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# Satellite derived spatio-temporal characteristics of aerosol optical depths and cloud parameters over tropical Indian region

**Adarsh Kumar**
Department of Physics, Amity Institute of Applied Sciences (AIAS), Amity University, Noida (UP) - 201 303, India.
Email: adarsh_phy@yahoo.co.in

## ABSTRACT

Moderate Resolution Imaging Spectro radiometer (MODIS) derived Aerosol Optical Depth (AOD) is well suited for the seasonal and inter-annual study of the aerosols distribution and their effects over a long period of time. Daily averaged MODIS retrieved satellite (collection 5 level 3) AOD data has been used to investigate AOD distribution in spatio-temporal domain over Indian subcontinent for the three years period, 2008-2010. In 2008, the average value of AOD over Indian subcontinent was found to be ~0.37±0.088, whereas in 2009 and 2010, the mean values of AOD were estimated as ~0.32±0.075 and ~0.35±0.058 respectively. The study revealed that during the monsoon season of 2009, the AOD decreased sharply with the increase of days. The highest and lowest values of AOD for the year 2008 were found to be ~1.098 and ~0.219, whereas for the years of 2009 and 2010, these values of AOD over Indian subcontinent were estimated to be ~0.61, ~0.21 and ~0.76, ~0.19 respectively. For these three years period of 2008-2010, the cloud parameters such as cloud fraction (CF), water vapor (WV), cloud optical depth (COD), and cloud top temperature (CTT), were also estimated and spatially correlated with the aerosol optical depths over Indian region. Results have been compared with some of the significant and important investigations made by other workers on AOD and cloud parameter values over entire region of India.

**Keywords:** Satellite data, TERRA, AOD, Indian region, Cloud parameters, Water vapor.

## INTRODUCTION

Aerosols have an impact on cloud formation processes and largely affect the monsoonal rainfall distribution over Indian subcontinent (Rodriguez et al., 2012). In fact, atmospheric aerosols influence the earth's climate in many characteristic ways (Chu et al., 2003). For example, higher aerosol loading causes substantial decrease in sunlight reaching to the surface, thereby affecting vegetation which primarily depends on sunlight for their growth (Satheesh and Ramanathan, 2000). Indo-Asian aerosols have impact on radiative forcing that cause cooling at surface and warming at top of the atmosphere (Kaufman et al., 2002). Tai et al., (2010) have found that this additional heating and cooling affects the tropical rainfall patterns and disturb hydrological cycle. AOD distribution during pre-monsoon affects cloud formation and hence rainfall distribution which was found to be prominent for 4 years period between 2000 and 2003 (Prasad et al., 2004). INDOEX experiments studied extensively the nature of aerosols, its transcontinental transport and its effect on climate (Panicker et al., 2010). Complex interaction between aerosols, clouds, climate and vegetation needs to be addressed in the light of harmful effects observed in several studies by different workers (Liao and Seinfeld, 1998; Kaufman et al., 2002). The Indian subcontinent is densely populated and has industrialized areas on the east and western sides (Dani et al., 2012).

A number of observational campaigns (Indian Ocean Experiment-INDOEX: Ramanathan et al., 2000; Land Campaigns (LC) LC-I: Moorthy et al., 2005; LC- II: Ramachandran et al., 2006) have been conducted over the Indian subcontinent and surrounding oceanic regions in recent times to investigate the role of aerosols in altering the atmospheric radiation budget and the cloud properties. Indo-Asian aerosols have impact on radiative forcing that cause cooling at surface and warming at top of atmosphere (Satheesh and Ramanathan, 2000; Faruque et al., 2009). INDOEX experiments studied extensively the nature of aerosols, its transcontinental transport and its effect on climate (Kaufman et al., 2002).

In the present work, aerosol optical depths at 550 nm derived from MODIS Terra, have been analyzed over Indian subcontinent for different seasons (Winter DJF, Summer MAM, Monsoon JJAS, and Post Monsoon ON) covering the three years period from 2008 to 2010. The cloud parameters such as cloud fraction (CF), water vapor (WV), cloud optical depth (COD), and cloud top temperature (CTT) were also spatially correlated with aerosol optical depth over Indian region during the these three years.

## MODIS DERIVED AOD AND METHODOLOGY

The Moderate Resolution Imaging Spectro-radiometer (MODIS) is a remote sensor with two Earth Observing System (EOS) Terra and Aqua satellites, which provide an opportunity to study aerosols from space with high accuracy and on a nearly global scale (Yu et al., 2004; Remer et al., 2005, Bansod et al., 2012). MODIS Terra

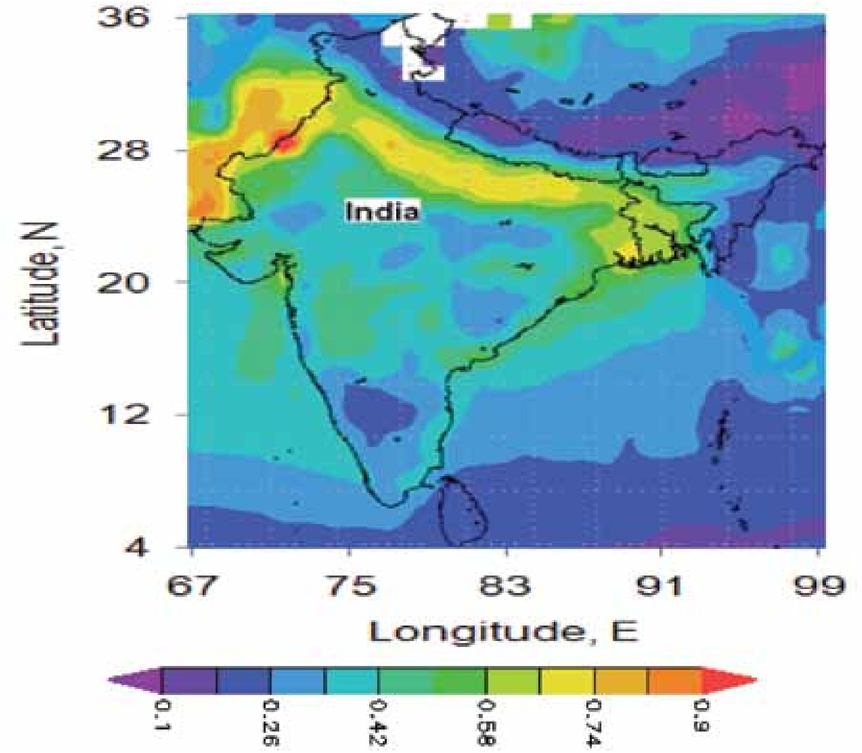


**Figure 1.** Spatial distribution of area averaged (a) Terra, (b) Aqua derived annual mean Aerosol Optical Depth at 550 nm over Indian region for the period 2008-2010.

and Aqua satellites operate at an altitude of 705 km with Terra spacecraft crossing the equator at about 10:30 LST ascending north-ward direction. Aerosol optical depth at 550 nm have been obtained using Level-3 MODIS gridded atmosphere daily global product 'MOD08_D3.051'. In this work, Level 3 MODIS collection 5 atmosphere daily global products (aerosol optical depth, 550 nm) at 1°x1° grid (Remer et al., 2005) are utilised. The aerosol products derived daily from Terra satellites are obtained and analyzed using statistical techniques for three consecutive years for the period 2008-2010.

## RESULTS AND DISCUSSION

### Spatial variation of Aerosol optical depth

The spatial mean variation of annual Terra and Aqua sensors derived AOD at a wavelength of 550 nm has been shown over Indian land tropical region for the three years period, 2008-2010 (Figure 1). The important feature of Figure 1 is that both Modis derived Terra and Aqua mean AOD values exhibit similar spatial pattern over Indian region for the study period. It is clear from Figure 1 that aerosols had a significant impact over the entire Indian region. High AOD values (>0.70) have been found over industrial areas with enhanced industrial, transport and anthropogenic activity like Delhi, Mumbai, Kolkatta, as these regions are dominated chiefly by the automobile, and industrial activities (Rotstayn et al., 2000, Ramachandran et al., 2006). AOD was found to be (>0.9) in great Indian desert in 2008, whereas in 2009, it was found to be (>0.6) in Indian desert region and it was near to 0.7 in regions like lower Ganga plains, Nepal, trans Indo-Gangetic plains and hills along with western Rajasthan in 2010. Southern parts of India show a much cleaner environment with AOD less than 0.42 in the study period (2008-2010). The spatial gradient of AOD is showed slight increase from southern part of Indian subcontinent to northern part up to Himalaya. The central India shows moderate AOD values. The Gujarat state in western India also shows a value of AOD (near to 0.4) in all the three years of 2008, 2009 and 2010, due to effect of Thar Desert in its north-east region and also transport of dust from Middle East (Dey et al., 2004). Input of aerosols from Thar Desert and dry season during pre-monsoon have caused high AOD in the Ganga basin (Beig et al. 2013).

### Inter annual variation of AOD at 550 nm

The monthly variation of AOD at 550 nm over Indian subcontinent for the period of 2008-10 is shown in Figure 2. In 2008, 2009 and 2010, the average values of AOD were found to be ~0.37±0.088, ~0.32±0.075, and ~0.35±0.058 respectively over Indian land region.

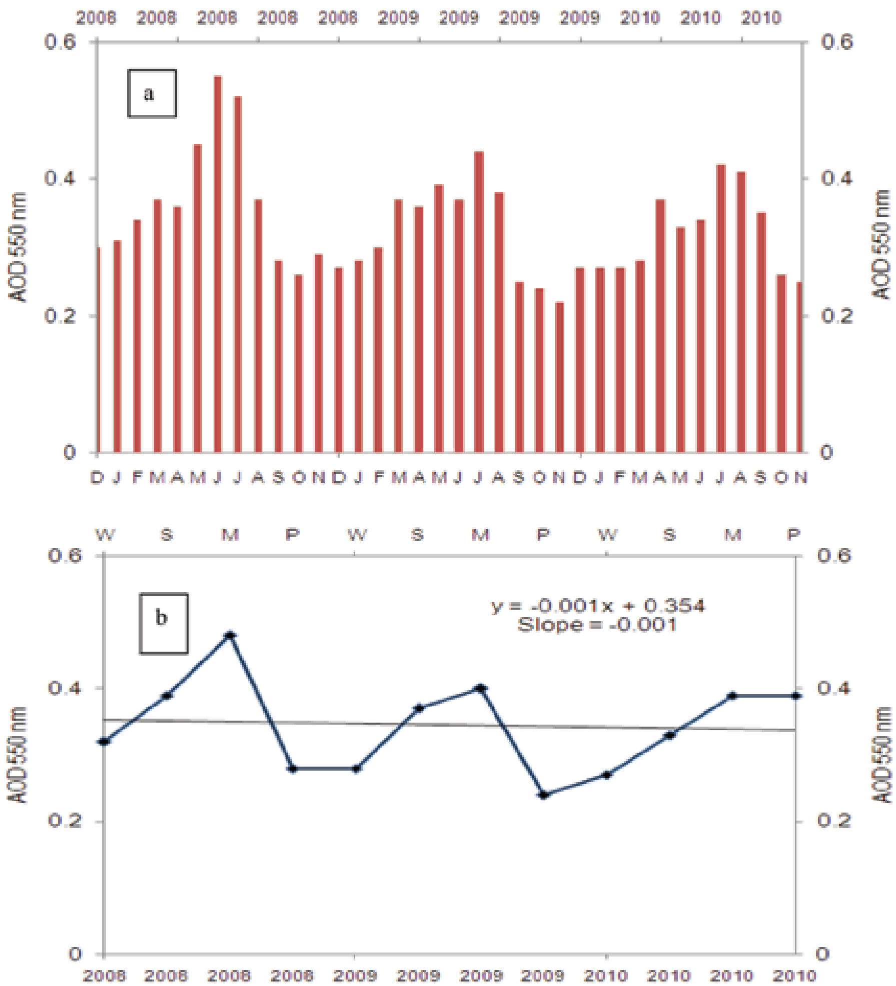


**Figure 2.** Inter annual, and (b) Monthly and seasonal variation of Aerosol Optical Depth at 550 nm over Indian region for the period 2008-2010.

Chowdhary et al. (2012) suggested that a low value of AOD (near to 0.4) is due to effect of Thar Desert in its north-east region and also transport of dust from Middle East. The highest and lowest AOD values for the year 2008 were ~1.098 and ~0.219 respectively, whereas for the years of 2009 and 2010, these values of AOD at 550 nm over Indian subcontinent were estimated as ~0.61, ~0.21 and ~0.76, ~0.19 respectively (Figure 2a). The R-squared values for these three years (2008, 2009, 2010) were estimated as ~0.0037, ~0.040, and ~0.015 respectively. Input of aerosols from Thar Desert and dry season during pre-monsoon, cause high value of AOD in the Ganga basin (Hoeve at al., 2012). Fine soil dust from dry non-vegetated agricultural land during summer is another big source of aerosols in some part of Indian region (Kirankumar et al., 2013).

## Monthly and seasonal variation of AOD at 550 nm

In winter season (DJF) of 2008, the AOD at 550 nm over Indian subcontinent varies between ~0.445 to ~0.219 with an average value of ~0.338±0.081 (Figure 2a). The R-squared values have been estimated to be ~0.259. The AOD in summer season (MAM) of 2008 over Indian region ranges between ~1.098 to ~0.267, with a mean value of ~0.39±0.024 (Figure 2b) whereas, the R-squared value has been estimated to be ~0.536 for the summer season of 2008. The nature of AOD in the monsoon season (JJAS) of 2008 over Indian subcontinent was found to be similar to the summer season of 2008 (Figure 2b). The maximum, minimum and average values of AOD over Indian subcontinent in Monsoon season (JJAS) of 2008 were found to be ~1.098, ~0.267 and ~0.48±0.047 respectively. In post monsoon season (ON) of 2008, the AOD measured at 550 nm over Indian subcontinent varies between ~0.426 to ~0.22, with an average value of 0.28±0.076 (Figure 2b). The high AOD values during the monsoon season may be due to various other meteorological causes occurring in the atmosphere. The trend line (Figure 2b) of ON season shows that the aerosol optical depth decreased slightly as the number

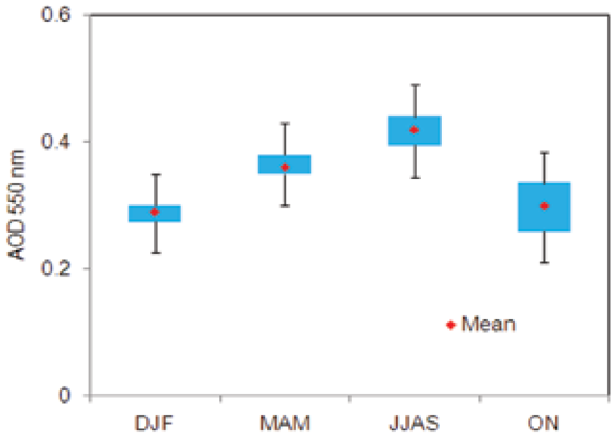


**Figure 3.** Box and whisker plot for the seasonal mean variation of Terra AOD at 550 nm over Indian region for the period of 2008-2010. Solid red dots indicate the mean values. The range of the whiskers indicates the standard deviation of the mean value.

days increased. It is clear from Figure 3a, that the max, min, R-squared, and average values of AOD in DJF winter season of 2009 at 550 nm over Indian subcontinent were found to be ~0.445, ~0.219, ~0.26, and ~0.28±0.025 respectively. The AOD in MAM summer season of 2009 over Indian region lies between ~0.552 to ~0.271, having the mean and R-squared values as ~0.42±0.052 and ~0.30 respectively. Similarly, the max, min, R-squared, and average values of AOD over Indian subcontinent in JJAS Monsoon season of 2009, were found to be ~0.619, ~0.244, ~0.63 and ~0.42±0.12 respectively (Figure 2b). It was investigated that during the monsoon season of 2009, the AOD decreased sharply with the increase in days. In ON post monsoon season of 2009, the AOD at 550 nm over Indian subcontinent lies between ~0.385 to ~0.215 with a mean value of 0.24±0.075. The trend line of Figure 2b shows that the aerosol optical depth at 550 nm increased slightly with the increase in the number of days in the ON season of 2009. One of the important and dominant factor responsible for the higher AOD values during these months is the surface wind speed (Kaskaoutis et al., 2012). Wind speed becomes stronger during this period and it can significantly pick up the soil, dust and biological particles in order to suspend in the atmosphere (Lee et al., 2009). In DJF winter season of 2010, Terra derived AOD values over Indian subcontinent were found to vary between ~0.56 and ~0.216, with an average value of ~0.32±0.028. The R-squared have been was estimated to be ~0.60 for winter DJF season of 2010. The AOD in MAM summer season of 2010 over Indian region lies between ~0.767 to ~0.31 having the R-squared and mean value of ~0.43 and 0.33±0.032 respectively. Figure 2a shows that the max, min and average values of AOD over Indian subcontinent in JJAS Monsoon season of 2010 are ~0.648, ~0.246 and ~0.39±0.037 respectively, with the R-squared values as ~0.47. In the post monsoon ON season of 2010, the R-squared value has been estimated to be ~0.13 whereas the AOD value measured at 550 nm over Indian subcontinent varied in between ~0.374 and ~0.19, with an average value of ~0.29±0.068.

The seasonal average variation of the Terra AOD values at 550 nm for the study period (2008-2010) is shown as a box and whisker plot in Figure 3. In Figure 3, solid dots inside the box represent the mean values; centre line indicates the median (50 percentile value); the range of the whiskers indicates the standard deviation of the mean value. Each of the seasonal average value has been obtained from a significant number of daily AOD values at 550 nm. The season-wise mean air temperature and synoptic wind pattern (at 850 hPa) for the study period (2008-2010) over the Indian subcontinent and surrounding regions are shown in Figures 4(a-d) and 5(a-d) respectively. The wind vector plots and back trajectory analysis provide the information about the synoptic circulation pattern and potential pathways of transport phenomenon (Kaufman et al., 2002; Kumar, 2013). It is well known that the sea-salt production is strongly influenced by over-ocean winds and increase exponentially with wind speed (Singh et al., 1999; Saxena et al., 2010, Yong et al., 2011). Also, the wind generated sea spray aerosols will be in coarse size regime (Tai et al., 2010, Bansod et al., 2012) and influence the size distribution parameters.

Singh et al., 2004 presented the seasonal and inter annual variability of the aerosol optical properties over an urban industrial site in the northern India region. The aerosol optical properties over that urban industrial site in north India were found to show a strong seasonal effect with the maximum variability during the monsoon season. They suggested that the industrial region is characterized by different types of aerosol loading by regional air mass, which changes from season to season. This may be attributed to the fact that the urban industrial regions have high aerosol loading due to industrial and urban domestic activities and some years may be drier with more dust

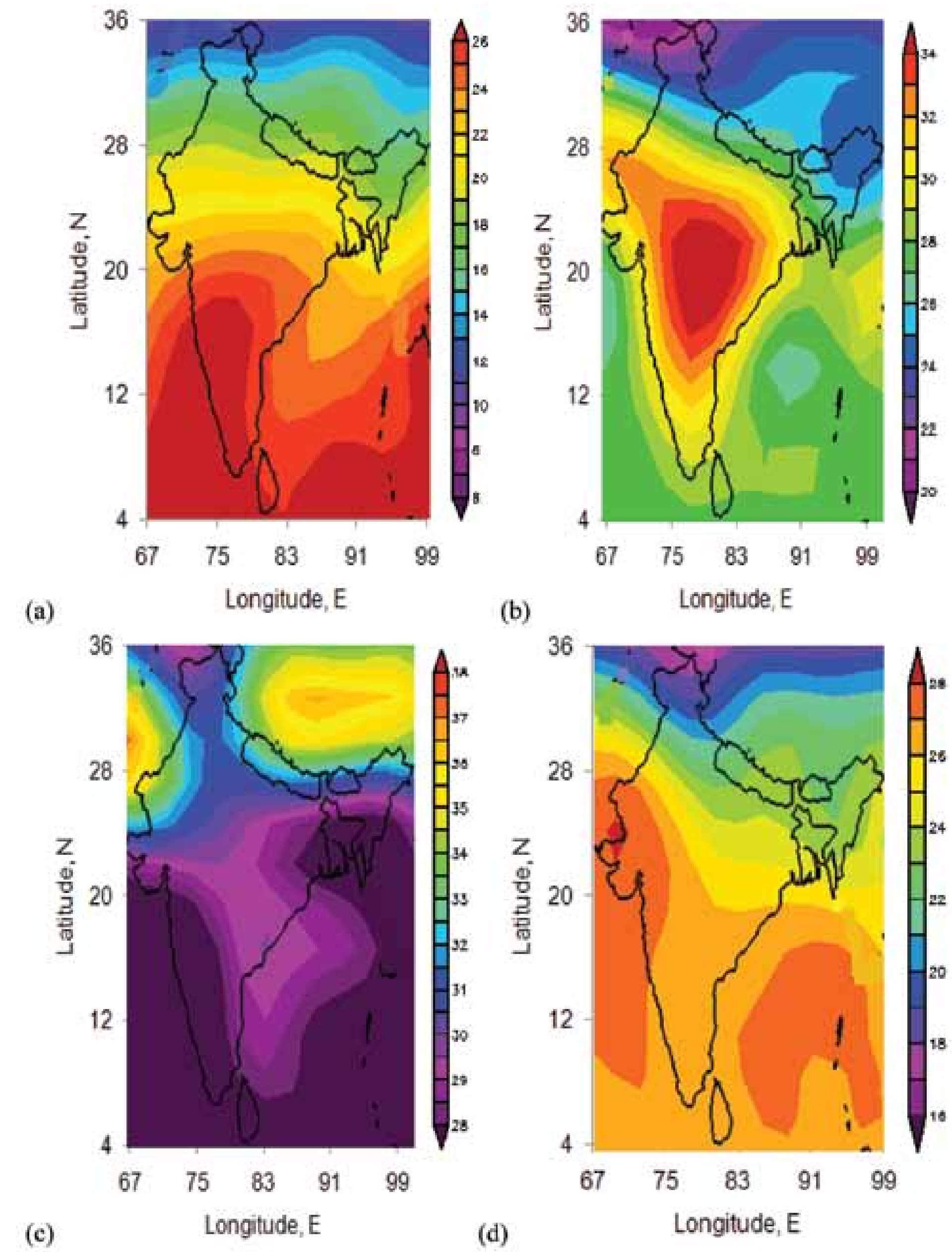


**Figure 4 (a-d).** Mean air temperature at 850 h Pa for various seasons (a: winter, b: summer, c: monsoon, d: post-monsoon) over Indian region for the period 2008-2010.

events. However, the enhanced aerosol loading may affect the rainfall over these places which may cause drought conditions (Jones et al., 2009). Long-range transport of atmospheric aerosols also contributes significantly to the columnar aerosol load besides the local emissions and changes of the aerosol concentrations with respect to the synoptic meteorological conditions. Transport of natural and anthropogenic aerosols mainly depends upon the synoptic scale circulation pattern (King et al., 2003). It is to be noted that the northern India region is significantly believed to have high aerosol laden, due to its dense industrial and urban areas. Further, at the north of Indian sub-continent, orography of the Himalayas act as a natural boundary to the dispersion of aerosols and low temperature conditions in winter leads to the confinement and build-up of aerosol particles (Sreekanth, 2013).

## RELATIONSHIP BETWEEN AOD AND CLOUD PARAMETERS

In order to understand the influence of aerosols on clouds, the aerosol cloud analysis needs to be done by

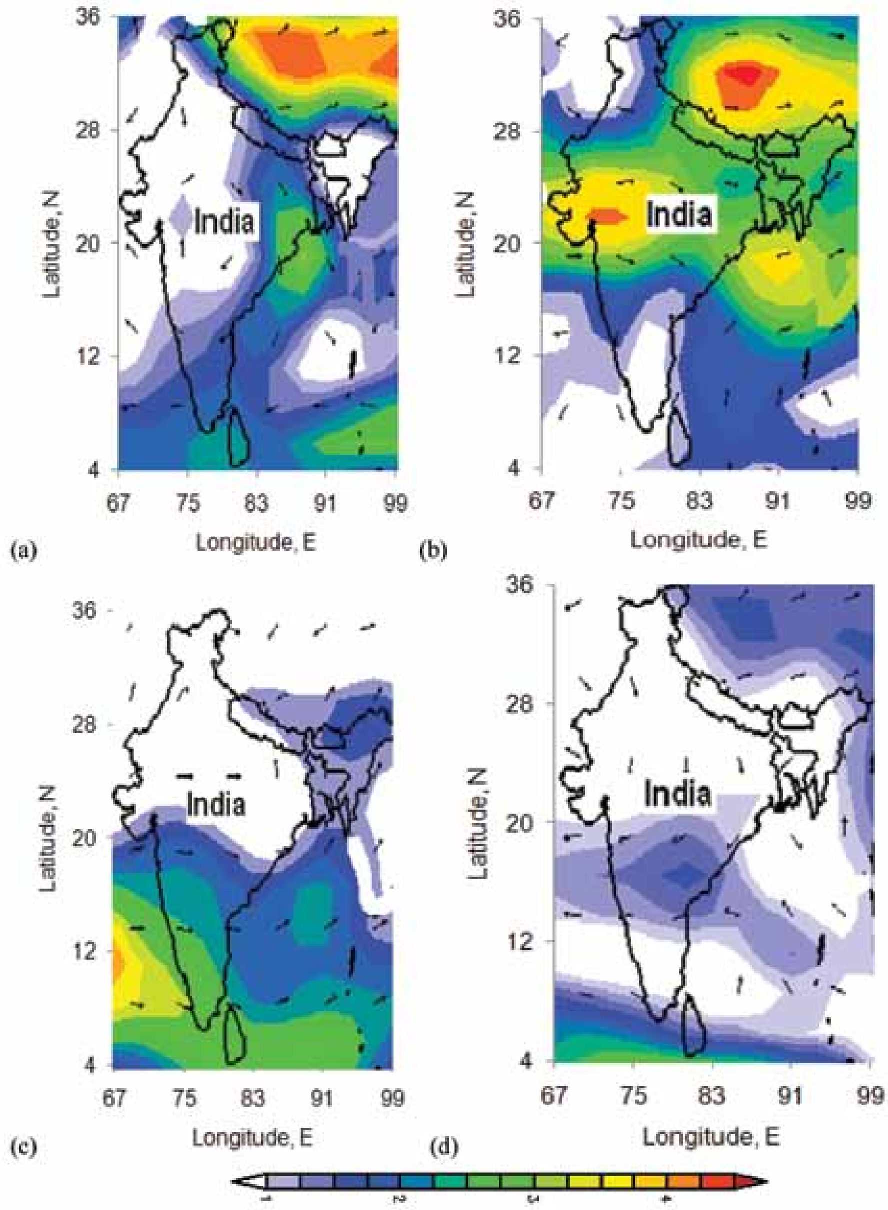


**Figure 5.** Mean synoptic vector wind pattern at 850 h Pa for various seasons (a: winter, b: summer, c: monsoon, d: post-monsoon) over Indian region for the period 2008-2010. Background color indicates the magnitude of the wind speed.

combining several techniques as hygroscopic behavior of aerosols that introduces complications in the study. Spatial relationships between the aerosol optical depth (AOD) and cloud parameters such as cloud fraction (CF), water vapor (WV), cloud top temperature (CTT) and cloud optical depth (COD) for the whole Indian region during the study period 2008-2010, were presented in this section. Larger amount of aerosol loadings tends to push the distribution and towards the higher clouds and larger cloud fractions neglecting the other factors of data sets. Each of these above relationships were discussed in detail and presented individually in the following sections.

## Spatial correlation between AOD and cloud fraction (CF)

The satellite data show a strong spatial correlation between AOD and total cloud fraction and AOD (Kumar, 1998; Quass et al., 2009; Saxena et al., 2010). Figure 6(a) shows the spatial correlation between AOD and cloud fraction for various Indian regions. Modis retrieved satellite data shows an increase in the cloud fraction (CF) with increasing AOD in all areas. MODIS provides cloud fraction data for day/night time and both. The combined spatial correlation satellite data has been used for the present study for the

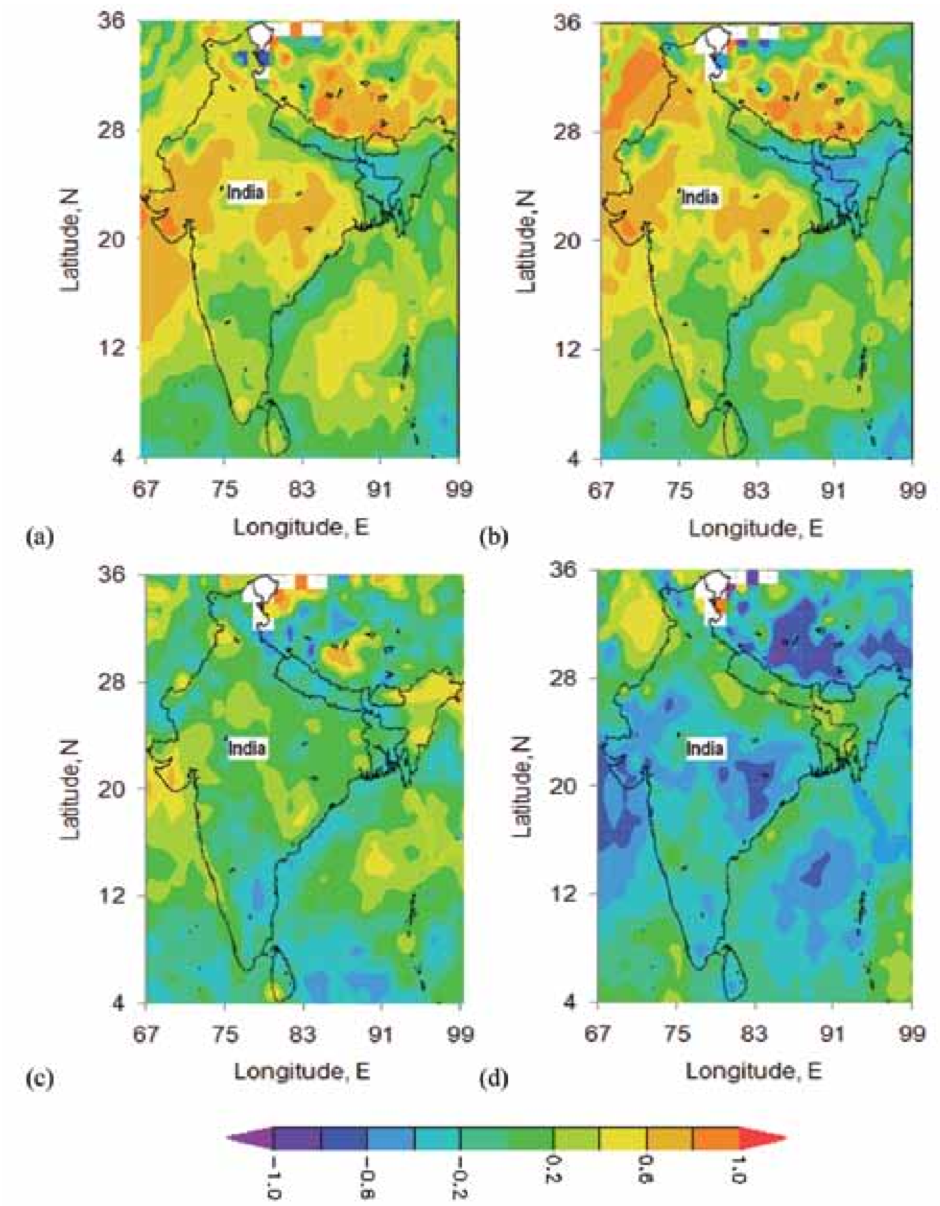


**Figure 6**. Spatial correlation map of AOD at 550 nm and cloud parameters (a) cloud fraction (CF), (b) water vapor (WV), (c) cloud top temperature (CTT), and (d) cloud optical depth (COD) over Indian region for the period of 2008-2010.

years 2008-2010. Correlation coefficients for AOD and CF were also calculated for this period. The correlation between cloud fraction and AOD was found to be higher at coastal stations. This may be noted that a significant increase in the correlation between AOD and CF were found in those regions, which were dominated by dust aerosols and biomass (Faruque et al., 2009).

## Spatial correlation between AOD and water vapor (WV)

The Modis satellite data provided a number of observations for water vapor in the clear sky and above clouds separately (Niranjan et al., 2011). We used the above clouds data obtained from Terra for water vapor for the period between 2008-2010. The spatial correlation between AOD and WV has been shown in Figure 6(b), which shows that AOD and water vapor had a stronger positive correlation at higher latitudes as compared to lower latitudes. Cloud formation also depends on the amount of water vapor available for condensation onto hydrophilic aerosols (Jones et al., 2009). Therefore, changes in aerosol water uptake behavior can lead to changes in both direct and indirect radiative forcing on climate (Kirankumar et al., 2013; Kumar, 2014). However, the hygroscopic behavior of aerosols depends upon the complex mixing of various types of atmospheric particles as well as on meteorological parameters such as humidity, wind speed, wind direction, and temperature (Lee et al., 2009). The water uptake behavior of atmospheric aerosols is significant, as it can alter both the size and the chemical composition of particles, and hence their prominent optical properties (Niu and Li, 2012).

### Spatial correlation between AOD and cloud top temperature (CTT)

In order to study the atmospheric and surface properties, investigations on cloud top temperatures are needed. CTT also plays an important role in the net earth radiation budget determinations. The spatial correlation between AOD and cloud top temperature (CTT) for the entire Indian region over the study period 2008-2010 indicates that CTT increased as AOD decreased in almost all regions investigated (Figure 6d). The cloud-top temperature was found to be insensitive to the change in the aerosol number, although there was a distinct negative correlation between the aerosol number and cloud temperature at which the cloud particle grows to a radius of 1.2 cm (King et al., 2003). It indicates that the atmospheric aerosols act on clouds so as to change cloud particle size near the cloud top. Moreover, in the real situation of increasing global aerosol particles, anthropogenic aerosols increase and hence they change the cloud-top temperature and atmospheric humidity profiles by the induced secondary circulation (Rodriguez et al., 2012). CTT is positively correlated with AOD for the year 2008 over the south Indian regions, whereas it shows a clear negative correlation during the remaining years of the study period.

### Spatial correlation between AOD and cloud optical depth (COD)

As cloud optical depth is a measure of attenuation of the light passing through the atmosphere due to the scattering and absorption by cloud, therefore, cloud optical depth has a large number of significant applications in climate change and hence in earth's radiation budget. A positive correlation (~0.50) is found between AOD and COD for the study period of 2008-2010 over Indian land regions (Figure 6d). Panicker et al., 2010 has earlier also found a positive correlation between aerosol optical depth and total cloud cover (TCC), using satellite retrievals and suggested that the dominant contribution to the AOD-TCC relationship can be attributed to aerosol swelling in regions, where humidity is high and clouds are coincidentally found. It also provides us a direction that much of the AOD-TCC relationship seen in the satellite data is also carried by such a process, rather than the direct effects of the aerosols on the cloud fields themselves (Ramachandran et al., 2006).

## CONCLUSIONS

Modis derived (collection 5, level 3) Terra/Aqua aerosol optical depth (AOD) at 550 nm over Indian subcontinent was investigated for three consecutive years, 2008 to 2010. The Modis satellite data was also used to investigate a correlation between aerosol optical depth (AOD) and cloud parameters such as cloud fraction, water vapor, cloud optical depth, and cloud top temperature for the same period. The major conclusions of the present study are

1. Both Modis derived Terra and Aqua mean AOD values exhibit similar spatial pattern over the entire Indian region for the study period of 2008-2010.
2. High AOD values (>0.70) have been found over industrial areas with enhanced industrial, transport and anthropogenic activities like Delhi, Mumbai, Kolkata, as these regions of India are dominated chiefly by the automobile and industrial activities.
3. Southern parts of India show a much cleaner environment with AOD less than 0.4 in the study period. The spatial gradient of AOD shows slight increase from southern part of Indian subcontinent to northern part up to Himalaya. The central India shows moderate AOD values.
4. High AOD is observed over the Ganga basin throughout the year, unlike the southern India. This high value of AOD at Ganga basin is alarming, as this region is one of the most productive basins of Indian subcontinent containing a huge population.
5. In 2008, the average value of AOD over Indian subcontinent was found to be $\sim 0.37 \pm 0.088$ whereas in 2009 and 2010, the mean values of AOD were estimated as $\sim 0.32 \pm 0.075$ and $\sim 0.35 \pm 0.058$ respectively. AOD is found to be increasing rapidly in all the years during summer season that may cause adverse effect to the agricultural crops and also to the human health. High aerosol loading may also affect the rainfall.
6. It may be noted that a significant increase in the correlation between AOD and CF were found in those regions, which were dominated by dust aerosols and biomass.
7. AOD and water vapor had a stronger positive correlation at higher latitudes as compared to lower latitudes. The spatial correlation between AOD and cloud top temperature (CTT) for the entire Indian region over the study period 2008-2010 indicates that CTT increased as AOD decreased in almost all regions investigated.

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## Compliance with Ethical Standards

The author declares that he has no conflict of interest and adheres to copyright norms.

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