)	(114 ± 34.3)	(104 ± 14.3)	(144 ± 20.5)
ADS period (2000.3.24)	1	232	260	217	304
After ADS period	4	111–148	83.9–159	117–139	132–172
(2000.3.25–2000.3.28)		(133 ± 17.1)	(112 ± 34.7)	(127 ± 9.3)	(151 ± 16.4)
Case II: In 2001					
Before ADS period	5	40.7–93.2	51.6–102	49.3–115	46.5–133
(2001.4.8–2001.4.12)		(64.3 ± 19.4)	(66.5 ± 20.7)	(70.5 ± 27.0)	(75.3 ± 34.3)
ADS period (2001.4.13)	1	156	186	142	175
After ADS period	5	66.4–123	69.2–138	87.6–116	72.2–145
(2001.4.14–2001.4.18)		(91.4 ± 27.3)	(92.5 ± 32.9)	(96.8 ± 16.2)	(98.3 ± 30.2)

Table 2
Atmospheric suspended particulates concentrations ($\mu g\,m^{-3}$) during ADS periods

Sampling date	PT (urban)				CC (rural)			
	$PM_{2.5}$	$PM_{2.5-10}$	PM_{10}	$PM_{2.5}/PM_{10}$	$PM_{2.5}$	$PM_{2.5-10}$	PM_{10}	$PM_{2.5}/PM_{10}$
2000.3.19	106	41.0	147	0.72	94.5	42.5	137	0.69
3.20	81.9	35.1	117	0.70	78.1	31.9	110	0.71
3.21	69.7	31.3	101	0.69	42.8	16.6	59.4	0.72
3.22	84.8	41.2	126	0.67	76.4	37.6	114	0.67
3.23	86.4	46.6	133	0.65	92.6	54.4	147	0.63
3.24*	**85.8**	**146**	**232**	**0.37**	**107**	**153**	**260**	**0.41**
3.25	85.8	42.2	128	0.67	62.4	25.5	87.9	0.71
3.26	106.6	41.4	148	0.72	57.1	26.8	83.9	0.68
3.27	75.5	35.5	111	0.68	87.3	30.7	118	0.74
3.28	94.2	50.8	145	0.65	106.5	52.5	159	0.67
Mean ± s.d.	87.9 ± 12.5	40.6 ± 5.98	128 ± 16.6	0.68 ± 0.03	77.5 ± 20.3	35.4 ± 12.6	113 ± 32.1	0.69 ± 0.03
2001.4.8	30.9	9.8	40.7	0.76	38.2	13.4	51.6	0.74
4.9	43.1	20.3	63.4	0.68	37.2	15.2	52.4	0.71
4.10	49.8	19.4	69.2	0.72	42.8	19.3	62.1	0.69
4.11	41.8	21.6	63.4	0.66	44.9	19.3	64.2	0.70
4.12	65.2	28	93.2	0.70	69.4	32.6	102	0.68
4.13*	**70.2**	**85.8**	**156**	**0.45**	**72.5**	**113.5**	**186**	**0.39**
4.14	72.6	46.4	119	0.61	80	58	138	0.58
4.15	82.4	40.6	123	0.67	74.9	42.1	117	0.64
4.16	51.4	21	72.4	0.71	49.2	17.3	66.5	0.74
4.17	55.7	20.6	76.3	0.73	49.4	22.2	71.6	0.69
4.18	45.8	20.6	66.4	0.69	49.8	19.4	69.2	0.72
Mean ± s.d.	53.9 ± 15.5	24.8 ± 10.9	78.7 ± 25.8	0.69 ± 0.04	53.6 ± 15.5	25.9 ± 14.2	79.5 ± 29.3	0.69 ± 0.05

Note: When calculate the mean in Table 2, the ADS days (**3.24* in 2000 and 4.13* in 2001)** are excluded.

between 3.2 and 5.6 μm in diameter. However, mass median diameter (MMD) in 2000 (i.e., 3.08 μm) was higher than that in 2001 (i.e., 2.04 μm). Unlike the mass size distribution at PT site, the mass size distribution at CC site shows bi-modal (Fig. 3). During the ADS periods, the highest peaks of PM mass size distributions were between 3.2 and 5.6 μm in diameter in both years, but the second high peaks occurred at 1.0–1.8 μm in 2000 and at 0.56–1.0 μm in 2001. Besides, at CC site, the MMD in 2001 (i.e., 1.35 μm) was lower than that in 2000 (i.e., 2.71 μm) (Table 3). Fig. 3 also shows that the particles sampled in 2000 had larger size than those sampled in 2001 during the ADS periods. Consequently, Figs. 3(a) and 4(b) show that coarse particles were dominant during the ADS periods in 2000 and 2001.

3.4. Size distribution of major aerosol species during ADS period

3.4.1. SO_4^{2-} and NO_3^-

At PT sites in non-ADS, the size distributions of SO_4^{2-} were uni-modal in fine size and peaked in the range from 0.56 to 1.0 μm (Fig. 4(a)). At CC sites in non-ADS days, the size distributions of SO_4^{2-} were bi-modal both in fine and coarse sizes with the fine part from 0.56 to 1.0 μm and the coarse part from 3.2 to 5.6 μm (Fig. 5(a)). In ADS days in 2000, at both sampling sites, the size distributions of SO_4^{2-} were bi-modal both in fine and coarse sizes with the fine part from 0.56 to 1.0 μm and the coarse part from 3.2 to 5.6 μm (Figs. 4(a) and 5(a)). However, the size distributions of SO_4^{2-} at both sampling sites in ADS days in 2001 were uni-modal in fine size and peaked in the range from 0.56 to 1.0 μm. At PT site, the size distribution of NO_3^- in ADS in 2000 was uni-modal in coarse size and peaked in the range from 3.2 to 5.6 μm (Fig. 4(b)), but those in 2001 were bi-modal in fine and coarse sizes with the fine part from 0.56 to 1.0 μm and the coarse part from 3.2 to 5.6 μm. At CC site, the distributions in 2000 were bi-modal in fine and coarse sizes with the fine part from 1.0 to 1.8 μm and the coarse part from 3.2 to 5.6 μm (Fig. 5(b)). Although the distributions of NO_3^- in 2001 were also bi-modal in fine and coarse sizes, the fine and the coarse parts were from 0.56 to 1.0 μm and from 3.2 to 5.6 μm, respectively. Moreover, at PT site, for NO_3^- during the ADS periods in both 2000 and 2001, the major mode occurred in coarse size in the range from 3.2 to 5.6 μm (Fig. 4(b)). However, at CC site, for NO_3^- during ADS periods, the major mode occurred in coarse size in 2000 but in fine size in 2001 (Fig. 5(b)). Table 3 shows that the MMDs of

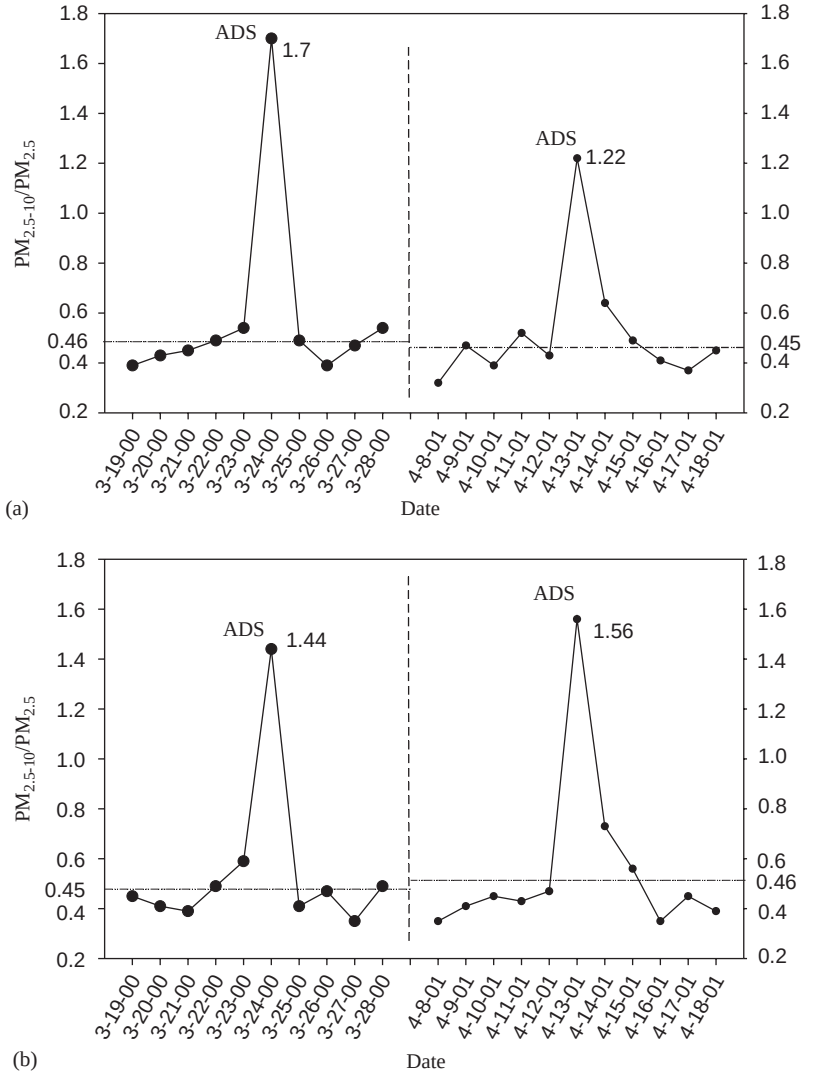

Fig. 1. $PM_{2.5–10}/PM_{2.5}$ variation during 2000 and 2001 ADS periods in southern Taiwan. (a) PT (urban), (b) CC (rural).

NO_3^- during the ADS period in 2000 at PT and CC sites (i.e., 2.37 and 1.88 μm, respectively) were higher than those in ADS days in 2001. In general, the levels of size distribution for both SO_4^{2-} and NO_3^- were elevated during ADS periods in comparison with those during non-ADS periods. The results reveal that partial SO_4^{2-} and NO_3^-, commonly found in secondary aerosols, were from foreign sources during the ADS periods in southern Taiwan.

3.4.2. NH_4^+ and Cl^-

NH_4^+ (i.e., ammonium sulfates and nitrates) is another secondary aerosol-associated species. At both sites, the size distributions of NH_4^+ in non-ADS periods were uni-modal and peaked in the range from 0.56 to 1.8 μm (Figs. 4(c) and 5(c)). The size distributions of NH_4^+ (i.e., ammonium sulfates and nitrates) in ADS in both 2000 and 2001 were uni-modal in fine size and peaked in the range from 0.56 to 1.0 μm (Figs. 4(c) and 5(c)). In contrast with NO_3^- and SO_4^{2-}, Table 3 indicates that the MMDs of NH_4^+ during the ADS period in 2000 at urban (PT) and rural (CC) sites were lower than those in ADS days in 2001. At PT site, the size distributions of Cl^- in ADS in 2000 were tri-modal in fine and coarse sizes and with the fine part from 0.18 to 0.32 μm and from 0.56 to 1.0 μm, and the coarse part from 3.2 to 5.6 μm (Fig. 4(d)). Likewise, the size distributions of Cl^- in ADS in 2001 were also tri-modal in fine and coarse sizes and with the fine part from 0.18 to 0.32 μm and from 0.56 to 1.0 μm, and the coarse part from 1.8 to

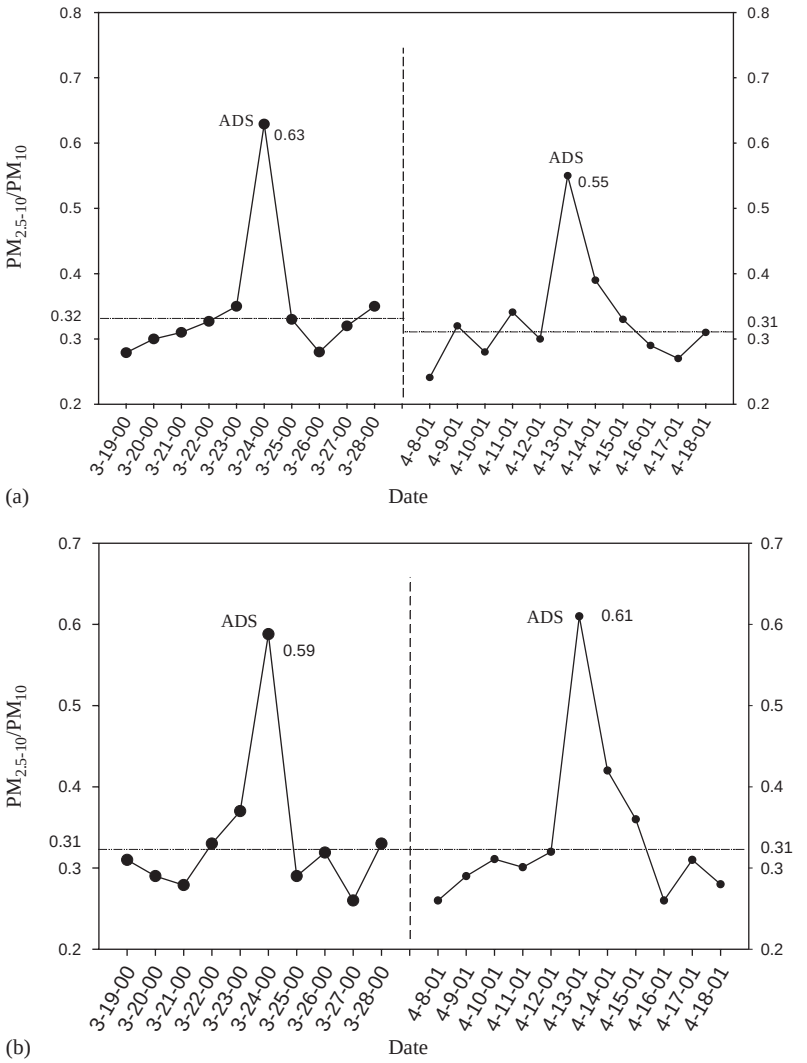

Fig. 2. $PM_{2.5–10}/PM_{10}$ variation during 2000 and 2001 ADS periods in southern Taiwan. (a) PT (urban), (b) CC (rural).

3.2 μm. Generally, the levels of size distribution for both NH_4^+ and Cl^- increased during ADS periods compared with those during non-ADS periods.

Ma et al. (2001) observed that even though Cl in the soils of desert and loess areas in northwest of China was not detected, significant concentration of Cl in coarse fraction in ADS events was detected in single particles; almost all of the single particles sampled on ADS days did contain sulfur and chlorine. In particular, high frequencies of chlorine were reported in other areas of Japan because dust particles are absorbed or coalesced with particles containing sea salts during the long-range transport (Wang and Guanghua, 1996). Therefore, they indicated that the high Cl concentration on non-ADS days compared to that on ADS days was possibly caused by marine components transported from Osaka bay (about 40 km southwest from the Kyoto sampling site) by southwest winds on non-ADS days. Accordingly, it is inferred that the high Cl concentration on non-ADS days in our study, was probably due to the marine species transported from Taiwan Strait (about 10 and 70 km west from the Kaohsiung and PT sites, respectively) by coastal winds on non-ADS days. In addition, the ADS particles might be altered by the mechanisms of absorption and oxidation during their long-range transport.

3.4.3. Ca^{2+} and others

At both sites, the size distributions of Ca^{2+} in non-ADS particles peaked in the range from 3.2 to 5.6 μm (Figs. 4(e) and 5(e)) and the size distributions of Ca^{2+} in ADS in 2000 were bi-modal in fine and coarse sizes with

the fine part from 0.18 to 0.32 μm and the coarse part from 3.2 to 5.6 μm. However, the distributions at PT and CC sites in 2001 were uni-modal in coarse size and peaked in the range from 3.2 to 5.6 μm (Figs. 4(e) and 5(e)). In southern Taiwan, for Ca^{2+} during the ADS periods in both years, the major mode occurred in coarse size in the range from 3.2 to 5.6 μm at both urban and rural sites (Figs. 4(e) and 5(e)). At PT site, the size distributions of Mg^{2+} in ADS in 2000 were bi-modal in fine and coarse sizes with the fine part from 0.32 to 0.56 μm and the coarse part from 3.2 to 5.6 μm, but the distribution in 2001 was uni-modal in coarse size and peaked in the range from 3.2 to 5.6 μm (Fig. 4(f)). Furthermore, at PT site, the size distributions of K^+ in ADS in 2000 were tri-modal in fine and coarse sizes with the fine part from 0.18 to 0.32 μm and from 0.56 to 1.0 μm, and the coarse part from 5.6 to 10 μm (Fig. 4(g)). Unlike the case at PT site, the MMD of K^+ at CC site in 2000 (0.73 μm) was lower than that in 2001 (0.75 μm). On the whole, the levels of size distribution for Ca^{2+}, Mg^{2+}, K^+, and Na^+ were raised during ADS periods in comparison with those during non-ADS periods. These results suggested that more contents of crustal elements from China were transported into the atmosphere of southern Taiwan during the ADS events.

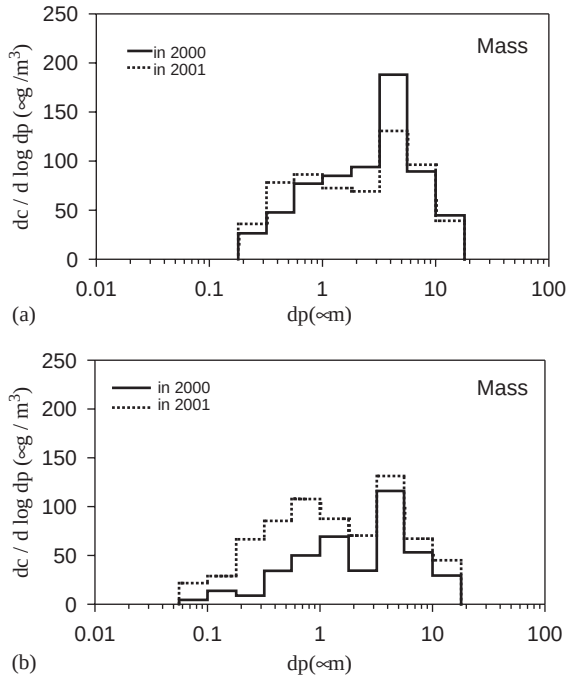

Fig. 3. Size distributions of particles sampled at PT (urban) (a) and CC (rural) (b) sites during the ADS periods in 2000 and 2001.

4. Conclusions

This study presents the first investigation of characteristics of particles sampled in southern Taiwan during the ADS periods in 2000 and 2001. The CC sampling site had the highest PM_{10} concentrations (260 μg m^{-3}) during the ADS period in 2000, approximately 2.3 and 3.3 times the non-ADS particle concentrations (i.e., 113 μg m^{-3} in 2000 and 79.5 μg m^{-3} in 2001) at the CC sampling site. Results show that the percentages of $PM_{2.5}/PM_{10}$ were approximately in the ranges from 60% to 70% before and after the ADS periods, but this ratio decreased to smaller than 45% during the ADS periods, because the coarse particulate concentrations ($PM_{2.5-10}$) increased during the ADS periods in southern Taiwan. For Ca^{2+} during the ADS periods in both 2000 and 2001, the major mode occurred in coarse size in the range from 3.2 to 5.6 μm at both the

Table 3
MMD for mass and major aerosol species sampled at PT and CC sites during the ADS periods in 2000 and 2001

Species	MMD (μm)			
	PT site urban		CC site rural	
	24 March 2000	13 April 2001	24 March 2000	13 April 2001
Mass	3.08	2.14	2.71	1.35
SO_4^{2-}	0.88	0.83	0.87	0.75
NO_3^-	2.37	1.88	2.27	1.17
NH_4^+	0.91	0.96	0.67	0.68
Cl^-	2.73	2.01	1.96	2.43
Na^+	3.42	2.17	2.32	3.31
K^+	1.39	1.60	0.73	0.75
Mg^{2+}	3.02	3.42	3.21	2.70
Ca^{2+}	4.04	3.55	2.39	3.16

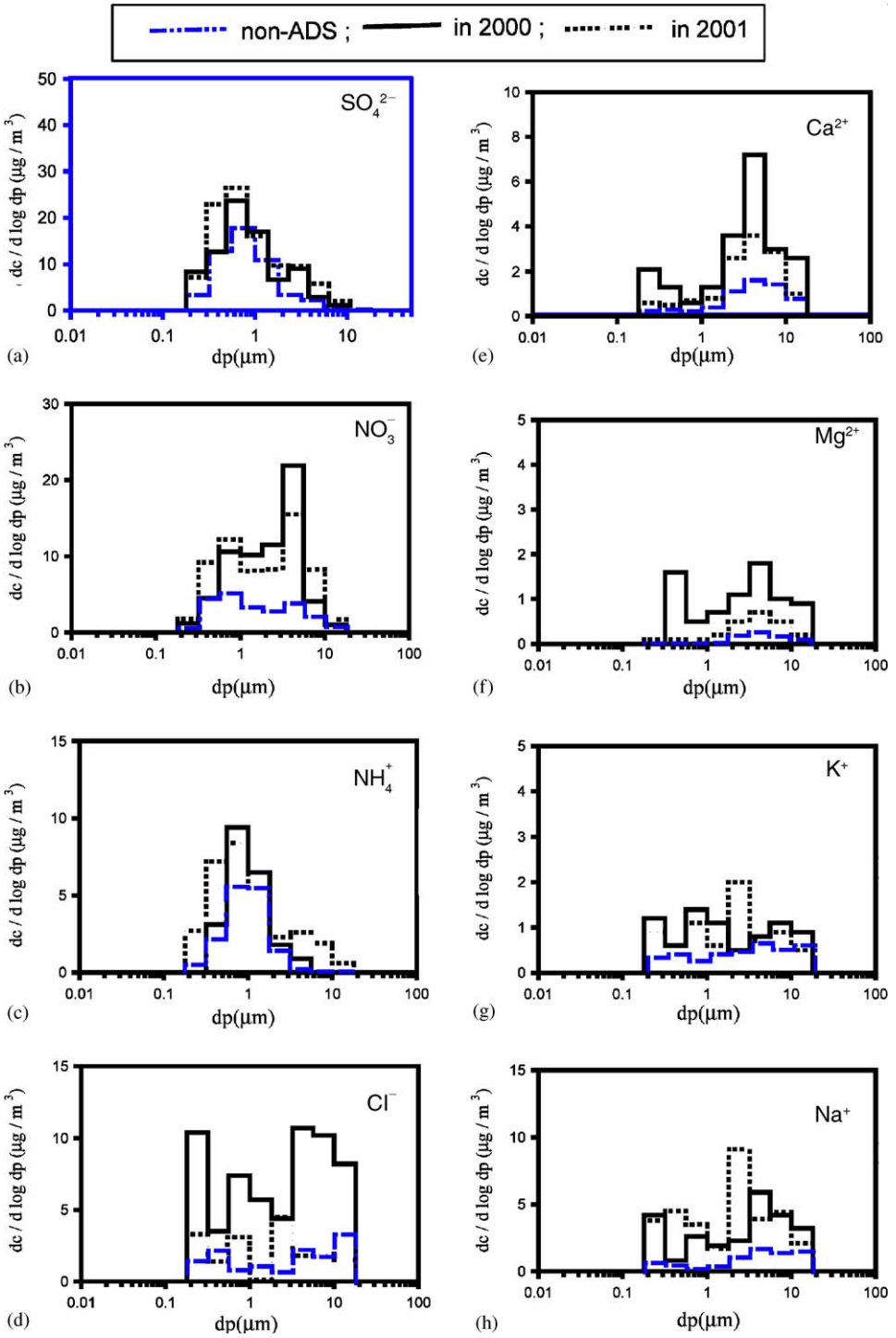

Fig. 4. (a–h) Size distributions of major aerosol species sampled at PT (urban) site during the non-ADS and ADS periods in 2000 and 2001.

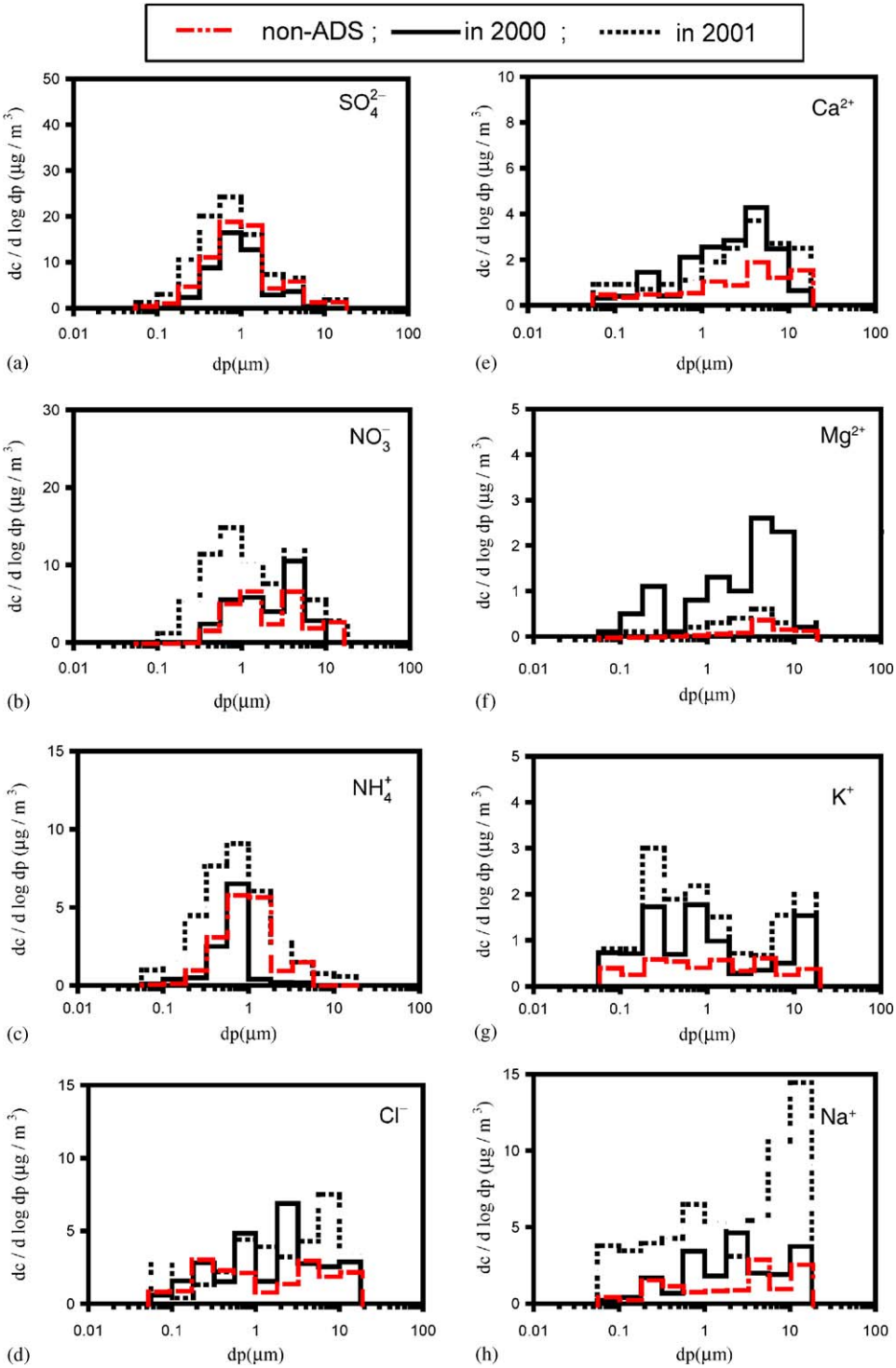

Fig. 5. (a–h) Size distributions of major aerosol species sampled at CC (rural) site during the non-ADS and ADS periods in 2000 and 2001.

urban and rural sites in southern Taiwan. At CC (rural) site, the size distributions of Na^+ in ADS in 2000 were bi-modal in fine and coarse sizes and with the fine part from 0.56 to 1.0 μm and the coarse part from 10 to 18 μm.

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References

Chen, S.J., Hsieh, L.T., Hwang, P.S., 1996. Concentration, phase distribution, and size distribution of atmospheric polychlorinated biphenyls measured in Southern Taiwan. Environment International 22 (4), 411–423.

Chun, Y., Kim, J., Choi, J.C., Boo, K.O., Lee, M., Oh, S.N., 2001. Characteristic number size distribution of aerosol during Asian dust episode in Korea. Atmospheric Environment 35 (15), 2715–2721.

Dockery, D.W., Pope, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.G., Speizer, F.E., 1993. An association between air pollution and mortality in six US cities. New England Journal Medicine 329, 1753–1759.

Duce, R.A., Unni, C.K., Ray, B.J., Prospero, J.M., Merrill, J.T., 1980. Long-range atmospheric transport of soil dust from Asia to the tropical North Pacific temporal variability. Science 209, 1522–1524.

Guo, J.H., Rahn, K.A., Zhuang, G.H., 2004. A mechanism for the increase of pollution elements in dust storms in Beijing. Atmospheric Environment 38 (6), 855–862.

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., Gueymard, 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. The Asian dust events of April 1998. Journal of Geophysical Research 106 (D16), 18,067–18,074.

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 (26), 4173–4187.

Kao, M.J., 2001. Size distribution of particulate and aerosol composition in Pingtung area. Master Thesis, Department of Environmental Engineering and Science, National Pingtung University of Science and Technology, Taiwan.

Ma, C.J., Kasahara, M., Thono, S., Yeo, H.G., 1999. A study on the characteristics and sources of the winter time atmospheric aerosols in Kyoto and Seoul using PIXE and supplementary analysis. First Asia Aerosol Conference, Nagoya, Japan, 27–29 July, pp. 330–331.

Ma, C.J., Kasahara, M., Höller, R., Kamiya, T., 2001. Characteristics of single particles sampled in Japan during the Asian dust storm period. Atmospheric Environment 35 (15), 2707–2714.

Mizohata, A., Mamuro, T., 1978. Some information about loess aerosol over Japan. Japanese Society of Air pollution 13, 289–297.

Mori, I., Nishikawa, M., Quan, H., Morita, M., 2002. Estimation of the concentration and chemical composition of kosa aerosols at their origin. Atmospheric Environment 36 (29), 4569–4575.

Ohlström, M.O., Lehtinen, K.E.J., Moisio, M., Jokiniemi, J.K., 2000. Fine-particle emissions of energy production in Finland. Atmospheric Environment 34 (22), 3701–3711.

Parrington, J.R., Zoller, W.H., Aras, N.K., 1983. Asian dust seasonal transport to the Hawaiian Islands. Science 220, 195–197.

Pueschel, R.F., 1995. Atmospheric Aerosol. Van Norstrand Reinhold, New York, pp. 120–175.

Ren, L.X., Lei, W.F., Lu, W.X., 1993. The physical and chemical characteristics of desert aerosol in HEIFE region. In: Mitsuda, V. (Ed.), Proceedings of International Symposium on HEIFE. pp. 663–669.

Shaw, G.E., 1980. Transport of Asian desert aerosol to the Hawaiian Islands. Journal of Applied Meteorology 19, 1254–1259.

Uematsu, M., Duce, R.A., Prospero, J.M., Chen, L., Merrill, J.T., McDonald, R.L., 1983. Transport of mineral aerosol from Asia over the North Pacific Ocean. Journal of Geophysical Research 88, 5343–5352.

Wang, M.X., Winchester, J.W., Cahill, T.A., Ren, L.X., 1982. Chemical elemental composition of windblown dust, 19 April 1980. Beijing Kexue Tongbao 27, 1193–1198.

Wang, X., Guanghua, Z., 1996. Some characteristics of the aerosol in Beijing. International Journal of PIXE 361–365.

Xuan, J., 1999. Dust emission factors for environment of Northern China. Atmospheric Environment 33 (11), 1767–1776.

Zaizen, Y., Ikegami, M., Okada, K., Makino, Y., 1995. Aerosol concentration observed at Zhangye in China. Journal of Meteorological Society of Japan 73, 891–897.

Zhang, D.H., Zang, J., Shi, G.G., Iwasaka, Y., Matsuki, A., Trochkine, D., 2003. Mixture state of individual Asian dust particles at a coastal site of Qingdao, China. Atmospheric Environment 37 (28), 3895–3901.

Zhou, M., Shaohou, Q., Ximing, S., Yuying, L., 1981. Properties of the aerosols during a dust storm over Beijing area. Acta Science Circumstantiae 1, 207–219.