Seasonal Variations of Aerosol Optical Depth over East China and India in Relationship to the Asian Monsoon Circulation

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ABSTRACT

Seasonal variation features of aerosol optical depth (AOD) over East China and India in association with the Asian monsoon system are investigated, based on the latest AOD data derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the *Terra* satellite, the NCEP Final (FNL) Operational Global Analysis data, the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) data, and the NCEP/NCAR reanalysis data from March 2000 to February 2017. The results indicate that AOD in East China is significantly larger than that in India, especially in spring. The seasonal mean AOD in East China is high in both spring and summer but low in fall and winter. However, the AOD averaged over India is highest in summer and lower in spring, fall, and winter. Analysis reveals that AOD is more closely related to changes in surface wind speed in East China, while no obvious relation is found between precipitation and the AOD distribution on the seasonal timescale. As aerosols are mainly distributed in the atmospheric boundary layer (ABL), the stability of the ABL represented by Richardson number (Ri) is closely correlated with spatial distribution of AOD. The upper and lower tropospheric circulation patterns significantly differ between East China and India, resulting in different effects on the AOD. The effect of advection associated with lower tropospheric circulation on the AOD and the influence of convergence and divergence on the AOD distribution play different roles in maintaining the AOD in East China and India. These results improve our understanding of the mechanism responsible for and differences among the aerosol changes in East China and India.

Key words: aerosol optical depth (AOD), monsoon circulation, East China, India

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1. Introduction

In recent decades, the Asian continent has experienced significant aerosol pollution due to industrial development and increasing anthropogenic activity (Streets et al., 2000; Chung et al., 2005; Ohara et al., 2007; Ramanathan et al., 2007; Zhu et al., 2012). Significant aerosol pollution, frequent haze days (Wu et al., 2010), decreased hours of average sunshine (Guo and Ren, 2006), and decreased visibility (Che et al., 2007; Zhang X. Y. et al., 2012; Han et al., 2013) have seriously affected transportation safety, aviation, and human health.

Air pollution is caused by different kinds of aerosols. The concentration and distribution of aerosols depend on variations in the aerosol emissions (IPCC, 2007, 2014) and the dry deposition and wet scavenging processes in the atmosphere (Zhao et al., 2003; Liu et al., 2011). In addition to these aerosol sources and sinks, the processes of air transport and diffusion via atmospheric circulation play a crucial role in the concentration and distribution of aerosols (e.g., Bao et al, 2008; Yoon et al., 2010; Zhang et al., 2010; Liu et al., 2011; Yan et al., 2011; Zhu et al., 2012; An et al., 2015).

Aerosols vary on different timescales. Using the monthly mean aerosol optical depth (AOD) data obtained from the Moderate Resolution Imaging Spectroradio-

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meter (MODIS), with a rotated principal component analysis, Bao et al. (2008) revealed that a unique spatial structure exists in the seasonal and interannual variability of AOD and this variability is shown to be closely related to the wind strength at 850 hPa. By using satellite data from MODIS, observational data from the Aerosol Robotic Network (AERONET), and precipitation data from the Global Precipitation Climatology Project (GPCP), Yoon et al. (2010) investigated the transport of aerosols by monsoon circulation and suggested that the AOD increases by 40%–50% and precipitation decreases significantly over the downwind region of China, including the Yellow River, the Korean Peninsula, and the East China Sea.

The aerosols and monsoon circulation patterns interact with each other. On the one hand, the monsoon has profound impacts on the aerosol distribution on different spatial and temporal scales (Zhao et al., 2003; Liu et al., 2011; Yan et al., 2011; Zhu et al., 2012; An et al., 2015). On the other hand, the aerosols, of course, may also contribute to feedback processes driving monsoon circulation variations (e.g., Zhang H. et al., 2009, 2012; Wang et al., 2015; Wu et al., 2015). However, in the present paper, we do not pay attention to the feedback issues. Instead, we focus only on the monsoon influences on aerosols.

Monsoon circulation strongly affects the distribution of aerosols, which can be revealed by use of observation data. Relative to the AOD over northern East Asia, the AOD over the southern parts of East Asia is higher during strong Indian summer monsoon years and lower during weak Indian summer monsoon years, because of the mechanisms of transmission and diffusion associated with the Indian monsoon circulation (Liu et al., 2011). Thus, monsoon circulation variations have significant impacts on the aerosol changes. The changes in the East Asian summer monsoon may lead to different influences on the AOD at various geographical locations via circulation transport, as reported in an observational study using satellite data from MODIS and NCEP/NCAR reanalysis by An et al. (2015).

Influences of the Asian monsoon on aerosol variations have also been widely studied by using numerical models, such as the regional coupled climate–chemistry/aerosol model (RegCM3). Rather than local emissions or dry and wet deposition processes, monsoon circulation has been found to be a predominant factor that determines the regional AOD distribution (Yan et al., 2011). In a simulation study using the GEOS-Chem (GEOS: the Goddard Earth Observing System) model with consideration of sulfate, nitrate, ammonium, black carbon, and organic aerosols, the concentration of surface-layer $PM_{2.5}$ over East China is found to increase by 17.7% in the weakest summer monsoon years than in the strongest summer monsoon years, indicating that the weakened East Asian summer monsoon can induce increases in the aerosol concentration via altering the atmospheric circulation (Zhu et al., 2012). Monsoon circulation also influences the aerosol distribution related to wet and dry deposition. By carrying out numerical experiments with the Northern Aerosol Regional Climate Model (NARCM), Zhao et al. (2003) found that dust aerosols were primarily removed via dry deposition in the vicinity of their sources and via wet deposition associated with precipitation during the inter-Pacific transport path over the regions downwind of the sources.

The above discussion reveals that most previous studies have focused on the Asian monsoon's strong influences on aerosol changes in Asia, especially in East China. However, as the Asian monsoon regime consists of two different but related subsystems, i.e., the East Asian monsoon system and the Indian monsoon system (Tao and Chen, 1985; Huang et al., 1998; Chen and Huang, 2006), it is interesting to discover different features of aerosol changes between China and India. In particular, during the seasonal cycle, what are the similarities and differences of aerosol variations between China and India? What are the relationships between aerosol changes and other meteorological quantities? Do the East Asian monsoon and the Indian monsoon have different impacts on aerosol properties? These questions have not been fully answered until now. In the present study, we try to answer these questions.

The paper is organized as follows. In the first section, a brief introduction is presented to summarize the previous studies on the influences of monsoons on aerosols. Then, the data and methodology employed in this study are briefly described. In Section 3, we investigate the spatiotemporal distribution features of AOD variations over East China and India. The relations of aerosol changes with monsoon circulation variations are analyzed in Section 4. The last section provides conclusions and discussion.

2. Data and methodology

2.1 *Data*

To investigate the influence of monsoon circulation on the aerosol distribution, we selected multiple datasets from March 2000 to February 2017, which include:

(1) Global data products from MODIS. MODIS is installed aboard the *Terra* satellite. The current study employed monthly average data on a spatial resolution of 1°

× 1° from the latest MODIS Version C06 Level-3 Datasets. This study is based on the AOD inverted from the combined deep blue and dark target algorithm at the wavelength of 550 nm.

The MODIS aerosol optical thickness data were improved by multiple inversion algorithms and have been updated to version C06. Compared with C05 data, C06 data perform better in the estimation of surface albedo (especially the vegetated and non-vegetated mixed surface albedo), aerosol cloud pattern selection, and screening program, and other processes (Hsu et al., 2013; Sayer et al., 2014). The coverage of the aerosol dataset extends from arid and semi-arid areas to the entire continent. Compared with that of the Aerosol Robotic Network (AERONET), the inversion error of the AOD data is lower. These data make up for the short time series of AOD data used in previous studies (Bao et al., 2008; Yoon et al., 2010), with relatively large errors in surface inversion (An et al., 2015). In this study, we use the latest version of C06 AOD data rather than other versions.

Note that AOD strongly depends on aerosol emissions, components, size, and optical properties. However, fully describing the AOD's dependence on aerosol emissions, components, size, and optical properties is beyond the scope of this paper, because of data problems related to particle size and chemical–physical properties. Nonetheless, in the present study, we focus on the effects of the East Asian and Indian monsoon circulations on the AOD seasonal variations, by comparing the situations between East China and India.

(2) Wind, temperature, and geopotential height at 21 isobaric surfaces from the NCEP Final (FNL) Operational Global Analysis on 1° × 1° horizontal grids. The data are operationally produced at 6-h intervals. Monthly averages are computed from these data for further analysis. In addition, surface wind data on a spatial resolution of 2.5° × 2.5° in the horizontal direction and 17 layers in the vertical direction from the NCEP/NCAR reanalysis dataset (Kalnay et al., 1996) are also employed.

(3) Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) on a spatial resolution of 2.5° × 2.5° (Xie and Arkin, 1997).

In this study, spring is defined as March, April, and May (MAM); summer is defined as June, July, and August (JJA); fall is defined as September, October, and November (SON); and winter is defined as December and January and February of the following year (DJF).

2.2 *Methodology*

The seasonal mean horizontal winds ($\boldsymbol{V}_{\rm m}$) are decomposed into rotational and divergent components as $\boldsymbol{V}_\psi$ and $\boldsymbol{V}_\chi$. In the atmospheric boundary layer (ABL), the Richardson number (Ri; Richardson, 1920) is expressed and calculated as:

$$\mathrm{Ri} = \frac{\dfrac{g}{\bar{\theta}}\dfrac{\partial\bar{\theta}}{\partial z}}{\left(\dfrac{\partial\bar{u}}{\partial z}\right)^2+\left(\dfrac{\partial\bar{v}}{\partial z}\right)^2}, \tag{1}$$

where $\bar{\theta}$ is the mean potential temperature, and $\bar{u}$ and $\bar{v}$ are the zonal and meridional components of the wind, respectively. The parameter Ri involves both thermodynamical and dynamical processes within the ABL and is related to the stratification stability and the vertical wind shear. This parameter can be used to partly explain the potential for pollutant diffusion and transport within the ABL.

3. Spatiotemporal distributions of AOD over East China and India

3.1 *Multiyear mean*

Two regions of high AOD values in Asia are observed in the annual average aerosol distribution for the past 17 years. Regions of high AOD, where the average AOD exceeds 0.4 and the local maximum exceeds 0.8, are primarily located in East China and India (Fig. 1a). Therefore, aerosol pollution is a more significant problem in East China and India than in other areas. Additionally, a large area of aerosol pollution occurs over East China from the Yangtze–Huai River basin to the big area of Beijing, Tianjin, and Hebei. Furthermore, North India also exhibits a wide belt of aerosol pollution. Because East China and India are affected by two different subsystems of the Asian monsoon, the AOD variability over these two regions may exhibit distinctive features.

To identify a proper region for comparison, both zonal and meridional averages of AOD are computed for the period 2000–16, as shown in Figs. 1b, c. The meridionally averaged AOD exhibits a bimodal structure from India to East China, with two peak values appearing over 72.5°–85°E and 107.5°–122.5°E (Fig. 1c). The zonally averaged AOD demonstrates a unimodal structure, with peak values observed within 12.5°–40°N (Fig. 1b). Based on these AOD distribution features, we select East China (22.5°–40°N, 107.5°–122.5°E) and the region to the south of the Tibetan Plateau (12.5°–30°N, 72.5°–85°E) as two representative regions for comparison.

3.2 *Seasonal variability*

The AOD distributions demonstrate significantly different seasonal variation features between East China and

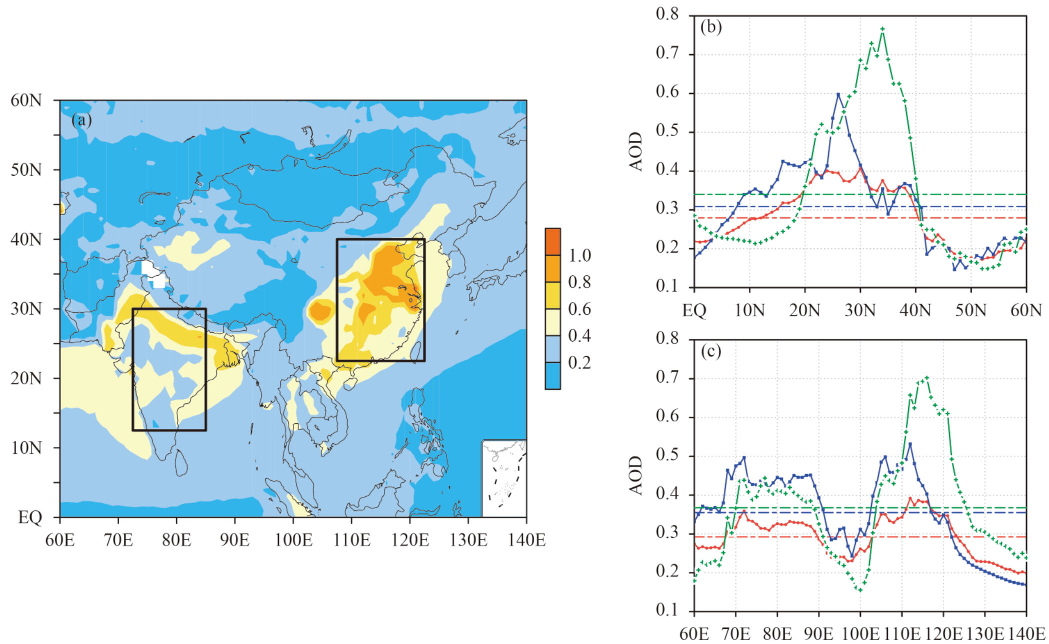

Fig. 1. (a) Annual mean AOD (shadings) averaged over the period 2000–16, (b) its zonal mean, and (c) its meridional mean. In (b), the red, blue, and green solid lines represent the zonal average over 60°–140°, 72.5°–85°, and 107.5°–122.5°E, respectively; whereas in (c) the red, blue, and green solid lines represent the meridional average over 0–60°, 12.5°–30°, and 22.5°–40°N, respectively. The red, blue, and green dashed horizontal lines represent the averages of the corresponding curves. The black boxes in (a) represent the two regions (India and East China) selected for comparison, same in the following figures.

India, as shown in Fig. 2. The local maximum AOD during spring and summer in East China exceeds 0.8, whereas smaller values are recorded during fall and winter. The local maximum AOD in India, which exceeds 0.8, is attained in summer; while smaller maximum values occur in spring, fall, and winter. Therefore, it is speculated that the large AOD in summer in both regions may be associated with abundant water vapor in the atmosphere in the monsoonal regions in addition to the emission of aerosols (Zhuang et al., 2014; Li et al., 2015; Zhang et al., 2015). Note that the AOD value averaged over East China always exceeds the AOD value averaged over India for all four seasons (Table 1). Particularly in spring, the AOD averaged over East China is almost twice the AOD averaged over India, suggesting that aerosol pollution is much more severe in East China than in India. This difference is most probably related to the greater emissions of pollutants in China due to its higher level of economic development.

Table 1. The AOD averaged over East China and India and their ratios as obtained from the multiyear mean climatology of AOD from 2000 to 2016

Season	East China	India	Ratio
Spring	0.69	0.40	1.73
Summer	0.69	0.57	1.21
Fall	0.51	0.40	1.29
Winter	0.51	0.38	1.38

The AOD distribution in East China demonstrates a southwest–northeast oriented belt with values gradually increasing from southwest to northeast. This distribution is likely related to the East Asian monsoon circulation (Zhang et al., 2010; Zhu et al., 2012). The AOD distribution in India demonstrates a U-shaped belt that is open to the south, with maximal values south of the Himalayas and in northeastern India, the Indus River basin northwest of North India, and the vicinity of the Bay of Bengal in eastern India. This could be the result of aerosols being transported through the Indian monsoon circulation from northwestern India to the Indian Ganges Plain and northern India and piling up on the southern side of the Himalayas (Gautam et al., 2009). The characteristics of the AOD distributions change only in intensity as the seasons change. All these distribution features of AOD in both East China and India suggest that monsoons play a very important role in the seasonal changes of the aerosol property.

4. AOD and monsoon circulation in East China and India

4.1 *Relationship between AOD and precipitation*

Precipitation can wash out aerosols (Zhao et al., 2003). The correlation between the spatial distributions of precipitation with AOD is not significant, except in

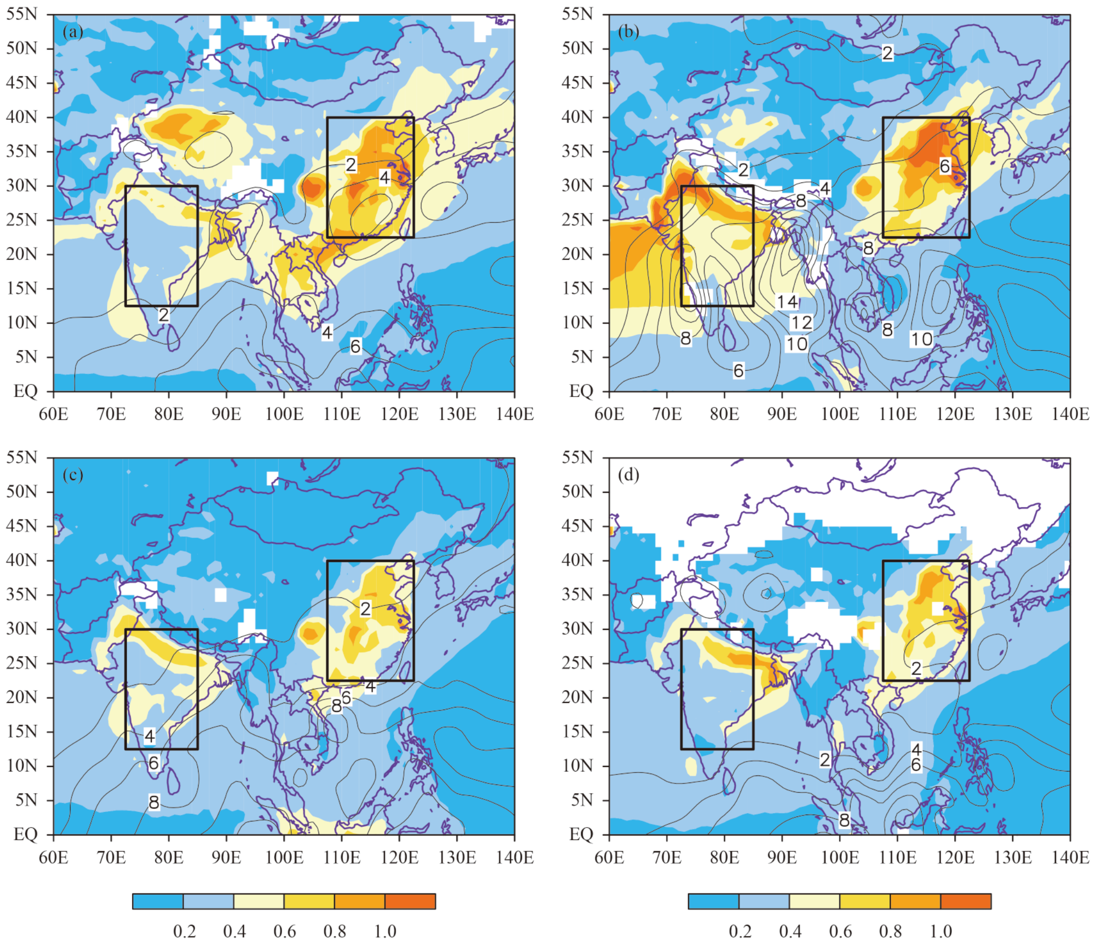

Fig. 2. Multiyear mean AOD (shaded) and precipitation (contour; mm day^{-1}) over the period 2000–16 for (a) spring, (b) summer, (c) fall, and (d) winter.

East China (Table 2). In East China, high AOD is observed in regions with high precipitation during spring and in regions with low precipitation during summer. This season-dependent difference is attributed not only to human activities but also to the changing atmospheric circulation patterns. In India, despite the weak correlation between precipitation and AOD, regions with higher AOD normally experience less precipitation.

The effect of precipitation on AOD is not evident on the seasonal timescale, despite the wash-out effect of precipitation on aerosols. The contours in Fig. 2 indicate that the southwest–northeast to east–west oriented belts of precipitation extend northward during the development and invasion of the summer monsoon in the seasonal transition from spring to summer. During the invasion of summer monsoon, the precipitation belts over both East China and India increase in both area and strength. During the transition from summer to fall and then to winter, the precipitation belts decrease in strength and retreat toward the southeast. The seasonal patterns of AOD and precipitation are featured by high AOD values in summer and low AOD values in fall with strong precipitation in summer and weak precipitation in winter; thus, a significant relationship between the variabilities in precipitation and AOD is not observed. For East China, the precipitation center during spring is primarily located south of the Yangtze–Huai River basin and covers all of East China, with strengthened amount during summer. However, AOD increases during the transition from spring to summer, and its high value center is located to the north of the Yangtze–Huai River basin, which produces severe pollution in the area of Beijing, Tianjin, and Hebei. During fall and winter, AOD decreases and precipitation weakens. The magnitude and area of summer and fall precipitation in India are larger than those in East China.

AOD is expected to significantly decrease from spring to summer if precipitation can wash out aerosols. However, a significant increase in AOD is observed during this seasonal transition, as shown in Fig. 2. Figure 3a provides the correlation coefficients of AOD seasonal variability and precipitation. AOD and precipitation

Table 2. Pattern correlations of the annual average (2000–16) AOD with that of precipitation and with that of surface wind speed in East China and India. The coefficients marked with asterisks are significant at/above the 95% confidence level

Season	East China		India	
	Precipitation	Surface wind speed	Precipitation	Surface wind speed
Spring	0.29*	–0.34*	0.03	0.10
Summer	–0.23	–0.31*	–0.09	–0.46*
Fall	0.01	–0.31*	–0.14	–0.36*
Winter	0.13	–0.28*	–0.06	–0.26

demonstrates a positive correlation in most regions but a negative correlation in a few areas, which implies that precipitation does not exert geographically consistent wash-out effects on the aerosol distribution. The spatial correlation between years of average AOD and precipitation does not indicate a significant correlation (Table 2). Such weak or insignificant correlations between AOD and precipitation may be due to several factors. On the one hand, it is reported that atmospheric humidity greatly affects AOD, leading to higher AOD values in summer and in southern China in response to high humidity levels in the ABL (Zhuang et al., 2014; Li et al., 2015; Zhang et al., 2015). Aerosols also affect the precipitation intensity. More and more evidence show that higher levels of aerosols are associated with less light rainfall (Li et al., 2011; Fan et al., 2012; Zhou et al., 2018). On the other hand, the weak AOD–precipitation relations may also be affected by the concentration and distribution of aerosol emissions (Mu and Liao, 2014), the ABL stability (e.g., Guan et al., 2013), the sizes and properties of aerosol particles (Zhu et al., 2014; Shen et al., 2015; Zhou et al., 2015; Che et al., 2018), and the influences of monsoon circulation patterns (Menon et al., 2002; Sun et al., 2015; Mao et al., 2017). All these factors make the AOD–precipitation relation during the seasonal cycle complicated and generally uncertain in different regions of China and India and therefore deserve further detailed investigations in the future.

4.2 *Relationship between AOD and surface wind speed*

The AOD changes are affected by the wind speed. Figure 3b shows the correlation coefficients of AOD seasonal variability and surface wind speed. AOD and surface wind correlations demonstrate a negative correlation over most parts of East China and North India; in areas where AOD is lower, surface wind is stronger. However, in the southern part of central India and southwest of Bohai Bay in China, higher AOD values correspond to higher wind speeds. This difference seems to be driven by the circulation patterns near the earth's surface. Similarly, we analyze the pattern correlation of AOD with surface wind speed over both East China and India for the four seasons (Table 2). The results show that AOD is negatively correlated with surface wind speed, except in spring in India. This negative correlation is most significant in East China. Note that AOD is also affected by wind direction. For instance, weak southerly wind tends to facilitate more intense pollution in Beijing, China (Zhu et al., 2012; Mu and Liao, 2014). However, the relationship between AOD and wind direction is not focused in the present paper, and will be saved for a future investigation.

4.3 *Influence of ABL stability on aerosols*

Aerosols are influenced by the ABL stability. For example, during a severe pollution event in Beijing in winter 2016, a sharp increase of approximately 84% in

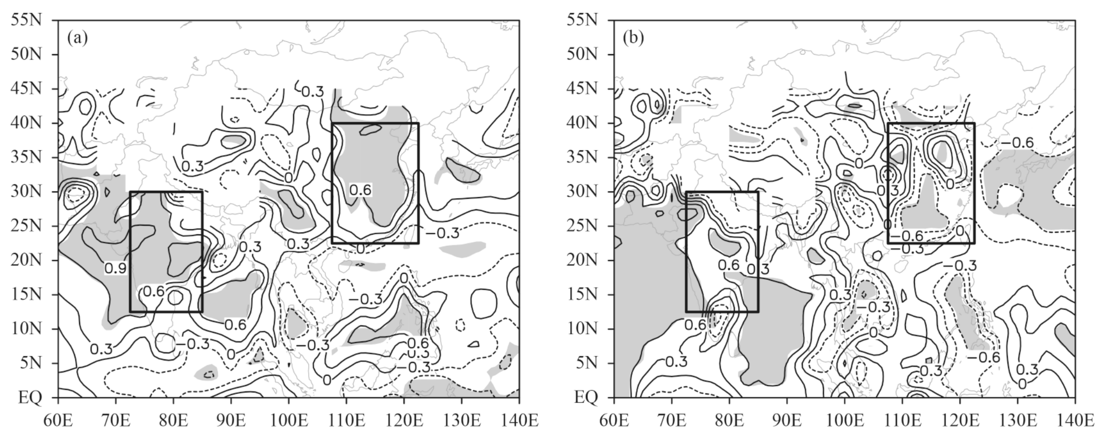

Fig. 3. Distributions of the correlation coefficient between multiyear mean monthly climatology of AOD over 2000–16 and that of (a) precipitation and (b) surface wind speed. Shadings indicate values significant at/above the 95% confidence level.

the regional $PM_{2.5}$ concentration was reportedly induced by the reinforced stability of the boundary layer (Zhong et al., 2017). Here, we want to determine the relationship between the AOD changes and the stability of ABL. Ri is a parameter that describes the atmospheric stability in the ABL and can be roughly estimated by using the wind and temperature data at 1000 and 850 hPa according to Eq. (1). Figure 4 provides a comparison of the annual averages of both monthly Ri and AOD over the past 16 years (Fig. 4a) and the pattern correlations between them (Fig. 4b). As shown in Fig.4a, Ri and AOD are negatively correlated in India with a coefficient of –0.72, which significantly differs from that in East China. In East China, the correlation coefficient between Ri and AOD is 0.32, suggesting that higher AOD may be associated with a larger Ri; that is, AOD increases when wind shear weakens under stable stratification. Figure 4b shows that the correlation between Ri and AOD is positive over the regions of high AOD values; for example, the correlation coefficient is approximately 0.6 over the regions of high AOD in both India and East China. It should also be noted that Ri is negatively correlated with AOD during the seasonal cycle in southern–central India and in Southeast China, suggesting that in the less polluted areas, the larger the Ri, the smaller the AOD, perhaps partly due to more water vapor in the atmosphere or influences of other factors (Zhuang et al., 2014; Li et al., 2015).

4.4 *Influence of tropospheric circulation on aerosols*

The seasonal variability in AOD is also affected by the horizontal circulation changes. As indicated by the distributions of mean climatological rotational and divergent winds (Fig. 5), during spring, an anticyclonic circulation dominates in the lower troposphere in East China with prevailing southerly winds (Fig. 5a). In the upper troposphere, northwesterly winds prevail over the west of the East Asian trough, which is located north of 35°N in East China. Concurrently, an anticyclone is maintained over the South China Sea. The dominant horizontal divergence of low level circulation produces downward motion in East China. These combined upper and lower level circulation patterns do not favor aerosol diffusion. Northwesterly winds along the southern edge of the Tibetan Plateau dominate North India whereas easterly winds from east to west dominate South India, which creates a cyclonic circulation over North India and an anticyclonic circulation over South India at the lower level. An anticyclonic circulation forms in the upper troposphere, whereas divergent flows are observed in the lower troposphere (Fig. 5a). This baroclinic structure in the vertical circulation also favors descending motion in this area, causing aerosol accumulation over the Indian continent.

The summertime rotational and divergent winds in the lower troposphere over East China during spring and summer look similar (Fig. 5b). However, the upper troposphere is controlled by an anticyclone due to the northwestward invasion of the South Asian high (Fig. 5f). This invasion produces a weak upward motion in East China, which is favorable for aerosol diffusion, although the AOD is relatively higher than that in other seasons due to the highest humidity levels in the ABL (Zhuang et al., 2014; Li et al., 2015; Zhang et al., 2015). Compared with that in spring, the lower tropospheric cyclonic circulation in North India during boreal summer is much stronger, especially west of the Bay of Bengal. The upper level circulation changes from the prevailing westerlies associated with the northern edge of the springtime South Asian high into prevailing easterlies associated with the southern edge of the South Asian high. This seasonal variation in upward motion is not favorable for

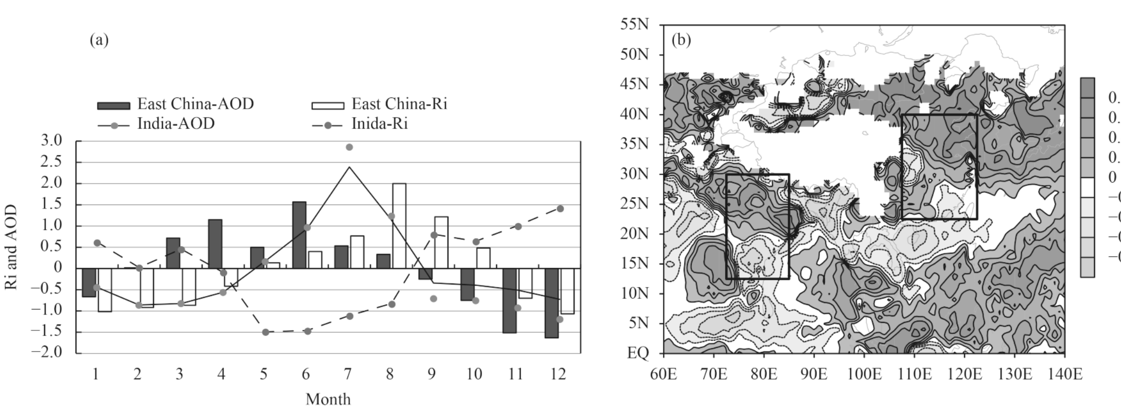

Fig. 4. (a) Multiyear mean monthly Ri and AOD values over the period 2001–16 and (b) the spatial distribution of the correlation coefficient between Ri and AOD.

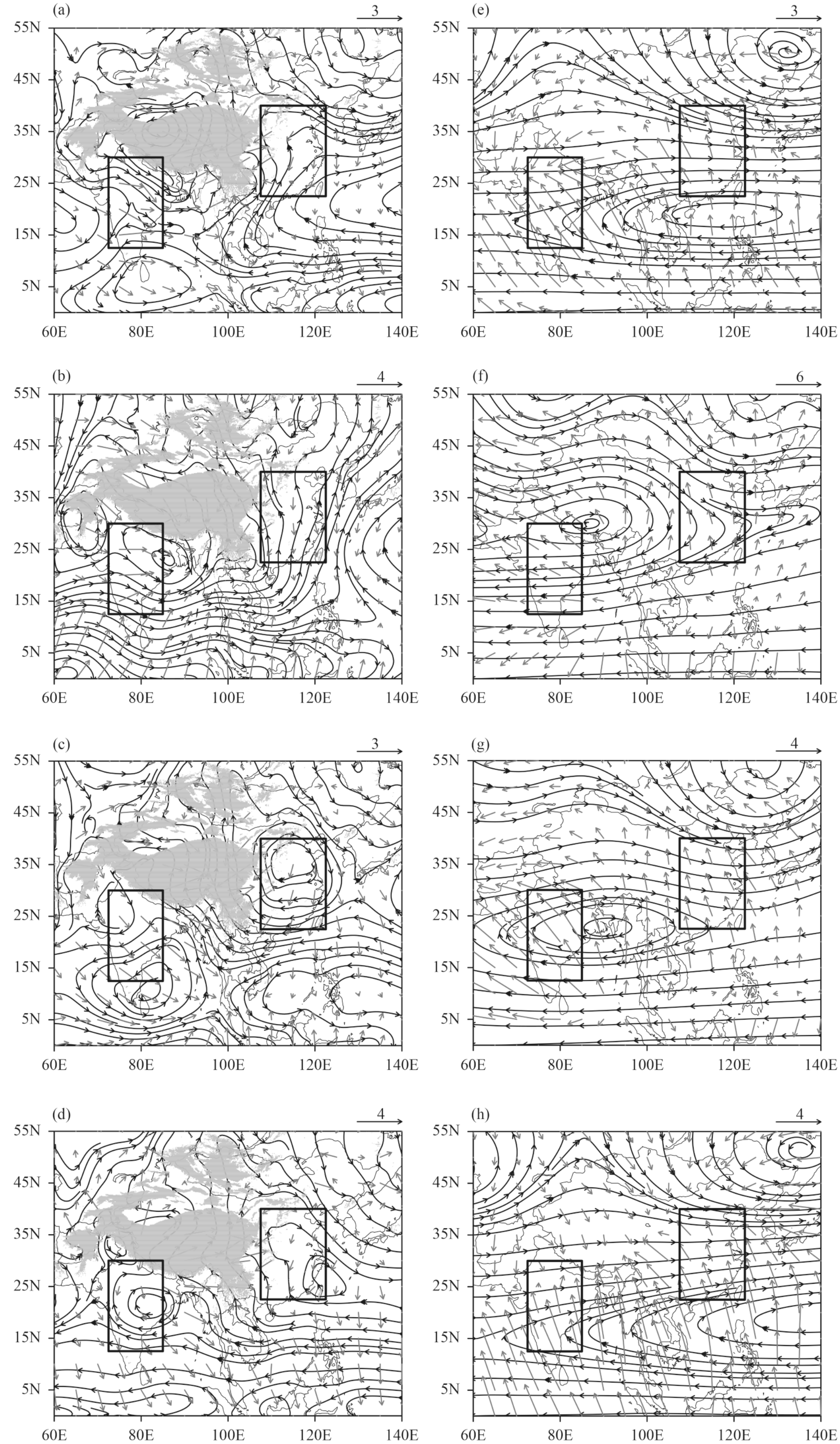

Fig. 5. Mean climatology of rotational (streamline) and divergent (arrow) wind components (m s^{-1}) at (a–d) 850 and (e–h) 200 hPa for (a, e) spring, (b, f) summer, (c, g) fall, and (d, h) winter.

eliminating pollution within the ABL in summer. The combination of upper tropospheric divergence and lower tropospheric convergence favors the upward transport of aerosols but does not favor horizontal diffusion. This situation, together with the higher atmospheric humidity, may produce higher AOD values.

During fall and winter, East China is controlled by the low level divergence associated with anticyclonic circulation (Figs. 5c, d). Distinct convergence occurs at the upper level in the westerly belt west of the East Asian trough (Figs. 5g, h). This combination of upper and lower tropospheric circulation patterns is not favorable for upward motion. Consequently, aerosols cannot be transported to the middle or upper troposphere but can be easily horizontally diffused when the surface wind is strong enough. In India, similar conditions are observed. The lower level circulation is dominated by anticyclonic circulation patterns that are associated with horizontal divergence and downward motions during fall and winter. This circulation is also not favorable for the vertical transport of aerosols into the upper troposphere.

The differences in the horizontal circulation and divergent motion patterns between East China and India may have different influences on the AOD distribution. To investigate the influences of the monsoon circulation patterns on AOD variability, we calculate the advection and divergent effects of winds on AOD based on the horizontal wind fields. Let $\langle\ \rangle = \frac{1}{p_s - p_t}\int_{p_t}^{p_s}(\ )\mathrm{d}p$. The seasonal mean AOD is denoted by M_{AODm}. Then, we have

$$\frac{\partial M_{\mathrm{AODm}}}{\partial t} = -\langle \boldsymbol{V}_{\mathrm{m}} \rangle \cdot \nabla M_{\mathrm{AODm}} - M_{\mathrm{AODm}} \nabla \cdot \langle \boldsymbol{V}_{\mathrm{m}} \rangle + S_{\mathrm{m}}, \tag{2}$$

where p_s is the surface pressure and p_t is the pressure at the top of the ABL and is set as 850 hPa. The first item on the right side of Eq. (2) represents the advection of AOD by horizontal wind. The second term on the right represents the influence of wind convergence/divergence on the AOD. The last term on the right, S_{m}, is the AOD source/sink term and represents the sum of the effects of other processes, including nonlinearities and external factors such as aerosol emissions. For the monthly mean, $\frac{\partial}{\partial t}(\ )$ is approximately zero and hence can be ignored. The intrinsic physics of Eq. (2) can be explained as follows: AOD variability is primarily attributed to wind effects on the aerosols retained in the ABL. Therefore, changes in ABL circulation will affect the AOD value.

Monsoon circulation patterns have strong impacts on AOD variability and demonstrate significant differences between East China and India (Fig. 6). During spring (Figs. 6a, e), monsoon circulation over East China has positive advection effects on the AOD north and southwest of the Yangtze River and negative effects elsewhere. The divergent effects of the monsoon circulation causes a reduction in AOD to the north but constant values to the south. In India, the convergence/divergence is favorable for AOD maintenance (Fig. 6e), whereas the advective effects tend to reduce the AOD (Table 3). During summer, maintenance of high AOD is greatly dependent on convergent flows in East China or India (Figs. 6b, f). During fall, both advective and divergent effects are negative in East China, which favors a decrease in AOD. In India, the advective effect favors an increase in AOD, whereas divergent circulation favors a decrease in AOD (Figs. 6c, g; Table 3). The advective and divergent effects in winter are similar to the effects in fall but with stronger variability (Figs. 6d, h; Table 3). As is known, Eq. (2) demonstrates that convergence (divergence) in the ABL will produce $\frac{\partial}{\partial t}(\ ) > 0$ $\left(\frac{\partial}{\partial t}(\ ) < 0\right)$, which is consistent with Fig. 6. Moreover, the results shown in the right panels in Fig. 6 are consistent with the divergent flows shown in the left panels in Fig. 5.

5. Conclusions and discussion

In this paper, the AOD seasonal variation features and the influence of monsoon circulation patterns on the AOD distribution over East China and India have been investigated and compared. There are some similarities and differences in the features of AOD changes associated with East Asian and Indian monsoon circulations (Table 4). The results are briefly summarized as follows.

The characteristics of the AOD changes are different between East China and India. The seasonal mean value of AOD in East China is significantly larger than that in India, suggesting the possible influence of more aerosol emissions in East China than in India, resulting from the more vigorous industrial economical development in East China. In East China, the AOD is higher in spring and summer but lower in fall and winter, whereas in India, the highest AOD is observed during summer and lower AOD values are observed in spring, fall, and winter. These variations in AOD may be related to the monsoon circulation changes; the AOD in East China is under the control of the East Asian monsoon system, whereas the AOD in India is under the control of the Indian monsoon system.

The surface wind speed matches well with the distribution of AOD, especially in East China. However, the

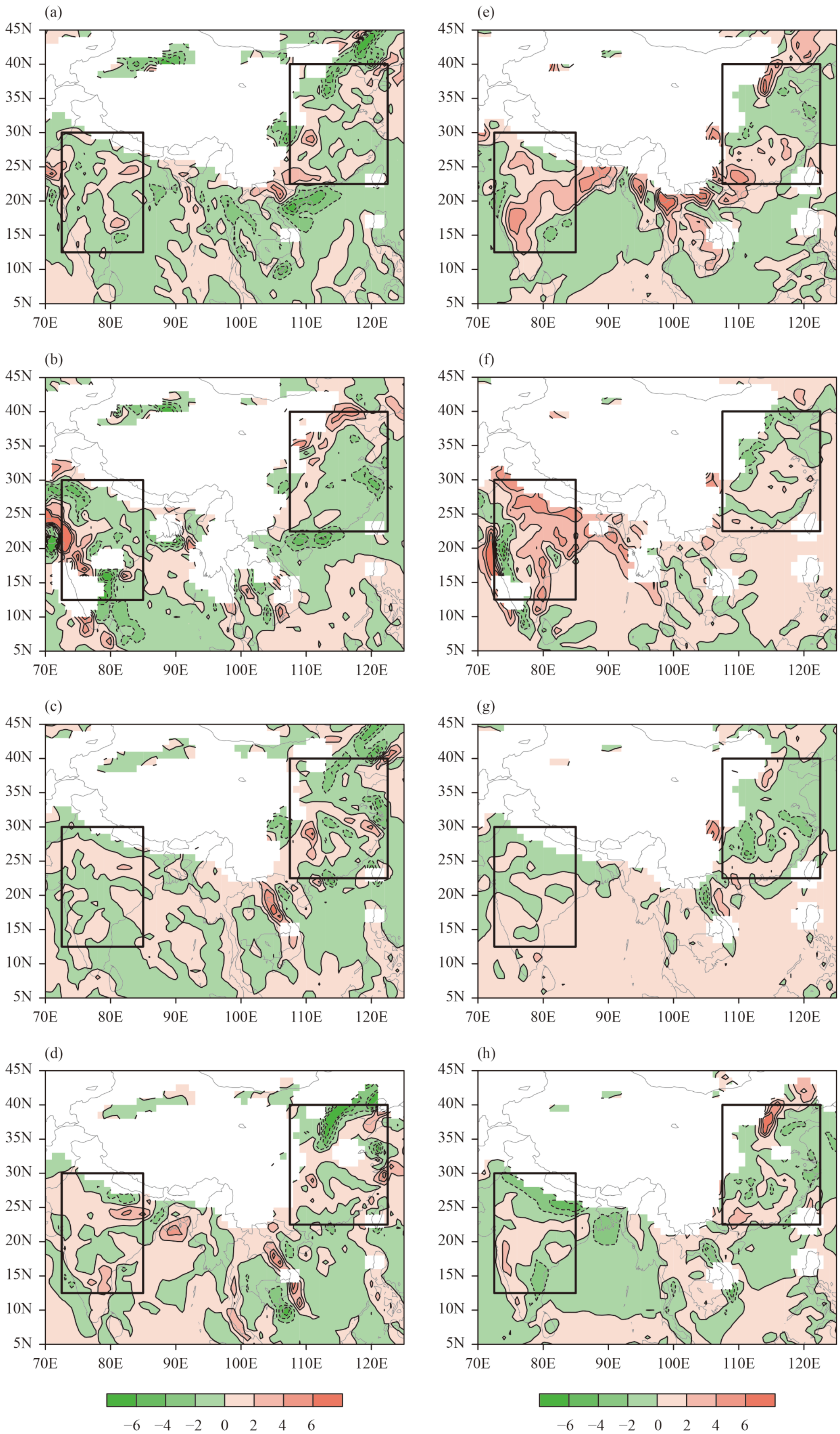

Fig. 6. (a–d) Advection of AOD by climatological mean (2000–16) winds ($\times 1.0^{-6}$ s^{-1}) and (e–h) the effects of divergent/convergent wind on AOD ($\times 1.0^{-6}$ s^{-1}) for (a, e) spring, (b, f) summer, (c, g) fall, and (d, h) winter.

Table 3. Seasonal variations in mean climatology of all items in Eq. (2) regionally averaged over East China and India (× 1.0^{-7} s^{-1})

Season	East China			India		
	Effect of wind advection	Effect of wind divergence/convergence	S_m	Effect of wind advection	Effect of wind divergence/convergence	S_m
Spring	0.17	0.72	–0.84	–1.48	6.91	–5.38
Summer	–1.95	0.62	1.32	2.76	17.64	–18.50
Fall	–1.57	–5.00	6.60	1.04	–0.06	–0.80
Winter	–1.81	–2.84	4.73	1.29	–5.40	3.98

Table 4. Correlation and differences between AOD variation and monsoon variability over East Asia and India

Variable	Similarity	Difference
AOD	Maximum AOD appears during summer in both regions	Different AOD values in the two regions; AOD in East China is significantly larger than that in India, with significant differences in AOD spatial distribution
Precipitation	No significant correlation between precipitation and AOD on seasonal timescale	
Ri number		Opposite correlations between AOD and Ri for the two regions: negative correlation in India; positive correlation in East China
$\boldsymbol{V}_m$	Lower level anticyclonic (cyclonic) flow favors (hinders) horizontal diffusion of aerosols	Different lower/upper circulation systems during different seasons produce different AOD spatial distribution features
$-\langle \boldsymbol{V}_m \rangle \cdot \nabla M_{AODm}$	AOD increase or decrease induced by advection in different locations within the two regions	Comprehensive advection effect causes increased local AOD in East China and decreased local AOD in India; opposite advection effect for local AOD during summer, fall, and winter
$-M_{AODm} \nabla \cdot \langle \boldsymbol{V}_m \rangle$	Convergence (divergence) during spring and summer (fall and winter)	Divergence/convergence effect differs in different seasons; different effects in AOD maintenance and diffusion are observed
S_m	Significant seasonal variability	Negative source/sink during spring; positive source/sink in summer, fall, and winter for East China. For India, negative source/sink during spring, summer, and fall; positive source/sink in winter

seasonal change in precipitation does not correlate well with the AOD in either East China or India.

The AOD maintenance in East China differs somewhat from that in India due to differences in the monsoon systems. The maintenance of high AOD values in East China during summer is mainly due to the anticyclonic circulation with weak divergence in the upper troposphere and the weak cyclonic circulation with convergence in the lower troposphere, facilitating the accumulation of aerosols in this region. The decrease in the AOD in fall and winter is mainly due to the influence of the divergence in the lower troposphere on AOD. However, in the Indian region, the high AOD maintenance in summer is primarily due to the influence of relatively stronger convergence in the lower troposphere on AOD. Because of the topography near the Tibetan Plateau in northern India, AOD tends to accumulate in northern India. The decrease in AOD in India during fall and winter is primarily caused by the divergence in the middle and lower troposphere.

Note that the AOD seasonal cycle is not well correlated with precipitation. Both AOD and precipitation are affected by many independent factors, making the relation between them complicated. In addition to the washout effect of precipitation, the AOD changes partly depend on the aerosol emissions (IPCC, 2007, 2014), the size and properties of aerosol particles (Zhu et al., 2014; Shen et al., 2015; Zhou et al., 2015; Che et al., 2018), the humidity of the air (Zhuang et al., 2014; Li et al., 2015; Zhang et al., 2015), the ABL stability, the wind properties, and the transport processes by monsoon circulation. The precipitation is determined by multiscale weather systems, moisture conditions, and vertical winds, and may be influenced by concentrations of aerosols (Li et al., 2011; Fan et al., 2012). All these factors need to be considered in investigating the variations in AOD and precipitation. The relationships between AOD and precipitation have until now been far from fully understood and therefore deserve further investigations in the future.

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