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A study of aerosol optical depth variations over the Indian region using thirteen years (2001–2013) of MODIS and MISR Level 3 data

Manu Mehta

Photogrammetry and Remote Sensing Department, Indian Institute of Remote Sensing (IIRS), ISRO, Govt. of India, 4-Kalidas Road, Dehradun 248001, India

HIGHLIGHTS

- Delhi and Kolkata are the most polluted amongst ten most populous cities in India.
- Agreement in annual and seasonal AOD variation observed from MODIS and MISR.
- Increasing AOD trends in winter and post-monsoon seasons.
- Decreasing AOD trends in monsoon season.

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ABSTRACT

Aerosols affect the earth's climate system both on a regional as well as on a global scale. Several studies have identified India (the second most populous country) as one of the regional hot spots of aerosols due its increasing anthropogenic activities. The paper presents a temporal (annual and seasonal) study of aerosol optical depth (AOD) in the country using satellite data for thirteen year period (2001–2013). The Indian region is divided into four sub regions i.e., north, west, east and south. The analysis is carried out using Level 3 data from two satellite sensors, namely, MODIS ($1° \times 1°$) and MISR ($0.5° \times 0.5°$), onboard NASA's Terra platform. Annual and seasonal mean AOD variation has been studied. It is found that annual aerosol loading remains highest in Indo-Gangetic Plains (IGP) in all the years. In winter season, the overall loading is lowest for the entire country while it reaches maximum in the monsoon season. This could be attributed to the relative humidity, wind and associated rainfall patterns in the country. Also, the aerosol tendencies have been computed using the first and last six year period change in aerosol optical depth. Further, annual and seasonal trends in AOD have been calculated using weighted least square regression approach and the results have been compared. Statistically significant trends are reported at 95% confidence level. Weights are assigned corresponding to the expected errors associated with the satellite data. There is a good agreement in the seasonal tendencies and trends computed from both the sensors for winter, monsoon and post-monsoon seasons. Significantly increasing trends are found in winter and post-monsoon seasons which could be due to increase in anthropogenic activities. All the observations are separately reported for ten most populous cities of India. Delhi and Kolkata are amongst the most polluted cities in India.

1. Introduction

Aerosols are considered to affect the climate system both directly (scattering and absorption) and indirectly by altering the cloud properties; and contribute to one of the largest uncertainties in the determination of radiative forcing. Aerosol optical depth (AOD) is one of the primary optical properties that is a measure of aerosol loading in the atmosphere. Hence, long term study of this quantity becomes important both globally and on a regional basis (Prasad et al., 2006). Asia being the world's largest continent occupies 30% of its total land and hosts 60% of its human population. Global and regional studies carried out using both ground based instruments and multiple satellite sensors indicate increasing anthropogenic activities and henceforth, increasing aerosol loading in south Asia, especially in the Indian region (Beegum et al., 2013; Moorthy et al., 2013; Satheesh et al., 2008, 2009; Vinoj et al., 2004a, b). Over Kanpur, the only AERONET station in India,

E-mail addresses: manu@iirs.gov.in, mehtamanu12@gmail.com.

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variability and trends of aerosol optical depth (AOD) have been estimated using field instruments for the period 2001–2010 (Kaskaoutis et al., 2012). In Delhi, which is one of the most polluted cities of the world, microphysics, long term trends and source strengths have been estimated for 11.5 year period (2001–2012) and a weak but statistically significant trend is found (Lodhi et al., 2013). Recently, AOD trends have been estimated for some of the locations of ARFINET which indicate statistically significant increasing trends with seasonal variability (Babu et al., 2013). In India, however, there are a limited number of observatories over selected places and hence, studies from satellite observations become crucial to study the entire region for long term evaluation of AOD. Also, ground based measurements may be considerably influenced by local conditions and due to spatial variability of aerosols; they could sometimes fail to represent the region accurately (Srivastava et al., 2014). Previous attempts have been made in this direction using multiple sensor datasets at different spatial resolutions but many of these are done either by combining multiple sensor data on a regional basis or using one sensor datasets for entire Indian region. Specific studies on Indo-Gangetic basin for the period 2000–2005, using Level 3 MODIS and MISR data for summer and winter seasons revealed decreasing trend during April–September which is not statistically significant (Prasad et al., 2006). Contrasting trends of AOD during 2000–2009 over south Asia have been reported based on MODIS observations with evidences of declining trend in the month of June, attributed to less dust activity in north India during the last decade (Kaskaoutis et al., 2011). AOD trends at global and regional levels have been simulated using SeaWiFS measurements at $1^\circ \times 1^\circ$ for 1997–2010 which indicate increasing trends over India (Hsu et al., 2012). A decadal study (March 2000–Feb 2010) over Indian subcontinent using MISR Level 2 data focusing on seasonal trends indicates hotspots which have statistically significant trends (Dey and Di Girolamo, 2011). Yet, in another study, MODIS Level 2 data has been used to study mean annual and seasonal linear trends for 2000–2009 (Ramachandran et al., 2012). In an another study over Hyderabad, multiyear MODIS AOD observations over the period 2002–2008 show an increasing trend and it is observed that the Level 3 datasets are in better agreement with the sun photometer measurements compared to Level 2 data (Kharol et al., 2011). A satellite based study for Delhi has been carried out using MODIS and MISR Level 3 datasets along with CALIOP data for the period March 2000–Feb 2011 (Srivastava et al., 2014).

This study deals with the determination of annual and seasonal variation of AOD from satellite perspective using two different satellite sensors i.e., MODIS and MISR Level 3 monthly datasets at different spatial resolutions over the entire Indian region for thirteen year period i.e. 2001–2013. The annual and seasonal variation of AOD has been studied. Also annual and seasonal AOD tendencies have been estimated using both the sensors. Further, it is tried to figure out if there is any linear trend and if so, is it statistically significant? In case, the nature of trends estimated is same from both the sensors, the trend can be taken as remarkable, else inputs from other sensors and/or ground observations need to be combined together to find out the actual trend.

2. Study area, data and analysis

Increasing industrialization plays a leading role in the air pollution rise (e.g., mineral dust, black carbon, sulphates etc.) from large industrial cities in India. In addition, biomass burning like fuel wood, dung cake etc. causes thick haze and smoke mainly in north-west India. Due to extreme temperatures, rainfall and humidity, there is a large variability in aerosol characteristics found in the country (Habib et al., 2006; Ramachandran and Cherian, 2008). The pattern of mean synoptic surface winds, relative humidity, land use, aerosol emissions over Indian region has been discussed elsewhere (Ramachandran and Cherian, 2008; Lawrence et al., 2010; Ramachandran et al., 2012, 2013). In this study, the whole Indian region is divided into four different parts; north, west, east and south (Fig. 1). Four climatological seasons are prevalent, i.e., winter (December–February), pre-monsoon (March–May), monsoon (June–September) and post-monsoon (October–November). Annual and seasonal analysis has been discussed for ten most populous cities in India in particular (Census of India, 2011) (Table 1).

In the analysis, data is taken from MODIS and MISR, both onboard Terra satellite orbiting at 705 km in a near-polar orbit. MODIS (Moderate resolution Imaging Spectroradiometer) is a sensor which has 36 spectral bands covering the range of 0.415–14.5 μm with a swath of ~2330 km and variable spatial resolution (1 km, 0.5 km and 0.25 km) depending on spectral band with repeat coverage of 2 days. The MODIS aerosol retrieval algorithm is based on “dark-target”and uses a Look-up-table (LUT) approach with a pre-defined set of aerosol types, loadings and geometry (Remer et al., 2005). In this study, MODIS Level 3 monthly AOD data product (MOD_08_M3) at $1^\circ \times 1^\circ$ spatial resolution from Collection 5.1 has been used.

MISR (Multi-angle Imaging Spectro-Radiometer) employs nine cameras, one viewing nadir and four each viewing in forward and aft directions and has four spectral bands i.e. blue, green, red and near-infrared (Diner et al., 1998). The global coverage time is every 9 days with repeat coverage between 2 and 9 days depending on the latitude. The aerosol retrieval algorithm over land is dependent on the surface types within a scene i.e., dark water bodies, heavily vegetated areas or high contrast terrain (Martonchik et al., 2009). Level 3 AOD products (MISR_AM1_CGAS) from F15_0031 collection obtained at $0.5^\circ \times 0.5^\circ$ from Level 2 products (17.6 km spatial resolution) have been used in the study.

The validation of satellite data products over Indian region has been done in many of the previous studies and would not be touched upon in the analysis. Nevertheless, it could be specified that validation of MODIS AOD over Ahmedabad (western India), Kanpur (Indo-Gangetic Basin) and south-east Arabian Sea has been carried out earlier specifically for Indian region (Jethva et al., 2007; Misra et al., 2008; Levy et al., 2010). Studies have also been reported in the past focusing on validation of MISR AOD products (Di Girolamo et al., 2004; Meij et al., 2010). It is worth to mention here that during winter, winds are dry and blow from northern hemisphere towards north-east, whereas, in pre-monsoon, winds travel from the west. In monsoon season, winds are moist and come from the marine areas while in post-monsoon season, winds start shifting from south-west to north-east.

The expected errors associated with the MODIS retrieved AOD fall within $\pm (0.15\text{AOD}_{\text{MODIS}} + 0.05)$ (Remer et al., 2005). Similarly, the uncertainty associated with MISR data is found to be greater of 0.05 or 0.2 AOD_{MISR} whichever is higher (Kahn et al., 2005, 2010). Though MODIS-MISR correlation studies have been reported in the past (Kahn et al., 2009; Xiao et al., 2009; Shi et al., 2011), nevertheless, a correlation analysis is carried out for MODIS and MISR datasets in the four seasons for entire Indian region. Similar results are found when the correlation studies are performed for the four sub regions of the country respectively. Fig. 2 depicts the correlation between the two datasets for two years, one with low aerosol loading (2001) and the other with high aerosol loading (2009) respectively. It is seen that correlation is higher in winter and post-monsoon seasons when the aerosol loading is low whereas the correlation is lower for pre-monsoon and monsoon seasons which witness higher AOD values. Hence, it is expected that findings from both the sensors could be in better agreement for winter and post-monsoon seasons.