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Monthly and annual variation of aerosol optical depth over Indian landmass using Oceansat 2 data

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Abstract
The monthly mean and annual mean AOD_{490} retrieved from Oceansat 2 and MODIS Terra and Aqua AOD_{550} nm are compared with the ground measured AOD data for the year 2019. The monthly mean analysis shows that Oceansat 2 AOD_{490} is overestimated and MODIS scientific data sets of dark target deep blue combined AOD_{550} nm is underestimated compared with ground measurements. The annual mean analysis shows that the Oceansat 2 and MODIS retrieved AOD values are closer to each other while underestimated compared with ground measurement. Analysis indicates that the cloud masking technique for MODIS is over estimated.
Key Words: Oceansat 2, AERONET, AOD_{490}, MODIS, AOD_{550}

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I. INTRODUCTION

The main sources of aerosols are sea spray, dust, biomass or fossil fuel burning, volcanic ash, or produced from gases like sulphates, nitrates, ammonium salts. Many studies validated the repercussions of atmospheric aerosol on regional air quality where high concentrations of fine particulate matter (PM) are associated with premature deaths, regional circulation system, crop health and decrease of life expectancy [23, 9].Aerosol emissions from anthropogenic activities are extensive and fluctuating rapidly over Asia [24].Application of satellite derived AOD products found to be essential for estimation of surface air quality and prediction [16,31, 18, 32, 35, 22, 33]. Aerosol optical depth (AOD) is retrieved from many remote sensing satellites like Moderate-Resolution Imaging Spectroradiometer (MODIS), Multiangle Imagining Spectroradiometer (MISR) and Medium Resolution Imagining Spectrometer (MERIS) in the past [28, 12, 29]. The SeaWiFS and OCM sensor also provided AOD over ocean in a regular basis. The SeaWiFS mission has come to an end during December 2010, the OCM sensor on Oceansat 2 is providing the AOD over ocean since 2009. Apart from the use in air quality, AOD retrieved from satellite sensors has many scientific applications especially in the fields of epidemiological and climate research. There is a significant effort by the scientific community to bring forward continuous improvement in retrieving techniques and methodology. In this context, the comparison and assessment of monthly or annual mean of AOD retrieved from contemporary satellite products are essential to evaluate the efficacy of the AOD products. This will provide further insight into the lacuna that is prevailing in retrieving the AOD from remote sensing platforms. In this investigation, the monthly mean AOD retrieved from Oceansat 2 data and MODIS data over the period from January to December 2019 is compared and analysed with the ground measured AOD values. In the present work, the study region (68^0 E - 97^0 E Longitude and 8^0 N to 37^0 N Latitude) is comprised of northern mountainous states mostly influenced by snow-clad Himalayan range, the Great Indian Desert in the north-west, Indo-Gangetic plains in the middle and the peninsular land mass in the south. The aerosol loading in this region is mainly influenced by Indian monsoon and the regional geography.

II. METHEDOLOGY

In this study, the satellite data (Oceansat 2, MODIS-Terra and MODIS-Aqua) for the year 2019, few ground based AOD observation and some published analysed historical observations have been taken for analysis. The daily Oceansat-2 data are procured from National Remote Sensing Centre (NRSC) and the monthly mean MODIS data are taken from website (https://neo.sci.gsfc.nasa.gov/).

The methodology adopted in the study to retrieve AOD over land from Oceansat 2 isbriefly presented below.

The top of reflectance at the satellite sensor ρ_{TOA}[13, 7, 4] is computed as,

$$\rho_{TOA}(\mu_s,\mu_v,\phi) = \rho_o(\mu_s,\mu_v,\phi) + [T(\mu_s)\,T(\mu_v)\rho_s(\mu_s,\mu_v,\phi)]/[1-\rho_s(\mu_s,\mu_v,\phi)S] \qquad (1)$$

where , ρ_o (= ρ_R+ ρ_A)is the path reflectance,T(μ_s) the total transmittance from the top of the atmosphere to the ground, T(μ_v) is the total transmittance from the ground to the top of the atmosphere, in the viewdirection of the satellite, ρ_s is the surface reflectance with no atmosphere above it, S is the reflectance of the atmosphere for isotropic light entering the base of the atmosphere,μ_s is the cosine of the solar zenith angle,μ_v is cosine of the view angle ϕ is the azimuthal difference. In the present study, the radiative transfer equation is based on plane parallel atmosphere.

In order to compute the total reflectance reaching at the satellite sensor (ρ_{TOA}), the ground reflectance has to be approximated. The ground reflectance is a function of reflectance contributed by different surface features and difficult to estimate using a single approach. There are few approaches available in the literature to approximatethe ground reflectance [7, 6, 19, 15].The detailstep for retrieving AOD at 490 nm from Oceansat 2 is provided in [19]. In the present study the monthly mean AOD_{490} is compared with the AOD observed by Microtops II sun photometer and AERONET measurements. The MODIS derived AOD_{550} is also compared with ground observations. The statistical analysis is carried out based on the absolute difference (AD) and percentage difference (PD) are given below:

$$AD = (1/N) \sum_{i=1}^{i=N} |yi - xi|/xi \qquad (2)$$

$$PD = 100 \cdot (1/N) \sum_{i=1}^{i=N} (yi - xi)/xi \qquad (3)$$

where *y* represents satellite derived AOD (OCM, MODIS), *x* represents ground measured AOD and N represents number of points compared in the analysis.

In this study, ground based measurements of AOD using hand held portable multiband sunphotometer MICROTOPS-II data over two locations, and AERONET observation over seven locations were taken for comparison (Table 1).

Table 1. Station names and positions taken for comparison of ground observed AOD with satellite retrievals.

Location	Latitude	Longitude
Dehradun*	30.3^0 N	78.03^0 E
Kanpur#	26.513^0 N	80.232^0 E
Gandhi College#	25.871^0 N	84.124^0 E
Dibrugarh#	27.451^0 N	94.897^0 E
Amity University#	28.317^0 N	76.916^0 E
Jaipur#	26.906^0 N	75.806^0 E
Pune#	18.537^0 N	73.805^0 E
Karunya University#	10.935^0 N	76.744^0 E

* MICROTOPS-II, # AERONET observations

III. RESULTS AND DISCUSSION

The monthly mean AOD_{490}generated from Oceanst2 data for the year 2019 is shown in figure 1.The MODIS images are taken from the scientific data sets of AOD_{550}dark target deep blue combined (https://neo.sci.gsfc.nasa.gov/).The monthly mean AOD for MODIS Aqua and Terra images are shown in figure 2 and 3 respectively.

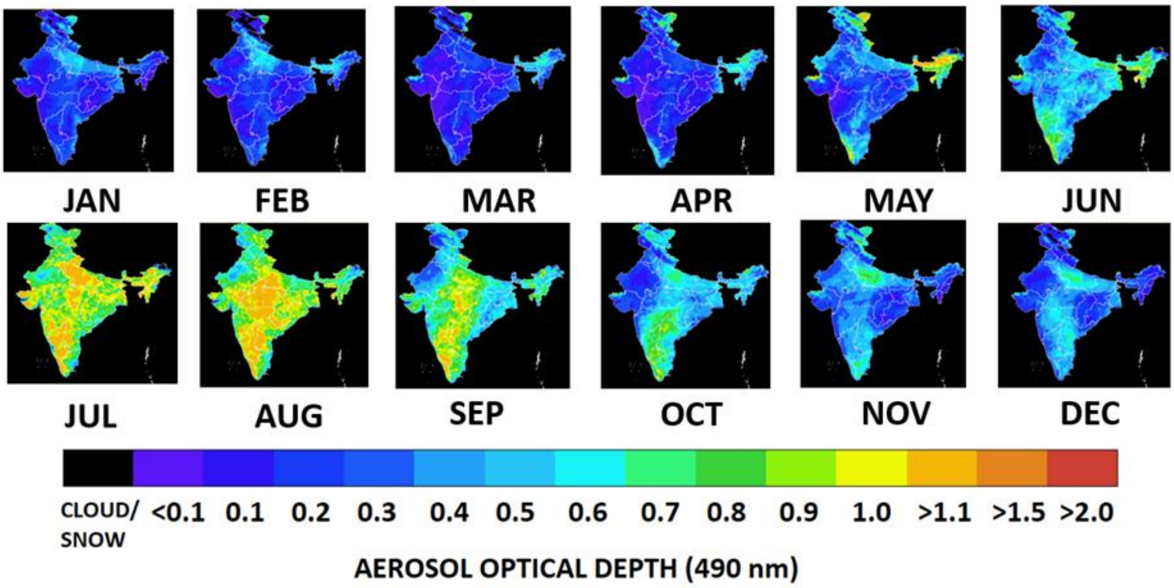


Figure 1. Mean monthly variation of AOD_{490} over India derived from Oceansat 2 data for the year 2019.

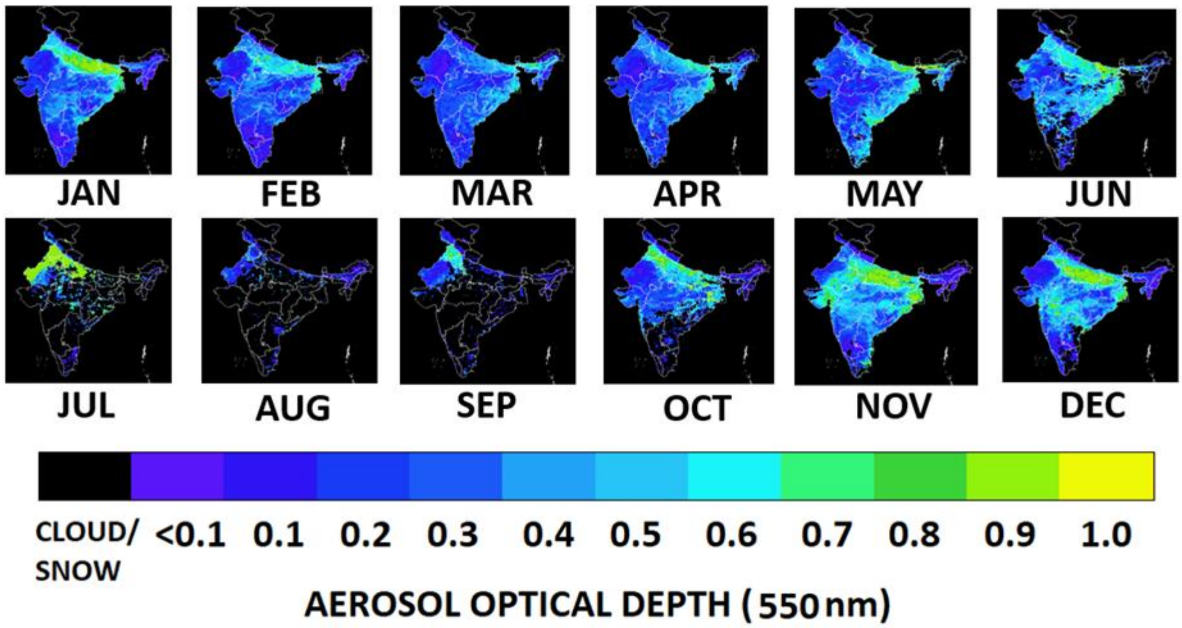


Figure 2. Monthly mean AOD_{550} over India derived from MODIS (Aqua) data for the year 2019.

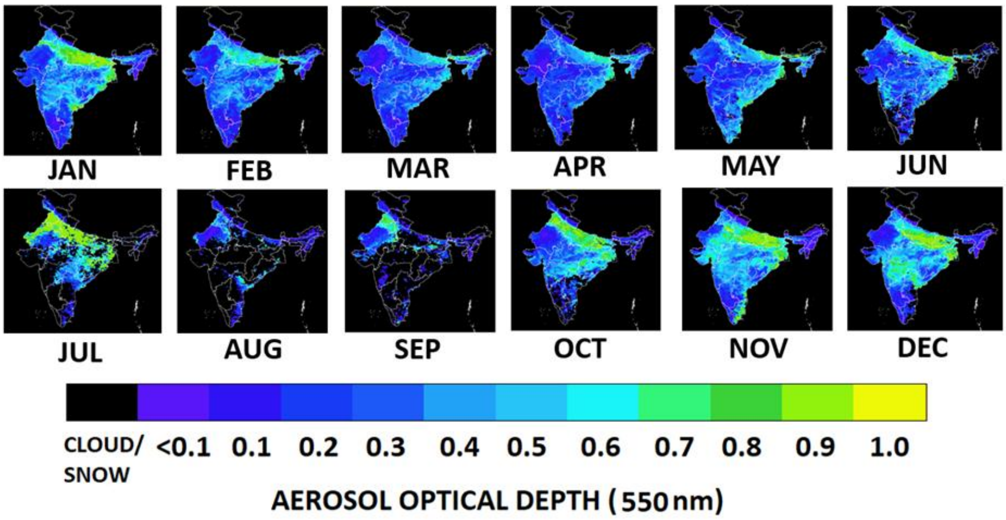


Figure 3. Monthly mean AOD550 over India derived from MODIS (Terra) data for the year 2019.

Comparison of monthly mean $AOD_{490}$and AOD_{550} from Oceansat 2 and MODIS (Terra, Aqua) with ground observation at Dehradun are shown in figure 4 and 5 respectively. Comparison of AERONET observation withOceansat 2, MODIS-Aqua and MODIS-Terra derived AOD over Kanpur, Dibrugarh, Gandhi College and Amity University, Jaipur and Pune are presented in Figure 6 - 11 respectively.It is observed that the in most of the pre monsoon months (MAM)the Oceansat 2 derived AOD is underestimated. During monsoonmonths (JJAS)monthly mean MODIS values are found to be masked over most of the stations while for Oceansat 2 AOD values are available for comparison though these are overestimated. Assuming, the difference of $AOD_{490}$and AOD_{550} values are minimum, the monthly mean AOD_{490} fromOceansat 2 and AOD_{550} values retrieved from MODIS (Aqua, Terra) over Indian region are shown in figure 12.

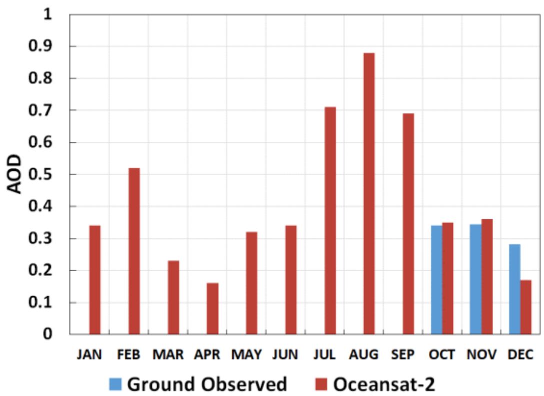


Figure 4: Comparison of Microtops II observation over Dehradun with (a) Oceansat 2 derived monthly mean AOD_{490} for the year 2019.

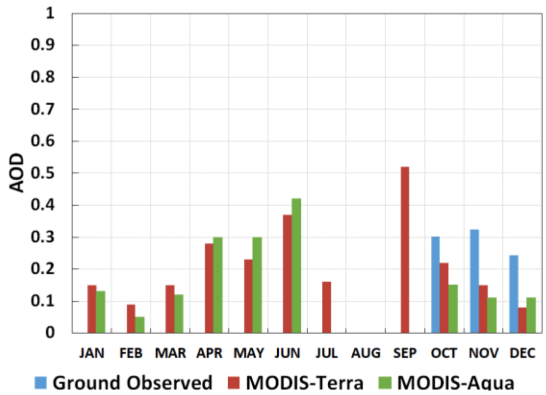


Figure 5: Comparison of Microtops II observation over Dehradun with MODIS-Terra and Aqua derived monthly mean AOD_{550} for the year 2019.

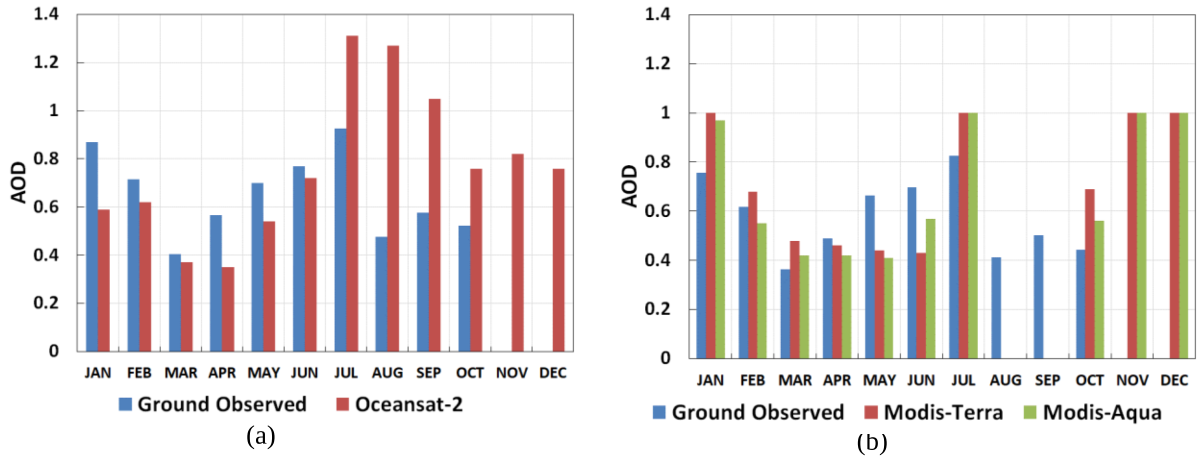


Figure 6: Comparison of AERONET observation over Kanpur with (a) Oceansat 2 derived monthly mean AOD_{490} (b) MODIS-Terra and Aqua derived monthly mean AOD_{550} for the year 2019.

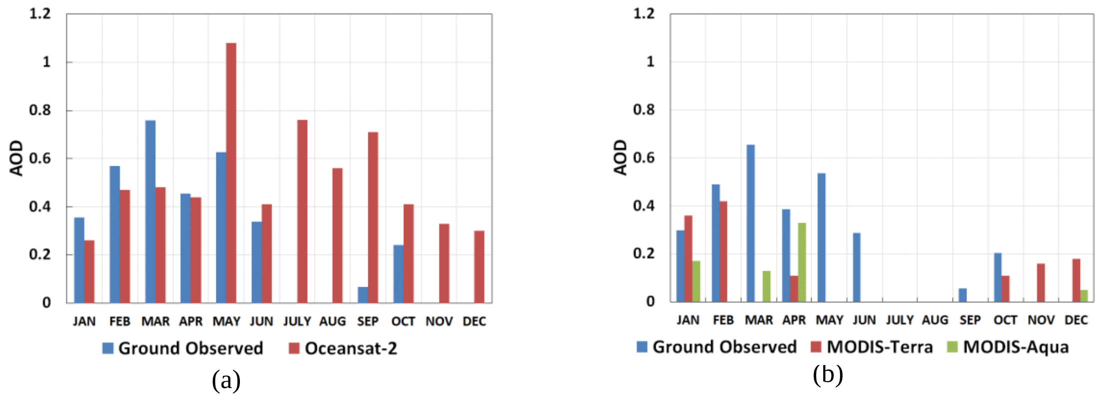


Figure 7: Comparison of AERONET observation over Dibrugarh with (a) Oceansat 2 derived monthly mean AOD_{490} (b) MODIS-Terra and Aqua derived monthly mean AOD_{550} for the year 2019.

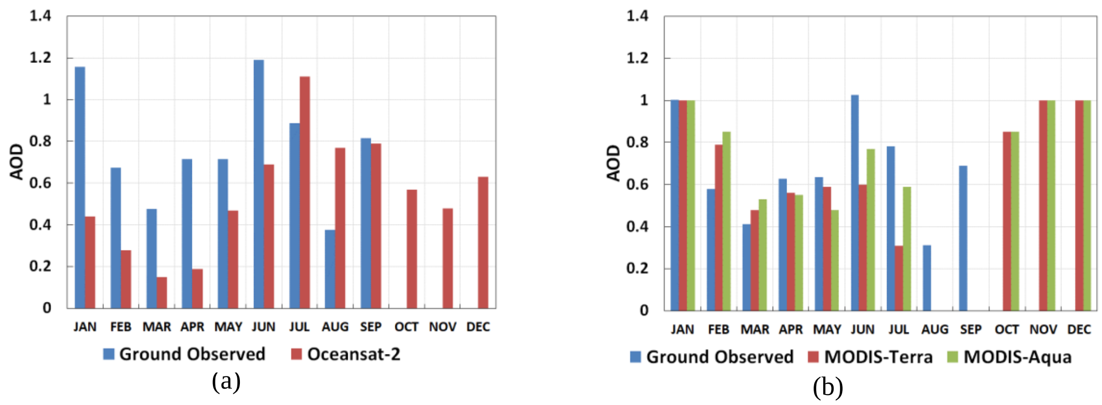


Figure 8: Comparison of AERONET observation over Gandhi College with (a) Oceansat 2 derived monthly mean AOD_{490} (b) MODIS-Terra and Aqua derived monthly mean AOD_{550} for the year 2019.

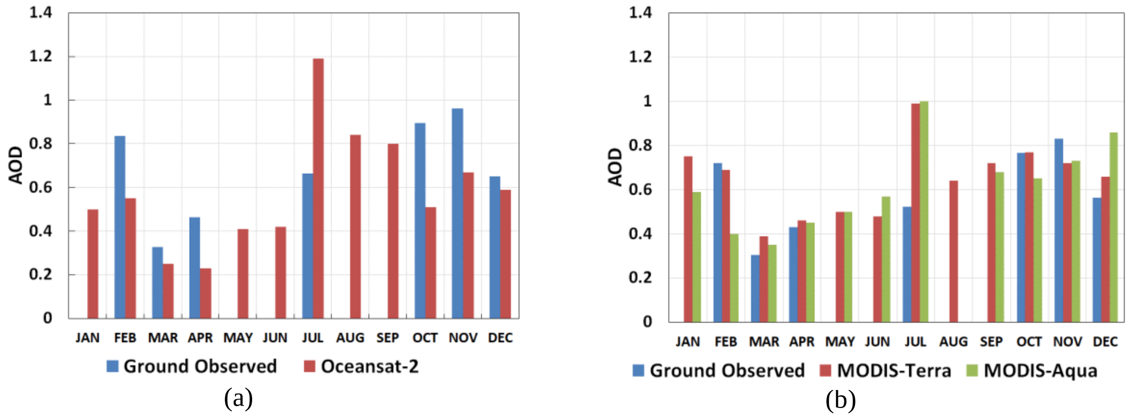


Figure 9: Comparison of AERONET observation over Amity University with (a) Oceansat 2 derived monthly mean AOD_{490} (b) MODIS-Terra and Aqua derived monthly mean $AOD_{550}$for the year 2019.

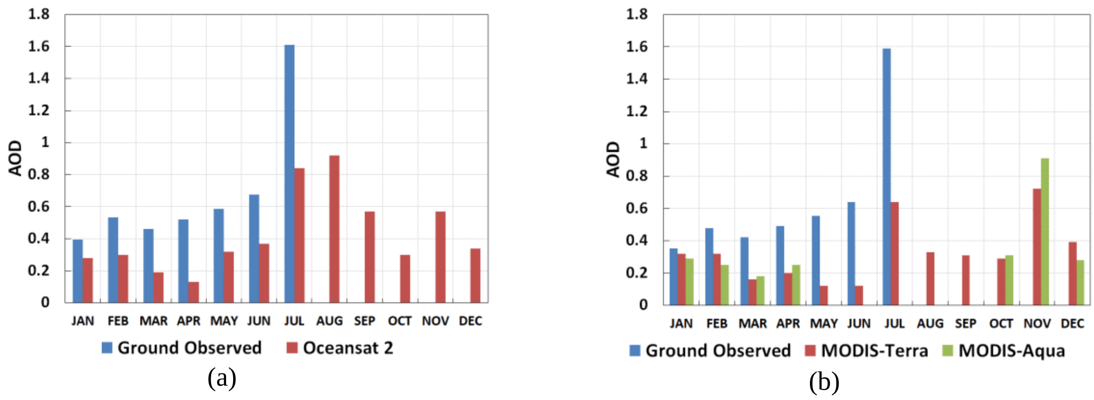


Figure 10: Comparison of AERONET observation over Jaipur with (a) Oceansat 2 derived monthly mean AOD_{490} (b) MODIS-Terra and Aqua derived monthly mean $AOD_{550}$for the year 2019.

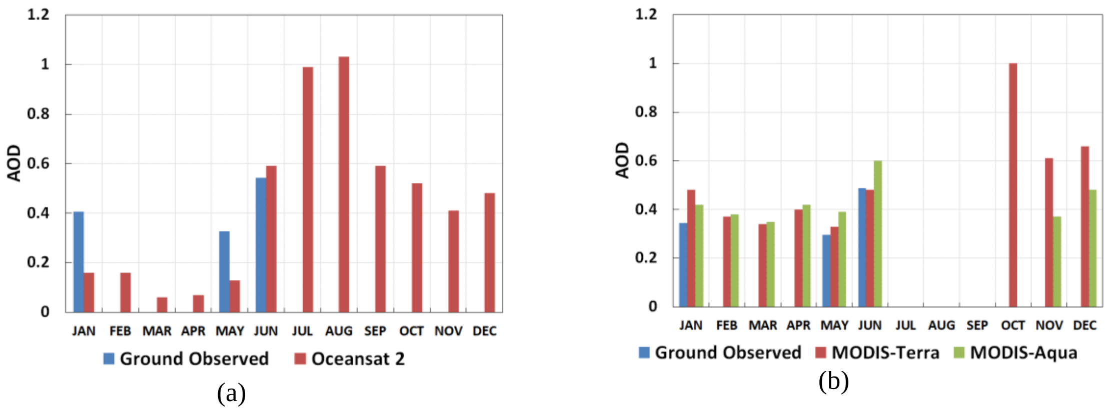


Figure 11: Comparison of AERONET observation over Pune with (a) Oceansat 2 derived monthly mean AOD_{490} (b) MODIS-Terra and Aqua derived monthly mean AOD_{550} for the year 2019.

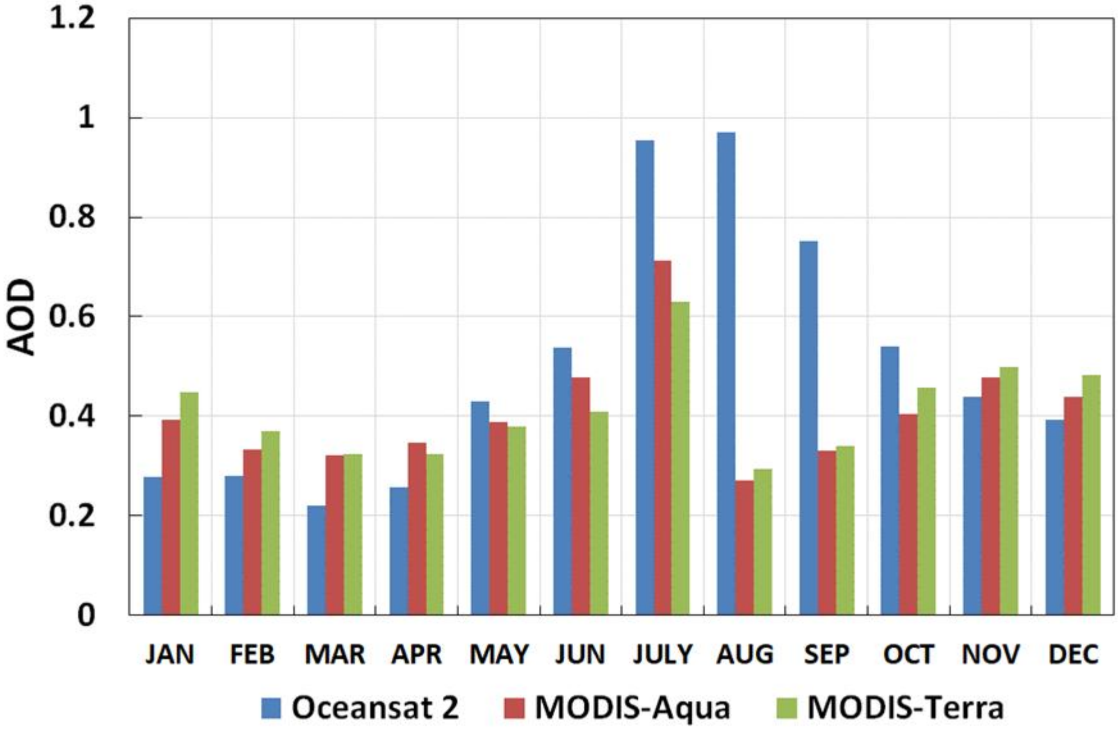


Figure 12. Monthly mean retrieved AOD_{490} from Oceansat 2 and AOD_{550} retrieved from MODIS Aqua and MODIS Terra over India for the year 2019.

The analysis indicates that there is maximum variation of AOD values during the month of July, August and September between Oceansat 2 and MODIS observations. This difference can be attribute to the different cloud masking approaches and the spatial resolution of the sensors. Since the spatial resolution of Oceansat 2 is better than MODIS the former has more scope to covers the cloud free area. However, analysis of Oceansat 2 image (figure 1) and MODIS (figure 2 and 3) indicate that the cloud masking is overestimated in case of MODIS. Since, Oceansat 2 sensor is devoid of thermal IR wavelength, the cloud masking has been carried out using the spectral signature analysis of top of reflectance (ρ) of all the eight bands of OCM [19]. The MODIS cloud masking technique has an advantage over Oceansat 2 for having IR band for its use. However, comparison of AOD and NDVI maps generated from MODIS Terra (Figure 13) confirms that the masking is over estimated while retrieving AOD from MODIS.

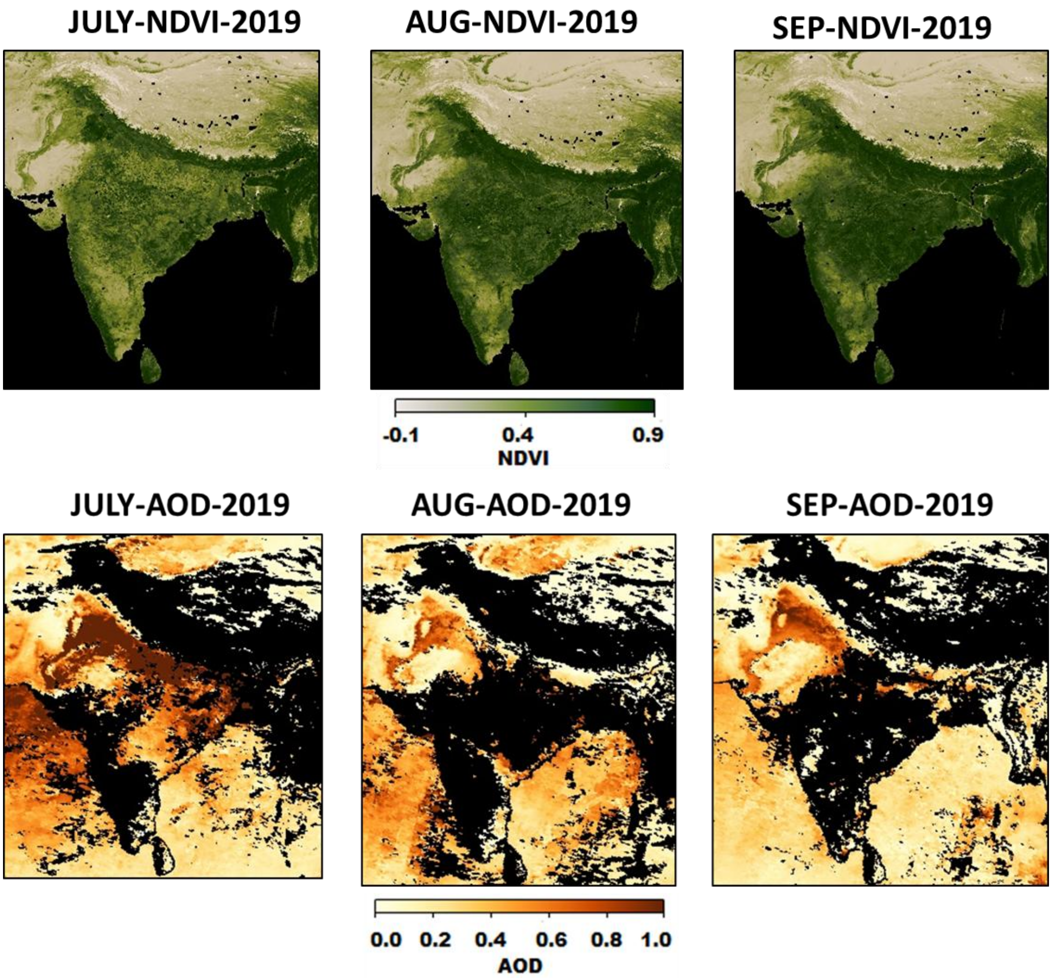


Figure 13.Comparison of NDVI and AOD products of MODIS-Terra for July, Aug and Sept 2019.

The seasonal variation of AOD derived from Oceansat 2 is depicted in figure 14. The mean AOD_{490}over India is found to be 0.31, 0.30, 0.80 and 0.49 during, winter, pre monsoon, monsoon and post monsoon respectively. The Indo-Gangetic Plain shows high AODloading (0.6 to- 1.0) during all seasons except in pre-monsoon (0.3-0.5) which is also observable from the ground values. Mean AOD_{490} value over Kanpur is observed to be maximum during winter (0.79) and minimum during pre-monsoon (0.56). The AOD values over Eastern India are found to be in the range of 0.3-0.9 with minimum and maximum value observed during winter and monsoon period respectively. The AOD value over north western India is found to be in the range of around 0.1- 0.5 with the minimum and maximum value during winter and monsoon season respectively. Over peninsular India the AOD values are found to be in the range of 0.3 – 1.0 with minimum occurring during pre-monsoon months and maximum during monsoon season withan exception over Kerala where the AOD is found to be minimum during winter season. Similar observationswerereported over Trivandrum by other investigators [25].

The seasonal variation of AOD using MODIS is presented in figure 15. The mean AOD_{550} over India is found to be 0.43, 0.34, 0.43 and 0.47 for Terra and 0.38, 0.35, 0.47 and 0.43 for Aqua during winter, pre monsoon, monsoon and post monsoon respectively indicating slight increase in AOD values in the afternoon (Aqua) compared to forenoon (Terra) observations except monsoon season. Comparison of seasonal maps of Oceansat 2 (figure 14) with MODIS (figure 15) shows prominent difference between monsoon season indicating higher AOD concentration in case of Oceansat 2 compared to MODIS retrievals. Analysis of the ground observations as well as satellite derived AOD value over Indian subcontinent by many investigators[17, 34, 10,11, 26, 27, 14] have also shown high AOD values during summer monsoon.

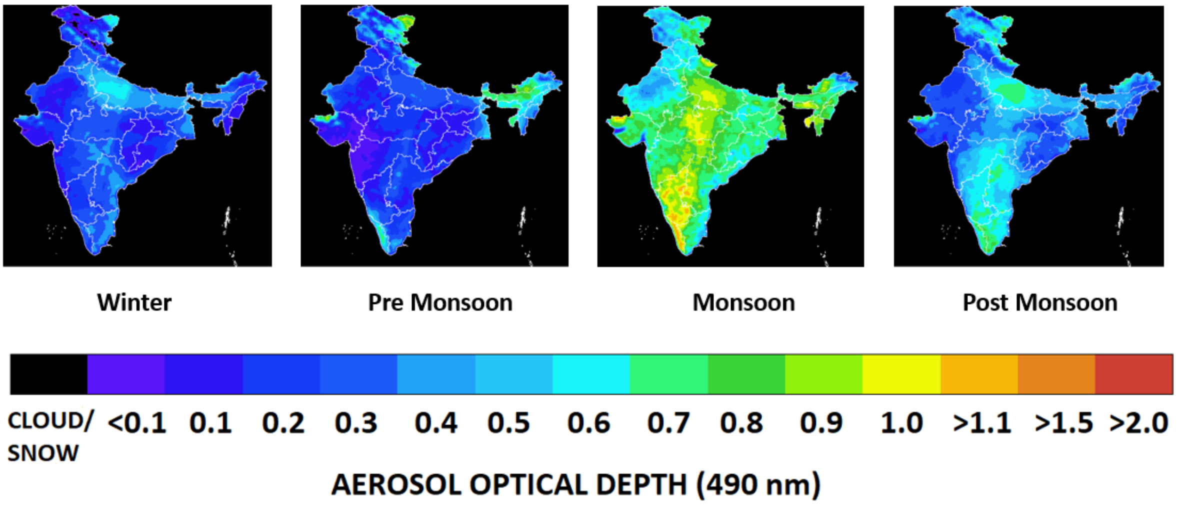


Figure 14. Spatial variation of AOD using Oceansat 2 data for winter (DJF), pre Monsoon (MAM), Monsoon (JJAS) and post Monsoon (ON) during 2019.

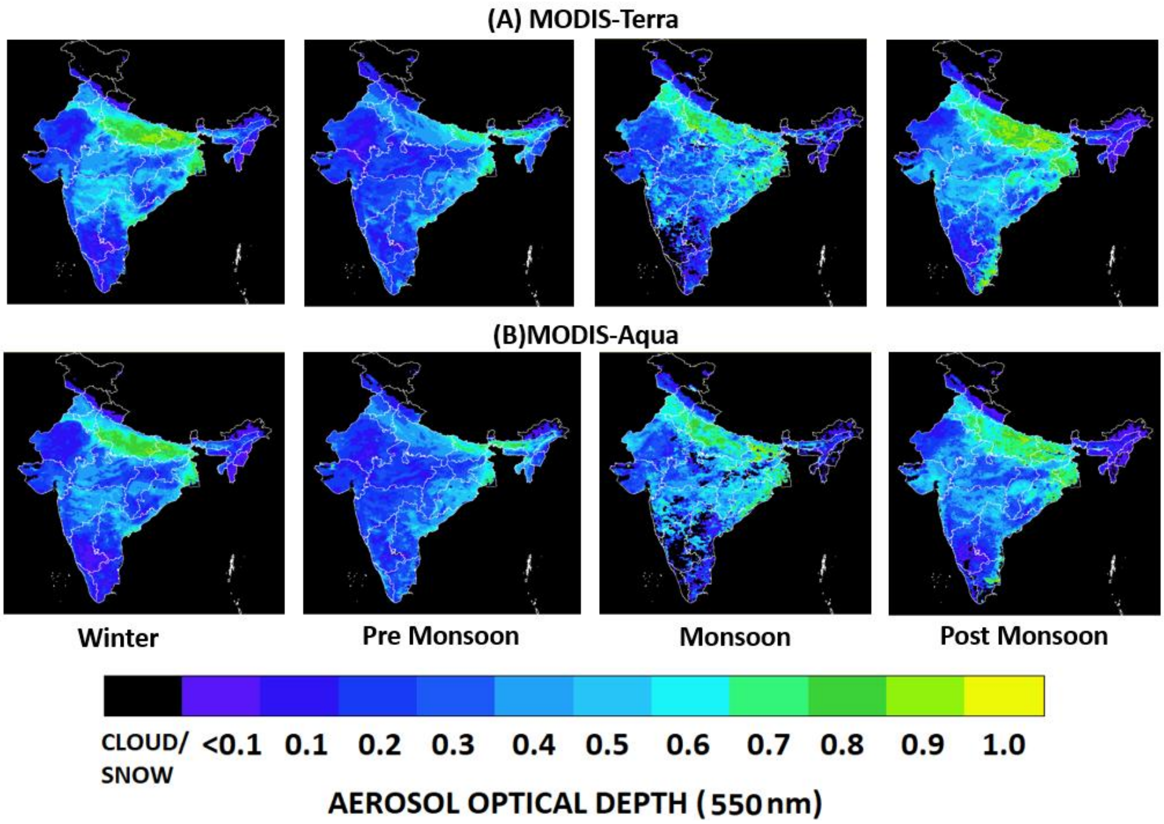


Figure 15. The spatial variation of AOD map generated from (A) MODIS-Terra (B) MODIS-Aqua observations for winter (DJF), pre Monsoon (MAM), Monsoon (JJAS) and post Monsoon season (ON) during 2019.

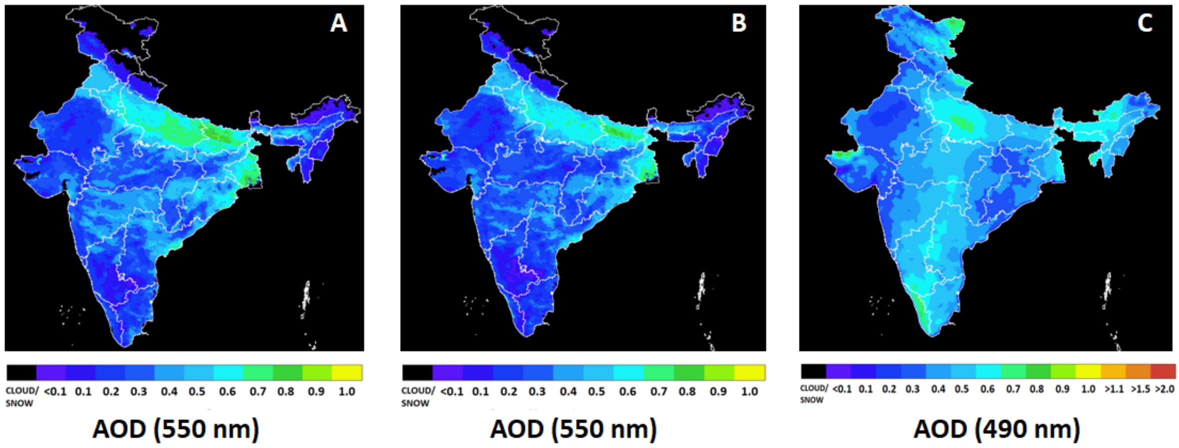


Figure 16. Annual variation of AOD over Indian region (A) MODIS-Terra, (B) MODIS-Aqua and (C) Oceansat 2 during 2019.

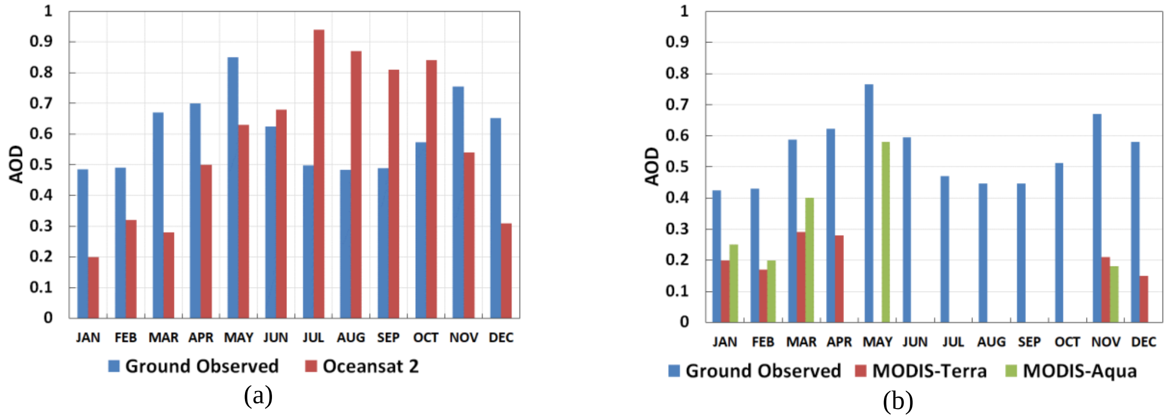


Figure 17. Comparison of the observed mean monthly AOD over Thiruvananthapuram during the year 2011-2015 (Sateesh et al., 2017) with (a) AOD_{490} from Oceansat-2 retrieved AOD (b) AOD from MODIS Aqua and MODIS Terra retrieved AOD_{550} for the year 2019

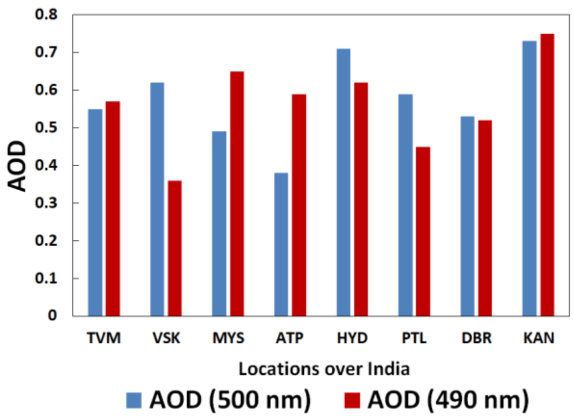
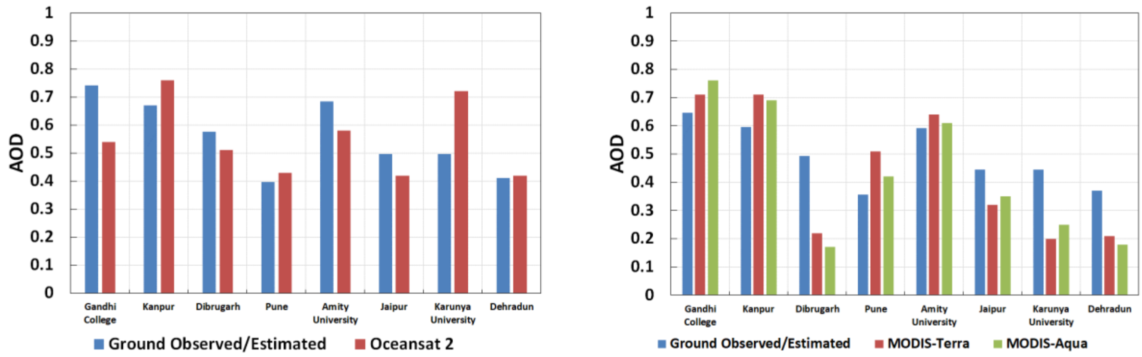


Figure 18: Comparison of AOD_{500} (ground measured historical data trend from Babu et al., 2013) with Oceansat 2 derived yearly mean AOD_{490} nm during 2019.



(a) (b)

Figure 19. Comparison of observed/estimated of annual mean AOD for the year 2019 with (a) annual mean AOD_{490} from Oceansat 2 (b) annual mean AOD_{550} from MODIS Terra and Aqua over Gandhi College, Kanpur, Dibrugarh, Pune, Amity University, Jaipur (estimated from trend analysis of AOD data during 2009-2017), Karunya University (estimated from trend analysis AOD data during 2014-18) and Deharadun (estimated from trend analysis AOD data during 2014-18).

Spatial variation of annual AOD estimated from Oceansat 2, MODIS-Terra/Aqua is depicted in figure 16. From the analysis of annual variation, it is evident that high AOD is observed over North East (NE) region in Oceansat2 image compared to MODIS. Similar observation is also found over Kerala and NE part of Jammu and Kashmir. Simulated AOD values by Goddard Earth Observing System (GEOS)-Chem [3] exhibits similar trend as seen with Oceansat 2 with some exception in the NE region of Jammu and Kashmir.

In the present analysis, filtering out the cloud masking points from the monthly analysis, the comparison with ground observation (table 2) shows that the MODIS retrieved monthly mean AOD is better than Oceansat 2. In case of Oceansat 2 data all the observed points are available for comparison which shows AOD from Oceansat 2 can be estimated with AD of 0.27 with a PD value of 9%. This indicates the AOD is overestimated with an AD value of around 0.3. In case of MODIS the estimated AOD values are underestimated (> -10%) with AD value approaching 0.2. These differences cannot be attributed to any single factor in the present analysis.

Table 2. Comparison of the mean absolute difference (AD) and the percentage difference (PD) of the satellite derived AOD values with ground observed values.

Satellite vs Ground Obsevation	Number of Points	AD	PD
Oceansat 2 vs Ground Observation	47	0.27	09.00
MODIS-Terra vs Ground Observation	39	0.19	-11.88
MODIS-Aqua vs Ground Observation	35	0.17	-09.00

The observed monthly mean aerosol optical depth at 490 nm during the year 2011-2015 over Thiruvananthapuram [30] is also compared with Oceansat2 retrieved $AOD_{490}$and MODIS Aqua and MODIS Terra retrieved AOD_{550} (figure 17). This comparison also indicated the MODIS cloud masking is over estimated.

Analysis of satellite AOD carried out by other investigators [21] indicate the satellite retrieval algorithm is mostly influenced by the cloudy weather conditions during monsoon seasons. Seasonal analysis reveals that the median value of AERONET AOD is higher than MODIS and MISR AOD in summer (MAM) and monsoon (JJAS) seasons and vice-versa in post-monsoon (ON) and winter (DJF) season at Gandhi College and Kanpur sites. Over Jaipur, AERONET AOD is higher in all the seasons. OMI AOD is underestimated throughout the seasons at all test-sites. In an another study, the MODIS deep blue AOD found to be lower compared ground measured AERONET AOD [1]. Comparison of surface-based aerosol optical depth with those retrieved from MODIS Terra and Aqua also exhibits similar trend (Mukherjee and Vinoj, 2020, Kannemadugu et al., 2015).

The analysis and comparison of yearly mean AOD_{490} from Ocensat 2 with trend analysis of ground measured historical data [13] of AOD_{500}over eight locations over India [Trivandrum (TVM), Visakhapatnam (VSK),Mysore (MYS), Anantapur (ATP), Hyderabad (HYD), Patiala (PTL), Dibrugarh (DBR),Kanpur (KAN)] are carried out and the results are shownin figure 17.The statistical analysis shows that AOD from Oceansat 2 data is matching with the historical trend data with AD value 0.11 and PD value -1.76%.

Table 3. Comparison of the mean absolute difference (AD) and the percentage difference (PD) of the satellite measured mean annual AOD values with ground observed annual mean AOD values over five AERONET sites (Gandhi College, Kanpur, Dibrugarh and Pune, Amity University), Trend analysis data over Jaipur, Karunya University (AERONET) and Dehradun (Microtops).

Satellite vs Ground Obsevation	Number of Stations	AD	PD
Oceansat 2 vs Ground Observation	8	0.10	-0.021
MODIS-Terra vs Ground Observation	8	0.15	-12.64
MODIS-Aqua vs Ground Observation	8	0.14	-15.93

The mean annual AOD_{490} and AOD_{550}(interpolated values) from AERONET sites (https://aeronet.gsfc.nasa.gov/) at eight locations over India (Gandhi College, Kanpur, Jaipur, Dibrugarh, Jaipur, Amity University, Pune and Karunya University) are compared with the annual mean value of AOD from Oceansat 2 and MODIS for the year 2019. Since the mean annual values over Jaipur, Karunya University and Dehradun are not available for the year 2019, the values are estimated from the trend analysis of the ground measurementsover Jaipur during 2009-2017, Karunya University during 2014-2018 and Dehradun during 2014-2018. The ground observed and estimated annual mean AOD is compared with satellite estimated annual mean AOD and the result is presented in figure 19. The statistical analysis is presented in table 3. The analysis shows Oceansat 2 estimated AOD_{490} to be in close agreement with ground estimated AOD. In case of MODIS, AOD is underestimated because of elimination of cloudy pixels.However, since the analysis is confined to a single year, more data needs to be studied to analyse the satellite derived AOD with respect to ground measured values. Taking average of the monthly and annual data together, the analysis shows that AOD from Oceansat 2 can be estimated with AD of 0.1 and PD of -0.02%. Similarly AOD from MODIS Terra and Aqua can be estimated with AD of 0.15, 0.14 and PD of -12.64% and -15.93% respectively. The analysis suggest a need of further investigation for evaluation of cloud masking techniques applied for retrieving AOD from satellite data. Since, the present study shows Oceansat 2 annual mean AOD data is in good agreement with the ground observation, the AOD retrieved from Oceansat 2 over Indian region can be utilised for studying the annual variability efficiently.

IV. CONCLUSION

Since the air quality is depending on atmospheric aerosol climatology, the retrieval of accurate/approximate AOD concentration from satellite data is the need of the hour. The AOD_{490} retrieved from Oceansat 2 over selected stations are found to be comparable with ground measurements. The analysis reveals that there is a wide scope to improve theapproximation of surface reflectance and cloud masking algorithm to derive AOD over land. The estimation of surface reflectance from surface land cover should be refined to get better estimate of AOD at a regional scale from satellite data.

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