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Characteristics of Meteorological Conditions Relevant to Asian Dust Outbreaks During Spring Months of 1998-2002

Sang-Keun Song and Yoo-Keun Kim
Department of Atmospheric Sciences, Pusan National University, Busan 609-735, Korea

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The characteristics of meteorological conditions relevant to Asian dust (AD) outbreaks and their occurrence frequencies were analyzed in four source regions (R1 to R4) during spring months (March to May) of 1998-2002. Moreover, the concentration variations of AD (e.g., PM_{10}) observed in Korea were investigated during the study period. In the relationship between AD outbreaks and three meteorological parameters (i.e., air temperature, wind speed, and aridity), the largest AD outbreaks in April (~250 observations) mostly occurred in R2 when air temperature ranging from 10.0 to 15.0℃ and surface wind speed from 7 to 9 m s^{-1} were recorded. Moreover, the aridity ($\geq$ 4) in April was significantly high in R2 with the maximum frequency of AD outbreaks (i.e., 206 observations). On the other hand, the number (percentage) of days belonging to AD events observed in five Korean cities were found to be 116 (44%), 121 (46%), and 26 days (10%) in March, April, and May, respectively. The mean PM_{10} concentrations were found to range from 150 to 220, 150 to 200, and 95 to 120 $\mu g\ m^{-3}$ in March, April, and May, respectively. Consequently, this implied that the AD events in Korea were found to be gradually frequent in early spring and to be affected from the large AD outbreaks observed in the source regions.

Key Words : Asian dust outbreaks, Gobi Desert, Surface wind speed, Aridity, PM_{10} concentration

1. Introduction

Asian dust (AD) has occurred frequently in springtime, between March and May[1], while the Sahara and Arabian dust events occur mainly in summer[2,3]. In general, the long-range transport (LRT) of these dust events is mostly determined by the circulation and advection of wind in the atmosphere where significant pathways for the transport of the dust aerosols exist[4,5]. Therefore, the meteorological conditions relevant to the LRT of AD (LRTAD) during severe episode (or high PM_{10} concentration) days is one of the key elements in identifying the dust origin and its transport path in East Asia.

In the past two decades, there have been a number of reports showing that specific meteorological conditions (e.g., surface weather conditions and synoptic patterns) affect the outbreaks, emission, and transport of the dust particles in the source regions[6~15]. Threshold values of surface wind speed were found to be one of important parameters for the estimation of the dust occurrence and its emission[7]. The threshold values depended on the effects of vegetative residue, roughness of the soil, live standing plants, soil texture, and atmospheric precipitation[6,7]. The dust emission using a numerical model was estimated by calculating friction velocity (including surface wind speed), surface roughness, and surface humidity[9]. Moreover, the uplifting of dust particles was found to be expressed as a function of surface wind speed and wetness[11].

On the other hand, several pieces of evidences of synoptic meteorological conditions relevant to the LRTAD have been reported in the literature. For instances, a cut-off low over the Japan Sea resulting in large amounts of the dust particles transported from the Asian source regions was observed by National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/AVHRR)[8].

Corresponding Author : Sang-Keun Song, Department of Atmospheric Sciences, Pusan National University, Busan 609-735, Korea
Phone: +82-51-583-2652
E-mail: songsk@pusan.ac.kr

Both the synoptic features of upper-level trough/cut-off low and surface high-pressure systems associated with tropopause folding caused the enhancement of aerosols over Korea during AD events[12]. Moreover, the cluster analysis techniques used to classify the dominant weather types (e.g., west-high and east-low pressure system and a trough passage over the central Korea) associated with the LRTAD over Korea could aid in understanding the diverse dust events[13,15].

Although many observational and modeling studies on the dust emission and its transport have been conducted worldwide, one of the largest uncertainties in the modeling for the LRTAD is still the source strength in emission regions[7,16,17]. This is most likely due to the little information on dust emission strength over the source regions and partly due to the lack of observational data (i.e., vertical aerosol profile) over both the source and receptor regions. Because dust emission strength in the source regions are greatly influenced by meteorological situations, specific analysis of the meteorological conditions during the AD events can help to solve its uncertainties of source strength in emission regions. In this study, the relationship between the AD events and meteorological parameters were analyzed in the source regions during spring months, March through May of 1998-2002. In addition, the occurrence frequency of AD and its concentration variations in Korea were compared and discussed during the study period.

2. Data and Methods

In order to find the AD origin and its distributions in the source regions, AD source regions were defined based on the dust generation and its transport path derived from the previous studies[18~20]. The source regions were classified into four different categories: (1) Takla-makan Desert and its surrounding areas as Region 1 (R1: 35-42°N, 75-90°E), (2) Gobi Desert and its surrounding areas as Region 2 (R2: 37.5-48°N, 95-110°E), (3) Inner Mongolia and Loess Plateau as Region 3 (R3: 34-45°N, 110-117°E), and (4) the northeastern part of China (or Manchuria) as Region 4 (R4: 42-45°N, 119-124°E) (Fig. 1).

Synoptic weather codes (or synoptic reporting data) were employed to analyze the occurrence frequency of AD outbreaks and their relationship with the meteorological parameters (e.g., air temperature, surface wind speed, and aridity) in the source regions during the study period. The synoptic weather codes in the Asian domain were obtained from Meteorological Research Institute (METRI) and Busan Regional Meteorological Office (BRMO) in Korea Meteorological Administration (KMA). In general, the entire synoptic weather codes represent meteorological codes and dust outbreaks codes and are recorded in 3-hourly intervals. Among the synoptic weather codes, dust outbreaks codes used in this study were defined as three categories: dust rise (code 7), dust whirl (code 8), and dust storm (code 9) (Table 1).

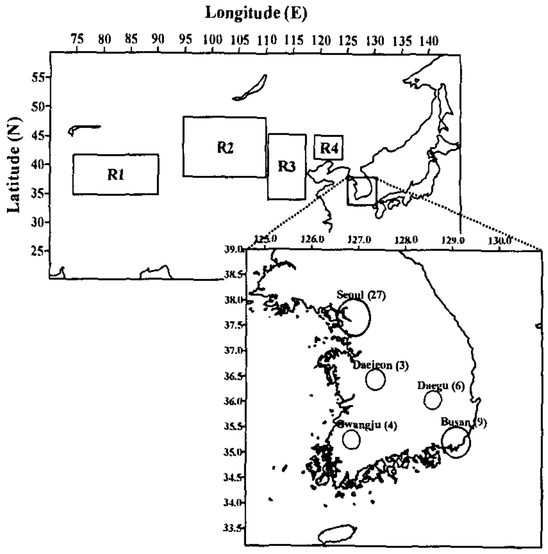

Fig. 1. Map showing the location of four different source regions (R1 to R4) in East Asia and five major cities in Korea. Solid circles on the map denote the locations of the five major cities and the values in parentheses indicate the number of monitoring sites in each city.

To assess the effect of the AD outbreaks during spring months on air quality in a receptor region (e.g., Korea), PM_{10} concentration at the surface was used. Hourly PM_{10} concentrations were measured by the beta-ray absorption method at monitoring sites located in five major cites of Korea such as Seoul (27 sites), Daejeon (3 sites), Gwangju (4 sites), Daegu (6 sites), and Busan (9 sites) (see Fig. 1).

3. Results and Discussion

3.1. Occurrence frequency of AD outbreaks in four source regions

Fig. 2 shows the temporal variation of the occur-

Table 1. Characteristics of synoptic weather codes associated with the AD outbreaks in the source regions

Code	Remark
7	Dust or sand raised by wind at or near the station at the time of observation (dust or sand raised by wind; no well-developed dust whirl(s) or sand whirl(s); no dust storm or sandstorm)
8	Well-developed dust whirl(s) or sand whirl(s) seen at or near the station during the preceding hour or at the time of observation (well-developed dust whirl(s) or sand whirl(s); no dust storm or sandstorm)
9	Dust storm or sandstorm within sight at the time of observation or at the station during the preceding hour (dust storm or sandstorm)

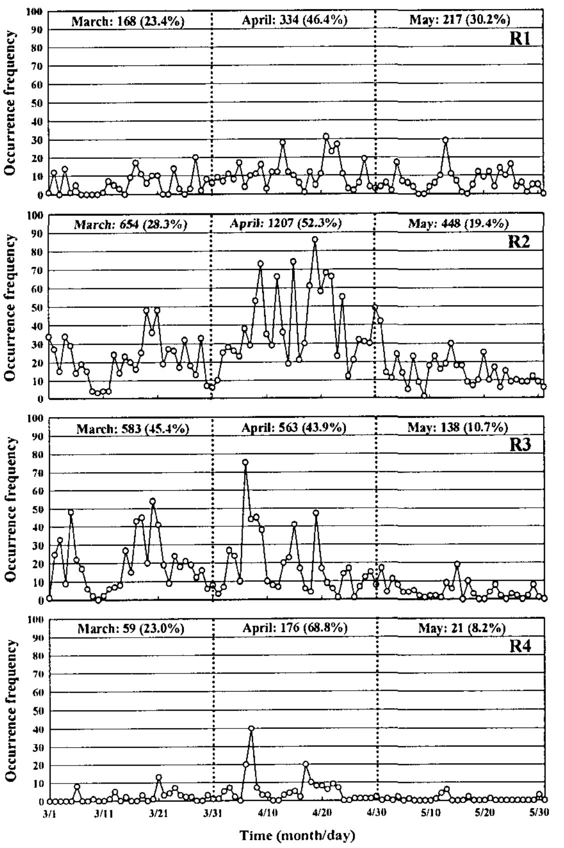

Fig. 2. Temporal variations of the AD outbreaks observed in the source regions (R1 to R4) during March through May, 1998-2002. The total frequencies and percentages of AD outbreaks are denoted in the top of each panel.

rence frequency of AD outbreaks in four source regions (R1 to R4) during the study period. Overall, the total frequencies of AD outbreaks were 719, 2309, 1284, and 256 in R1 through R4, respectively. In particular, the high frequency of AD outbreaks in April was found to occur in most of the source regions (except for R3). The occurrence frequencies of AD outbreaks (334 (46%), 1,207 (52%), and 176 observations (69%) for R1, R2, and R4, respectively) in April were significantly higher (e.g., two times or more) than those (168 (23%), 654 (28%), and 59 (23%)) in March and those (217 (30%), 448 (19%), and 21 (8%)) in May. In addition, the maximum frequencies of AD outbreaks in R1, R2, and R4 were found to be 31 on 21 April, 86 on 19 April, and 40 observations on 7 April, respectively. For R3, however, the occurrence frequency of AD outbreaks (i.e., 583 observations, 45%) in March was found to be higher than that (i.e., 563, 44%) in April and that (i.e., 138, 11%) in May. On the other hand, the occurrence frequency of AD outbreaks in R4 was found to be significantly low ($\leq$ 10 observations) in the most spring days (except for the early April).

To identify the horizontal distribution of the dust sources in this study, the AD source regions were reclassified into two categories: a high frequency (HF) and extra-high frequency (EHF) region. The HF and EHF regions have the AD outbreaks ranging from 80 to 160 and more than 160 observations, respectively. The HF regions mostly covered main deserts of R1 through R4, while the EHF regions partially covered Tarim Basin in R1 and Gobi Desert in R2 (Fig. 3). In particular, the large AD outbreaks (e.g., $\geq$ 320 observations) were found to be observed in R2 (see Fig. 3). It could be found that R2 is the most prevalent dust source regions in East Asia. This implied that there was no doubt that the HF and EHF of AD outbreaks were important indicators of the source regions. However, because strong AD outbreaks could be transported over large distances and reported at the weather stations located outside of an actual active source, the specific analysis of meteorological parameters affecting the AD events could be required. In this study, thus, three meteorological parameters used to estimate dust

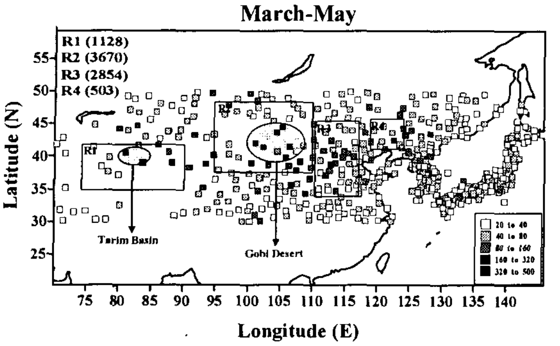

Fig. 3. Horizontal distributions of AD outbreaks observed in East Asia during March through May, 1998- 2002. The four big rectangles represent the four source regions (R1 to R4) and small shaded rectangles indicate the magnitude of the occurrence frequency of AD outbreaks.

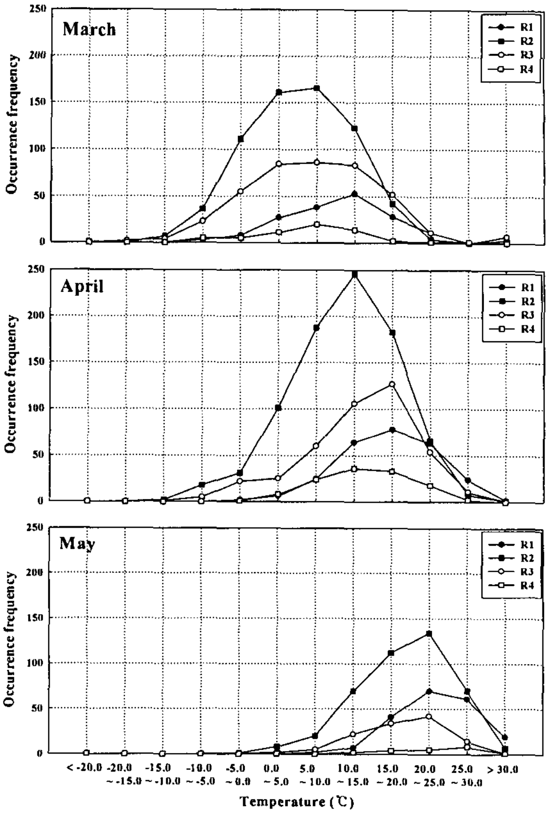

Fig. 4. Relationship between the occurrence frequency of AD outbreaks and air temperature in the source regions (R1 to R4) during March through May, 1998-2002.

emissions and its origin in the previous studies[9,21,22] were analyzed.

3.2. Relationship between the AD outbreaks and meteorological parameters in the source regions

The occurrence frequencies of AD outbreaks observed in R1 through R4 during the study period are analyzed with the specific range of three meteorological parameters (i.e., air temperature, surface wind speed, and aridity) (Figs. 4, 5, and 6). Overall, the range of three meteorological parameters corresponding to the large AD outbreaks was highly variable, especially air temperature, depending on observational locations (e.g., high and middle latitudes) and periods (e.g., March, April, and May).

In March of Fig. 4, the maximum frequencies of AD outbreaks were more than 50, 150, 75, and 20 observations in each source region, respectively. The larger AD outbreaks for the most source regions (except for R1) were shown at the air temperature ranging from 5.0 to 10.0℃. In particular, the HF region of the AD outbreaks was also shown in R2 with the air temperature ranging from 5.0 to 10.0℃. On the other hand, the maximum frequencies of AD outbreaks in April were approximately 75, 250, 125, and 40 observations, while those in May were 70, 125, 45, and 5 observations in each source region, respectively. The occurrence frequency of AD outbreaks was shown at the diverse ranges of air temperature. For instance, the large AD outbreaks in April were observed in R2 and R4 (R1 and R3) when the air temperature ranged from 10.0 to 15.0℃ (15.0 to 20.0℃); whereas those in May were observed in the R1, R2, and R3 when the air temperature ranged from 20.0 to 25.0℃. For R4, the large AD outbreaks occurred when the air temperature ranged from 25.0 to 30.0℃.

In Fig. 5, the large AD outbreaks apparently occurred with the surface wind speed of more than 5 m s^{-1} in the most source regions (except for R4). The greater wind speed, having a threshold value ranging from 5 to 12.5 m s^{-1}, causes the larger fraction of dust particles to be lifted from the surface, increasing the dust event rates[23)]. In March, the maximum frequencies of AD outbreaks were about 50, 200, 100, and 20 observations in R1 through R4, respectively. The larger AD outbreaks were shown in R2 and R3 with the surface wind speed ranging from 7 to 9 m s^{-1}; whereas, the smaller AD outbreaks in R1 and R4 occurred with that ranging from 5 to 7 and 11 to 13 m s^{-1},

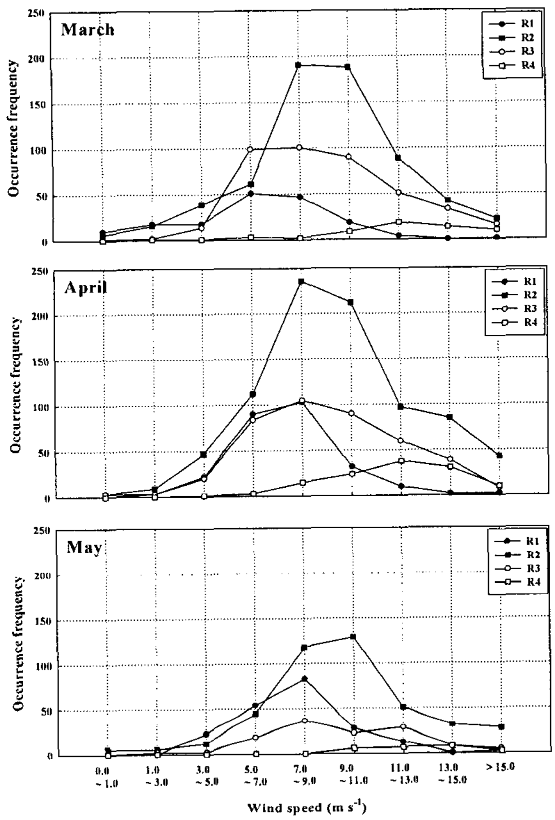

Fig. 5. Same as Fig. 4 except for surface wind speed.

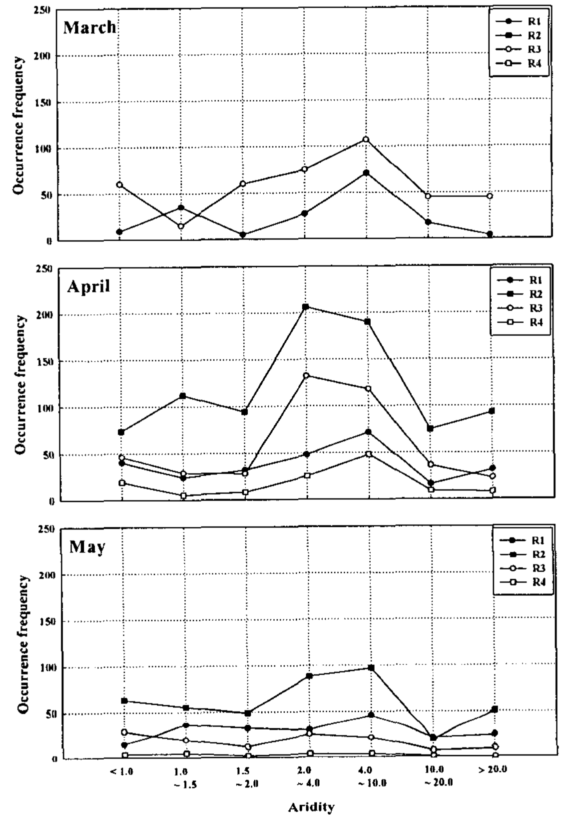

Fig. 6. Same as Fig. 4 except for aridity.

respectively. In case of April, the maximum frequencies of AD outbreaks were approximately 100, 250, 100, and 40 observations for each region, respectively. The larger AD outbreaks were observed in the most regions (except for R4), when the surface wind speed ranging from 7 to 9 m s^{-1} was recorded. In May, the maximum frequencies of AD outbreaks were also shown as about 80, 125, 45, and 5 observations from R1 through R4, respectively. The larger AD outbreaks were observed in the most regions (except for R2 and R4), when the surface wind speed ranged from 7 to 9 m s^{-1}. Moreover, the HF and/or EHF regions of AD outbreaks were found to be mostly shown in R2 with the surface wind speed ranging from 7 to 9 m s^{-1}.

In this study, we analyzed the relationship between the AD outbreaks and two meteorological parameters (e.g., air temperature and wind speed). However, this was found to be somewhat limited to account for the identification of dust emission and its origin. Recently, Xuan and Sokolik[24] reported that drought and flood in the AD source regions play an important role in the dust origin and its emission conditions. They found that the precipitation in the source regions sharply decreased from east to west in Northern China. The HF and EHF regions of AD outbreaks had the precipitation of less than 400 and 200 mm yr^{-1}, respectively. Therefore, in order to better identify the dust origin, aridity (indicating the extent of drought and flood with air temperature and precipitation) used in the classification of climatic zones was employed in this study (Fig. 6)[21]. The aridity is defined as $R = 0.16 \times \sum T/P$, where $\sum T$ is the accumulated diurnal mean air temperature higher than 10°C and P is the precipitation for the same time period[21]. In general, aridity $R = 1.5\text{-}2.0$ defines the semi-arid region, $R > 2.0$ is for the arid region, and $R > 4.0$ is for the deserts.

Fig. 6 illustrates the aridity values corresponding to the occurrence frequency of AD outbreaks in each source region (R1 through R4) during the study period. The aridity was calculated by using synoptic reporting data (e.g., air temperature and precipitation) during the AD outbreaks. Overall, the high occurrence frequency of AD outbreaks (~200 observations) in April, compared with March (~100) and May (≤ 100), was shown at the high value of aridity (≥ 4).

In case of March, because of the missing data of precipitation in R2 and R4, the aridities for two source regions were excluded in the data evaluation. The maximum frequencies of AD outbreaks were more than 70 and 100 observations in R1 and R3, respectively, with the aridity ranging from 4 to 10; whereas, the smaller AD outbreaks (≤ 50 observations) occurred at the other diverse ranges of aridity. On the other hand, the maximum frequencies of AD outbreaks in April were found to be approximately 70, 200, 140, and 50 observations; whereas those in May were about 50, 100, 30, and 5 observations from R1 through R4, respectively. Moreover, the large AD outbreaks in April were observed in R2 and R3 (R1 and R4) when the aridity ranging from 2 to 4 (4 to 10) was recorded. However, the larger AD outbreaks in May were observed in the most regions (except for R3) when the aridity ranged from 4 to 10.

3.3. Variations of AD concentration levels in Korea

Fig. 7 shows the daily distribution of dusty days in the five major cities, Korea during the study period. Overall, the largest first peak (a maximum value of 15 days) occurred on 23 March and the two secondary peaks (a maximum of 11 days) appeared on 8 and 17 April, respectively. From March to May, the number (percentage) of days belonging to the AD events were found to be 116 (44%), 121 (46%), and 26 days (10%), respectively. The percentage of dusty days in this study was different from that reported by Sun et al.[25], occurring in March (20%), April (58%), and May (22%) during the period of 1960-1999. This implied that the AD events were gradually high frequent in early spring (e.g., from late March to mid-April) because of the desertification due to global warming and deforestation. The highest frequency of dusty days indicated during the period from March 20 to April 20 (except for early April) (Fig. 7).

In the meantime, the total dusty days at each city of Korea were investigated during the study period (not shown). The AD events in Seoul and Daejeon were found to be higher frequency of more than 60 compared with the other cities (e.g., Gwangju, Daegu, and Busan). Of particular interest was the fact that the AD events occurred significantly frequent in the western cities of Korea such as Seoul (69 days), Daejeon (64 days), and Gwangju (59 days) and the high occurrence region of AD events gradually moved to the

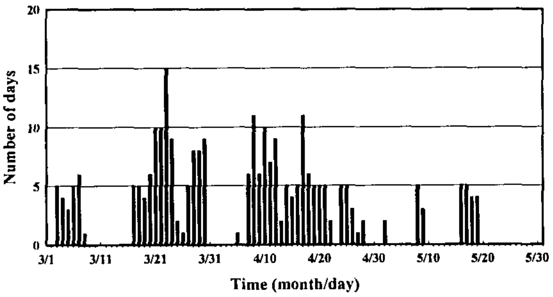

Fig. 7. Number of days of the AD events observed in five major cities of Korea during March through May, 1998-2002.

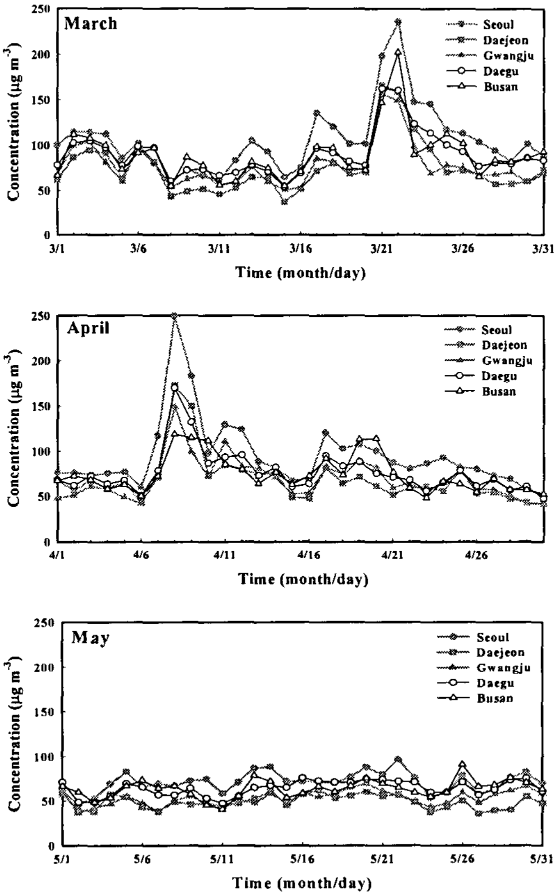

Fig. 8. Temporal variations of daily mean PM_{10} concentration observed in the five major cities of Korea during March through May, 1998-2002.

eastern cities of Korea such as Daegu (53 days) and Busan (49 days) (not shown).

Fig. 8 illustrates the temporal variations of mean PM_{10} concentration in the five major cities of Korea during the study period. As seen in the figures, two large peaks (or high PM_{10} concentration days) occurred in the five major cities on 22 March (a mean PM_{10} concentration of $\geq$ 200 $\mu g\ m^{-3}$) and 8 April (a mean of ~250 $\mu g\ m^{-3}$) when the LRTAD from the source regions to Korea was clearly identified[26~28]. During these dust events, there were many patients with the environmental diseases including tonsillitis, allergy, and asthma because the heavy dust events occurred in whole cities of Korea on 21-22 March 2002[26]. In contrast, there was no peak in May with low PM_{10} concentration of less than 100 $\mu g\ m^{-3}$. This implied that the larger AD outbreaks observed from R1 through R4 in early spring (e.g., from late March to mid-April) were found to affect the increase of PM_{10} concentrations in the receptor regions (e.g., Korea) (see Figs. 2 and 8).

4. Summary and Conclusions

The occurrence frequency of AD outbreaks and their relationship with three meteorological parameters (i.e., air temperature, wind speed, and aridity) were performed in the four different source regions (R1 to R4) during March through May, 1998-2002. The concentration variations of AD observed in Korea were also analyzed during the study period. Among the four different source regions, the HF regions mostly covered main deserts of R1 to R4, while the EHF regions partially covered the two source regions such as R1 and R2. In addition, the largest AD outbreaks (2309 observations) were found to be observed around R2 where the most prevalent dust source regions in East Asia.

In the relationship between AD outbreaks and meteorological parameters, the range of three parameters corresponding to the large AD outbreaks was highly variable, especially air temperature, depending on observational locations (e.g., high and middle latitudes) and periods (e.g., March, April, and May). When the air temperature was recorded as 5.0-10.0℃ (March), 10.0-15.0℃ (April), and 20.0-25.0℃ (May), the large AD outbreaks ranging from 140 to 250 observations (a mean of 180) frequently occurred in R2. In contrast, when the surface wind speed ranged from 7 to 9 $m\ s^{-1}$, the large AD outbreaks ranging from 120 to 240 observations (a mean of 185) mainly occurred in R2. Moreover, the maximum frequency of AD outbreaks (206 observations) in April was significantly high in R2 with the high value of aridity ($\geq$ 4), compared with March (~100) and May ($\leq$ 100). Consequently, the characteristics of three meteorological parameters relevant to the AD outbreaks during the study period could be found to imply the climate conditions of rapid desertification (e.g., arid and desert conditions) in northeastern Asia, especially in R2.

On the other hand, the number (percentage) of days belonging to the AD events observed in the five Korean cities were found to be 116 (44%), 121 (46%), and 26 days (10%) from March to May, respectively. The mean PM_{10} concentrations in the five Korean cities were found to range from 150 to 220, from 150 to 200, and from 95 to 120 $\mu g\ m^{-3}$ in March, April, and May, respectively. This implied that the large AD outbreaks in the source regions were found to affect the increase of PM_{10} concentrations in Korea and the AD events were also gradually frequent in early spring (e.g., from late March to mid-April).

In this study, our results can help to understand the dust origins and to estimate the dust emission in the source regions. However, additional studies for the identification of the dust sources are still needed in order to estimate the accurate dust emission strength. In the future, if the other meteorological surface data (e.g., hourly soil moisture and snow cover) for the estimation of dust emission are accurately calculated from the source regions, the more accurate dust origins and its emission conditions can be identified.

Acknowledgements

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