Influence of Indian Summer Monsoon on Aerosol Loading in East Asia

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ABSTRACT

The spatial and temporal variations of aerosol loading over eastern Asia specified in terms of the aerosol optical depth (AOD) at the 550-nm wavelength during July are examined in conjunction with the intensity of the Indian summer monsoon. AOD derived from Moderate Resolution Imaging Spectroradiometer (MODIS) observations, gridded reanalyses, and ground-based measurements are used in the analysis. Two contrasting years, 2002 and 2003, which represent weak and active Indian summer monsoon events, respectively, are selected for the study, with a focus on an eastern Asian southern subregion (SR; 23°–32°N, 105°–120°E) and an eastern Asian northern subregion (NR; 35°–44°N, 115°–130°E). It is shown that the interannual variation of July mean wind intensity is a major factor in regulating the midsummer spatial pattern of aerosols over eastern Asia when the Indian monsoon index is anomalously large. The AOD anomalies in the NR and SR are positive and negative, respectively, during an active monsoon year, whereas the opposite is observed during a weak monsoon year. The variation patterns of less cloudy-day visibility, observed at four meteorological stations in the SR and NR subregions, also show spatial–temporal aerosol variability evident in the MODIS AOD data. Relative to the case of a weak monsoon year, meridional winds and convection are stronger and more clouds and precipitation are observed in the NR subregion during the active monsoon year. The opposite pattern is observed in the SR subregion. The spatial–temporal variation pattern of aerosols over eastern Asia illustrates the nonnegligible role of transport and dispersal mechanisms associated with the Indian summer monsoon in the region.

1. Introduction

The sources and spatial–temporal distributions of aerosols in the atmosphere have drawn much attention because they play an important role in the earth’s radiation budget, the water cycle, and climatic change. As a region with dense human population and rapid economic growth in recent years, Asia is one of the most aerosol-laden regions in the world (Remer et al. 2008; Li 2004). Surface in situ measurements of Asian aerosols have been collected through several major field campaigns in recent years (Ramanathan et al. 2001a; Huebert et al. 2003; Lau et al. 2008; Moorthy et al. 2008). Meanwhile, satellite observations provided an unprecedented opportunity to study aerosol properties from various perspectives (Christopher and Jones 2007; Christopher et al. 2008; Chylek et al. 2005, 2006; Kahn et al. 1998, 2005; Kaufman et al. 2002; Mishchenko et al. 2003, 2007).

Previous studies have documented the spatial–temporal characteristics of Asian aerosols from both surface- and satellite-based aerosol observations (Luo et al. 2001; Qian et al. 2007; Krüger and Graßl 2004; Kim et al. 2007; Eck et al. 2005; Cheng et al. 2006; Ramachandran and Cherian 2008; Porch et al. 2007; Nair et al. 2008). The distribution
of atmospheric aerosol optical depth (AOD) is influenced by both surface and atmospheric conditions. Asia is the most prominent monsoon region (Wang 2006); the monsoon circulation as a large dynamical system occurs over southern and eastern Asia and affects one-third of the world’s population. Recent studies show a close interaction between airborne aerosols and Asian monsoons. The natural and anthropogenic aerosol forcing can influence the regional cloud microphysics, atmospheric heating, and monsoon rainfall distribution over southern and eastern Asia (Menon et al. 2002; Ramanathan et al. 2005; Lau and Kim 2006; Satheesh et al. 2008).

On the other hand, the monsoon circulation may influence the spatial and temporal variation patterns of aerosol loading. For example, Bao et al. (2008), using rotated principal component analysis, showed that the spatial and temporal characteristics of the AOD over eastern Asia were closely associated with wind fields. Statistical analyses on the Moderate Resolution Imaging Spectroradiometer (MODIS) data proved that wind direction is responsible for the observed negative and positive AOD anomalies, corroborating the negative and positive rainfall anomalies observed over the Arabian Sea in July (Rahul et al. 2008), and that variations in aerosol properties are associated with active and break spells of the Indian summer monsoon (Kirar et al. 2009). It is found that the winter AOD over the Indian Ocean region is significantly influenced by the transport of aerosols from the Indian subcontinent, Southeast Asia, and Arabia by the winter monsoon (Nair et al. 2003; Rajeev et al. 2000). Li and Ramanathan (2002) used 5 yr of satellite-derived AOD data to document the large seasonal variations in the AOD modulated by the monsoons. Moreover, the monsoon transitions can affect the microphysical and optical properties of aerosols over the tropical Indian Ocean (Corrigan et al. 2006).

During the boreal summer when the atmosphere over the Asian continent becomes much warmer than the neighboring ocean surface, the lower-tropospheric warm moist air moves from the Southern Ocean to the Arabian Sea, India, and the Bay of Bengal after crossing the equator and turns to the north after its arrival at the South China Sea to extend farther into northern China (Liu and Ding 2008). Although satellite-based aerosol property retrievals have provided useful information for determining variations of aerosols and for estimating anthropogenic climate forcing in eastern Asia during the last decade, previous studies of the influence of the monsoon circulation on the aerosol distribution were mainly limited to southern Asia and the Indian Ocean.

The intent of this study is to determine the relationship between the aerosol distribution over eastern Asia (23°–44°N, 105°–130°E) and the Indian summer monsoon in order to demonstrate the responses of the eastern Asian aerosol patterns to the variations in the intensity of the Indian summer monsoon. At present, the effect of this macroscale circulation pattern on the aerosol distribution over eastern Asia is not understood well. In this study, we used MODIS level-3 AOD data and multisource meteorological data. For the typical monsoon circulation pattern in the study region, we chose to analyze July data of the AOD and wind fields because July is the month of peak monsoon intensity, the month of the northernmost location of the monsoonal boundary during the year, and the month of the strongest impact of the Indian monsoon on eastern Asia.

2. Data

The datasets from 2000–08 satellite-observed July AODs at the 550-nm wavelength, in addition to other aerosol and cloud parameters, including the fine-mode fraction (FMF), the liquid water cloud water path (CWP), and the cloud fraction (CF), were extracted from the level-3 MODIS global gridded daily and monthly average products with a 1° × 1° spatial resolution (Tanré et al. 1997; Schuster et al. 2006). The FMF (Remer et al. 2005, 2008) is the ratio of fine-mode (effective radius 0.1–0.25 μm) to total AOD, describing the fraction of the AOD contributed by fine-mode-sized particles. The MODIS level-3 aerosol data are ungridded 10-km retrievals of various aerosol parameters measured at the time of the satellite overpass. The National Aeronautics and Space Administration MODIS sensors are on board the Earth Observing System (EOS) Terra and Aqua polar-orbiting satellites, which were launched on 18 December 1999 and 4 May 2002, respectively. The MODIS instruments acquire data globally at 36 spectral bands ranging from visible to thermal infrared wavelengths. The MODIS aerosol algorithm employs different approaches to retrieve parameters over land (Kaufman et al. 1997) or over ocean (Tanré et al. 1997). The information on the retrievals and results from validations are described in Remer et al. (2005). In this paper, we use data from the Terra platform for the MODIS collection-5 products (Levy et al. 2007), which have shown substantial improvements over eastern Asia in comparison with their collection-4 counterparts (Mi et al. 2007; Li et al. 2007; Zhang and Sun 2010). Satellite-based observations can provide detailed information about aerosol variability on a long time scale covering a large spatial area (Kaufman et al. 2002). Recent studies have demonstrated that the AOD data obtained from MODIS offer a reasonable estimate of atmospheric
aerosols over eastern Asia (Xia et al. 2004; Kim et al. 2007; Li et al. 2007; Mi et al. 2007; Wang et al. 2007; Zhang and Sun 2010). The MODIS cloud retrievals used in this study are described in detail in Platnick et al. (2003).

The data we used for the various meteorological parameters were collected from numerous other sources. The 2000–08 July monthly and daily averaged horizontal winds ($u$ and $v$), speed of vertical movement $w$, and surface air temperature at 2 m were obtained from the National Centers for Environmental Prediction–U.S. Department of Energy reanalysis data with a 2.5° × 2.5° resolution (Kanamitsu et al. 2002). The precipitation values across eastern Asia were extracted from the National Oceanic and Atmospheric Administration Climate Prediction Center Merged Analysis of Precipitation (CMAP) global gridded dataset (Xie and Arkin 1997). The corresponding satellite-observed outgoing longwave radiation (OLR) at the top of the atmosphere, often used to indicate tropical convection, was retrieved from a publically accessible online source (http://www.cdc.noaa.gov/), and the technique for interpolating the OLR data was reported by Liebmann and Smith (1996). The station-observed data of wind, relative humidity (RH), cloud cover, and visibility were obtained from the China Meteorological Science Data Sharing Service Network (information online at http://cdc.cma.gov.cn/).

The Indian monsoon index (IMI) data for each July from 2000 to 2008 were obtained from the monsoon monitoring Web page of the International Pacific Research Center, University of Hawaii (http://iprc.soest.hawaii.edu/~ykaji/monsoon/index.html). The IMI is defined in terms of the difference of the 850-hPa zonal winds between the western tropical Indian Ocean (5°–15°N, 40°–80°E) and northern India (20°–30°N, 70°–90°E) based on the studies reported by Wang and Fan (1999) and Wang et al. (2001). Such a defined IMI reflects both the intensity of the tropical westerly monsoon flow and the lower-tropospheric vorticity anomalies associated with the Indian summer monsoon trough, representing well the rainfall anomalies averaged over an extended region including the Bay of Bengal, India, and the eastern Arabian Sea. Thus, higher IMI values generally indicate stronger Indian summer monsoon intensity.

3. Results and discussion

To examine the linkages between aerosol distribution patterns over eastern Asia and the Indian summer monsoon intensity, we first calculated the climatological wind field at the 850-hPa level and the AOD distribution in July averaged for 2000–08 across eastern Asia. Figure 1a shows that the monsoon flow originates from the Indian Ocean, passes through the Indian subcontinent and the Bay of Bengal, turns north over the South China Sea, and then reaches the eastern Asian landmass. The summer monsoon in July is strongest along 110°E in southern China. To the west and east, the monsoon wind is influenced by the Tibetan cyclone and the northwestern Pacific subtropical anticyclone and deviates toward the west and east. The northern limit of the monsoon wind can reach approximately 40°N in July. The entire region from the lower reaches of the Yangtze River to northern China and the Korean Peninsula is under the influence of southwesterly winds at the 850-hPa levels, indicating that during July the southwesterly monsoon wind is one of the major weather systems over the eastern Asian landmass.

Figure 1b shows the mean July AOD distribution pattern over eastern Asia during 2000–08. High AOD values (>0.8) were found over the North China Plain, the Sichuan Basin, and the foothills of the Himalaya in northern India. It is interesting to note that the areas with high AOD values were mostly located downwind of the strong monsoon winds and that in these areas the wind velocities were generally low. The monsoon wind strength and direction are likely related to the AOD distribution pattern.

To examine further the influence of Indian summer monsoon intensity on the July spatial distribution of
AOD over eastern Asia, weak and active monsoon years were identified using the IMI (Wang and Fan 1999; Wang et al. 2001). As shown in Fig. 2, during 2000–08 the lowest July IMI value was −2.70 in 2002, whereas the highest July IMI was 1.70 in 2003. The July IMI values for all other years were within a range from −1.0 to +1.0. Therefore, 2002 was identified as a typical weak monsoon year and 2003 was identified as an active monsoon year. For comparison, the highest July IMI during 1948–2008 was 1.715 in 1959 and the lowest July IMI was −2.948 in 1987. In fact, the 2002 Indian summer monsoon was exceptionally weak (Fasullo 2005) and the date for the monsoon to cover India entirely was 1 month later than the norm (Khole 2009). In the following analyses, we focus on the contrasts between 2002 (weak monsoon year) and 2003 (active monsoon year).

From Fig. 3, it is evident that the anomaly wind fields across eastern Asia varied in response to the anomalous Indian summer monsoon intensity. The 850-hPa mean $u-v$ wind anomalies during the weak monsoon year (2002) indicate that the westerly component was stronger than its normal counterparts at low latitudes south of 20°N, whereas the northwestern Pacific subtropical high (NWPSTH) was positioned farther to the east. Therefore, the monsoon wind component moving toward the eastern Asian landmass was weakened, as shown in Fig. 3a. During the active monsoon year (2003), the landward component over the Bay of Bengal was strengthened, whereas the westerly component at low latitudes was weakened, as is evident in Fig. 3b. At the same time, the position of the NWPSTH was farther to the west. The contrasting characteristics in the horizontal winds over eastern Asia between the weak and active monsoon years were more prominent from the anomaly fields. In this study, the July anomaly of a specific year is defined in terms of the difference between the July mean value of that year and the corresponding 9-yr July mean from 2000 to 2008. Negative $u$ and $v$ anomalies were dominant across the entire eastern Asian landmass, particularly in southeastern China in the weak monsoon year (Fig. 3c), whereas positive anomaly winds occurred across eastern Asia in the active monsoon year (Fig. 3d). In other words, stronger- (weaker-) than-normal southwesterly winds over eastern Asia respond to higher (lower) IMI in midsummer for their interannual variations. Based on the
preceding analysis of the relationship between AOD and the wind field across eastern Asia, two key subregions are identified, the southern subregion (SR; 23°–32°N, 105°–120°E) and the northern subregion (NR; 35°–44°N, 115°–130°E), with the most significant changes between the weak and active Indian monsoon years. As will be seen in the subsequent text, there are considerable variations in a range of meteorological and environmental elements over eastern Asia in response to the Indian summer monsoon intensity.

The interannual variations in the AOD over eastern Asia are substantial. From Fig. 4, which shows the anomalies of regional mean July AOD values in the SR and NR subregions during 2000–08, we can directly observe the AOD interannual variation. Here, the anomaly is defined as the difference between the value of each year and the corresponding climatological value averaged for 2000–08, excluding 2002 and 2003. It can be seen that during nonextreme years the regional mean AOD series in the two subregions tended to vary more or less in phase, whereas during the extreme monsoon years (2002 and 2003) the AOD anomalies in the two subregions became opposite. During the weak monsoon year of 2002, the mean AOD anomaly of the SR was positive at 0.23 while the AOD anomaly of the NR was slightly negative at −0.07. During the active monsoon year of 2003, the AOD of the SR was negative at −0.11 while that of the NR became positive at 0.14. The preceding results suggest that the monsoon intensity affected the spatial distribution pattern of the AOD as opposite anomalies occurred in the SR and NR subregions during extreme monsoon years. When the monsoon intensity is weak, the AOD in southern China is high while the AOD in the northern part of eastern Asia is low, and the pattern is reversed when the monsoon intensity is strong. A comparison between the two subregions shows that the reversal of the anomaly wind field in the southern subregion was more prominent than that in the northern subregion. We also note that the NR AOD is relatively high in July of 2007 although the SR AOD is close to normal and the IMI is slightly low (refer to Fig. 2). The variation in the midsummer AOD over eastern Asia is likely to depend on local emission or regional meteorological conditions without the presence of an extreme anomaly in the Indian summer monsoon.

There are distinct differences in the spatial patterns of the 2002 and the 2003 AOD values. As shown in Fig. 5, the high AOD values were mainly concentrated in southeastern China and northern India along the southern edge of the Himalaya in July of 2002, whereas the high AOD values moved northward to northern China in July of 2003 (Fig. 5b). In the anomaly fields (Fig. 5c and Fig. 5d), the positive (negative) AOD anomalies are located in southeastern China and northern India in July of 2002 (2003), whereas the AOD anomalies in northeastern China centered at the NR are opposite to those in the southern areas.

From the preceding analysis, the aerosol distribution in these two subregions had a contrasting pattern in response to the wind anomaly fields across eastern Asia. During periods of weak monsoon circulation, the southern part of the eastern Asian landmass tended to have high regional mean AOD values, whereas the regional AOD was reduced under conditions of strong monsoon circulation. For the northern part of eastern Asia, the relationship between the regional mean AOD and monsoon circulation was reversed.

According to Remer et al. (2005), the least uncertainty in the AOD is ±(0.05 + 0.15AOD) over land. Based on this criterion, we can estimate the upper and lower values of uncertainty for AOD at a given grid as follows: \( AOD_{\text{max}} = AOD + 0.05 + 0.15AOD \) and \( AOD_{\text{min}} = AOD - 0.05 - 0.15AOD \). For the SR subregion, the July AOD values in 2002 were higher than those in 2003 at over 92% of the grids in the SR subregion, and the \( AOD_{\text{min}} \) in 2002 was higher than the \( AOD_{\text{max}} \) in 2003 at over 68% of the grids. For the NR subregion, in a similar way, the July AOD values in 2002 were lower than those in 2003 at over 83% of the grids, and the \( AOD_{\text{max}} \) in 2002 was lower than the \( AOD_{\text{min}} \) in 2003 at over 54% of the grids (figures not shown). If the uncertainties are considered, the July AOD differences between these two years are significant for more than 50% of the grids in both the SR and NR subregions.

To quantify the relationship between regional AOD and the characteristics of the wind field, we performed regression analysis of the daily anomaly 850-hPa wind velocities at each grid point (including both the \( u \) and \( v \) directions) against the daily regional average AOD for all July days of the 9 yr during 2000–08 (sample size \( N = 279 \)). The linear regression coefficients of the \( u \) and \( v \) wind velocities with the AOD averaged for the SR or
NR can constitute a vector field (hereinafter referred to as the regression wind field) to represent the statistical association of the anomaly wind field with the regional mean AOD values. By mapping the regression wind field across the study area (Fig. 6), we identified variations in the wind vectors corresponding to the fluctuations of the regional mean AOD to illustrate further the influence of monsoon intensity on the AOD spatial distribution patterns. Figure 6a shows the regression wind field against the daily mean AOD in the SR subregion. When the AOD is high in the SR, the wind field in the subregion is dominated by negative anomalies (northeasterly flows). At the same time, the westerly component in the low latitudes is strengthened over Indochina and the South China Sea, and the location of the confluence of the southwesterly and southeasterly flows moves farther to the east, where the southerly flow turns north and then northwest over the East China Sea, forming a cyclonic pattern over southern China in the anomaly field (Fig. 6a). This flow pattern may strengthen the transport of aerosols from southern and eastern China, which then become stagnant and accumulate over the SR subregion. There probably are increased chances for the occurrence of wind shear and convection activities in the SR subregion. When the AOD is low in the SR subregion, the anomaly wind field pattern is reversed. In a similar way, Fig. 6b shows the regression anomaly wind field corresponding to the regional mean AOD in the NR subregion. When the southerly and southwesterly flows were enhanced over eastern Asia, high regional AOD occurred in the NR subregion, accompanying the strong Indian summer monsoon. The confluence of the southeasterly and northeasterly flows is located over the east coast of China, in conjunction with an enhanced NWPSTH anticyclonic flow pattern over the East China Sea. This flow pattern should strongly facilitate the transport of aerosols into northern and northeastern China. When the monsoon intensity is weak, the anomaly wind field is reversed and the regional mean AOD is low in the NR subregion. The calculation of the horizontal wind divergence in the lower troposphere also indicates a stronger convergence, which helps the accumulation of aerosols, in the NR (SR) subregion for the active (weak) monsoon year (not shown).

To validate the satellite AOD estimates for atmospheric aerosol levels for the weak and active monsoon years, we examined the visibility data at four representative meteorological stations: Guilin (World Meteorological Organization station number 57957; 25.33°N, 110.30°E) and Guiyang (57816; 26.58°N, 106.72°E) in the SR subregion and Beijing (54511; 39.93°N, 116.28°E) and Jinan (54823; 36.68°N, 116.98°E) in the NR subregion (see Fig. 6 for the positions of the stations). The visibility
is usually regarded as a proxy indicator of near-surface aerosol loading over land (Wang et al. 2009), although it is susceptible to atmospheric humidity and local factors. In processing the station visibility data, daily total cloud cover was used to determine the occurrence of a less-cloudy day, which is defined as a day with daily mean total cloud cover of less than 0.5. In this case, days with a cloud fraction of greater than 0.5 were eliminated and then the average visibility of the remaining days in a month is defined as the less-cloudy-day visibility in that month. The reasoning behind using the above criterion to determine a less-cloudy day is to avoid cloud influence on visibility as much as possible and at the same time to ensure that there are sufficient days to be used for the average in a given month. In addition to the visibility at these stations, we calculated the July mean total cloud fraction, surface wind velocity, and relative humidity for the corresponding less-cloudy days in the weak (2002) and active (2003) monsoon years.

From Table 1, a clear contrast can be seen in the visibility between the weak and active monsoon years. The less-cloudy visibility during the active monsoon year increased by approximately 8300 and 5600 m at Guilin and Guiyang in the SR subregion, respectively, relative to that of the weak monsoon year. In the meantime, the less-cloudy visibility at Beijing and Jinan in the NR subregion decreased by 6800 and 7300 m, respectively. The surface wind velocities at all four stations during the active monsoon year (2003) were higher than those during the weak monsoon year (2002), and the differences in cloud fraction and relative humidity were small. It is apparent that the monsoon circulation associated with the wind velocity, rather than cloud cover and relative humidity, can significantly influence visibility through the transport of aerosol. During the period of weak monsoon circulation, the visibility is relatively low in the southern part of eastern Asia and is high in the northern part of eastern Asia. During the period of active monsoon circulation, this pattern is reversed, which is consistent with the relationship between the AOD distribution and monsoon intensity.

We surveyed the statistics of the other parameters from the MODIS products, such as FMF, CWP, and CF, as well as the corresponding gridded meteorological elements including winds, OLR, precipitation, and temperature in the two representative subregions in eastern Asia to detect possible responses to the contrasting Indian summer monsoon intensities. Table 2 lists the regional means of these variables to represent the atmospheric conditions during the periods of weak and strong monsoon circulations. During the period of weak monsoon intensity, the regional mean anomalies of the meridional wind at 850 hPa ($v_{850}$), which determine the northward transport of aerosol, were negative in both subregions. During the period of active monsoon circulation, the meridional component is enhanced, especially

<table>
<thead>
<tr>
<th>Station</th>
<th>Year</th>
<th>Visibility (m)</th>
<th>Cloud (%)</th>
<th>Wind (m s$^{-1}$)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guilin</td>
<td>2002</td>
<td>10 885</td>
<td>33</td>
<td>0.8</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>2003</td>
<td>19 156</td>
<td>23</td>
<td>2.0</td>
<td>65</td>
</tr>
<tr>
<td>Guiyang</td>
<td>2002</td>
<td>17 382</td>
<td>31</td>
<td>2.5</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>2003</td>
<td>23 625</td>
<td>42</td>
<td>3.1</td>
<td>74</td>
</tr>
<tr>
<td>Beijing</td>
<td>2002</td>
<td>19 646</td>
<td>21</td>
<td>2.1</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>2003</td>
<td>12 875</td>
<td>33</td>
<td>2.4</td>
<td>66</td>
</tr>
<tr>
<td>Jinan</td>
<td>2002</td>
<td>19 866</td>
<td>27</td>
<td>3.2</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>2003</td>
<td>12 512</td>
<td>33</td>
<td>4.2</td>
<td>73</td>
</tr>
</tbody>
</table>
in the SR subregion. The vertical movement at the 500-hPa level (ω500) has an opposite pattern between the two subregions: the ω500 in the SR is enhanced during weak monsoon circulation and is weakened during active monsoon circulation; in the NR subregion, the relationship between ω500 and monsoon intensity is reversed. Thus, the OLR in the SR was lower (higher) in 2002 (2003) and its pattern was opposite to that of the NR, indicating that the stronger convection occurs in the SR (NR) during the weak (active) monsoon year. When monsoon circulation is relatively weak, the moisture from the ocean is accumulating in the SR, as indicated by the cyclonic flow pattern in Fig. 6a. The CF, CWP, and rainfall in the SR in the weak monsoon year were consequently all higher than those in the period of active monsoon circulation. During the period of active monsoon circulation, moisture-laden monsoon winds can reach 40°N or farther. In the NR, therefore, the CF, CWP, and rainfall were all higher in the active monsoon year than in the weak monsoon year. With greater cloud cover and precipitation corresponding to the intense monsoon circulation, surface air temperature (T2m) in the NR was lower during the active monsoon year, and vice versa. The midsummer variations in meteorological elements consistently show the close relationship of the weather conditions in the northern part of eastern Asia to the extremely anomalous Indian monsoon intensity as compared with that in the southern part of eastern Asia.

The responses in the subregions of the AOD to monsoon intensity have been described in an earlier section. Meanwhile, the FMF was relatively high (low) in the SR (NR) subregion during the weak (active) monsoon circulation in 2002 (2003), which was consistent with the changes in the AOD. From the FMF results, it can be concluded that the effects of monsoon intensity on aerosol distribution are mostly reflected in the fine particles. On the other hand, the impact of aerosol on the local climate is not immediately clear. The intensive atmospheric dynamic processes related to the monsoon may be more important than the aerosol’s direct and indirect effects in determining the spatial–temporal patterns of the cloud and precipitation. It is difficult to detect the variations of cloud properties and precipitation amounts independent of the large-scale monsoonal forcing. Further exploration will be required to determine by how much the decline in the T2m and OLR over eastern Asia is associated with the direct radiation effect of aerosols independent of the monsoon dynamics (Penner et al. 2001; Ramanathan et al. 2001b).

### 4. Conclusions

In this study, the spatiotemporal variation pattern of aerosols over the eastern Asian landmass in midsummer (July) and its response to the Indian summer monsoon activity were investigated from 9 yr (2000–08) of the MODIS 550-nm wavelength AOD data. On the basis of the Indian monsoon index (Wang et al. 2001), we chose two contrasting years of extreme Indian summer monsoon intensities: 2002 (weak monsoon year) and 2003 (active monsoon year). Our emphasis was on comparing the spatial patterns of July AOD and the horizontal and vertical wind fields over eastern Asia during the active and weak monsoon years, especially between the southern subregion of eastern Asia in southern China and the northern subregion, which includes northern China and the Korean Peninsula.

The results show that the extreme Indian summer monsoon intensity has a noticeable impact on the interannual variation of the midsummer aerosol spatial pattern over eastern Asia, although more data analyses and modeling studies are needed to verify this conclusion. The aerosol variations in the two subregions respond with opposite patterns to the monsoon intensity. The weak monsoon year corresponds to positive AOD

### Table 2. Statistics of various regional-average meteorological variables. See the text for abbreviations of variables.

<table>
<thead>
<tr>
<th>Subregion:</th>
<th>SR</th>
<th>NR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>2002</td>
<td>2003</td>
</tr>
<tr>
<td>Variable</td>
<td>Mean</td>
<td>Anomaly</td>
</tr>
<tr>
<td>v850</td>
<td>0.94</td>
<td>−2.65</td>
</tr>
<tr>
<td>ω500</td>
<td>−0.031</td>
<td>−0.004</td>
</tr>
<tr>
<td>OLR</td>
<td>233.81</td>
<td>−0.89</td>
</tr>
<tr>
<td>CF</td>
<td>0.72</td>
<td>−0.02</td>
</tr>
<tr>
<td>CWP</td>
<td>147.63</td>
<td>13.68</td>
</tr>
<tr>
<td>Rainfall</td>
<td>8.68</td>
<td>0.99</td>
</tr>
<tr>
<td>T2m</td>
<td>25.24</td>
<td>−0.50</td>
</tr>
<tr>
<td>AOD</td>
<td>0.66</td>
<td>0.22</td>
</tr>
<tr>
<td>FMF</td>
<td>0.83</td>
<td>0.10</td>
</tr>
</tbody>
</table>
anomalies in the SR subregion and negative AOD anomalies in the NR subregion, whereas the pattern is reversed in the active monsoon year. There is consistently a south–high/north–low (north–high/south–low) pattern of the less-cloudy-day visibility during the weak (active) monsoon year. By examining the corresponding wind fields in the subregions, we found that in the active monsoon year the 850-hPa meridional winds are stronger than those in the weak monsoon year in both subregions, but a greater enhancement was seen in the southern subregion. The regression wind field corresponding to the AOD variation in the SR subregion suggests that the tendency of a cyclonic 850-hPa flow pattern over southern China causes accumulation of aerosols over the region. At the same time, the regression wind field associated with the AOD variation in the NR subregion indicates that the enhanced southwest flow across eastern Asia help to transport aerosols into northern and northeastern China. The meteorological variables examined in this study show contrasting patterns between the two subregions during the weak and active monsoon years. For example, during the active monsoon year lower outgoing long-wave radiation associated with stronger convection and, therefore, greater cloud amount and more precipitation are seen in the northern subregion than in the southern subregion. In the weak monsoon year such patterns are reversed. Our results suggest that the spatial and temporal variation patterns of aerosols over eastern Asia during the peak time of the Asian monsoon season can be partly explained by the transport and dispersal functions of the monsoon circulation.

Note that our conclusions are mainly drawn from only two contrasting Indian monsoon years. More analyses and data accumulation are needed to verify the conclusions statistically. Although the July rainfall increases (decreases) in the NR (SR) subregion with strengthening of the Indian monsoon, the AOD is still increased (decreased) in the NR (SR) subregion because more aerosols are transported from the south to northern China with the intensified monsoon. This suggests that the transport of aerosols by wind could be more important than the flushing of aerosols by rainfall in determining the spatial pattern of aerosol change over eastern Asia. Therefore, the comparative effects of wind transportation and precipitation scavenging on aerosol patterns, the transient natures of aerosol and circulation variations on the seasonal to interannual time scales, the contributions of local aerosol emission or regional atmospheric conditions, and their lead–lag or cause–effect relationships require further investigation with data of higher spatial–temporal resolution and with better modeling capabilities.

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