Roles of surface wind, NDVI and snow cover in the recent changes in Asian dust storm occurrence frequency

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HIGHLIGHTS

► This study describes the recent dust occurrences over source regions.
► Severe dust activation (2000–2002) and decrease (2003–2004) were well contrasted.
► Higher dust occurrence area has been shifting toward northwest since 2003.
► Highest month has been delayed and secondary peaks were newly found.
► Strong wind speed, NDVI, and snow cover are main factors in dust occurrence.

ABSTRACT

This paper describes the recent variations in dust outbreak during the period from 1996 to 2007 over the Asian dust source regions. The Asian dust source regions were divided into four sub-regions; S1, Taklamakan; S2, Gobi; S3, Inner Mongolia-Manchuria; and S4, Loess, and the WMO SYNOP observation and satellite data were employed to analyze the features of recently changed dust outbreak frequencies (DOFs). There was no particular variation in region S1, but the recent spatiotemporal variations in DOFs over S2–S4 were well characterized by a severe and widespread increase in 2001–2002, and significant decreasing in 2003–2004 over the most source regions, with a steadily increasing trend again during 2005–2007. Seasonal features showed that the highest DOFs occurred in March–April before 2002, but was delayed by a month toward April–May during the next five years because of the shift in the month of highest strong wind-speed frequencies (SWFs). A secondary peak of DOF was also found, occurring in October–November since the year 2000. Over all the source regions, the primary controlling factor for explaining the spatiotemporal DOF patterns was the SWF, with a pattern correlation coefficient (PCC) of 0.66–0.76. Other secondary controlling factors varied from region to region. For example, the DOFs observed in region S2–S3 showed relatively greater sensitivity to the snow-cover fraction, and region S4 showed a better correlation with the normalized difference vegetation index (NDVI) than the other regions. Other recent significant changes in DOFs over the Asian dust source regions and their causes are also discussed in this study.

1. Introduction

Aeolian dust is generated by strong surface wind in areas where there is low vegetation cover in arid and/or semi-arid regions. East Asian cyclone activity is generally strong in spring around the Gobi Desert (Chen et al., 1991), which is well known as a major dust source region in East Asia. Recently, it has been reported that source areas of dust outbreaks extended into the western parts of the Mongolia and the western Loess Plateau (Kurosaki and Mikami, 2003; Kim, 2008).

There were an average of 5.2 dust days per year in Korea from 1915 to 2000 (Chun et al., 2002), but East Asian dust events have been reported to be unusually active in recent years, and the numbers of Asian dust days over northeast countries have increased significantly since 2000, with much higher intensities, especially during the period 2000–2002. Kurosaki and Mikami (2003) highlighted the role of strong wind speed in severe dust event by analyzing surface wind velocity at a height of 10 m from January 1993 to June 2002, focusing on the uncommon activation of Asian dust in the period 2000–2002. However, in 2003–2004, there were remarkable decreases in dust observations over
downstream areas of the source regions, and it was reported that the statistics of higher dust-source regions changed significantly over East Asia; however, further quantitative studies of Asian dust occurrences over the various source regions in recent years have not yet been substantiated.

Moreover, the relationship between dust outbreak frequencies (DOFs) and other parameters such as vegetation, temperature, and precipitation is also studied. For example, the normalized difference vegetation index (NDVI) was employed to associate with dust storms. NDVI is determined by the degree of absorption by chlorophyll in the red wavelengths, and it is a good parameter being proportional to green leaf density (Tucker et al., 1985). Zou and Zhai (2004) also indicated that poor vegetation coverage is one important factor for the frequent occurrence of spring dust storms in northern China. Suh and Nam (2003) reported that the NDVI in April increased over the most parts of East Asia in the 1980s, but it showed a decreasing tendency in the 1990s over the Asian source regions, i.e., the region from Mongolia to upstream of the Yellow River. Some studies on NDVI associated with temperature were reported. Myneni et al. (1998) showed that the geographical distribution of the increase in NDVI matches well with the springtime warming pattern. Since there was a large NDVI values in the relatively warm years and less vegetation in the cold years (Suh and Nam, 2002), it has been also been shown that the variation of NDVI has a close relationship with temperature in East Asia.

Upon examination of dust occurrence, Gao et al. (2003) showed that temperature and precipitation are important factors in the occurrence of sandstorms. However, it is also found that the combination of temperature and precipitation plays a certain role, because frequent dust occurrence normally corresponds with cold, dry periods, while dust occurrence generally decreases in a warm, wet period (Lim and Chun, 2006). In contrast, some studies have shown that the relationship between dust phenomena and these three parameters (vegetation, temperature, and precipitation) is not clear (e.g., Lim and Chun, 2006), so further studies are still necessary.

This paper reports the recent trend in dust outbreaks over the various Asian dust-source regions including the comparison of the inter-annual period during and after the period of 2000–2002. The causes of the different occurrence frequencies over the source regions between two periods were explored in various ways, by examining the inter-annual trends of number of factors, including both meteorological parameters (e.g., wind speed, temperature) and land surface conditions (e.g., vegetation cover, snow cover, and land cover). The dust outbreak frequencies observed over the various source regions are also discussed in relation to the recent inter-annual variations in dust occurrence frequencies over East Asia.

2. Analysis region, data used, and methodology

Fig. 1 shows the maximum monthly averaged dust outbreak frequency (DOF), defined as the percentage of dust outbreaks compared to the total number of observations, over a period of twelve years (1996–2007). In the current study, we subdivided dust-source regions into four analysis regions according to the previous research (Lim and Chun, 2006; Kurosaki and Mikami, 2003, 2005): S1 (Taklamakan) at 37°N–41°N, 75°E–88°E; S2 (Gobi) at 42°N–48°N, 95°E–110°E; S3 (Inner Mongolia) at 41°N–46°N, 110°E–122°E; S4 (Loess Plateau) at 34°N–38°N, 105°E–113°E (Fig. 1). Each box in Fig. 1 indicates a high-potential dust-outbreak region in East Asia as used in the previous observation studies. The Taklamakan Desert (S1) is located in the Tarim Basin, surrounded by high mountains comprising the Tibetan Plateau, Pamirs Mountains, and the Tian Shan Mountains. The elevation of the source region S1 is 2000 m above sea level. The Gobi Desert (S2) extends from the south of Mongolia to the north of China, and its major land cover type is semi-desert shrubs. Region S1 and western part of S2 is climatologically characterized by its low annual total precipitation of about 100 mm with the prevailing northwesterly winds. The land cover type of Inner Mongolia (S3) is grassland. The annual occurrence frequencies of the strong wind speed exceeding 15 m s⁻¹ is more than 20% and there are an average of 50 dust storm days annually (Batsukh, 2004; Kurosaki and Mikami, 2007). The Loess Plateau (S4) consists of several major land-cover types: semi-desert shrubs in the west, cultivated land in the southeast, and grassland in the northeast, as indicated in Global land cover characteristics data base in USGS.

For the investigation of the recent DOFs in all of the source regions, we used the following procedures. First, we investigated the weather code and surface wind velocity at a height of 10 m, obtained from SYNOP reports for the period 1996 to 2007 over East Asia, and estimated the occurrences of strong surface winds over all the source regions. In this study, a strong wind was defined as one with a wind speed exceeding threshold velocity. It should be noted that a constant threshold velocity of 6.5 m s⁻¹ was used in many previous numerical models (e.g., Tegen and Fung, 1994; Uno et al., 2003). However, as expected, the threshold velocity cannot be approximated to a single unique value, and it would be desirable to estimate individual values taking into account the different land-surface conditions of the individual source regions. We first calculated individual, different threshold velocities over each of the four source regions following the methodology of Park and In (2003) but employing more recent meteorological records obtained from all of the source regions. Threshold velocity was obtained through the three steps. As a first step, the occurrence frequencies of wind speed, dust storm or dust-rise with respect to the wind speed were calculated. The second step is to determine the ratio of the occurrence frequency of dust-rise to that of the wind speed, and the final step is to determine the normalized cumulative ratio of the occurrence frequency of the dust-rise to that of the wind speed with respect to the wind speed over the individual source regions. In our study the threshold wind speed is defined as the wind speed at the normalized cumulative ratio of the dust occurrence frequency being 3.5%, as employed by Park and In (2003).

Second, the recent annual trend of DOFs and strong wind frequency (SWFs, defined as the percentage of strong winds compared to the total number of observed wind speeds) were investigated for each of the source regions. Here again, a strong wind speed is a speed exceeding the individual threshold velocities at which the dust can occur in a given source region.
Third, NDVI data, derived from the Moderate-Resolution Imaging Spectroradiometer (MODIS) on the NASA Terra satellite, were used to investigate the spatiotemporal distribution over the surface for an eight-year period (2000–2007). The vegetation indices are designed to enhance the vegetation signal from measured spectral responses by combining two (or more) different wavebands, and are considered to be robust, empirical measures of vegetation activity on the land surface. Values of NDVI for vegetated vegetation typically range from 0.1 to 0.7, and NDVI value greater than 0.5 generally indicates dense vegetation.

Lastly, monthly snow and ice maps are derived from daily snow and cover charts produced at NOAA/NESDIS within Interactive Multi-sensor Snow and Ice Mapping System (IMS). Original IMS snow/ice charts (http://www.ssd.noaa.gov/PS/SNOW/index.html) are employed to calculate an average of all daily fractions of snow and ice for a given month, and the monthly climatology was obtained through averaging monthly data for individual years.

The DOF were investigated against many controlling factors for dust activity over the source regions, in order to identify the physical reasons for the recent spatial and temporal variations in DOFs. In order to calculate the similarity of the spatial distributions for two variables $A$ and $B$ (e.g., DOF and SWF), we used the pattern correlation coefficient (PCC). The PCC between two variables ($A_i$ and $B_i$) is defined as $PCC = \frac{\sum(A_i - \bar{A})(B_i - \bar{B})}{\sqrt{\sum(A_i - \bar{A})^2 \sum(B_i - \bar{B})^2}}$. Where $N$ is the number of pairs of the two variables ($A_i$ and $B_i$), and $\bar{A} = (1/N(\sum A_i))$ and $\bar{B} = (1/N(\sum B_i))$ are space-averaged values.

### 3. Results

#### 3.1. Recent changes DOF distributions

Fig. 2 illustrates the spatiotemporal distributions of mean DOFs, as well as the mean and anomalies of springtime (March, April, and May) NDVIs over the study period. Fig. 2a shows spatial DOFs averaged over the period 2000–2007 (the whole NDVI data period in this study), and Fig. 2b–d show those separately for 2000–2002, 2003–2004, and 2005–2007, respectively. This subdivision of analysis periods are based on the discontinuity of measurement of Asian dust days. In most Korean observation sites showed big discontinuities between the sub-periods (2000–2002, 2003–2004, and 2005–2007). For example, Baengnyeong island site (western-most site of Korea, being located close to dust source regions) recoded Asian dust days of 27–19, 2–8, and 13–16 for the periods of 2000–2002, 2003–2004, and 2005–2007, respectively. These gaps made us divide our analysis period (Table 1). In addition, the mean NDVI averaged over 2000–2007 is given in Fig. 2a, and anomalies of NDVIs for the periods 2000–2002, 2003–2004, and 2005–2007 are shown in Fig. 2b–d, respectively. A previous study reported that higher DOFs in the period 1996–1999 were frequently found around southern Mongolia (about 44°N, 105°E), the Badain Jaran Desert (about 42°N, 102°E), and the western Loess Plateau (about 40°N, 105°E), and these can mostly be indicated in Fig. 2a (Kurosaki and Mikami, 2003).

<table>
<thead>
<tr>
<th>Source region</th>
<th>Year</th>
<th>March</th>
<th>April</th>
<th>May</th>
</tr>
</thead>
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<tr>
<td>1) Number of dust days</td>
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<td>4</td>
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<tr>
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<td>9</td>
<td>8</td>
<td>-</td>
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<tr>
<td>2003</td>
<td>5</td>
<td>1</td>
<td>-</td>
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<tr>
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<td>5</td>
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<td>1</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td></td>
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<tr>
<td>2006</td>
<td>6</td>
<td>8</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>2) Dust outbreak frequencies (DOFs)</td>
<td>S2</td>
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<td>1.45</td>
<td>2.66</td>
</tr>
<tr>
<td>2000–2002</td>
<td>3.00</td>
<td>5.74</td>
<td>2.09</td>
<td></td>
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<tr>
<td>2003–2007</td>
<td>2.42</td>
<td>5.35</td>
<td>3.61</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>1996–1999</td>
<td>0.41</td>
<td>0.95</td>
<td>0.38</td>
</tr>
<tr>
<td>2003–2007</td>
<td>1.42</td>
<td>2.29</td>
<td>1.68</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Spatial distributions of DOFs and NDVIs over the East Asia during springtime (March, April, and May). Dots, black circles, stars and rhombus indicate DOF and color bar represents NDVI. Mean DOFs were plotted for the period of a) the whole study period (2000–2007), b) 2000–2002, c) 2003–2004, and d) 2005–2007. The NDVI indicates mean patterns averaged over a) the whole study period (2000–2007), and deviations from the mean pattern over the period of b) 2000–2002, c) 2003–2004, and d) 2005–2007, respectively.
In 2000–2002, as illustrated in Fig. 2b, higher DOF areas were found over the southeastern part of region S3 and most of region S4, with significant increases in DOF in both regions. However, during the period 2003–2004, there were remarkable decreases in DOFs over all of source regions, including both the S3 and S4 regions (Fig. 2c). This meant that the region of highest DOF was shifted back to region S2, where it had been highest for the period 1996–1999 (not shown here). In 2005–2007, the DOF steadily increased again in regions S2 and S3, shifting the highest DOF region toward the area further north, as indicated in Fig. 2d. The NDVI Distributions also changed significantly after 2002. In 2003–2004, there were widespread increases in NDVI in all source regions; the NDVIs then decreased steadily during the period 2005–2007, following the higher DOF areas (Fig. 2d).

As there were previous studies reporting that more vegetation (higher NDVI) was found in warmer years and less vegetation (lower NDVI) in cold years (Suh and Nam, 2003; Myneni et al., 1998), we analyzed the temperature trends over all of the source regions. Fig. 3 shows temperature anomalies over all of the source regions for both March and spring season (March, April, and May) against average over 2000–2007. In Fig. 3, we analyzed spring season plus March because there was a relatively bigger variability in DOFs during March than other months as indicated in Table 1. It was noted earlier that, during the whole spring season in 2000–2002, large negative anomalies in NDVI were found over most of regions S2–S4 (Fig. 2b), where there were clearly lower temperature (Fig. 3a and d), while there was a high positive anomaly during 2003–2004 (Fig. 2c), which is also believed to reflect the high temperature indicated in Fig. 3b and e. However, in 2005–2007, only small decreases (over western S2) and increases (over eastern S3) in temperature were found, but, on the contrary, a lower NDVI was seen in the western part of region S3 (Fig. 2d), showing a slight opposite relation between temperature and NDVI during the given period.

In order to estimate SWF, we calculated the threshold velocities over each of the four source regions for the period 1996–2007; the threshold velocities yielded were 1.71, 9.55, 10.75, and 5.46 m s\(^{-1}\) for regions S1, S2, S3, and S4, respectively. The smallest threshold velocity in S1 is associated with the highest maximum monthly DOF in region S1 with a maximum value of 40%, as indicated in Fig. 1. The calculated mean and anomalies of the SWF, together with the snow-cover fraction, are shown in Fig. 4. Here again, the mean of SWF (Fig. 4a) is averaged over years 2000–2007, and the deviations (Fig. 4b–d) are indicated for the periods 2000–2002, 2003–2004, and 2005–2007, respectively. The mean SWF in

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**Fig. 3.** Spatial distributions of temperature anomalies for 2000–2002, 2003–2004, and 2005–2007; a)–c) show for March only (left), and d)–f) for spring season (right).
As illustrated in Fig. 4, there was almost no snow covers over regions S2 and S3 during the period 2000–2002, but it increased significantly in 2003–2004. This matches very well with the DOFs, which were highest in 2000–2002 and lowest in 2003–2004 (Fig. 2). However, in 2005–2007, the snow cover decreased steadily, approaching (but not reaching) the level of 2000–2002.

These patterns were much more obvious with the SWF. For example, the SWFs increased in 2000–2002, especially in region S3, which matched the DOFs quite well, as indicated in Fig. 2. Of the four source regions, the most significant increase in DOF was found in region S3 during the three years 2000–2002, because of the significantly increased SWF, as illustrated in Fig. 4, which resulted in significantly higher PM$_{10}$ concentrations over 1000 m away at most monitoring sites located in downstream areas (Park and In, 2003). A cluster analysis method of four-days backward trajectories also identified S3 region (including Inner Mongolia) as a major source regions of these severe concentrations during the years 2000–2002 (Kim, 2008).

On the contrary, lower SWFs and DOFs were found in 2003–2004. Therefore, in this study, the SWF and the snow-cover fraction both show good correlations with DOFs, especially in region S3. At this point, we did not determine which factor was more influential in controlling the DOF in region S3. We can conclude that, in region S3, the snow-cover fraction was one of the important factors over the study period. During the period 2005–2007, no significant relationships between SWF and DOF were found, with only smaller perturbation patterns (especially at S4) observed, again implying that the recent changes in DOF became weaker and more complicated during this time.

3.2. Seasonal variations of dust outbreak frequency

Fig. 5 shows the monthly variations in DOF and SWF averaged over the period from January 1996 to December 2007. The indicated DOF shows the highest frequency in spring and the lowest in summer, except for S1, where the DOF is also high in summer. Nearly two-thirds of the dust outbreaks were observed in March, April, and May. This is agreeing well with both DOFs (Kurosaki and Mikami, 2003) and the features of dust storm case (Littmann, 1991; Parungo et al., 1994). Of particular interest is the monthly variation; there were remarkable increase in DOFs during March and April, although the changes in May were small before 2002, as Kurosaki and Mikami (2003) described previously. However, significant increases in DOF have been observed in May, especially in S2 after 2002.

The SWF exhibited the same tendency as the DOF before 2002. After 2002, however, steady annual increases in DOF occurred mainly in May in both S2 and S3. DOF still showed its maximum in April; it then gradually increased in May, with values even higher than in March (Table 1). This means that the month of most frequent dust occurrence over dust-source regions was now delayed by a month (i.e., from March–April to April–May) because of the shift in the month of highest SWF. It is also interesting to note that weak secondary DOF peaks over S2, S3, and S4 were found in October–November, where the secondary peaks of SWF were also observed. This is discussed in more detail in the Discussion session.

3.3. Year-to-year variations of dust outbreak frequency

Fig. 6 shows inter-annual variations in DOF and SWF over each of the four source regions. A strong positive correlation was found
between DOF and SWF from year to year, as also indicated in previous study (Kurosaki and Mikami, 2003; Lee and Kim, 2008). Kurosaki and Mikami (2003) pointed out one exception of April 1998, but current study shows no such anomaly. This is mostly because of the application of the different threshold velocity for different source regions, whereas previous studies employed a constant wind speed (6.5 m s\(^{-1}\)) as the threshold velocity (e.g., Tegen and Fung, 1994; Uno et al., 2003). We also tentatively carried out some tests within our domain by applying constant threshold values (i.e., threshold velocities \(= 6.5 \text{ m s}^{-1}\)), and reached the same result as Kurosaki and Mikami (2003), indicating indirectly that the different threshold velocity over different source regions induces better explanation on DOFs.

In Fig. 6, the DOF in spring was greater during the three years from 2000 to 2002, especially in S3 and S4, in comparison with both the previous four (1996–1999) and following five (2003–2007) years. These year-to-years variations observed in downstream areas such as Korea, Japan and other Northeast Asian countries show also almost equal DOF patterns (Kurosaki and Mikami, 2003; Lee and Kim, 2008).

Fig. 7 shows year-to-year variations in DOF versus NDVI over the source regions. Overall, a weak negative correlation was found. Correlation coefficients between DOFs and NDVI show –0.01, –0.13, –0.23, and –0.28, respectively (springtime: –0.27, –0.18, –0.38, and –0.51, respectively) with the 99% confidence level (by Mann–Whitney U significance test) over each of the four source regions. Here, region S4 was found to be the most variable and sensitive to NDVI in this study. In region S4, the NDVI was relatively lower before 2002 (the highest year of DOF), but increased after 2002 (overall DOF decreased). However, the SWF in region S4 was as high as that in region S2; nevertheless, the DOF after 2002 approached almost half that of region S2, because of the doubled NDVI in region S4 (as indicated in Fig. 7), implying significant changes in surface conditions after 2002.

March, April, and May were the most active months in terms of dust occurrences, with the highest dust outbreaks generally occurring in April. However, the DOFs in March are frequently higher than those in April in regions S3 (i.e., in 2002, 2004, and 2007) and S4 (i.e., in 2001–2002, 2004, and 2007). However, there were some exceptions for both S3 and S4 in 2002: the SWF in March was found to be almost equal to or even lower than that in April (Fig. 6) and there were no significant changes in the NDVI cycles in 2002 (Fig. 7).

These features can be explained well in S3 by examining the monthly snow-cover fractions; the higher DOFs in region S3 in March correspond to a much lower snow-cover fraction in 2002 than in other years. Some previous studies also indicated that snow cover is the primary factor in controlling the DOFs over some parts.
Fig. 6. Time variations of monthly DOF and SWF. Black bar and line graph with black dots indicate DOF and SWF, respectively.
of Mongolia and the Loess Plateau in early spring (i.e., March), rather than the strong wind velocities (Kurosaki and Mikami, 2004). In the current study, it is found that the snow-cover fraction in region S3 is sometimes the primary influential factor, rather than the SWF. However, little snow was observed in region S4, and other distinctive reasons were not found here for the period studied.

4. Discussion

Table 2 summarizes the statistical values associated with the DOFs over the four source regions. The threshold velocities for the calculation of SWF were estimated to be 1.71, 9.55, 10.75, and 5.46 m s$^{-1}$ for S1, S2, S3, and S4, respectively, and good correlations were found between the DOFs and SWFs in the spatial distributions.

Fig. 7. Time variations of monthly DOF and NDVI. Black bar and red line graph with red dots indicate DOF and NDVI, respectively, and black line graph with Black Square represents spring average NDVI. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
with high pattern correlation coefficients (PCCs) of 0.66–0.77, respectively, contrasting with the PCCs of other parameters of ~0.5. This supports the idea that SWF is the primary factor controlling the DOFs over the all the source regions. However, a simple strong wind speed (e.g., >6.5 m s\(^{-1}\)) was used in many studies as the threshold value. While this is still a good factor for explaining the occurrence frequencies, in the current study, some regions (i.e., S4) experienced strong wind speeds higher than those in S2 or S3, but the observed DOFs were much lower. We also calculated the PCCs between the DOF and simple strong wind speeds exceeding 6.5 m s\(^{-1}\). This yielded rather lower PCCs of 0.47 and 0.62 for S2–S4, respectively, 11–22% lower than the values obtained above.

As listed in Table 2, each region shows unique characteristics. For example, S1 shows a relatively lower PCC with both SWF and NDVI, but shows a significantly higher correlation with temperature than the other regions, with an \(r^2\) value of more than 0.5. In region S4, the correlation coefficient between the DOF and NDVI is the highest of the four regions, with a minimum \(r^2\) value of ~0.31, indicating that this region is more sensitive to the surface conditions than to the other factors.

The monthly variations in DOFs show that the primary peaks are generally observed in April–May. There was a remarkable increase in the DOFs in March–April only for the analysis period before 2002, but the months of highest DOFs were shifted to April–May during the next 5 years (2003–2007), especially over source regions S2 and S3. In addition, secondary DOF peaks were observed after 2002 over most of the source regions. We carried out various correlation studies between the secondary peak and NDVI, temperature, and soil moisture, but no significant correlation could be found except for the SWF variance. Therefore, this secondary peak is believed to be due to the wind speed variation.

The snow-cover fraction varied depending on the month, and region S2–S3 was relatively more sensitive to snow cover in this study. The month-dependent factor of snow-cover fraction is negatively correlated with the DOF in March in this study, whereas no correlation was found in April. Basist et al. (1996) described how snow cover is also associated with strong wind. When the snow is powdery, strong winds can sweep the snow away and entrain dust particles, even if the snow-cover fraction is 100%. However, we did not find any relationship between snow cover and strong wind.

### 5. Conclusion

This study has clarified the recent dust observations over the four dust-source regions. The variation in DOF was investigated and characterized in relation to the threshold wind velocity, NDVI, and snow-cover fraction, using the observed WMO SYNOP and satellite data for each of the four subdivided source regions; S1, Taklamakan; S2, Gobi; S3, Inner Mongolia-Manchuria; and S4, Loess.

The results showed inter-annual variations in DOFs, with significant increases in 2001–2002 and decreases in 2003–2004. Of the source regions, region S3 showed the most significant change, and thus, the area of highest DOF (region S3) in 2000 was shifted back to the source region S2 after 2002.

Seasonal analysis showed that March, April, and May are the most active months, and there was a remarkable increase in the DOFs in March–April before 2002. However, during the next five years (2003–2007), the months of highest DOF were April–May.
over regions S2 and S3. In addition, the DOF showed a weak secondary peak during the winter (October–November) for S2, S3, and S4 after 2000. Of the factors controlling the DOF, the strong wind speed (i.e., speed exceeding the threshold velocity) was found to be the best factor for explaining the DOF, with a PCC of 0.66–0.77 between DOFs and SWFs over most source regions. There were some exceptions, but these could be explained by the impact of NDVI and snow cover. Other secondary controlling factors were found to vary from region to region. For example, region S1 showed a high correlation with temperature, with an $r^2$ value of more than 0.5. Regions S2–S3 showed relatively more sensitivity to the snow-cover fraction, and region S4 showed a relatively stronger correlation with the NDVI than the other regions.

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