Linkage of aerosol optical depth with rainfall and circulation parameters over the Eastern Gangetic Plains of India

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The aerosol optical depth (AOD) is an important physical parameter and dimensionless number. The possible link between AOD and variability of summer monsoon rainfall and surface temperature over the densely populated Gangetic Plain may be used to assess change in weather and climate over the Plain. For examining the impact of AOD on summer monsoon rainfall and surface temperature, monthly data of AOD for the period of 2000–2015 are obtained from a remotely sensed moderate resolution imaging spectro-radiometer sensor at 550 nm and at a surface resolution of $1^\circ \times 1^\circ$. For the period of 2000–2015, rainfall and surface temperature data at a resolution of $1^\circ \times 1^\circ$ are obtained from Indian Meteorological Department (IMD) and surface wind data are obtained from National Centers for Environmental Prediction (NCEP). Summer monsoon rainfall and AOD are inversely related during 2000–2015. On an average, a difference in the mean monthly surface maximum and minimum temperatures increases (decreases) with a decrease (increase) of AOD. The high degree of correlation exists between AOD and a difference in $T_{\max}$ and $T_{\min}$ during January to June–July. In winter months, relative strength of negative vorticity over the Gangetic Plain and positive vorticity in the adjacent area may be cause of more dispersion of AOD in February in comparison with that in December and January and therefore more AOD is noticed in January and December.

Keywords. Aerosol optical depth (AOD); Indian Gangetic Plain; temperature; vorticity; MODIS.

1. Introduction

Aerosols originating from natural and anthropogenic sources have been influencing air quality, Earth's radiation budget (through scattering and absorbing the incoming solar and outgoing terrestrial radiation) and consequently changing regional and global climate. The variability in aerosol concentration has been significantly impacting the regional scale. The anthropogenic aerosols (sulphate and carbonaceous aerosols) have increased

substantially in recent decades, especially over urban's industrial regions and have direct impact on cloud formation and the rainfall distribution because aerosols act as cloud condensation nuclei (CCN) and influences cloud formation, rainfall and climate through radiative forcing and microphysical effects (Rosenfeld 2000; Li 2004; Li *et al.* 2007, 2011a, b; Nakajima *et al.* 2007; Huang *et al.* 2014; Guo *et al.* 2016). For assessing changes in weather and climate due to aerosol concentration, aerosol optical depth (AOD) is an important physical

parameter and denotes aerosol distribution within a column of air from Earth's surface to the top of the atmosphere and is used to measure urban haze, smoke particles, desert dust, sea salt and others (Massie *et al.* 2004).

In order to understand the variation of aerosols and their impact on regional climate and monsoon rainfall, several field experiments such as INdian Ocean EXperiment (INDOEX), Aerosol Characterization Experiment (ACE) Asia and East Asian Studies of Tropospheric Aerosols: An International Regional Experiment (EAST-AIRE) have been carried out (Ramanathan *et al.* 2001; Li *et al.* 2007). The observational study on the relationship between aerosols and monsoon rainfall, and associated change in wind circulation over Indian subcontinents and other places of the world has been carried out by various researchers (Hansen *et al.* 1997; Ackerman *et al.* 2000; Satheesh and Ramanathan 2000; Ramanathan *et al.* 2001, 2005; Kaufman *et al.* 2002; Meehl and Arblaster 2002; Jin *et al.* 2005; Chung and Ramanathan 2006; Goswami *et al.* 2006; Kaufman and Koren 2006; Lau and Kim 2006; Lau *et al.* 2006; Wang *et al.* 2009a, b; Bell *et al.* 2008; Lau *et al.* 2008; Meehl *et al.* 2008; Ramachandran and Kedia 2010; Cowan and Cai 2011; Prabha *et al.* 2011; Freud and Rosenfeld 2012; Konwar *et al.* 2012; Manoj *et al.* 2012; Nair *et al.* 2013; Solomon *et al.* 2015). The modelling study on aerosol, monsoon rainfall (Parth Sarthi *et al.* 2015, 2016) and associated changes in circulation over Asian regions has also been examined by previous researchers (Ramanathan *et al.* 2005; Li *et al.* 2009; Zhang *et al.* 2009, 2010a, b, 2012; Guo *et al.* 2013; Jiang *et al.* 2013; Song *et al.* 2014). They suggested the reduction in surface solar radiation due to absorption and scattering by aerosols cools the northern Indian Ocean, reduces evaporation, causes a spin down of the local Hadley cell circulation and weakens the Indian summer monsoon precipitation (Menon *et al.* 2002; Ramanathan and Crutzen 2003; Bollasina *et al.* 2011; Ganguly *et al.* 2012a, b). The spatial and temporal variation in AOD is important due to a fast increase in aerosol emissions over India in the last two decades (Ramachandran and Jayaraman 2003; Streets *et al.* 2009) and therefore seasonal and annual trends in AOD over different regions in India may be helpful in understanding the effect of aerosols on summer monsoonal rainfall variability. Gautam *et al.* (2009a) found that the remotely sensed total ozone mapping spectrometer (TOMS) aerosol index over

northern India (25–35°N; 69–82°E) during the pre-monsoon (March–April–May) shows an increasing trend since 1979. The trends in AOD over the different regions, seasons (winter and summer) and annual mean scales are studied.

Another impact of AOD is changes in surface temperature. Over industrialised parts of China, Zhou *et al.* (2004) found a larger decrease in the diurnal temperature range at 194 meteorological stations during 1979–1998. Roy (2008) found higher concentrations of AOD over the densely populated Gangetic basin for summer and winter seasons for the period of 2000–2005 and showed contrary relationship during the winter season. In recent years, aerosols have been substantially increased over the Indo-Gangetic Plain (IGP); dust particulates accumulated and significantly influenced AOD properties (Dey *et al.* 2004; Singh *et al.* 2004; El-Askary *et al.* 2006; Prasad and Singh 2007a, b; Gautam *et al.* 2009b) as well as the regional radiation budget (Singh *et al.* 2005; Pandithurai *et al.* 2008). Prasad *et al.* (2006) show very high AOD (>0.6) over the Gangetic Plain during the summer season. During 2002, a high concentration of AOD (>0.6) is observed in the western part of the Ganga basin and AOD of greater than 0.5–0.6 in the central region which may be due to the failure of summer monsoon rainfall in 2002. The lowering of AOD in 2003 may be correlated with good summer monsoon in 2003. They found that very high AOD is present over the Ganga basin throughout the year.

An earlier study is mostly focused on the spatial and temporal variability of AOD over all India and but not much confined to the states of Bihar and Uttar Pradesh over the Eastern Gangetic Plain of India. These states are entirely land locked and adjacent to West Bengal (a deep humid state). The current study is focused on the temporal and spatial variability of remotely sensed AOD over the Eastern Gangetic Plain (includes the states of Uttar Pradesh and Bihar) of India where AOD dominates and related erratic behaviour of summer monsoon largely affecting agriculture as well as night-time temperature during the winter season. Further, increasing pollution load over the study area is very much concerned to human health (Pisudde *et al.* 2017) during the winter season (December–January–February). Therefore, in the current paper, the following objectives are aimed for the study period of 2000–2015:

Figure 1. Study area showing the state of IGP, Uttar Pradesh, Bihar, West Bengal and Bangladesh.

- (1) The spatial and temporal variability of AOD over the Gangetic Plain of India.
- (2) The linkage of AOD with rainfall and circulation parameters (i.e., temperature and vorticity).

The importance of this research work is focused on the probable cause of occurrence of AOD in terms of surface temperature and vorticity and how it is influencing the summer monsoon rainfall pattern. The study area and data are discussed in section 2. Results and discussion are given in section 3 and conclusion is provided in section 4.

2. Study area and data

In the current study, the states of Uttar Pradesh and Bihar over the Eastern Gangetic Plain of India are considered for the analysis purpose (as shown in figure 1); however, the discussions are

conceded over adjacent areas like foothills of the Himalayas, West Bengal and Bangladesh. The plain of the river Ganga is a densely populated area and agriculture is dominant profession for their economy. Therefore, any change in the rainfall pattern would affect agriculture production. Also, the change in surface temperature during the winter is important for crops. To fulfil aimed objectives, the remotely sensed moderate resolution imaging spectro-radiometer (MODIS) derived AOD data are considered. These remotely sensed data are collected twice daily by NASA's Terra and Aqua satellites and is available at medium to high resolution across the globe at different spatial and temporal scales. In current analysis the MODIS (at 550 nm) at a resolution of $1^\circ \times 1^\circ$ is considered for the period of 2000–2015.

The rainfall and surface temperature data at a resolution of $1^\circ \times 1^\circ$ during 2000–2015 are obtained from the Indian Meteorological Department (IMD)

Table 1. Details of data type, source, resolution and period.

Data type	Data source	Surface resolution	Period
Rainfall	IMD	$1^\circ \times 1^\circ$	2000–2015
Surface temperature ($T_{\max}$ and $T_{\min}$)	IMD	$1^\circ \times 1^\circ$	2000–2015
Surface wind	NCEP	$2.5^\circ \times 2.5^\circ$	2000–2015
AOD	giovanni.gsfc.nasa.gov/ giovanni	$1^\circ \times 1^\circ$	2000–2015

while the surface wind data are obtained from the National Centers for Environmental Prediction (NCEP) for the period of 2000–2015. Details of the data are given in table 1.

3. Results and discussion

3.1 AOD, rainfall and surface temperature

In this section, the relationship among the remotely sensed AOD, observed rainfall and surface temperature of IMD over India is examined during different time periods. Figure 2 shows the variation of AOD during the pre-monsoon (March–April–May), monsoon (June–July–August–September), post-monsoon (October–November) and winter (December–January–February) seasons during 2000–2015. It reveals that AOD is remarkably increased during the winter season followed by the monsoon, post-monsoon and pre-monsoon. Probably, the high AOD during the monsoon may be arised by advection of dust from the Arabian Desert and transported by surface westerly winds. The aerosol during the pre-monsoon months (March, April and May) (Dey *et al.* 2004), post-monsoon (October, November) and winter (December, January and February) may be due to the dust and biomass burning, over the study area. During the winter season (December–February), the aerosol loading is dominated by the anthropogenic contribution (Tripathi *et al.* 2006; Jimenez *et al.* 2009) especially by agricultural waste burning and the urban/industrial aerosols (Guttikunda *et al.* 2003; Sharma *et al.* 2003) over the Gangetic Plain.

To examine the relationship between AOD and summer monsoon rainfall, the time series of average AOD and JJAS (June–July–August–September) rainfall during 2000–2015 is considered (figure 3). Both are varying in almost opposite directions (Ramachandran and Cherian 2008; Ganguly *et al.* 2012a, b) i.e., during high (low) AOD, rainfall is

Figure 2. Variation of AOD in pre-monsoon (MAM), monsoon (JJAS), post-monsoon (ON) and winter (DJF) seasons during 2000–2015.

Figure 3. Variation of rainfall (in mm) and AOD in JJAS during 2000–2015.

Figure 4. Monthly variation of $T_{\max}-T_{\min}$ and AOD during 2000–2015.

low (high). During 2002–2004 and 2008–2015, the inverse relationship exists between AOD and JJAS rainfall. It seems that aerosol particles are being

Figure 5. Spatial distribution of AOD in (a) December, (b) January and (c) February during 2000–2015.

Figure 6. Spatial distribution of vorticity at 1000 hPa in (a) December, (b) January and (c) February during 2001–2015.

washed during that period. This inverse relationship does not exist for the individual years of 2001, 2005, 2006 and 2007; the inverse relationship is dominating during 2002–2004 and 2008–2015. The increasing level of AOD affects the Earth-atmosphere radiation budget by scattering and absorbing the incoming solar radiation. Such a process influences the formation of cloud through cloud CCN and consequently the rainfall. Aerosol may increase the reflectivity of the cloud and causes cooling effect on land surface that may further decrease the rainfall. AOD may also absorb, reemit as thermal radiation, heat the air mass and may cause evaporation of cloud droplets and finally decreases the rainfall. In other words, it may be possible that AOD increases the temperature of the lower atmosphere by heat and evaporates cloud droplets and therefore rainfall seizes.

Figure 4 shows the monthly mean distribution of AOD and differences in monthly mean of surface maximum temperature ($T_{\max}$) and surface minimum temperature ($T_{\min}$) during 2000–2015. During February to June–July, mean monthly AOD and difference in monthly $T_{\max}$ and $T_{\min}$ ($T_{\max} - T_{\min}$) show significant ($P = 0.00108$, i.e., < 0.05) high-negative Pearson's correlation (0.9). The comparatively large difference in monthly $T_{\max}$ and $T_{\min}$ during February to June–July results in more unstable atmospheric conditions and therefore there is more movement of AOD in both vertical and horizontal directions and consequently the level of AOD is reduced. From September to January, AOD increases and then begin to decrease until April. The relatively low AOD and relatively maximum difference in $T_{\max}$ and $T_{\min}$ are found in March and April (Pant *et al.* 2006; Bonasoni *et al.* 2010; Gobbi *et al.* 2010; Marinoni *et al.* 2010; Ram and Sarin 2010). The comparatively minimum difference in $T_{\max} - T_{\min}$ during October, November, December and January (winter month) indicates a relatively stable atmosphere and therefore the level of AOD is increasing during these months. In other words, whenever AOD is more, the more radiation is being trapped into the Earth's atmosphere and therefore the difference between $T_{\max}$ and $T_{\min}$ would be relatively less during winter months.

Almost a similar pattern of AOD over different locations of IGP was found by Lodhi *et al.* (2013) and Giles *et al.* (2011). The variation of difference between $T_{\max}$ and $T_{\min}$ over the Gangetic Plain was well supported by Nair *et al.* (2007).

3.2 AOD and vorticity at 850 hPa during the winter season

In recent years, the spatial and temporal variability of AOD over the Gangetic Plain during winter months (December–January–February) (Girolamo *et al.* 2004; Ramachandran and Cherian 2008) received a lot of importance because of an adverse impact on health, visibility and other atmospheric conditions. Figure 5(a–c) shows a spatial distribution of AOD in December, January and February, respectively. Over foothills of the Himalaya including north Bihar regions, more AOD is seen in December and January months. The spatial changes in AOD may be correlated with wind speed and vorticity over the eastern parts of the Gangetic Plain over Uttar Pradesh, Bihar and West Bengal in India as well as over Bangladesh. Therefore, vorticity at 850 hPa in December, January and February over the study area is shown in figure 6(a–c). The negative vorticity means clockwise rotation of the wind whereas positive vorticity represents anti-clockwise rotation of the wind. The Gangetic Plain is marked by negative vorticity (anti-cyclonic circulation) and positive vorticity (cyclonic circulation) in the east and north sides (foot hills of the Himalaya) which triggers advection of vorticity over the Gangetic Plain. The negative vorticity is found relatively more during January and December with respect to February. The relative strength of negative vorticity over the Gangetic Plain and positive vorticity over the adjacent area may be responsible for more wind dispersion in February compare to December, January and consequently relatively less AOD is noticed in February (as shown in figure 5) with respect to January and December. This could be a cause of shifting of AOD distribution slowly towards West Bengal and Bangladesh regions in February.

4. Conclusions

The variability of AOD over the Gangetic Plain (includes here only state of Bihar and Uttar Pradesh) and its relationship with rainfall, surface temperature and vorticity is examined. During JJAS rainfall is correlated with AOD over the Gangetic Plain and both are having inverse correlation. On an average, a difference in mean monthly surface maximum and minimum temperatures increases (decrease) with a decrease

(increase) in AOD. It seems that strong negative correlation exists between AOD and a difference in $T_{\max}$ and $T_{\min}$ during January to June. In winter months, more AOD is noticed in January, followed by December and February. It seems that dust aerosol is dominated during January–June while anthropogenic aerosol (agricultural waste burning) is dominating in remaining months. The relative strength of negative vorticity over the Gangetic Plain and positive vorticity in the adjacent area may be cause of more dispersion of AOD in February (and shifted to Bangladesh region) in compare to that of December and January and therefore more AOD is seen in January and December.

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