LONG-TERM VARIABILITY OF MODIS 3 KM AEROSOL OPTICAL DEPTH OVER INDIAN REGION

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ABSTRACT:

The study examined the spatio-temporal variability, validation and climatological trend of MODIS Terra and Aqua level-2 Dark Target retrieval algorithms 3-km AOD over India region during 2001-2017. Analysis reveal the MODIS AOD shows significant variability in spatial extent; Indo-Gangetic plane having high aerosol loading and Southern peninsula shows relatively low aerosol loading in all seasons. The climatological zonal averaged (throughout India) AOD_{500} are 0.401±0.23 and 0.324±0.64 for Terra and Aqua respectively whereas the ground measured all stations averaged AOD_{500} is 0.43±1.2 during study period. For validation we obtained daily AOD data from nine ground network stations across India. MODIS 3-km AOD shows good agreement with ground measurements. A total of 5646 and 4920 data points are utilized for validation of MODIS Terra and Aqua AODs respectively and the overall correlation coefficients and RMSE values are 0.94 & 0.08 and 0.72 & 0.17 for Terra and Aqua over the Indian region. However, during monsoon season, both the MODIS AODs are highly overestimated because of atmospheric noise and turbidity. Trend slopes and significances were calculated using Mann-Kendell test at nine selected stations and whole region. AOD shows a significant positive trend (99.9% confidence level) over India with an increasing rate of 2.35 yr^{-1} and 2.03 yr^{-1} for Terra and Aqua respectively. All stations annual AODs shows the increasing trend with different significance levels except Patiala. This study reveals the potential applications of the 3-km AOD product in aerosol climatology over Indian region.

1. INTRUDUCTION

The knowledge of spatial and temporal distribution of aerosols on regional scale is essential to understand the dynamics of aerosol and its associated effects on regional and global climatic conditions (Morel *et al*. 2018). Aerosol is an important component of the earth system which substantially affect the climate both directly (scattering and absorption of solar radiation) and indirectly (altering the cloud microphysical properties) (Ramanathan *et al*. 2001; Satheesh and Ramanathan 2000; Shaik *et al.*, 2017). Apart from the climate, it also affects regional air quality, hydrological cycle, human health and ecosystems (Dumka *et al.* 2016; Babu *et al.* 2011). Aerosol substances evolve in the atmosphere either through natural processes (like soil dust, sea salt, biogenic and volcanic emissions) or anthropogenic activities (like combustion of fossil fuel, industrial emissions and crop residue burning) (Mhawish, *et al*. 2017). Aerosols are generated at one place and transported over long distances *via* winds, and produce consequent effects at locations far away from the source (Guleria, *et al.* 2012). Hence, study of aerosol properties (e.g., Aerosol Optical Depth (AOD)) are important on regional and global scales. However, the observations of aerosols is geographically limited, and their impacts on climate changes still remain uncertain (IPCC 2013). In this context, satellite remote sensing has the advantage of generating spatial and temporal distribution of aerosol optical properties. Aerosol retrieval satellite sensors like Moderate-Resolution Imaging Spectroradiometer (MODIS), Multiangle Imagining Spectroradiometer (MISR), Ozone Monitoring Instrument (OMI), Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), ocean colour monitor (OCM) and Medium Resolution Imagining Spectrometer (MERIS) are widely used (Shaik *et al*. 2017; Torres and Jethva 2014;Dumka *et al*. 2016; Mishra *et al.* 2018). Among various sensors that routinely provide AOD throughout the globe, MODIS on board Terra and Aqua is recognized as the most extensively used and validated (Mhawish *et al.* 2017). MODIS derived AOD have been extensively applied in many field of research including air-quality assessment, aerosol direct radiative forcing, climate model simulations, aerosol sources and transport process, and aerosol-cloud-precipitation interactions etc. (Valenzuela *et al*. 2012; Sayer *et al.* 2014). For the validation of MODIS aerosol products and for qualitative ground based measurements of aerosols, a network of ground sun-photometers worldwide AERONET (Aerosol Robotic Network) has been established and successfully maintained for the last two decades (Holben *et al.* 2001). An aerosol network of ground stations is also established over India for the last three decades (ARFINET) (Moorthy *et al.* 1989; Babu *et al*. 2013).

Asia is the largest source of aerosols and their precursor gases in the world, particularly in China, India, and Pakistan regions were annual averaged AOD exceeds the global background levels by 4–5 times based on the AERONET measurements (Nichol and Bilal 2016). Several field campaigns have already been undertaken in the Asian region to study the aerosol properties and its impacts on the continent and the surrounding ocean regions like Indian Ocean Experiment (INDOEX), the Arabian Sea Monsoon Experiment (ARMEX), the Bay of Bengal Monsoon Experiment (BOBMEX), the Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB) and the overview of these results are reported elsewhere (Ramanathan *et al.* 2001; Mandal *et al.* 2006; Moorthy *et al.* 2008). There have been numerous studies done on aerosol

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properties over north Indian region, particularly Indo Gangetic Plain (IGP) (Kaskaoutis *et al.* 2013; Srivastava *et al.* 2014; Kant *et al.* 2015). All of these studies have significantly improved our understanding of aerosol optical and microphysical properties and their variability across the Indian subcontinent. However, a complete spatial analysis remains hindered because of the spatially limited nature of these data sets. The present study aims to develop an integrated picture of the spatial and temporal distribution of aerosol loading over the Indian region based on MODIS Terra and Aqua Dark Target (DT) algorithm 3-km AOD data for a period of 17 years and evaluate the accuracy and feasibility of MODIS aerosol products with ground based network (ARFINET, AERONET & SKYRADNET) datasets. Finally aerosol seasonal characteristics, as well as the variation in trends and their significance has been studied.

2. DATA AND METHODOLOGY

2.1 Satellite Observations

Moderate Resolution Imaging Spectrometer (MODIS) on-board Terra/Aqua satellites provide the daily global information on Earth atmospheric aerosol properties by measuring the reflected sunlight from the earth's atmosphere & the surface and emitted thermal radiation at 36 wavelengths (Levy *et al.* 2013). MODIS swath resolution approximately 2330 km wide and makes 14 to 15 orbits per day to covers the entire globe. There are two different algorithms used to retrieve aerosol properties over land and over ocean and these algorithms are improved in day by day manner (Levy *et al.* 2007; Remer *et al.* 2008). A comprehensive description of the MODIS aerosol retrieval algorithms can be found at MODIS aerosol science team publications (Remer *et al.* 2005; Levy *et al.* 2013). For the present study we have used the daily Level-2 MODIS/Aqua (MOD04) and MODIS/Terra (MYD04), Dark Target retrieval algorithm Collection-6 3-km AOD products over Indian region during January 2001 to December 2017. MODIS AOD parameter is substantially validated regionally and globally and have been used for aerosol studies (Kosmopoulos *et al.* 2008; Mhawish *et al*. 2017). The excepted errors in determining these parameters are ±0.05 and the uncertainties are generally attributed due to the non-spherical size distribution of aerosols and different algorithms used for land and ocean (Levy *et al.* 2010).

2.2 Ground based Measurements

2.2.1 AERONET

The AERONET (AErosol RObotic NETwork) program is a ground-based optical aerosol monitoring global network established by National Aeronautics and Space Administration (NASA), USA. The main purpose of the AERONET program is to maintain a long-term database of aerosol products and it utilised to validate the satellite remote sensing algorithms at different environments (Holben *et al.* 1998). The network hardware consists of CIMEL sun photometer, which measures the direct-solar flux at 0.340μm - 1.020μm and diffuse measurements at 0.44μm - 1.02μm with different spectral wavelengths. The direct-solar flux measurements are used to estimate the columnar AOD, total perceptible water vapor content (0.940 μm) and Ångström exponent (0.440 and 0.870 μm) whereas the diffuse Sky measurements are used for aerosol profiles such as columnar size distribution, phase function and single scattering albedo (Tripathi *et al*. 2005; More *et al.* 2013). The CIMEL instrumentation, working principle, retrieval algorithms and calibration details described in elsewhere (Dubovik *et al*. 2000; Holben *et al.* 2001). The uncertainty in CIMEL retrieval of AOD is <±0.01 under cloud free conditions. In this study, the daily-averaged Level 2.0 AOD products (final cloud-screened and quality assured products) are taken from five AERONET stations *i.e.,* Jaipur (26.90 N, 75.80 E), New Delhi (28.63 N, 77.17 E), Nainital (29.35 N, 79.45 E), Kanpur (26.51 N, 80.23 E) and Gandhi College (25.87 N, 84.12 E).

2.2.2 ARFINET

ARFINET is a national network of aerosol observatories (Aerosol Radiative Forcing over India Network) established by Indian Space Research Organization (ISRO) with the objective of generating long-term data sets over Indian region (Moorthy *et al.* 2013). These observatories uses multi-wavelength Solar Radiometer (MWR) (Babu *et al.* 2013) in addition to handheld Sun photometer (Morys *et al.* 2001) to measure columnar spectral AOD. Ground station over Dehradun measures direct solar flux measured by MWR at 10 wavelengths (380, 440, 450, 500, 600, 650, 750, 850, 935 and 1024 nm) were analyzed using Langley plot technique and slope of this plot provides the AOD. The instrument details, AOD retrieval method and error associated with measurement are discussed elsewhere (Kompalli *et al.,* 2010). On the other hand, Sun photometer provided the spectral AOD at five wavelengths *viz*. 380, 440, 500, 675 and 870 nm. The measurement protocol is based upon the principal of measuring the intensity of incoming solar radiation at particular wavelength and then converting it into optical depth using its internal calibration and Langley-method. More details about the design, calibration, performance and errors of Sun photometer is described elsewhere (Morys *et al*. 2001). The strong correlation between MWR and Sun photometer AOD were reported by earlier studies (Babu *et al*. 2013 and references therein). For our analysis, we used AOD measured at two stations of ARFI network database *i.e.,* Dehradun (30.30 N, 78.03 E) and Patiala (30.33 N, 76.40 E).

2.2.3 SKYRAD NETWORK

Network of skyradiometer stations situated in different geographical locations over India initiated by India meteorological Department (IMD), New Delhi for studying the aerosol impacts on local and global climate. Aerosol optical depth (AOD) is retrieved from the Sky Radiometer (POM-II, PREDE, Japan) which measures direct, diffuse radiation at 11 wavelengths (315, 340, 380, 400, 500, 670, 870, 940, 1225, 1600, and 2200 nm). The Aerosol optical depth retrieval using SKYRAD.pack (version-4.2) can be found elsewhere (Nakajima, 2003). This optical depth data is further cloud screened based on the Cloud screening algorithm developed by the Khatri *et al.,* (2009). In this study we have obtained AOD data from two SKYRAD network stations; Delhi (28.63 N, 77.17 E) and Trivandrum (8.54 N, 76.94 E). The time series of AOD at 500nm is extrapolated to AOD at 550nm using Angstorm exponent calculated at 400, 670 nm wavelengths (Sateesh *et al.* 2018).

2.3 Methodology

In this study, MODIS 3 km AOD product and ground based observations are analyzed to understand the spatio-temporal characteristics of aerosols over the Indian region. The long term daily MODIS AOD (MOD04_3K/MYD04_3K) data has been taken from NASA Atmosphere Archive and Distribution System (http://ladsweb.nascom.nasa.gov). The daily AOD data was processed and spatial maps generated extensively over the Indian region for a period of 17 years (Terra) and for 16 years (Aqua) respectively. For the validation of MODIS AOD product

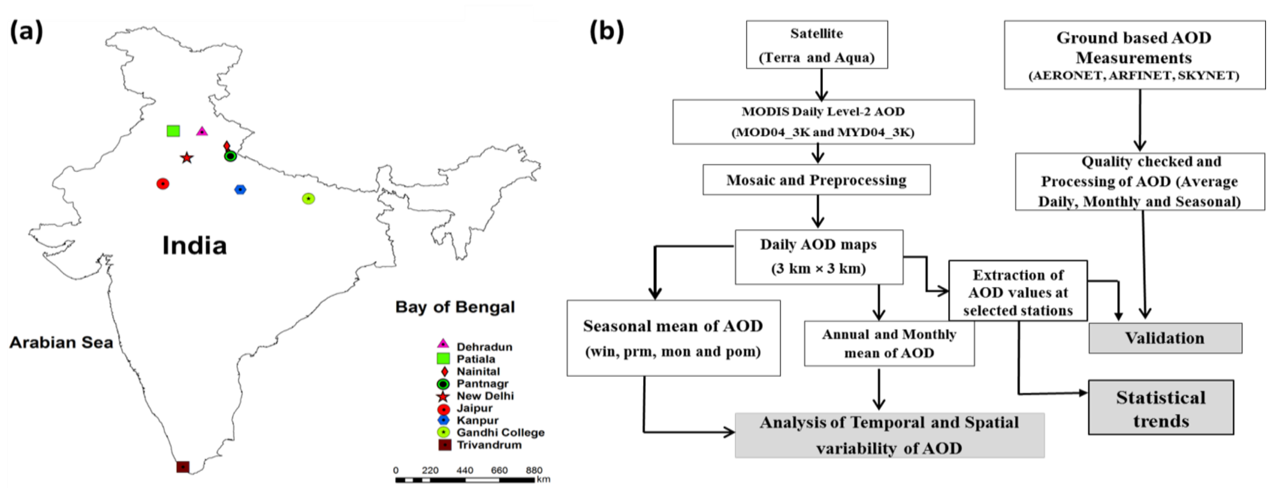

Figure 1. (a) Locations of ground based measurements and (b) Flowchart of methodology adapted in this study.

we extracted AOD values at different geographical locations where the ground based measurements are available. Figure 1 shows the locations of ground based measurements and flowchart of methodology adopted in this study. The ground measurement data were averaged within 30 min of the satellite overpass time and compared with MODIS AOD averaged within a 3 × 3 pixel window of the measurement site. Monthly averages, correlations and their trends were obtained from MODIS and ground observations (AERONET, ARFINET, SKYRADNET) of all valid AOD values. For validation of MODIS AOD, we examined the statistical parameters such as correlation coefficient (R), root-mean-square error (RMSE), mean absolute error (MAE), relative mean bias (RMB), and the expected error (EE) at all ground observational locations:

$$\mathrm{RMSE}=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\mathrm{AOD}_{(MODIS)_i}-AOD_{(Ground)i}\right)^2} \qquad \text{--------- (1)}$$

$$MAE=\frac{1}{n}\sum_{i=1}^{n}\left|AOD_{(MODIS)i}-AOD_{(Ground)i}\right| \qquad \text{--------- (2)}$$

$$RMB=\frac{1}{n}\sum_{i=1}^{n}\left|AOD_{(MODIS)i}\ /\ AOD_{(ground)i}\right| \qquad \text{--------- (3)}$$

$$EE=\pm\left(0.05+0.015AOD_{(MODIS)}\right) \qquad \text{--------- (4)}$$

The multi-year trends in MODIS AOD over all the stations were estimated using a non-parametric Mann-Kendall (M-K) statistical test. The M-K test has been applied extensively to estimate aerosol trend globally (Collaud *et al.* 2013; Fan *et al.* 2018), and over Indian sub-continent (Srivastava and Saran 2017). We applied the M-K test with the null hypothesis (H0) considering no trend exists in the AOD values and two alternative hypotheses (H1) were that there is a negative, or a positive trend in the data. The significance of correlation were also determined via the M-K test, where p-values are smaller than the significance thresholds i.e., $p<0.001$, $P < 0.01$, and $p < 0.05$ implies that statistically with 99.9% , 99% and 95% confidence level of significance (Drapela and Drapelova 2011). The M-K test is suitable for evaluating the long-term trend with missing and/or extreme values and with non-normal distributions in the data samples (Kumar *et al.* 2018).

3. RESULTS AND DISCUSSIONS

3.1 Climatological seasonal distribution of AOD

Figure 2 shows the climatological seasonal distribution of AOD based on 17 years record of MODIS data. Prevailing meteorological conditions over the Indian sub-continent, the four seasons are considered; winter (Win) (December-February), pre-monsoon (PrM) (March-May), monsoon (Mon) (June-September) and post-monsoon (PoM) (October-November) (Kumar *et al.* 2012). The dominance of the monsoon over the Indian subcontinent controls the seasonal highs and lows of aerosol concentration. In general, during PrM and Mon, the concentration of aerosol particles remains high in the atmosphere as compared to PoM and Win seasons.

As observed from figure 2, during winter both MODIS Aqua and Terra (AOD550nm) show high aerosol loading over northern India, (seasonal mean from 2001-2017) particularly over Central and eastern IGP (AOD from 0.5 to 0.7) because of cold surface conditions coupled with the abundance of cold air, which produces dense fog, mist, and haze, through condensation of water vapor on carbonaceous aerosols. The comparatively low concentration of AOD was observed over south and central part of India (averaged AOD_{500} in range of 0.15-0.34) while high aerosol loading over Indo-Gangetic region (AOD_{500} >0.4) is attributed to biomass burning activity coupled with local emissions and meteorological conditions. During PrM, aerosol loading is somewhat controlled by the surface moisture content over the region. The shifting of the inter tropical convergence zone in Indian region produces intense heating at the surface level resulting in several local convections developed and associated with strong dust storms. These dust storms transfer the huge amount of soil and mineral dust to the atmosphere (Pandithurai *et al.* 2008). In north India several such local-level convections are experienced during PrM season and produce a wide range of dust particles responsible for moderate to high AOD (AOD_{500} ~ 0.2-0.6) over northern India (Prasad and Singh2007; Tian *et al.* 2018). Mon season having high AOD (AOD_{500} >0.40) is observed during Mon season over entire Indian region. In this season, large spatial extent of aerosol loading with maximum over IGP is clearly visible (AOD_{500} >0.7) while moderate loading (AOD_{500} ~ 0.4-0.6) over central India. The variability (spatio-temporal) of AOD depends on the onset of monsoon, duration of monsoon, frequency and intensity of rainfall over Indian region.
The PoM season is the transition period between the wet and dry seasons over Indian sub-continent. By the end of the monsoon, aerosol levels starts to rise to a peak during the post-monsoon and winter, especially over IGP due to open agriculture waste burning occurring during this season.

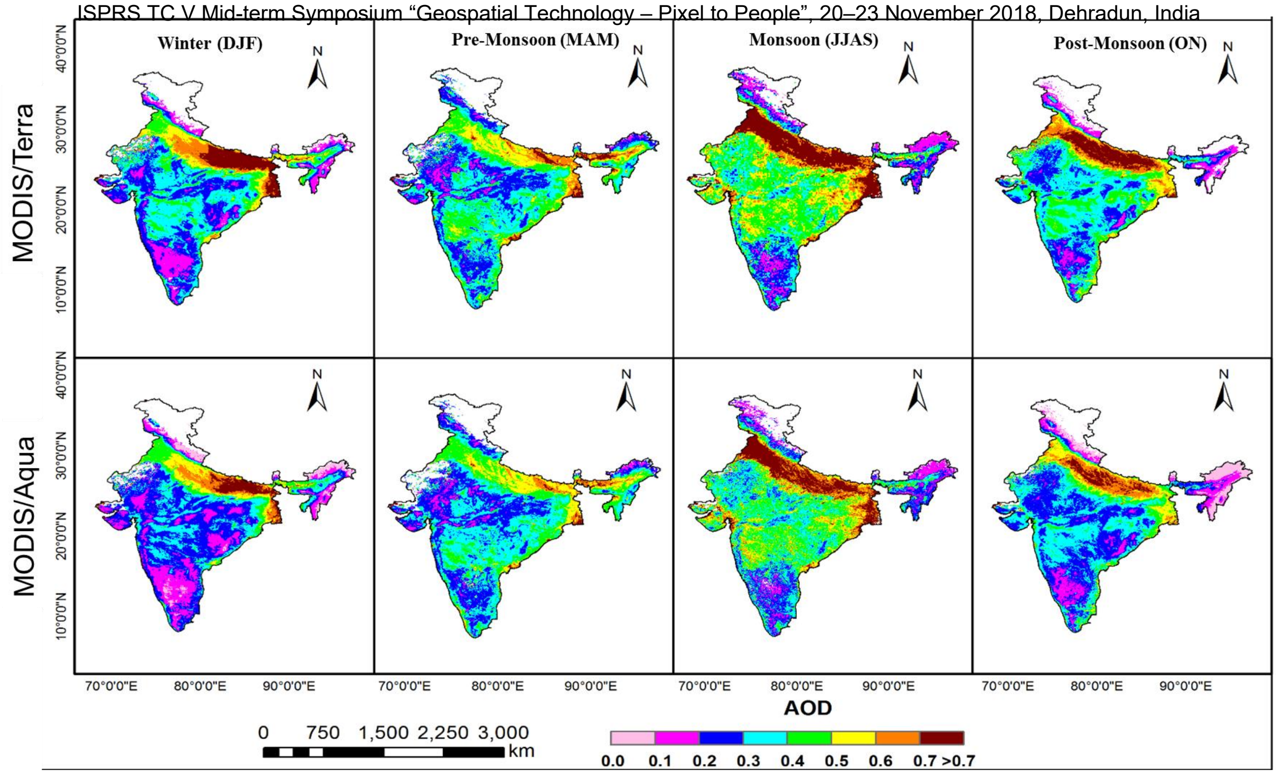

Figure 2. Seasonal spatial distribution of climatological (2001–2017) average AOD over the Indian based on MODIS 3-km Terra (top panel) and Aqua (bottom panel).

AOD500 are below 0.3 throughout India except IGP (AOD500 >0.6). The occurrence of agricultural residue burning was reported during these seasons and add up the column concentration of aerosol particles leading to increase in AOD values. The crop residue burning emissions are common practices in Punjab and Haryana region and transported to downwind Indo-Gangetic Plane regions and eastern part of Bay of Bengal.

Similar seasonal results with longer databases were observed at geographically distributed nine ground measurements (AERONET-5nos, ARFINET-2nos and SKYRADNET-1no.) across India. A strong seasonal pattern is clearly visible in both the data sets with higher AOD values in the PrM and PoM and lower AOD values in the monsoon and winter seasons. The ground stations shows distinct seasonal variability over Indian sub-continent (figure 3). Maximum AOD values observed over New Delhi (AOD500~0.88) along with Kanpur (AOD500~0.59) while minimum values are at Nainital station (AOD500~0.20). Ground and satellite observations clearly shows that the pre-monsoon air mass carries dry dust particles from the western regions and Thar desert to north India which produces high aerosol loading while during the post-monsoon and winter seasons, the region is dominated by most of the aerosols of anthropogenic sources (biomass burning and fossil fuel combustion) (Singh et al. 2015). Monsoon rainfall washout the aerosol particles in the atmosphere that leads to low AOD. Overall, the seasonal variation and magnitude of MODIS AODs are similar to those from ground measurements, as an exception, during monsoon season, i.e, MODIS AOD is biased high (up to a factor of 2) during monsoon season may be MODIS algorithm capture the cloud condensation as aerosols (Shaik et al., 2017a; Pan et al., 2015).

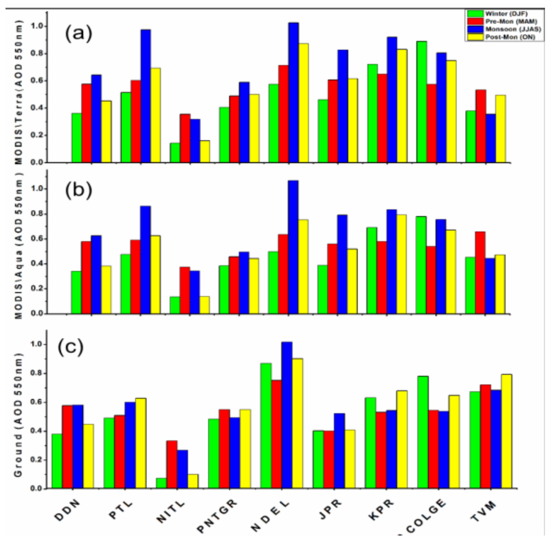

Figure 3. Climatological (2001-2017) seasonal variation of AOD at 550nm (a) Terra , (b) Aqua and (c) ground measured at different locations over India.

Sl. No	Stations	Number of observations – Terra (Aqua)	Correlation Coefficient- Terra (Aqua)	Mean Absolute Error- Terra (Aqua)	RMSE- Terra (Aqua)	RMB-Terra (Aqua)
1	Dehradun	591 (490)	0.94 (0.82)	0.063 (0.076)	0.08 (0.09)	0.955 (0.984)
2	Patiala	667 (568)	0.85 (0.74)	0.116 (0.109)	0.11(0.14)	1.005 (0.934)
3	Nainital	210 (192)	0.77 (0.90)	0.108 (0.075)	0.13(0.07)	1.259 (1.196)
4	Pantnagar	195 (191)	0.86 (0.83)	0.095 (0.116)	0.10 (0.09)	1.038 (1.005)
5	New Delhi	832 (739)	0.81 (0.84)	0.142 (0.114)	0.19 (0.09)	0.981(0.983)
6	Jaipur	567 (474)	0.85 (0.84)	0.135 (0.093)	0.12 (0.11)	1.292 (1.113)
7	Kanpur	1720 (1420)	0.84 (0.75)	0.16 (0.134)	0.17 (0.17)	1.217 (1.076)
8	Gandhi College	594 (625)	0.82 (0.87)	0.142 (0.117)	0.19 (0.14)	1.136 (1.014)
9	Trivandrum	275 (255)	0.80 (0.88)	0.157 (0.098)	0.11 (0.16)	0.759 (0.903)

Table 1. Statistical parameters between MODIS 3-km AOD at 550nm Terra (Aqua) and ground measured AODs at selected stations across the India during 2001-2017.

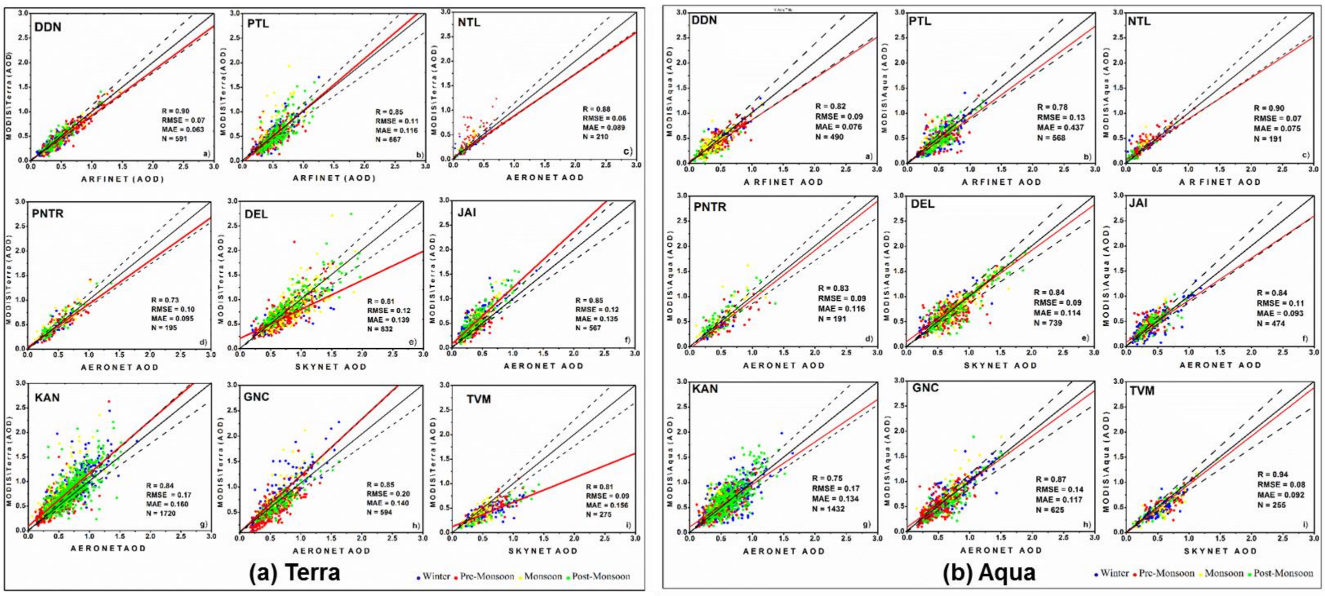

Figure 4. Scatter plot of MODIS DT 3-km daily AOD against ground measured AOD at nine stations across India (a) Terra and (b) Aqua. The red solid line represents ‘regression line’, the dash lines stand for the MODIS ‘Expected error lines’, and the black solid line is ‘1:1 line’. The colour code represents the daily AODs with corresponding seasons.

3.2 Comparison of satellite AOD with ground measurements

Daily AOD values of MODIS Terra and Aqua at nine selected stations are plotted against the ground based AOD measurement (AERONET, ARFINET and SKYRADNET) sites over Indian region (figure 4). A total of 10,566 collocated MODIS Aerosol retrievals spanning of 2001 to 2017 with the recommended QA (Quality Assurance) AOD product. The statistical parameters of all the stations for Terra and Aqua are reported in table 1. Terra daily AOD data is compared with daily ground based AODs, and the highest correlation coefficient (R~ 0.94) was observed over Dehradun and lowest value over at Nainital (R~0.77) whereas comparison of Aqua AOD with the ground AODs reveals the correlation coefficient is highest over Nainital (R~0.90) and lowest over Kanpur (R~0.75).

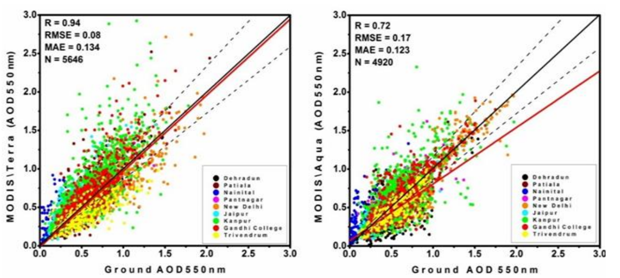

Figure 5. Scatter plots between MODIS 3-km AOD at 550nm (a) Terra and (b) Aqua against ground measured AOD for all locations across India during 2001- 2017. The red solid line represents ‘regression line’, the dash lines stand for the MODIS ‘Expected error lines’, and the black solid line is ‘1:1 line’.

Overall, the correlation between *in-situ* and MODIS (Terra and Aqua) AODs are having strong correlation coefficient (R) as 0.94 and 0.72 with RMSE as 0.08 and 0.17 for Terra and Aqua respectively. The mean absolute error of overall daily AODs over Indian region is 13% for Terra and 12% for Aqua satellite (figure 5). Differences of statistical parameters found in the study might be due to lack of appropriate MODIS aerosol retrieval algorithms, MODIS AOD representative of geographical pixels and site specific aerosol sources and types.

3.3 Long-term trends in aerosol loading over Indian region

A trend is a significant change over time exhibited by a random variable, detectable by statistical parametric and non-parametric procedures (Longobardi and Villani 2009). To identify the trends in each of the nine stations during the study period, we carried out a non-parametric Mann- Kendall test for the MODIS Terra and Aqua averaged monthly and seasonal AODs. Monthly time series of averaged AODs over nine stations are presented in figure 6. A statistically significant increasing trend was observed (0.007 $year^{-1}$ and 0.004 $year^{-1}$ for terra and Aqua respectively) over entire Indian region. The seasonal and annual statistics are presented in table 2&3 for terra and aqua respectively. The Sen's slope represent the overall change in trend (either positive or negative) of data samples. In the last seventeen years record of MODIS Terra AOD over India, most of the locations shows increasing annual trend except at Patiala where the trend is weakly negative (-0.0725). The increasing trend of aerosols over Indian region, is may be due to growth of industries and vehicular transport, increasing in residential/agricultural biomass burning and demand of energy (Reddy and Venkataraman 2002; Kumar *et al.* 2018). Observations from Terra AOD shows, Nainital stations as highest negative trend during post and pre- monsoon seasons (-0.026 $year^{-1}$ and -0.651 $year^{-1}$) followed by New Delhi station in winter (-0.027 $year^{-1}$) and Kanpur station in monsoon (-0.094 $year^{-1}$) while positive trend is highest over Trivandrum in winter season (4.203 $year^{-1}$; 95% confidence level) followed by Jaipur in annual trend (3.6 $year^{-1}$; 99% confidence level). Based on the Aqua records, the monsoon season only shows negative trends in which Pantnagar (rural location in the IGP) as -0.021 $year^{-1}$ and rest of the seasons are all in positive trend. Similar results are observed with 25 years extensive database of ARFINET ground measurements over Indian region (Babu *et al.* 2013) and long-term (2006-2015) MODIS/Terra AOD trends over IGP region (Kumar *et al.* 2018). The analysis is first of the comprehensive attempt to recognize and understand spatio-temporal changes in aerosol loading over Indian region considering the enhanced MODIS C6 dark-target 3km AOD product.

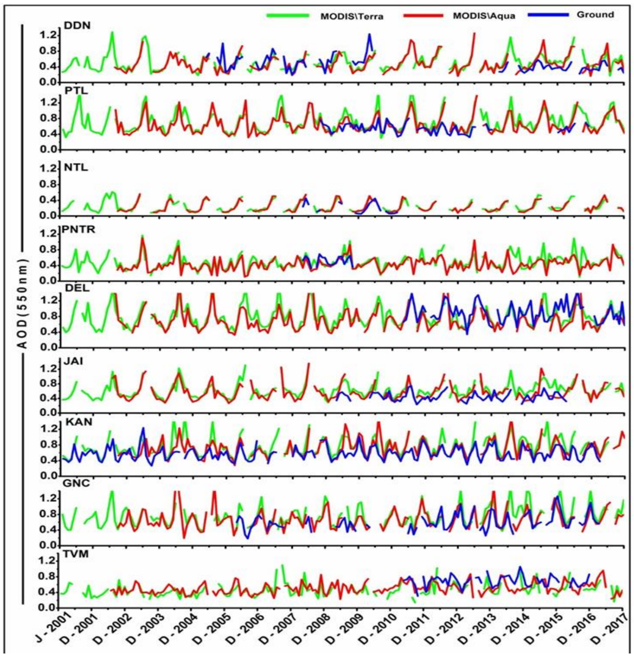

Figure 6. Time series of monthly averaged AOD_{550nm} at selected stations over India during January 2001-December 2017

Stations	Duration		Base AOD	Slope	Z Value	Significance	Trend
Dehradun	2001-2017	**Annual**	**0.38**	**0.0052**	**2.18**	*	**1.37**
		Win	0.29	0.0087	2.93	**	2.99
		Prm	0.46	0.0047	0.70	NS	1.02
		Mon	0.52	0.0126	0.95	NS	2.44
		Pom	0.50	0.0086	2.02	*	1.71
Patiala	2001-2017	**Annual**	**0.51**	**0.0039**	**1.44**	**NS**	**0.77**
		Win	0.45	0.0089	3.74	***	1.97
		Prm	0.57	0.0024	1.28	NS	0.42
		Mon	0.93	0.0037	0.78	NS	0.40
		Pom	0.73	0.0071	2.51	*	0.97
Nainital	2001-2017	**Annual**	**0.37**	**0.0031**	**1.52**	**NS**	**0.86**
		Win	0.11	0.0032	2.30	*	3.05
		Prm	0.31	-0.0020	-0.45	NS	-0.65
		Mon	0.14	0.0061	0.95	NS	4.32
		Pom	0.24	-0.0001	-0.12	NS	-0.03
Pantnagar	2001-2017	**Annual**	**0.55**	**0.0037**	**1.52**	**NS**	**0.68**
		Win	0.32	0.0083	3.20	**	2.56
		Prm	0.42	0.0022	0.70	NS	0.52
		Mon	0.48	0.0064	0.78	NS	1.34
		Pom	0.62	0.0116	2.18	*	1.85
New Delhi	2001-2017	**Annual**	**0.65**	**0.0044**	**1.52**	**NS**	**0.68**
		Win	0.47	0.0121	2.93	**	2.56
		Prm	0.69	-0.0002	-0.04	NS	-0.03
		Mon	0.92	0.0010	0.12	NS	0.11
		Pom	0.89	0.0061	1.11	NS	0.69
Jaipur	2001-2017	**Annual**	**0.30**	**0.0111**	**3.75**	***	**3.67**
		Win	0.38	0.0092	2.84	**	2.44
		Prm	0.50	0.0042	1.44	NS	0.84
		Mon	0.65	0.0058	0.87	NS	0.89
		Pom	0.47	0.0154	3.58	***	3.26
Kanpur	2001-2017	**Annual**	**0.59**	**0.0142**	**3.83**	***	**2.40**
		Win	0.58	0.0152	3.47	***	2.61
		Prm	0.51	0.0013	0.21	NS	0.26
		Mon	0.86	-0.0008	-0.37	NS	-0.09
		Pom	0.71	0.0186	3.01	**	2.63
Gandhi College	2001-2017	**Annual**	**0.63**	**0.0137**	**3.75**	***	**2.16**
		Win	0.68	0.0236	3.29	**	3.47
		Prm	0.50	0.0034	1.11	NS	0.68
		Mon	0.79	0.0001	0.00		0.01
		Pom	0.68	0.0151	2.10	*	2.21
Trivandrum	2001-2017	**Annual**	**0.37**	**0.0072**	**2.92**	**	**1.96**
		Win	0.27	0.0112	3.20	**	4.20
		Prm	0.54	0.0118	2.51	*	2.20
		Mon	0.37	-0.0041	-0.66	NS	-1.12
		Pom	0.42	0.0124	1.28	NS	2.95

Table 2. Statistics of MODIS Terra AOD_{550nm} at different locations over India for the time period of 2001–2017.Trend analysis was done with non-parametric Mann-Kendall test. Note: *** for 99.9% confidence level of significance, ** for 99% confidence level of significance, * for 95% confidence level of significance, + for 90% confidence level of significance and NS for no significance.

Stations	**Duration**		**Base AOD**	**Slope**	**Z Value**	**Significance**	**Trend**
Dehradun	2002-2017	**Annual**	**0.25**	**0.0077**	**2.12**	*	**3.12**
		Win	0.30	0.0058	2.87	**	1.93
		Prm	0.52	0.0035	0.74	NS	0.68
		Mon	0.45	0.0099	1.17	NS	2.23
		Pom	0.32	0.0097	1.85	+	3.06
Patiala	2002-2017	**Annual**	**0.76**	**-0.0006**	**-0.27**	**NS**	**-0.07**
		Win	0.43	0.0048	1.68	+	1.11
		Prm	0.54	0.0056	1.73	+	1.03
		Mon	1.08	0.0049	0.72	NS	0.46
		Pom	0.55	0.0018	0.32	NS	0.32
Nainital	2002-2017	**Annual**	**0.32**	**0.0044**	**1.40**	**NS**	**1.36**
		Win	0.14	0.0022	1.58	NS	1.53
		Prm	0.37	0.0010	0.15	NS	0.27
		Mon	0.11	-0.0020	-0.12	NS	-1.76
		Pom	0.15	0.0040	1.76	+	2.74
Pantnagar	2002-2017	**Annual**	**0.56**	**0.0023**	**0.50**	**NS**	**0.41**
		Win	0.31	0.0056	1.58	NS	1.82
		Prm	0.41	0.0072	1.83	+	1.75
		Mon	0.73	-0.0002	0.00	NS	-0.02
		Pom	0.33	0.0099	1.85	+	3.02
New Delhi	2002-2017	**Annual**	**0.65**	**0.0049**	**2.75**	**	**0.75**
		Win	0.49	0.0068	1.31	NS	1.39
		Prm	0.65	0.0025	0.45	NS	0.39
		Mon	1.14	0.0001	0.00	NS	0.01
		Pom	0.61	0.0051	0.77	NS	0.84
Jaipur	2002-2017	**Annual**	**0.43**	**0.0078**	**2.57**	*	**1.82**
		Win	0.36	0.0068	2.47	*	1.91
		Prm	0.57	0.0051	1.24	NS	0.90
		Mon	0.78	-0.0001	0.00	NS	-0.01
		Pom	0.46	0.0031	1.31	NS	0.66
Kanpur	2002-2017	**Annual**	**0.58**	**0.0078**	**2.84**	**	**1.36**
		Win	0.57	0.0116	2.47	*	2.03
		Prm	0.49	0.0075	1.93	+	1.55
		Mon	0.75	0.0115	1.44	NS	1.54
		Pom	0.59	0.0152	2.48	*	2.59
Gandhi-College	2002-2017	**Annual**	**0.64**	**0.0092**	**1.76**	+	**1.42**
		Win	0.69	0.0108	2.18	*	1.58
		Prm	0.47	0.0102	2.53	*	2.15
		Mon	1.29	-0.0255	-1.62	NS	-1.97
		Pom	0.55	0.0120	2.66	**	2.20
Trivandrum	2002-2017	**Annual**	**0.34**	**0.0054**	**2.34**	*	**1.60**
		Win	0.44	0.0098	2.47	*	2.21
		Prm	0.58	0.0139	3.02	**	2.37
		Mon	0.42	0.0032	0.99	NS	0.76
		Pom	0.44	0.0052	1.04	NS	1.17

Table 3. Statistics of MODIS Aqua AOD_{550nm} at different locations over India for the time period of 2002–2017. Trend analysis was done with non-parametric Mann-Kendall test. Note: *** for 99.9% confidence level of significance, ** for 99% confidence level of significance, * for 95% confidence level of significance, + for 90% confidence level of significance and NS for no significance.

4. CONCLUSIONS

The multiyear assessment of MODIS Terra and Aqua, Collection 6 DT algorithm based 3km-AOD product over the Indian region highlights some key findings on spatial climatology of AOD, comparison and validation, long-term statistical trends and current rate of change in aerosol loading. This study is the first to report comprehensive analysis of MODIS 3km AOD over the Indian region and it may be important for future improvements in retrieval algorithms and for air quality policy makers. Some important findings are:

1. Analysis clearly shows that the northern India, especially the Indo-Gangetic region, is affected by high aerosol optical depth throughout the year. High aerosol concentration over the IGP region is due to intensification of crop residue burning, industrialization and other economic activities associated with increasing population. Apart from the IGP, the southern part of India also emerged with substantial aerosol loading during the study period.
2. Climatological (2001-2017) zonal averaged AOD_{550} are observed to be 0.401±0.23 and 0.324±0.64 measured using Terra and Aqua respectively whereas ground measured averaged AOD_{500} is 0.43±1.2.
3. The Performance of MODIS 3km AOD product varies geographically across the Indian region. The overall validation

results within the Indian domain is satisfactory, with correlation coefficient (R) and RMSE as 0.94 & 0.08 for Terra and 0.72 & 0.17 for Aqua respectively. The MODIS dark target 3km AOD product is obviously underestimated over Indian region except monsoon season.

4. During the last 17years, the aerosol loading over Indian region reveals a uniform positive trend with different significance levels. Both Terra and Aqua zonal mean of AODs shows increasing trends (2.35 yr^{-1} for Terra and 2.03 yr^{-1} for Aqua) with highest (99.9%) confidence level of significance. Almost over all the stations, annual AOD show an increasing trend, except at Patiala where the trend is negative.

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