Synopsis, transport, and physical characteristics of Asian dust in Korea

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Abstract. Historical records in association with Asian dust events were retrieved from ancient Korean literature, which in conjunction with modern observations, indicate that dust events have occurred most frequently in the springtime during the last two centuries. Recent observations through surface network exhibit that Asian dust took place more often in the western part of the Korean peninsula over the last 20 years. In this study, two dust cases, April 1998 and January 1999, were selected to examine detailed conditions most favorable for dust generation, emission, and transport to Korea and to investigate the effect of dust particles on physical and optical properties of aerosols collected in Seoul. Dust transported to the Korean peninsula is closely linked to dust storms generated in upstream regions of the Yellow River or Manzurian plain, which are known as main source regions. Judged from synoptic conditions for both spring and winter dust events, meteorological settings favorable for dust emission are high surface winds and baroclinic instability at 1.5 km level. A strong wind belt, formed at a 5 km level, expedites dust transport, and this is typically much faster in winter. It was confirmed from a backward trajectory analysis that the air carrying mineral dust particles originated from deserts in central Asia and in 1 day passed through the Korean peninsula during wintertime. The effect of mineral dust on aerosol particles is well depicted in the size-separated number concentrations of aerosols observed in Seoul. In both cases, concentrations of coarse particles larger than 0.82 μm were distinctly enhanced while those of fine particle smaller than 0.5 μm were reduced. The measurements of optical depth also indicate that the atmosphere is more turbid with larger particles during dust events.

1. Introduction

The entrainment, transport, and deposition of dust particles driven by wind is an important geological process on Earth [*Pye*, 1992]. Arid and semiarid regions of the world, covering about a third of the Earth's land surface, are the major sources for aeolian dust. The mobilization of the dust and its further emission into the atmosphere occur throughout the year, depending on meteorological conditions. The global production of windblown dust is ~1000–3000 Tg/yr [*International Panel on Climate Change* (IPCC), 1995], which may be increasing substantially due to desertification by human activity [*Sheehy*, 1992]. Mineral dust particles, found in the atmosphere, originate mainly from desert regions in northern Africa and central Asia, are transported distances over thousands of kilometers by the general circulation of the atmosphere [*Prospero*, 1990], and are well observed by satellite [*Jankowiak and Tanre*, 1992; *Husar et al*., 1997, this issue]. Model studies have illustrated that mineral dust found in the North Pacific originates mainly from Asian desert regions and is transported to and in the upper levels of the westerlies in the springtime [*Merrill*, 1985]. In eastern Asia, spring is a period of high aerosol loading caused by frequent Asian dust outbreaks, which contribute to several environmental effects such as reduced visibility. Atmospheric dust is also found to be closely linked to the biogeochemical cycles of major compounds and further involved in the Earth's radiation budget [*Li et al*., 1996; *Sokolik and Toon*, 1996; *Tegen et al*., 1996].

Dust phenomena are historical events in east Asian countries. In China, dust storms have been documented for more than 2000 years [*Zhang*, 1984; *Liu et al*., 1985]. In Korea, dust-related events for the last two centuries can be found in various kinds of historical records [*Wada*, 1917; *Chun*, 2000]. It is, however, quite recent that Asian dust has drawn much attention as one of the important biogeochemical processes, and the scientific investigation of dust particles began [*Duce*, 1989, and references therein]. Since then, there have been several sets of measurements made in the eastern part of China [*Zhou et al*., 1981; *Wang et al*., 1982], Korea [*Chung*, 1992], Japan [*Mizohata and Mamuro*, 1978; *Iwasaka et al*., 1983, 1988; *Kai et al*., 1998], the North Pacific Ocean [*Duce et al*., 1980; *Uematsu et al*., 1983, 1985], and source regions [*Ren et al*., 1993; *Zaizen et al*., 1995]. However, the physical and chemical properties of mineral particles still remain to be determined. The knowledge of mechanisms for dust generation in source regions and subsequent transport is also poor.

This paper provides climatological data of dust observed in Korea. Regions of Asian dust uplift were identified, and synoptic conditions for dust generation and transport to the Ko-

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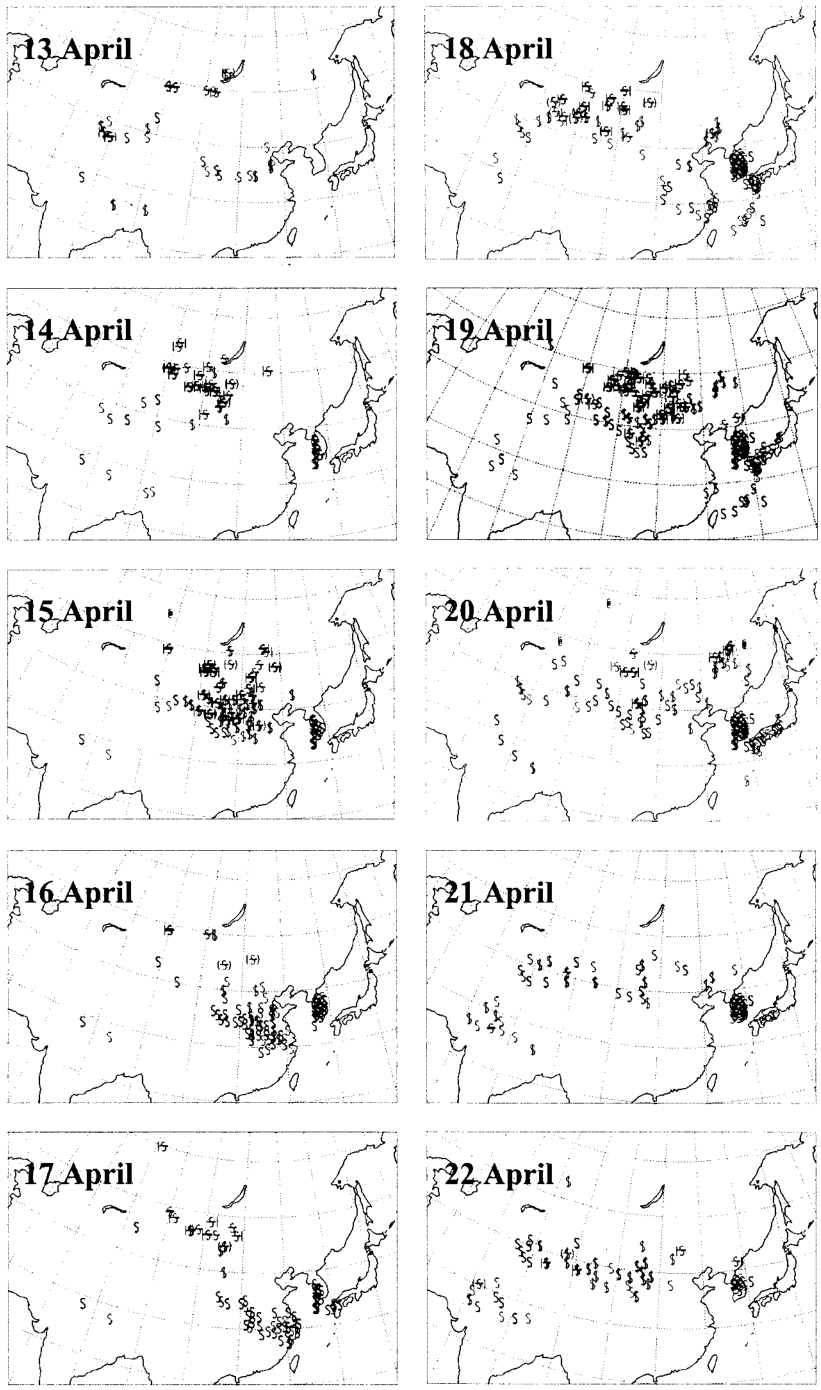

Figure 1. Daily dust phenomena reported every 3 hours over east Asia in April 1998. S indicates widespread dust suspended in air but not raised at the time of observation. S with an arrow pointing upward denotes dust or sand raised by wind at the time of observation. The shape of spring with two turns represents a well-developed dust devil within the past hour. S with a horizontal arrow stands for dust or sand storm.

rean peninsula were examined. In April 1998 there were unusually intense dust storms observed in Asian desert regions (Figure 1), which was also clearly shown from a satellite [*Husar et al.*, this issue]. One of them was transported across the Korean peninsula, and the dust signature was well captured in aerosols collected in Seoul on April 19 and 20. A rarity in Korea, a dust event took place in the winter of 1999 (January 25–27), about a day after dust storms were detected in the source regions (Figure 2). In this study, the two cases were selected for a detailed discussion, including the effect of dust particles on physical and optical characteristics of aerosols.

2. Climatological Data of Asian Dust in Korea

Asian dust events in Korea over historical times were retrieved from old literature, such as the chronicles for several

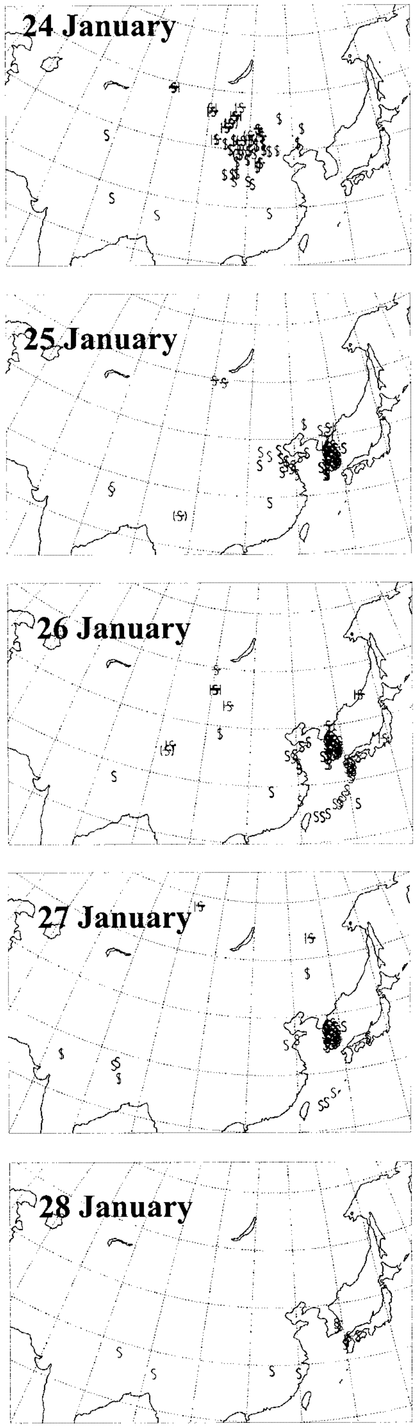

Figure 2. Daily dust phenomena over east Asia in January 1999. Other phenomena are the same as those of Figure 1.

dynasties established in the Korean peninsula [*Chun*, 2000]. These records are statements regarding dust phenomena detected all over the Korean peninsula, which were often associated with rain, snow, fog, or hail. The earliest record started in 174 A.D., but there were only seven descriptions left until 936 A.D. The number of records increased afterward, and 50 records were extracted for 936–1392 A.D. (Koryo dynasty) and 57 for 1392–1910 A.D. (Lee dynasty). These records were plotted against the lunar month when they were observed (Figure 3). Lunar calendars were officially used in Korea until

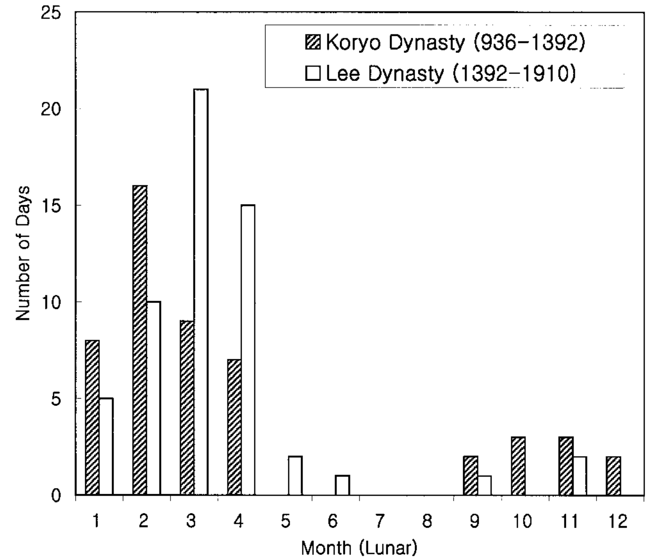

Figure 3. Monthly distribution of records related to dust events in Korea over historical times. The data were retrieved from old literatures and plotted against a lunar month. The boxes on the left are for the Koryo dynasty during 936–1392 A.D. and on the right for the Lee dynasty during 1392–1910 A.D.

the end of 1800s. In general, the lunar date is about a month behind the solar date. These archives indicate that the occurrence of Asian dust was most frequent during spring (February–April in lunar date) and irregular during winter or fall. There was no dust outbreak recorded during summer, which is the period of the Asian monsoon with heavy rainfalls. This trend is in accordance with the results of recent observations.

Modern meteorological observations began in the early 1900s, and dust events have been formally observed since that time. For Seoul, records of dust events are available for the last century from 1915 to 1999 except for 1923–1954, of which period all meteorological data were lost (Figure 4). Figure 4 exhibits the number of days during which dust events were observed each year. Dust events seem to occur erratically: the

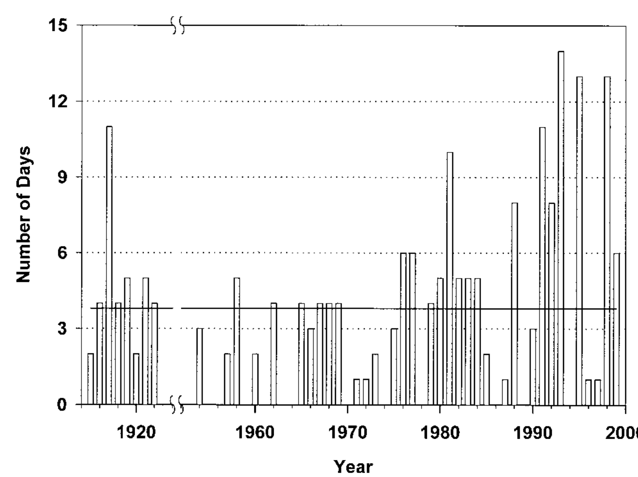

Figure 4. Yearly frequency of Asian dust observed in Seoul during 1915–1999. The data were missing for 1923–1953. The solid line represents the average number of dust occurrences (3.8 days) for the same period.

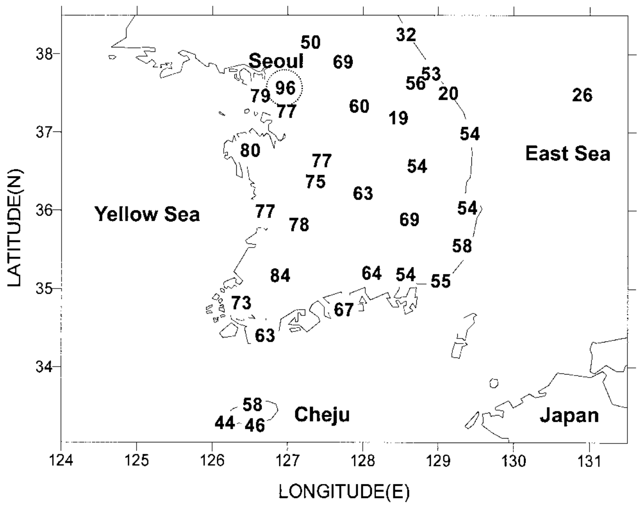

Figure 5. Total number of days with Asian dust observed in South Korea during 1982–1999. The dotted circle roughly represents the size and location of Seoul.

maximum number of dust outbreaks is 14 in 1993, while no dust was detected in some years. On average, dust took place in Seoul for about 4 days a year during the last century. However, the occurrence of dust appears to be more frequent during the last decade. The monthly distribution of these data is very similar to that shown in Figure 3, confirming that the Asian dust event is most prevalent in spring.

Figure 5 displays the spatial distribution of dust occurrence over South Korea. These numbers are the sum of days when Asian dust was observed at each surface station during 1982–1999. Asian dust has been detected more than once a year even in a remote island located in the easternmost part of Korea. It indicates that all parts of South Korea are under the influence of the Asian dust. In general, the number of dust occurrences is greater in the western part of Korea. This implies that Asian dust was transported from the Asian continent in the westerly airstream. Hence these climatological data in Korea confirm that dust events have continually occurred through historical times and are most dominant in spring.

3. Identification of Source Regions for Asian Dust

Gao et al. [1992] defined the source regions of Asian dust as central and eastern Asia and the northeast of the Tibetan Plateau by examining patterns of dust storm reports over Asia during 1988–1989. In this study, the source region was identified by analyzing meteorological codes over the Asian continent reported to the World Meteorological Organization every 3 hours. These records were obtained from the Cassette Tape Library of the Japan Meteorological Agency. The synoptic codes include information on dust phenomena, which is further classified into 10 categories. Of these, the code designated for "dust or sand raised by wind at the time of observation" was counted for the spring (March–May) as the number of dust uplifts or rises. The number of dust uplifts during 1993–1995 is shown over a topographic map in Figure 6. Although the frequency of dust rise varies slightly from year to year, there are regions with a steadily higher occurrence of dust rise over 8, generally between 35°–50°N and 100°–110°E and 80°–90°E. This area includes the upstream regions of the Yellow River (40°N, 100°–110°E), the northwest of the Tibetan Plateau with the Taklimakan desert (40°N, 80°–90°E), the loess plateau (37°N, 100°–115°E), and the Gobi desert (43°N, 100°–110°E), which have been commonly regarded as dust source regions. These are all high-plateau zones at the altitude of 1–2 km, of which the climate is warm and dry and favorable for dust generation. It is worthy to note that the number of dust uplifts reached 8 in the Manzurian plan close to the Korean peninsula. The station with the highest frequency of dust generation is located at 39.8°N and 105.8°E (1033 m above mean sea level), where the total number of dust uplifts was 193 during the spring of 1993–1995. For the top 20 stations, the average number of dust uplifts was 28 in 1993, 22 in 1994, and 25 in 1995.

In the spring of 1998 and winter of 1999 when Asian dust events occurred frequently in east Asia, dust swirls and storms were pervasive in the wide areas of the source region (Figures 1 and 2). These figures show daily records of dust phenomena observed from weather observatories, including dust rise, dust devils, dust storms, and dust suspended in the air. Dust activities in source regions, particularly along the borders between China and Mongolia, are well matched to dust incidents observed in Korea 3–5 days later in April and 1–3 days later in January. In addition, the movement of air masses containing dust particles was much faster in the wintertime. Dust storms generated in source areas on January 24 were detected over Korea on the next day and then reached the western part of Japan in 2 days.

3.1. Synoptic Conditions for Dust Generation in Source Regions

Dust incursion in Korea has been related to the synoptic features of source regions 2–3 days before [*Chung and Park*, 1995; *Chun*, 1997]. *Chen and Chen* [1987] described that the high wind velocity and low humidity of the lower troposphere was necessary to generate dust storms. The analysis of meteorological parameters over source regions showed that for the spring of 1993–1995, air temperature and wind speed were higher, but relative humidity was lower than annual averages when dust uplift was observed [*Chun*, 1997]. *Jhun* [1999] also reported that in April 1998 a higher temperature and lower specific humidity were the dominant weather conditions right over the Gobi desert and the loess plateau. In this study, common meteorological conditions in source regions were investigated for April 15 and January 24, which days were believed to be responsible for dust outbreaks in Korea on April 19, 1998, and January 26, 1999, respectively. On April 15, a strong pressure gradient was found at the surface around 50°N and 100°–110°E. This area gradually moved toward the south following the trough in the upper level, where baroclinicity was well developed, causing dynamic motions. On the 500 hPa surface, there was a strong wind belt in the south of the baroclinic region. This is a characteristic pressure pattern for maturing cyclonic vorticity. On April 19, when there were also strong dust activities detected in the source regions, weather conditions were very similar to those of April 15. In this case, a stronger wind belt developed at 500 hPa and flow was almost zonal, which was a perfect condition for dust to be transported far into North America, missing the Korean peninsula. For the winter dust case, the meteorological setting in the source region was very similar to that of the spring dust event: a strong pressure gradient at surface, a strong baroclinic instability at 850 hPa, and a strong wind belt toward Korea at 500 hPa. On

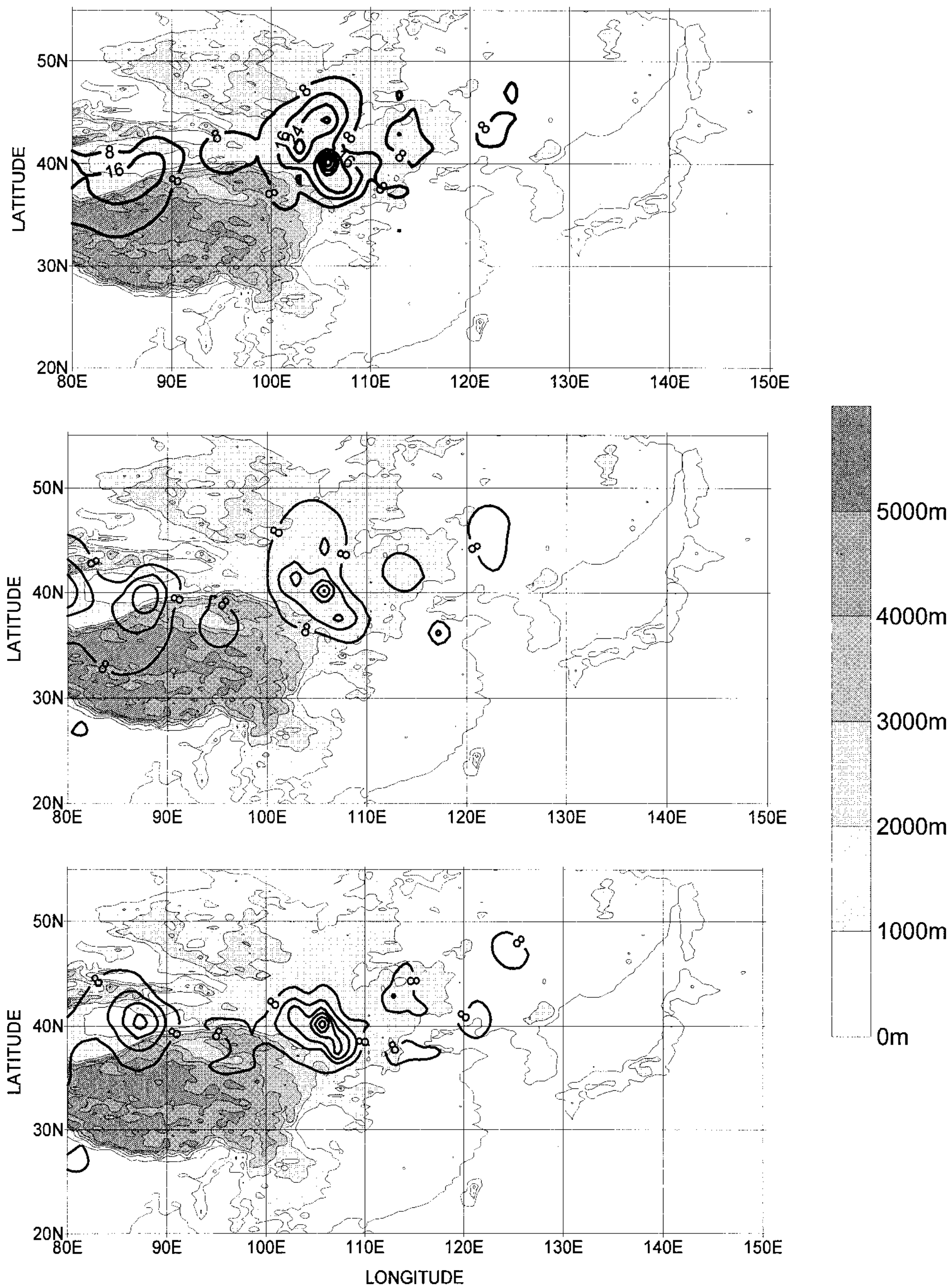

Figure 6. Number of dust rise observed during the spring (March–May) for 1993–1995. The details can be found in the text. The interval of the frequency contour is 8, and topographic heights were projected in the underlying map.

this particular day (January 24) the wind speed reached 15 m/s at the surface, 20 m/s at 850 hPa, and 50 m/s at 500 hPa. The high wind speeds at the surface and baroclinic instability at the 1.5 km level were necessary for dust generation, and the strong wind belt developed at the 5 km level expedited the dust transport toward Korea. During the wintertime a stronger wind belt in the upper level suggests a more rapid transport of dust.

4. Transport of Asian Dust

Gao et al. [1992] showed that the mean midtropospheric flow in April 1988 was accompanied by a frequent cold airflow from the northwest to the southeast within the continent. In comparison, the mean flow for April 1989 was of a reduced curvature, which was consistent with the relatively lower frequency of dust storms in that year. *Jhun* [1999] analyzed the anomaly of the wind speeds to figure out the most favorable conditions for the long-range transport of Asian dust. In this study, backward trajectory analysis along the isentropic surface was performed to predict the transport path of Asian dust. Air trajectories from Seoul at 0600 UTC were calculated back in the time for 96 hours and shown in Figure 7 for April 19, 1998, and January 26, 1999. Figure 7 clearly illustrates that the air sampled on April 19 originally came from desert regions in Mon-

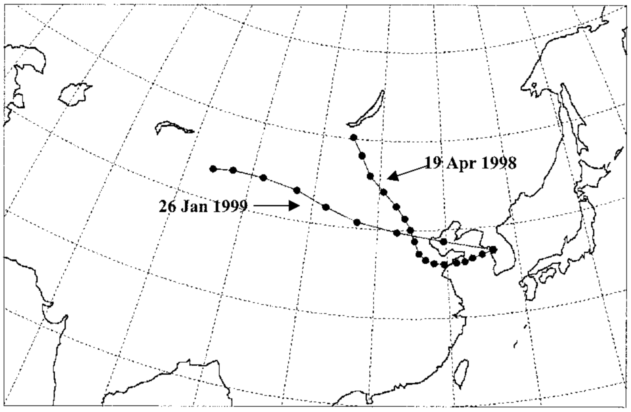

Figure 7. Backward trajectories on a 295 K isentropic surface from Seoul for April 19, 1998, and January 26, 1999, at 0600 UTC. Circles represent the trajectory every 6 hours, and the period of trajectories is 4 days for April 19 and 2 days for January 26.

golian plateau. For winter dust, trajectories at a 290 K surface calculated for 48 hours show that the air originating from Asian deserts reached Seoul in 2–3 days. The result of trajectory analysis also confirmed a faster transport of dust in winter than in spring. As mentioned in the previous section, the transport of dust was strongly related to the meteorological conditions at 500 hPa. It is clearly seen on the weather map that the wind belt developed at 500 hPa was stretched almost as a straight line to Korea in January, while in April, a migratory low was lingering over the Korean peninsula. As a result, the transport was faster during the winter.

5. Physical and Optical Characteristics of Aerosols Collected in Seoul

Asian Dust events were persistent all over the Korean peninsula during April 14–22, 1998, with an especially heavy dust deposition on April 19 and 20. In 1999, dust events were observed for 4 days in the wintertime (January 25–28). During these dust events, size-separated number concentrations of aerosols were measured in Seoul using optical particle counters (HIAC/ROYCO 5230) [*Chun et al.*, 2000]. Particles were equivalently divided into eight dynamic ranges between 0.3 μm and 25 μm at log-decimal scale. Three-minute-averaged data were obtained every hour.

The size-separated number and volume concentrations during April 1998 and January 1999 are displayed in Figures 8 and 9, respectively. During the heavy dust period the number of fine particles decreased, while that of large particles, particularly in the range of 2–3 μm, distinctively increased. Volume concentrations for particles in 2–3 μm size enhanced remarkably on both April 19 and January 26. This trend is more pronounced for the winter dust events, which is probably associated with lower photochemical activities producing secondary particles during winter. The reduction in small particles indicates less anthropogenic influence. For the case of spring dust, the air passed through heavily industrialized regions in China as well as Korea (Figure 7). Furthermore, a slower movement of air mass during the summer possibly allowed a

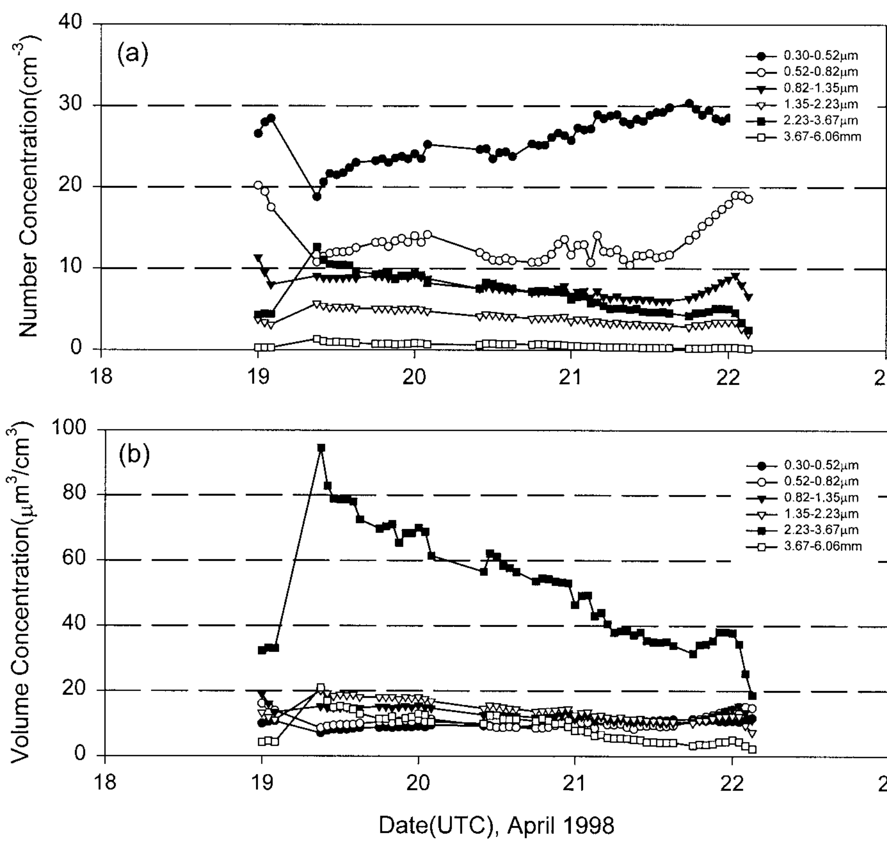

Figure 8. Time series variation of (a) number and (b) volume concentrations of aerosols observed in Seoul during April 19–21, 1998. The particles larger than 6 μm are not shown in the figure.

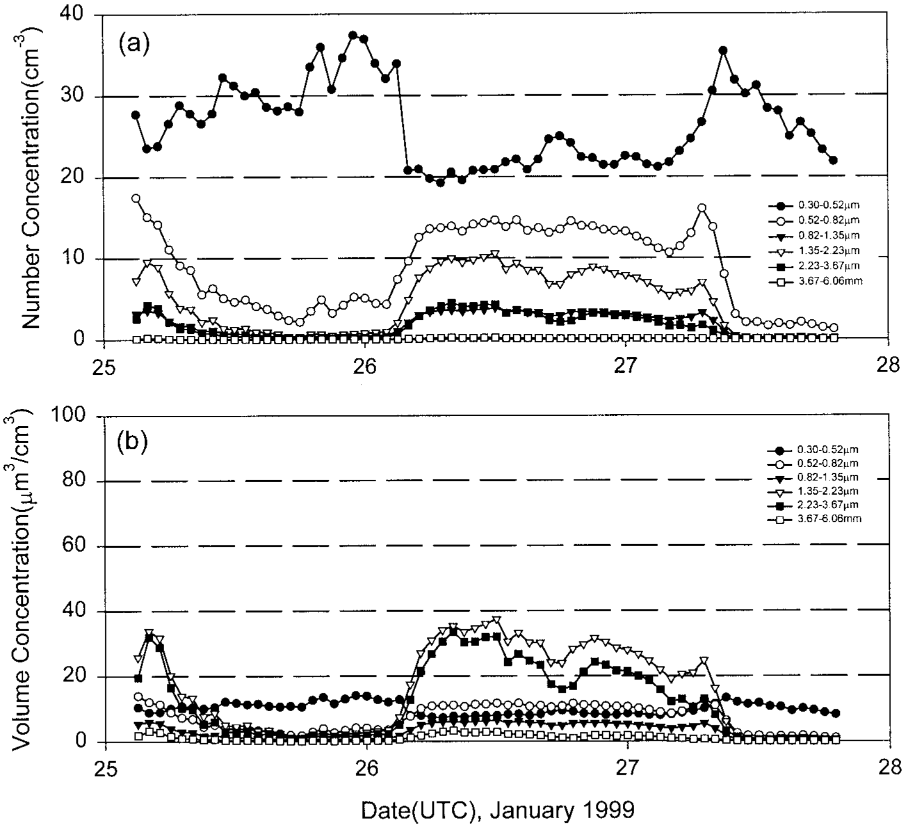

Figure 9. Time series variation of (a) number and (b) volume concentrations of aerosols observed in Seoul during January 25–27, 1999. The particles larger than 6 μm are not shown in the figure.

longer time to contact with pollution sources. The chemical analysis of spring aerosol also suggests that the pathway of air mass affected the composition of aerosol [*Choi et al.*, this issue]. These results indicate that the main component of aerosols during the dust events was dust minerals in the size range between 1 and 10 μm.

Aerosol optical depth (τ) was measured in Seoul with a Sun photometer. Figure 10 shows the time series variation of optical depth on April 19, which is compared with that measured on May 3 as a typical nondust and clear day. It is apparent that aerosol optical depth was greatly increased during the heavy dust incident. The Ångström exponent (α) is a function of particle size being higher with decreasing size. The plot of α against optical depth at 500 nm is a good tool to distinguish different air masses (Figure 11). When there was a heavy dust outbreak, aerosol optical depth was thicker and more variable. On the other hand, the size parameter remained low, which implies that the aerosol was mostly composed of larger particles. It was just the opposite for the nondust day, in which optical depth was much thinner but with higher and more variable α. Thus, on a clear day, aerosols can be postulated to consist of smaller particles distributed over a wider dynamic range. These optical properties of aerosols strongly suggest that the origin and composition of aerosols for dust periods is unequivocally distinguished from that for nondust periods.

6. Conclusions

The climatological data of Asian dust in Seoul reveal that dust events took place consistently for the last century. The frequency of dust incursion differs from year to year with an average of 4 days a year. However, it is more often over the last decade that the number of dust occurrences was greater than 10 days. In April 19–20, 1998, there was a heavy dust incident over the Korean peninsula, which was linked to intense dust storms observed in Asian deserts 3–5 days before. In a rare incident, a dust event took place in Korea on January 25–27 in 1999. Of the dust source regions identified, the Korean peninsula is likely more affected by desert areas between 100°E and 110°E, which was also demonstrated by isentropic trajectory analysis. In source regions, dust was usually raised by a strong wind caused by a cold front system or a strong pressure

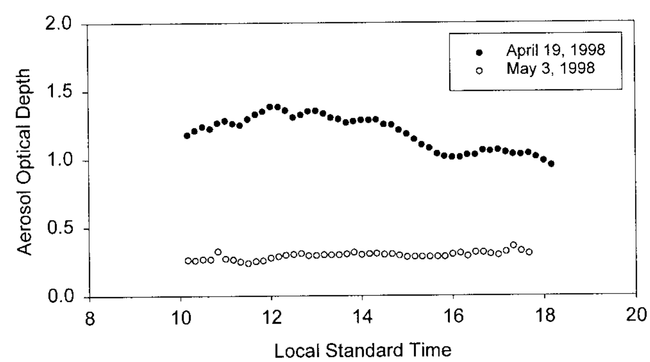

Figure 10. Aerosol optical depth at 500 nm observed in Seoul on April 19, 1998, for dust incident compared with that of May 3, 1998, for a nondust and clear day.

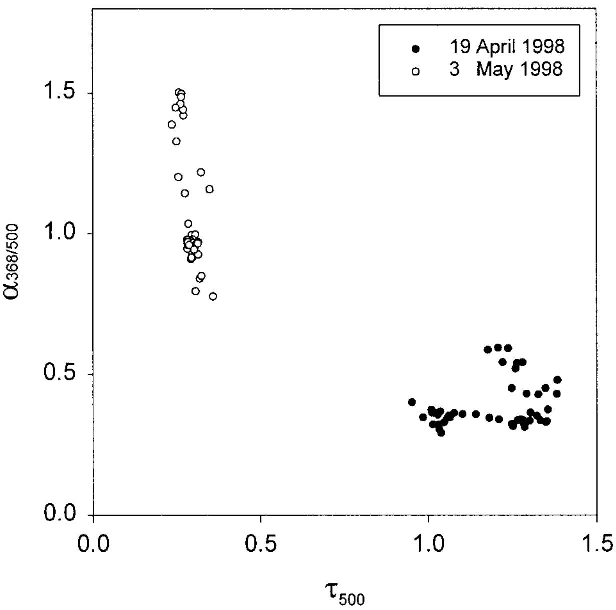

Figure 11. Ångström exponent (α) against aerosol optical depth at 500 nm for April 19, 1998, and May 3, 1998.

gradient at the surface. Baroclinic instability on the 850 hPa surface was another crucial synoptic condition for dust generation. Isentropic trajectories indicate that air mass moved much faster during the winter, when it took only a day for dust to be transported over the Korean peninsula from the source area. Mineral dust had a great influence on physical and optical properties of aerosols. During the dust periods, the mode of aerosols was shifted to lager sizes, 2–3 μm in both number and volume. The optical depth of the atmosphere was much thicker with bigger particles during heavy dust incursion compared with that of a clear nondust day.

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