Validation of MODIS aerosol optical depth retrievals over a tropical urban site, Pune, India

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Summary

This paper attempts to validate the MODIS dark target aerosol optical depth product over tropical urban location in India. The ground truth data used in this study has been collected using Microtops hand held sun-photometer on cloud free days during 2008-2010. AERONET measurements have also been compared against MODIS and Microtops. Aerosol properties derived from the AERONET over the same location have been analyzed as well. This is the first ever systematic validation of the MODIS aerosol products over Pune. MODIS AOD retrievals are well correlated with the AERONET and Microtops AODs. MODIS AODs underestimate during winter and overestimate during pre-monsoon. MODIS retrievals are capable of characterizing AOD distributions over Pune. Systematic error in the MODIS aerosol products needs further investigation. Single scattering albedo shows seasonal variability, winter months were dominated by absorbing type of aerosols whereas summer time scattering aerosols dominates the AOD values. Both winter and pre monsoon months do not shows large diurnal variations at the station.
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Abstract

In the present paper, MODIS (Terra and Aqua; level 2, collection 5) derived aerosol optical depths (AODs) are compared with the ground-based measurements obtained from AERONET (level 2.0) and Microtops - II sun-photometer over a tropical urban station, Pune (18°32'N; 73°49'E, 559 m amsl). This is the first ever systematic validation of the MODIS aerosol products over Pune. Analysis of the data indicates that the Terra and Aqua MODIS AOD retrievals at 550 nm have good correlations with the AERONET and Microtops - II sun-photometer AOD measurements.

During winter the linear regression correlation coefficients for MODIS products against AERONET measurements are 0.79 for Terra and 0.62 for Aqua; however for pre-monsoon, the corresponding coefficients are 0.78 and 0.74. Similarly, the linear regression correlation coefficients for Microtops measurements against MODIS products are 0.72 and 0.93 for Terra and Aqua data respectively during winter and are 0.78 and 0.75 during pre-monsoon. On yearly basis in 2008-2009, correlation coefficients for MODIS products against AERONET measurements are 0.80 and 0.78 for Terra and Aqua respectively while the corresponding coefficients are 0.70 and 0.73 during 2009-2010. The regressed intercepts with MODIS vs. AERONET are 0.09 for Terra and 0.05 for Aqua during winter whereas their values are 0.04 and 0.07 during pre-monsoon. However, MODIS AODs are found to underestimate during winter and overestimate during pre-monsoon with respect to AERONET and Microtops measurements having slopes 0.63 (Terra) and 0.74 (Aqua) during winter and 0.97 (Terra) and 0.94 (Aqua) during pre-monsoon.

Wavelength dependency of Single Scattering Albedo (SSA) shows presence of absorbing and scattering aerosol particles. For winter, SSA decreases with wavelength with the values 0.86 ±0.03 at 440 nm and 0.82 ±0.04 at 1020 nm. In pre-monsoon, it increases with wavelength (SSA is 0.87 ±0.02 at 440nm; and 0.88 ±0.04 at 1020 nm).
1 1. Introduction

The knowledge of spatial and temporal distributions of aerosols on regional and global scale is essential to understand the dynamics of aerosols and the associated influence on regional and global climatic conditions (Tripathi et al., 2005). Satellites-based remote sensing technique provides systematic retrieval of aerosol optical properties on regional and global scale (Kaufman et al., 2005, Kahn et al., 2010). The MODerate Resolution Imaging Spectroradiometers (MODIS) aboard the Terra (launched in 1999) and Aqua (in 2002) observe the earth-atmosphere systems twice daily. Columnar aerosol optical properties such as aerosol optical depth (AOD) and aerosol small mode fraction (ASMF) are retrieved from these observations over both land and ocean (Kaufman et al., 1997; Tanre et al., 1997). Satellite observations have advantages that they can provide information in the larger spatio-temporal domain (Kaufman et al., 2002) as most of the ground measurements are limited to very small area (point observations). However, aerosols from the space is challenging in areas where surface reflectance is high as it may introduce considerable errors in the derived results. So as to improve the accuracy of the MODIS data, it is essential to compare and validate the MODIS data with independent ground-based measurements. Several research studies have compared and validated MODIS data with the data obtained from the ground-based Microtops II sun-photometers and that measured from federated network instruments viz., Aerosol Robotic Network (AERONET) (Jing-Mei et al., 2010; Retalis et al., 2010; Aloysus et al., 2009; Misra et al., 2008; Levy at al., 2010,Remer et al., 2005; Tripathi et al., 2005; Ichoku et al., 2002a; Chu et al., 2002; Holben et al., 1998, Hyer et al., 2011). Since the
launch of MODIS, validation studies suggested that the expected error (EE) over land
could be represented by $EE = \pm 0.05 \pm 0.15x\text{AOD}$ (Remer et al., 2005).

In India, several validation of MODIS derived AOD has been carried out by
various groups (Jethva et al., 2005, Tripathi et al., Prasad and Singh, 2007). Tripathi et
al., (2005) using MODIS level 2 and collection 4 AOD data with AERONET data for
2004 found an overestimation by MODIS during dust and an underestimation during non-
dust seasons having slopes and intercepts in the two cases 2.46, -0.63 and 0.69, 0.12
respectively with nearly same correlation coefficients (0.72 and 0.71 respectively). For
the Indo-Gangatic basin, Jethva et al.,(2005) compared the monthly mean AOD at 550
nm from MODIS level 3 daily gridded data with AERONET sunphotometer derived
monthly mean AOD values for Kanpur, India during January 2001 to July 2003 and
found a systematic overestimation by MODIS during summer and underestimation
during winter. Prasad and Singh (2007) also found MODIS overestimating AOD values
during summer and underestimating during winter with the slopes and intercepts with two
cases 0.51, 0.52 and 0.48, 0.15 respectively. The correlation coefficients in the two cases
were less than 0.5.

In the present study, we compare MODIS (Terra and Aqua) AOD retrievals with
AERONET AODs of level 2.0 and Microtops II sun-photometer measurements at Pune
(18°32'N; 73°49'E, 559 m amsl), India. CIMEL sun-sky radiometer installed at Indian
Institute of Tropical Meteorology (IITM) as a part of AERONET global network, and it
makes measurements at 440, 675, 870, 940, and 1020 nm and three polarized channels at
870 nm. In the present study, data retrieved from 440, 675, 870 and 1020 channels are
used The Microtops II sun-photometer (five channels) is operated from Pune University
campus on cloud free days observing seasons spanning over Dec-May for the period 2008-09 and 2009-10. To the best of our knowledge this is the first kind of systematic study that validates MODIS data over Pune. The study also presents seasonal behaviour of AERONET inversion products viz., aerosol columnar volume size distribution (ACVSD), single scattering albedo (SSA), and Angstrom Exponent (α).

2. Study Location and Local Meteorology:

The study location, over which the validation has been performed, is Pune (18°32′N; 73°49′E, 559 m amsl). It is about 100 km from the west coast of India and Lee-ward side of Sahyadri Range (Western Ghats). Pune has tropical wet and dry climate. Figure (1) shows the NCEP/NCAR reanalysis mean vector wind composites at 850 hPa for winter and pre-monsoon seasons during 2009 and 2010 over the Indian region (0 – 40°N; 60 – 100°E). In winter (Dec, Jan and Feb), minimum temperature is up to 3 to 4°C with light winds and continental air mass passing over the region. During the Pre-monsoon (Mar, Apr and May) the weather is very hot with the maximum temperature of about 40°C and surface winds mostly gusty and dust content in the atmosphere is maximum.

The study region mainly comprises of semi arid region and has six types of land use and land cover as shown in Figure (2). It mainly consist of fallow land (39.42%), dense scrub (20.88%), agriculture land (15.96%), settlement (13.02%), vegetation (9.51%) and water body (1.18%). It contains 377 villages and has a population of 44,54,509 (Census of India 2001). The population and the number of vehicles and industrialization has been increasing at a steady rate over Pune since 2001.
3. Data and Methodology:

3.1 Data

MODIS data are available at different processing levels, level 1.0 (geolocated & calibrated brightness temperatures and radiances), level 2.0 (derived geophysical data products) and level 3.0 (Gridded time-averaged product) (King et al., 2003). AERONET data are also available at three different levels, level 1.0 (raw or unscreened data), level 1.5 (cloud screened data) and level 2.0 (quality assured data) (Holben et al., 1998). For this study, we have employed MODIS (both Terra & Aqua) level 2 collection 5 instantaneous AOD data at 550 nm. MODIS AOD retrievals are compared with level 2.0 AERONET and Microtops II sun-photometer measurements of AODs.

3.2 MODIS

Radiant energy reflected and emitted by the Earth carries a signature of atmospheric and surface properties. Satellite sensors can quantify several atmospheric properties by measuring the wavelength, angular and polarization properties of this radiant energy (Kaufman et al., 2002). The MODIS has been designed with aerosol and cloud remote sensing in mind (King et al., 1992). It is sun-synchronous and near polar orbiting, with a circular orbit of 705 km above the surface. MODIS has 36 bands ranging from 0.4 to 14.4 μm wavelengths with three different spatial resolutions (250, 500 and 1000 m) and views the Earth with a swath of 2330 km thereby observing the entire globe every day, with equatorial crossing local time 10:30 am and 1:30 pm (Terra and Aqua respectively).

The MODIS retrievals of aerosol use two separate algorithms for land and ocean. Both the algorithms were developed before the Terra launch and are well described in
Kaufman et al. (1997) for land and Tanre et al. (1997) for ocean. MODIS retrievals of AOD over land uses three spectral channels centered at 0.47, 0.66, and 2.13 μm wavelength. The retrieval of AOD is performed and reported at 10x10 km² pixel size although the original observations are made at 250-1000m resolution. Each high resolution pixel in the 10x10km² box is evaluated for cloud, ice/snow and then mean reflectance values are utilized to retrieve AOD using lookup table approach. More details on AOD retrieval can be found elsewhere [i.e. Remer et al., 2005, Levy et al., 2007a, 2007b]

3.4 AERONET (AErosol RObotic NETwork)

The AERONET (AErosol RObotic NETwork) is a federation of ground-based remote sensing aerosol networks established by NASA and is greatly expanded by collaborators from other agencies. The program provides a long-term, continuous database of aerosol optical, microphysical and radiative properties for aerosol research and characterization, validation of satellite retrievals, and synergism with other databases. The network imposes standardization of instruments, calibration, processing and distribution.

AERONET provides globally distributed observations of spectral AOD, inversion products, and precipitable water in various aerosol regimes. It employs CIMEL sun-sky spectral radiometer which measures the direct sun radiances at eight spectral channels centered at 340, 380, 440, 500, 670, 870, 940 and 1020 nm. The accuracy of direct sun measurements are within ±0.01 and ±0.02 for larger wavelengths (greater than 440 nm) and shorter wavelength (Holben et al., 1998; Eck et al., 1999). Optical depth is calculated from spectral extinction of direct beam radiation at each wavelength based on the
Lambert-Beer-Bouguer Law. Aerosol optical depth (AOD) is determined by correcting optical depth for attenuation due to Rayleigh scattering, absorption by ozone and gaseous pollutants. In addition to direct solar radiance, instrument also measures the diffuse sky radiance at four spectral bands (440, 670, 870 and 1020 nm) along the solar principal plane and solar almucantar through a constant aerosol profile to retrieve size distribution, phase function and AOD (Holben et al., 1998).

Indian Institute of Tropical Meteorology (IITM) is one of the stations of this network. CIMEL sun/sky radiometer is installed in the campus of IITM and continuously operational since 2004 (Sumit and Devara, 2011). The automatic sun-sky tracking radiometer at IITM makes measurements with a 1.2° full field of view at every ~15 min interval at five spectral channels (440, 675, 870, 940, 1020nm). In this study data retrieved form 440, 675, 870 and 1020 nm are used for its comparison with MODIS AOD retrievals. To determine aerosol columnar volume size distribution and Single Scattering Albedo ($\omega_0$) solar principal plane (constant azimuth angle, with varied scattering angles) and solar almucantar (constant elevation angle, with varied azimuth angles) geometry is used at 440, 675, 870 and 1020 nm.

3.5 Microtops II Sun-photometer

The ground based measurements have been carried out at Pune University campus (18°32'N; 73°49'E) using handheld Microtops II Sun-photometer from morning till evening at an interval of 10 min. during 2008-09 and 2009-10 on clear sky days. The instrument is well calibrated (Manufactured by Solar Light Company, Philadelphia, USA.). The design, calibration and performance details have been described by Devara et al., (2001) and Morys et al., (2001). The expected accuracy of the sun-photometer
retrievals is comparable with those of CIMEL sun-photometer used in AERONET network with uncertainties in the range of 0.01 to 0.02 (Ichoku et al., 2002b). The instrument measures the intensity of direct solar irradiance at five spectral narrow band spectral channels centered at 440, 500, 675, 870 and 1020 nm. From this data, AOD value for each wavelength is estimated. These data are used along with AERONET as a “ground truth” for the validation of the MODIS AOD products for this study.

3.6 Methodology

For validation purpose, MODIS retrievals must be collocate in space and time with AERONET and Microtops measurements. We averaged the quality controlled MODIS AOD values at 10 km² spatial resolution over 50 km × 50 km grid box centered at ground measurements site. For this, we choose 50 km × 50 km grid box because in larger window size, topography and aerosol type heterogeneity play a role and could bring in errors where as smaller grid box contain insufficient data (Ichoku et al., 2002a).

In order to accomplish realistic comparison of AOD’s from these instruments viz., MODIS, AERONET and Microtops II sun-photometer. AERONET and Microtops measured AODs are adjusted to the MODIS derived 550 nm wavelength AODs using the Angstrom exponent (α) and Angstrom turbidity coefficient (β) derived from Microtops and AERONET measured AODs at the wavelengths 440, 500, 675, 870 and 1020 nm (440, 675, 870 and 1020 nm for AERONET) on the corresponding day through a logarithmic regression using the Angstrom empirical formula viz., AOD = β × λ⁻α. This yields the corresponding retrieved AOD value at 550 nm for the AERONET and Microtops within ±30 min of MODIS overpass time. Thus, over the two years period (i.e. 2008-09 and 2009-10), we obtained 118 and 119 identical data sets for MODIS (Terra)
and AERONET (48 and 60 data sets for Microtops) during 2008-09 and 2009-10 respectively. Similarly, there were 101 and 96 identical data points for MODIS (Aqua) and AERONET (41 and 50 data points for Microtops) during the same period. Thus MODIS - AERONET and MODIS - Microtops data sets form the subject matter of the present paper.

4 Results and Discussion

4.2 Aerosol Properties

4.2.1 AOD Variation and Angstrom Exponent (α)

The spectral variation of aerosol optical depth and frequency distribution of α during winter and pre-monsoon season for the period of Dec 2008-May 2010 over Pune is shown in Figure 3(a b). Seasonal variation of α is monomodal in winter and bimodal in pre-monsoon. The modal value of α of 1.4 during winter suggests dominance of submicron aerosol particles originating from anthropogenic activity like fossil fuel combustion and biofuel burning (Pandithurai et al., 2007, Venkataraman et al., 2005,). During pre-monsoon, bimodal nature of α has modal values 0.5 and 0.95 indicating that dominance of both fine and coarse mode particles. This reveals that the aerosol system over Pune is controlled by different sources.

Figure (4) reveals monthly mean value of aerosol optical depth and α obtained from AERONET measurements during Dec 2008-May 2010. From the figure, high AE values at low AODs during winter and low α at high AOD values during pre-monsoon also indicates the dominance of fine mode and coarse mode particles in winter and pre-monsoon respectively.
4.2. 2 Aerosol Columnar Volume Size Distribution

Atmospheric aerosols, which come from many natural and man-made sources, present a wide range of particle sizes and concentrations. Their behavior and the atmospheric effects produced by them depend on their size. The inversion algorithm developed by Dubovik and King (2000) has been used.

Results of this analysis are given in Figure (5) which depicts seasonal variation of aerosol columnar volume size distribution over Pune using AERONET data during the period Dec 2008 – May 2010. It is clear from the figure that the modal volume size concentration of both accumulation mode (< 1 μm) and coarse mode (> 1 μm) are low during winter. As compared to winter, during pre-monsoon there is no considerable change in accumulation mode but there is significant increase in modal volume concentration (about 1.5) for the coarse mode. The dominance of coarse mode particles may be due to dust generation by strong winds (wind blown dust) and strong surface heating. Low value of α (0.85) also supports the dominance of coarse mode particles in pre-monsoon. The sources of fine mode particles are fossil fuel combustion and industrial pollutants.

The observed Aerosol Columnar Volume Size Distribution (ACVSD) is found to be bimodal and is represented by

\[
\frac{dV}{d\ln r} = \frac{V_0}{\sigma(2\pi)} \exp\left(-\frac{\ln[r/r_m]^2}{2\sigma^2}\right)
\]

where \(dV/d\ln r\) is volume size distribution, \(V_0\) is columnar volume of particle per cross section of atmosphere, \(r\) is radius, \(r_m\) is mode radius and \(\sigma\) is standard deviation of the natural logarithm of particle radii.
The bimodal nature of volume size distribution may be due to different sources of aerosols such as combination of two air masses with different aerosol origin (Hoppel et al., 1985), generation of new fine particles in the air by the process of heterogeneous nucleation or by homogeneous heteromolecular nucleation and growth of larger particles by condensation of gas-phase reaction products (Singh et al., 2004).

The ACVSD parameters and $\alpha$ are given in Table I. During winter, the average values of volume concentration of accumulation mode and coarse mode are $0.020 \pm 0.016$ and $0.025 \pm 0.017$ respectively and in pre-monsoon, the corresponding average values are $0.022 \pm 0.015$ and $0.047 \pm 0.032$. For accumulation mode, the model value of volume concentration (peak) is almost same ($0.046$ and $0.0.044$) for winter and pre-monsoon respectively. For coarse mode, values of volume concentration are $0.053$ and $0.087$ for winter and pre-monsoon respectively.

4.2.3 Single Scattering Albedo

Single scattering albedo (SSA) is a common measure of the relative contribution of absorption to extinction and is a key variable in assessing the climatic effects of aerosols (Jacobson, 2000; Dubovik et al., 2002). Its value is mostly dependent on the composition and size distribution of aerosols. It is studied by using AERONET inversion product (level 2.0) during Dec 2008 to May 2009. For this, the retrieval algorithm of Dubovik and King (2000) is used to obtain SSA from direct sun and sky radiance measurements by AERONET (CIMEL sun photometer).

Figure (6) depicts the wavelength dependence of SSA. During winter, SSA decreases with wavelength having a value $0.86 \pm 0.03$ at 440 nm and $0.82 \pm 0.04$ at 1020nm. Lower
SSA at longer wavelength shows dominance of absorbing urban aerosol over Pune, which is attributed to the presence of a mixture of aerosols from multiple sources like vehicular pollution, industrial pollutants, biomass burning in the field. However, in pre-monsoon season, the SSA slightly increases with wavelength (SSA is $0.87 \pm 0.02$ at 440nm; and $0.89\pm0.04$ at 1020 nm). This suggests the dominance of coarse particles (mostly dust) during pre-monsoon, which may be either due to local activities like urbanization, industrialization and construction activities or windblown dust due to strong surface heating. Similar observations have been reported by Singh et al., (2004) over Kanpur, Smirnov et al., (2002) in the Persian Gulf, Xia et al., (2005) and Cheng et al., (2006) over Northern China and Lyamani et al. (2006) over Europe and the Mediterranean region. Monthly variation of SSA for the period of 2008-10 and 2009-10 is shown in Figure (7). It reveals that during 2008-09 there is a sharp increase in SSA from Dec to May while the increase is moderate during 2009-10. Seasonal variation and spectral dependence of SSA is well reflected in the monthly variation.

4.3 Inter-comparison between MODIS-AERONET-Microtops II Sun-photometer

4.3.1 MODIS and AERONET

Figure (8) shows seasonal comparison of MODIS AOD retrievals against AERONET derived AODs, during the winter (Dec-Feb, 2008-2010) and pre-monsoon (Mar-May, 2009-2010). From the figure, it is seen that during winter the correlation coefficient of linear regression fit ($R$) are 0.79 and 0.62 for Terra and Aqua respectively. While during pre-monsoon the corresponding coefficients are 0.78 and 0.74. These correlation coefficients are significant at 0.01 level. The root mean squared error (RMSE)
between the ground based AERONET and MODIS AODs lies in the range 0.09 to 0.10 for the data under study.

Intercepts of linear regression fit are 0.09 for Terra and 0.05 for Aqua during winter whereas during pre-monsoon intercept values are 0.04 and 0.07 for Terra and Aqua respectively. Slopes of the regressed lines, for Terra and Aqua are 0.63 and 0.74 respectively during winter and 0.97 and 0.94 (for Terra and Aqua respectively) during pre-monsoon.

Results of regression model for MODIS derived AODs against AERONET measurements at 550 nm during 2008-2009 and 2009-2010 are shown in Table II. It is clear from the table that during 2008-2009 and 2009-2010, MODIS retrievals bear a good correlation with AERONET measurements with correlation coefficients 0.80 and 0.78 for (Terra and Aqua respectively) during 2008-2009 while the corresponding coefficients are 0.70 and 0.73 during 2009-2010. Intercept of linear regression model during 2008-2009 are 0.05 and -0.01 for Terra and Aqua respectively and the corresponding intercept during 2009-2010 is 0.11 for both Terra and Aqua. Slopes of the regressed line are 0.86 and 1.05 during 2008-2009 for Terra and Aqua respectively while during 2009-2010, the corresponding slopes are 0.65 and 0.73.

**4.3.2 MODIS and Microtops II Sun-photometer**

Figure (9) shows scatter plot of MODIS AOD retrievals against Microtops measured AODs, during the winter (Dec-Feb, 2008-2010) and pre-monsoon (Mar-May, 2008-2010). MODIS AOD retrievals also show a good correlation with Microtops II sun-photometer measurements. Correlation coefficients during winter are 0.73 and 0.93 while for pre-monsoon values are 0.78 and 0.75, for Terra and Aqua respectively. RMSE
between ground based Microtops II sun-photometer and MODIS AODs lie in the range 0.06 – 0.10 for winter and pre-monsoon during the study period.

Intercepts of the linear regression fit for MODIS and Microtops AODs are 0.03 for Terra and 0.04 for Aqua during winter whereas for pre-monsoon, intercept values are 0.05 and 0.09 for Terra and Aqua respectively. Slopes of the regressed lines are 0.54 & 0.70 during winter and 0.58 & 0.76 during pre-monsoon for Terra and Aqua respectively.

4.3.3 AERONET and Microtops II Sun-photometer

Figure (10) reveals the scatter plot of AERONET against Microtops at 675nm for all collocated data points during 2008-2010. The linear regression analysis between these data points shows that the correlation coefficient is 0.81 while slope and intercept are 0.97 and 0.10 respectively. The seasonal inter-comparison between AERONET and Microtops is shown in Figure (11). It is clear form the Figures (10 and 11) that, Microtops AODs are consistently overestimating compared to those of the AERONET AODs during winter and pre-monsoon over the study period with mean bias is about 0.1 in AOD.

From the Figures 8 and 9 it is clear that, the MODIS retrievals systematically underestimate during winter and overestimate during pre-monsoon over Pune. Similar results have been reported by Jethva et al.,(2005) and Prasad and Singh (2007) over Kanpur. Monthly variation of AOD using MODIS and AERONET measurements shown in Figure (12) also support this result.

The linear regression model for MODIS-AERONET (Fig. 8) and MODIS-Microtops II (Fig 9) and Table II show non-zero intercepts. This indicates that the retrieval algorithm
is biased at low AOD values which may be associated with a sensor calibration error or an improper assumption about ground surface reflectance (Tripathi et al., 2005; Zhao et al., 2002). Also, large errors in surface reflectance may lead to large intercepts (Tripathi et al., 2005; Chu et al., 2002).

The inconsistency between aerosol microphysical and optical properties used in the MODIS retrieval algorithm and that in the ground truth retrievals generated by AERONET and Microtops is signified by the deviation of the slope from unity. Similar observations have been reported by in other studies (i.e. Jing-Mie, 2010; Tripathi et al., 2005; Zhao et al., 2002).

The effect of slope and intercept on the correlation of MODIS derived AODs with AERONET and Microtops measurements shown in Figure (8) and Figure (9) is well represented in the average monthly variation of AOD values from MODIS and AERONET during the study period (2008-10) as shown in Figure (12). Error bars in the figure represent standard deviation of AOD in the month which generally ranges between 0.05 - 0.2. The number of days used in the analysis is also indicated on bar chart. It is clear from the figure that the variation patterns of both MODIS (Terra and Aqua) and AERONET AOD data are well matched for both the years with MODIS AOD values relatively lower than those of AERONET AOD values in winter i.e. in relatively low dust period. While in dust loading period (pre-monsoon), MODIS AOD values are higher or tend to be higher than the AERONET AODs. Similar observations have been reported by Tripathi et al., (2005).

As overpass time of MODIS Terra and Aqua are 10:30 and 1:30 respectively the monthly variation of AERONET-Microtops-MODIS-Terra data sets corresponds to
monthly variation of AOD during morning hours and that of AERONET-Microtop-MODIS-Aqua to monthly variation of AOD during afternoon. This may be regarded as the diurnal asymmetry in AOD data. This has its origin in the meteorological conditions over Pune. Weather conditions in Pune in winter are conducive to the formation of low level capped inversion of $8 - 10^\circ$ K per 100 meter in the atmospheric boundary layer (ABL) during February and to some extent also in March. (Vernekar et al., 1993, Pandhurai et al., 2007). High value of AOD in January/February for Terra and Microtop is produced by the processes such as atmospheric moisture precipitating as haze particles on cold mornings in winter, inversion episodes and the influx of aerosol due to atmospheric circulation as discussed in NCEP/NCAR reanalysis mean vector wind composites at 850 hPa for winter and pre-monsoon seasons (Figure 1). April/May maximum in AOD is normal pre-monsoon high. High value of AOD in pre-monsoon is also a global feature attributed to increased aerosol inputs due to surface heating, wind-blown dust and influx of aerosols (Holben et al., 2001)

Seasonal frequency distribution for collocated data points of Terra and Aqua of MODIS and AERONET measured values for 2008-09 and 2009-10 presented in Figure (13). It is clear from the figure that, the frequency distribution is maximum at the range AOD < 0.3 and 0.3-0.4 during winter and pre-monsoon respectively. During winter in the range of AOD < 0.3-04 the frequencies of MODIS AODs are higher than those of AERONET AODs while during pre-monsoon reverse of this case can be seen clearly. The frequencies of MODIS AODs during pre-monsoon found lower than those of AERONET AODs at the range of AOD <0.3-0.5. Maximum frequency difference is 5.86 % for winter and 7.04 % during pre-monsoon.
In the range of AOD > 0.5 MODIS AODs are consistently lower than AERONET AODs during winter while in pre-monsoon in the AOD range > 0.6 MODIS AODs are consistently higher than AERONET AODs. The frequency distribution pattern also supports the underestimation of AOD by MODIS during winter and overestimation during pre-monsoon.

5. Summary and Conclusion

The paper presents the comparison of MODIS AODs (Terra and Aqua) retrievals with ground-based measurements made by AERONET and Microtops II sun-photometer for 2 years over a tropical urban station, Pune. The main conclusions from the study are:

1. Higher value of $\alpha$ during winter is associated with low AODs and an opposite trend is found to prevalent during pre-monsoon. This confirms occurrence of fine and coarse mode particles during these seasons.

2. Aerosol volume size distribution is shows a bimodal distribution during both winter and premonsoon seasons. The volume concentration of coarse mode particles in pre-monsoon is 1.5 times higher as compared to that winter. Similarly, volume concentration of fine mode particles is nearly same in both winter and pre-monsoon. Bimodal structure of volume size distributions indicates the presence of a mixture of aerosols from multiple sources during respective seasons in the atmosphere over Pune.

3. The SSA observer over Pune is found to be highly wavelength dependent. It decreases with wavelength in winter indicating the dominance of absorbing aerosols mainly arising from vehicular pollution, industrial pollutants and biomass
burning. During pre-monsoon an opposite trend is observed showing the presence of coarse mode particles which may be due to construction activity, wind blown dust and strong surface heating.

4. The MODIS AOD retrievals are well correlated with the AERONET and Microtops measurements as indicated by the high correlation coefficients. These are found to be 0.79 for Terra and 0.62 for Aqua during winter; 0.78 for Terra and 0.74 for Aqua during pre-monsoon against AERONET data. The corresponding values for Microtops measurements are 0.72 for Terra and 0.93 for Aqua during winter; 0.78 for Terra and 0.75 for Aqua during pre-monsoon with small intercepts.

5. MODIS AODs underestimate during winter and overestimate during pre-monsoon with respect to the AERONET and Microtops measurements with slopes less than unity (0.63 for Terra and 0.74 for Aqua during winter; 0.97 for Terra and 0.94 for Aqua during pre-monsoon against AERONET and 0.54 for Terra and 0.70 for Aqua during winter; 0.58 for Terra and 0.76 for Aqua during pre-monsoon against Microtops II sun-photometer).

6. Average monthly variation of AODs of MODIS and AERONET shows a similar pattern of variation with MODIS AOD values systematically less than those of AERONET during winter and higher during pre-monsoon. High AODs are observed during January/February and April/May. Jan/Feb high is mainly due to higher relative humidity during morning hours, light wind and associated low level capped inversions in the morning. Higher AOD values in April/May are
associated with increased aerosol inputs due to surface heating, wind-blown dust and influx of aerosols.

7. Microtops AODs are consistently overestimating than those of AERONET AODs during the study period with mean bias is about 0.1 in AOD.

8. Although, there is systematic error in the MODIS products which needs further investigation. In spite of this, results presented in the present paper indicate that the Terra and Aqua MODIS retrievals are capable of characterizing AOD distributions over tropical urban region Pune.

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Table I: Observed seasonal columnar volume size distribution parameters of aerosol particles and Angstrom Exponent ($\alpha$)

<table>
<thead>
<tr>
<th>Season</th>
<th>$V_a$</th>
<th>$R_a$</th>
<th>$\sigma_a$</th>
<th>$V_c$</th>
<th>$R_c$</th>
<th>$\sigma_c$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>0.047</td>
<td>0.148</td>
<td>0.025</td>
<td>0.053</td>
<td>3.857</td>
<td>0.028</td>
<td>1.307 (±0.189)</td>
</tr>
<tr>
<td>Premonsoon</td>
<td>0.044</td>
<td>0.113</td>
<td>0.027</td>
<td>0.087</td>
<td>3.857</td>
<td>0.047</td>
<td>0.851 (±0.315)</td>
</tr>
</tbody>
</table>

$V$ is columnar volume of atmospheric aerosol particles per unit cross section of the atmospheric column, $R$ is the radius and $\sigma$ is standard deviation (subscripts “a” and “c” stands for accumulation mode and coarse mode respectively) and $\alpha$ is mean Angstrom Exponent.
Table II: Results of regression analysis for MODIS (Terra and Aqua) derived AOD against AERONET measurements at 550 nm during 2008-09 and 2009-10

<table>
<thead>
<tr>
<th>Year</th>
<th>Slope</th>
<th>Intercept</th>
<th>R</th>
<th>RMSE</th>
<th>% in EE</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008-09</td>
<td>Terra</td>
<td>0.86</td>
<td>0.05</td>
<td>0.80</td>
<td>0.09</td>
<td>83.89</td>
</tr>
<tr>
<td></td>
<td>Aqua</td>
<td>1.05</td>
<td>-0.01</td>
<td>0.78</td>
<td>0.10</td>
<td>73.26</td>
</tr>
<tr>
<td>2009-10</td>
<td>Terra</td>
<td>0.65</td>
<td>0.11</td>
<td>0.70</td>
<td>0.11</td>
<td>68.07</td>
</tr>
<tr>
<td></td>
<td>Aqua</td>
<td>0.73</td>
<td>0.11</td>
<td>0.73</td>
<td>0.11</td>
<td>69.79</td>
</tr>
</tbody>
</table>
Figure 1: NCEP /NCAR reanalysis mean vector wind composites at 850 hPa level for winter and pre-monsoon season during 2008-09 and 2009-10
Figure 2: Land cover and land use of the study region (50 x 50 grid box)
Figure 3: (a) Spectral variation of AOD and (b) frequency distribution of Angstrom exponent over Pune using AERONET measurements for the period Dec 2008 – May 2010.
Figure 4: Monthly mean value of aerosol optical depth and Angstrom exponent ($\alpha$) using AERONET data during Dec 2008-May 2010.
Figure 5: Seasonal variation of aerosol columnar volume size distribution over Pune using AERONET measurements during the period Dec 2008 – May 2010.
Figure 6: Wavelength dependency of single scattering albedo over Pune using AERONET measurements for the period Dec 2008 – May 2010.
Figure 7: Monthly variation of single scattering albedo over Pune using AERONET measurements during 2008-09 and 2009-10.
Figure 8: Scatter plots of MODIS (Terra and Aqua) AOD retrievals against AERONET derived AODs, during the winter and pre-monsoon during 2008-2010. (The thick solid lines, dashed lines and dotted lines represent linear regression, EE and 1:1 line respectively).
Figure 9: Scatter plots of MODIS (Terra and Aqua) AOD retrievals against Microtops measured AODs, during the winter and pre-monsoon during 2008-2010. (The solid lines represent linear regression and dotted lines are 1:1 lines).
Figure 10: Scatter plot of AERONET and Microtops AOD measurements at 675 nm during 2008-2010. (Red line is regression line and blue and green lines are forced lines at intercept = 0 and slope = 1 respectively; dotted black line is 1:1 line).
Figure 11: Seasonal inter-comparison of AERONET and Microtops II Sun-photometer during 2008-2010
Figure 12: Monthly mean AODs for MODIS (Terra and Aqua) and AERONET during 2008-2009 and 2009-2010 over Pune.
Figure 13: Seasonal frequency distribution of MODIS and AERONET AODs during Dec 2008-May 2010.