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Comparison of Aerosol Products Retrieved from AERONET, MICROTOPS and MODIS over a Tropical Urban City, Pune, India

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ABSTRACT

Aerosol Optical Depth (AOD) measurements from Aerosol Robotic NETwork (AERONET; level 2.0), Microtops - II sun-photometer and MODerate Resolution Imaging Spectroradiometer (MODIS) (Terra and Aqua; level 2, collection 5, dark target) were compared and used to characterize aerosols over Pune, India. AODs from Microtops and MODIS were compared with those measured by AERONET to evaluate the measurement quality. To the best of our knowledge, this is the first systematic comparison of MODIS aerosol products over Pune, India. The results of the analysis show that during 2008–10, 68% to 84% of the MODIS AODs fell within an expected error, as defined by the MODIS science team, and thus the retrievals from this system are validated and accepted. In addition, during pre-monsoon periods MODIS retrievals are better-matched with ground-based measurements. On the seasonal scale, MODIS retrievals corroborate well with ground-based measurements, with correlation coefficients ranging from 0.62 to 0.93. Despite an overall satellite-ground agreement, MODIS tends to under-estimate AOD during winter, and this may be due to improper assumptions of surface reflectance and the incorrect selection of aerosol types. AERONET retrieved single scattering albedo (SSA) values in winter (0.82–0.86), suggesting the dominance of absorbing aerosols, slightly increased (0.87–0.89) in pre-monsoon season, indicating more scattering type of aerosols. These values are about 8.9%–1.1% lower than those of the assumed SSA values in the MODIS algorithm.

***Keywords*:** Inter-comparison; AOD; MODIS; AERONET; MICROTOPS.

INTRODUCTION

The knowledge of spatial and temporal distributions of aerosols on regional and global scale is essential to understand the dynamics of aerosols and associated influence on regional and global climatic conditions (Kaufman *et al.*, 2002). Ground-based measurements of aerosols play an important role in characterizing and quantifying aerosol optical and microphysical properties, aerosol loading and their radiative effects over a particular region (Jethva *et al.*, 2007a). However, satellite-based remote sensing techniques provide systematic retrieval of aerosol optical properties on regional and global scale (Kaufman *et al.*, 2005; Kahn *et al.*, 2010). The MODerate Resolution Imaging Spectroradiameters (MODIS) aboard Terra (launched in 1999) and Aqua (launched in 2002) satellites observe the earth-atmosphere system twice daily. The columnar aerosol optical depth (AOD) is retrieved from these observations over both land and ocean (Kaufman *et al.*, 1997; Tanré *et al.*, 1997). Satellite observations have advantages over the ground-based measurements, in that they provide information over the larger spatial domain (Kaufman *et al.*, 2002), as most of the ground-based measurements are limited to smaller area (i.e., point observations). However, aerosol measurements from the space is challenging in areas where the surface reflectance is high as it may introduce considerable errors in the derived aerosol products. MODIS obtain visible reflectance using an empirical relationship between reflectance in 2.1 μm and visible wavelengths (red and blue) as function of scattering angles and vegetation index. These relationships work well over dark vegetated surfaces but not very well over bright and heterogeneous surfaces. This can introduce an error in estimated surface reflectance, which goes into radiative transfer calculations to retrieve aerosols optical depth values. MODIS algorithm has to assume an aerosol model (SSA plus size distribution) and therefore, uncertainty in both assumptions can lead to errors in the aerosol retrieval. Also, the calibration accuracy

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affects these retrievals. 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 studies have compared and evaluated MODIS aerosol products with the ground-based AOD measurements obtained from the Aerosol Robotic NETwork (AERONET) and MICROTOPS-II sunphotometers (Holben *et al.*, 1998; Chu *et al.*, 2002; Ichoku *et al.*, 2002a; Remer *et al.*, 2005; Tripathi *et al.*, 2005; Misra *et al.*, 2008; Aloysius *et al.*, 2009; Levy *et al.*, 2010; Retalis *et al.*, 2010; Yang *et al.*, 2010; Hyer *et al.*, 2011). Since the launch of MODIS, validation studies have suggested that the expected error (EE) over land could be represented by $\pm (0.05 + 0.15 \times AOD)$ (Remer *et al.*, 2005; Levy *et al.*, 2007a).

In India, several studies on the validation of MODIS derived AODs have been carried out by various groups e.g., Jethva *et al.* (2005), Tripathi *et al.* (2005), Jethva *et al.* (2007a), Prasad and Singh (2007) and Jethva *et al.* (2010). Tripathi *et al.* (2005) compared MODIS (level 2_C004) AODs with AERONET data over Ganga Basin for 2004 and found an overestimation by MODIS during dust and an underestimation during non-dust seasons. For the Indo-Gangetic basin, Jethva *et al.* (2007a) compared monthly mean MODIS (level 3, daily gridded data) AODs at 550 nm with AERONET sun-photometer 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 AODs overestimating during summer and underestimating during winter. Over the study region, the dominant type of aerosols encountered in winter are submicron aerosols originating mainly from biofuel burning and fossil fuel combustion sources while in pre-monsoon, combination of pollution and dust generation due to surface heating and strong winds contribute to aerosol loading (Khemani, 1989; Devara *et al.*, 2005; Pandithurai *et al.*, 2007; Vijaykumar *et al.*, 2012).

Additionally, numerous studies have also been carried out to understand the optical and physical properties of aerosol over the Indian region. Several campaigns over land and ocean have been conducted to study the aerosol microphysics and its spatial distribution properties under the ISRO-GBP ARFI and ISRO GBP ICARB programmes (Beegum *et al.*, 2009; Kaskaoutis *et al.*, 2010). Pandithurai *et al.* (2007) observed seasonal diurnal asymmetry in aerosol optical properties over Western India. Dani *et al.* (2010) studied long-term (1998–2007) AOD variations over Pune and found significant long-term increasing trend. They observed dominance of smaller size particles during winter and coarse-mode particles during pre-monsoon.Over Indore, Gupta *et al.* (2003) also found low AOD during winter and high AOD during pre-monsoon. Variations in aerosol characteristics and radiative forcing have been studied by Jayaraman *et al.* (2006) over the north-west Indian region in a land campaign. Their study indicates spatio-temporal variation in aerosol characteristics over the north-west India which is mainly caused by the naturally produced dust particles. Absorbing aerosols play major role in variety of ways in the climate system. For example, Gadhavi and Jayaraman (2010) showed that the spectral dependence of absorbing aerosols can reduce the radiative forcing at top of the atmosphere by about 8%. Over the locations in the central India, Ganguly *et al.* (2005a) found varying nature of composition and sources of absorbing aerosols. Further, they reported up to 30% of excess absorption by absorbing aerosols coming mainly from biofuel burning used for cooking.

In the present study, MODIS aerosol products have been inter-compared with AERONET and MICROTOPS to understand deviations, if any, between satellite retrievals and ground-based measurements for the first time over urban city, Pune. Also, AERONET retrieved aerosol properties such as the Angstrom Exponent, the columnar volume size distribution and the single scattering albedo over the region have been discussed. The paper is structured as follows. "Study location and local meteorology", introduces the local meteorology of the study location. Data and methodology employed in the study is described in "Data and Method". Results are discussed in "Results and Discussion" and finally the study is summarized in "Summary".

STUDY LOCATION AND LOCAL METEOROLOGY

The study is performed over Pune urban area (18°32′N; 73°49′E, 559 m amsl), located at about 100 km from the west coast of India and Leeward side of the Sahyadri Range (Western Ghats). Pune has tropical wet and dry climate. In winter (Dec-Jan-Feb), minimum temperature is up to 3 to 4°C with light winds and continental air mass passing over the region. During pre-monsoon (Mar-Apr-May), weather is very hot with the maximum temperature of about 40°C. Surface winds are mostly gusty and wind-blown dust content in the atmosphere is maximum.

DATA AND METHOD

MODIS data are available at different processing levels viz., level 1.0 (geolocated & calibrated brightness temperatures and radiances), level 2.0 (derived geophysical data products) and level 3.0 (gridded time-averaged products) (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 (cloud-screened and quality assured data) (Holben *et al.*, 1998). For this study, we employed MODIS level 2 collection 5 instantaneous AODs at 550 nm. MICROTOPS data is screened by the method described by Pandithurai *et al.* (2007), in which AOD measurements are eliminated if they differ from the daily mean by 3σ (where σ is one standard deviation of daily mean).

MODIS

The radiant energy reflected and emitted by the Earth's surface carries a signature of atmospheric and surface properties. Satellite sensors can quantify several atmospheric properties by measuring the spectral, angular and polarization properties of this radiant energy (Kaufman *et al.*, 2002). MODIS sensor has been designed with aerosol and cloud remote sensing in mind (King *et al.*, 1992). MODIS has 36 spectral bands ranging from 0.4 to 14.4 µm with three varying different spatial resolutions (250, 500 and 1000 m) and views the Earth with a swath of 2330 km thereby providing near-global coverage on daily scale, with equatorial crossing local time 10:30 am and 1:30 pm for Terra and Aqua, respectively.

The MODIS retrievals of aerosols use two separate algorithms for land and ocean. Both the algorithms were developed before the launch of Terra and are well described in Kaufman *et al.* (1997) for land and in Tanré *et al.* (1997) for ocean. Retrievals of the aerosol properties from the MODIS over land use three spectral channels centered at 0.47, 0.66, and 2.13 µm wavelength and are mainly influenced by surface reflectance and aerosol type. In collection C005, improved algorithm is used to retrieve aerosol properties with assumptions as: a) the 2.13 µm channel contains the information about surface reflectance as well as coarse-mode aerosols b) the surface reflectance at the 0.47 and 0.66 µm wavelengths is a function of surface reflectance at 2.13 µm as well as it is a function of the scattering angle and "greenness" of the surface in the SWIR spectrum given by the normalized differential vegetation index (NDVI) based on 1.24 and 2.13 µm channels.

The retrieval of AOD is performed and reported at 10 × 10 km^2 pixel size although the original observations are made at 250–1000 m resolution. Each high resolution pixel in the 10 × 10 km^2 box is evaluated for cloud, ice/snow and then the 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, b, 2010).

AERONET

The AERONET (Aerosol Robotic NETwork) is a federation of ground-based remote sensing aerosol networks established by NASA (Holben *et al.*, 1998) and is expanded by collaborators from other agencies in order to incorporate a large spatial coverage. 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. Optical depth is calculated from spectral extinction of direct beam radiance at each wavelength based on the Lambert-Beer-Bouguer law which is termed as the "direct method". The aerosol optical depth (AOD) is determined by correcting optical depth for attenuation due to Rayleigh scattering, absorption by ozone and gaseous pollutants. Uncertainties in the direct sun measurements are within ± 0.01 for longer wavelengths (longer than 440 nm) and ± 0.02 for shorter wavelengths (Holben *et al.*, 1998; Eck *et al.*, 1999). In addition to direct solar radiance, instrument also measures diffuse sky radiance at four spectral bands centered at 440, 670, 870 and 1020 nm along the solar principal plane and solar almucantar through a constant aerosol profile. These data are used to retrieve the aerosol columnar volume size distribution, phase function and single scattering albedo by following method described by Holben *et al.* (1998) and Dubovik and King (2000) which may be termed as the"inversion method". In this study, data retrieved from the direct method at 440, 670, 870 and 1020 nm channels are used for its comparison with the MODIS AOD retrievals while data obtained from the inversion method is employed to characterize the temporal behaviour of aerosol properties (viz., aerosol columnar volume size distribution and single scattering albedo) at a tropical urban city Pune.

MICROTOPS-II Sun-Photometer

The ground-based aerosol measurements have been carried out in the Pune University campus (18°32′N; 73°49′E, 559 amsl) using handheld MICROTOPS II sun-photometer from morning to evening at an interval of 10 min during 2008–10 on clear sky days. The instrument measures the intensity of direct solar irradiance at five narrow-band spectral channels centered at 440, 500, 675, 870 and 1020 nm. From this data, AOD value for each wavelength was estimated. The instrument is calibrated using the Langley plot technique based on the measurements made initially at Mauna-Loa observatory (Shaw, 1983) and subsequently at Mt. Sinhgad (18°21′N, 73°45′E, 1450 amsl) situated to the south-west of Pune (Pawar *et al.*, 2012; Vijaykumar and Devara, 2013). It is found that the overall uncertainty in AOD measurements is ± 0.03 (Devara *et al.*, 2001; Morys *et al.*, 2001; Porter *et al.*, 2001; Ichoku *et al.*, 2002b). These data are used along with AERONET as a "ground truth" for the comparison with MODIS AOD products in this study.

METHODOLOGY

For inter-comparison purpose, MODIS retrievals must be collocated in space and time with AERONET and MICROTOPS measurements. This is essential since the MODIS sensor scan consists of spatial coverage of the study region from the space whereas AERONET is point measurement at the ground. Hence, the whole purpose of the spatio-temporal collocation technique is to capture/co-locate the air mass seen by MODIS sensor from the space over the study region, which under the influence of wind, is also measured by AERONET from the ground simultaneously. In order to facilitate this, we averaged the quality controlled (QA Flag 3) MODIS AOD values at 10 × 10 km^2 spatial resolution over 50 km × 50 km grid box centered at Pune (Ichoku *et al.*, 2002a). Further, in order to accomplish realistic comparison of AODs from these measurements, AERONET and MICROTOPS measured AODs are collocated with the MODIS AOD retrievals within ± 30 min of its overpass time and then interpolated to derive the AODs at 550 nm wavelength by evolving a linear regression fit to the log-log plot of the spectral AODs, using the Ångström empirical formula: AOD = $\beta \times \lambda^{-\alpha}$. This process yields the corresponding AODs at 550 nm for AERONET and MICROTOPS within ± 30 min of MODIS overpass time. Thus, over two years period (i.e., during 2008–09 and 2009–10), we obtained 118 (for 2008–09) and 119 (for 2009–10) collocated data sets for MODIS (Terra)- AERONET and 48 and 60 data sets for MODIS (Terra)-MICROTOPS during 2008–09 and 2009–10, respectively. Similarly, there were 101 and 96 collocated data points (during 2008–09 and

2009–10, respectively) for MODIS (Aqua) - AERONET and 41 (for 2008–09) and 50 (2009–10) data points for MODIS (Aqua) - MICROTOPS.

RESULTS AND DISCUSSION

Prior to the comparison with the MODIS data, first we analyze aerosol properties and their variation using AERONET data at Pune.

Spectral and Seasonal Variations in AERONET Derived Aerosol Properties

Fig. 1(a) and Fig. 1(b) portrays the spectral variation of AOD (on log-log scale) and frequency distribution of the Angstrom Exponent (α) during winter (Dec-Jan-Feb) and pre-monsoon (Mar-Apr-May) seasons for the study period 2008–10. The figure brings out the seasonal distinctive features of the spectral variation. It is steeper during winter and relatively less steeper during pre-monsoon. This is indicated by the slope of the spectral curve (i.e., Ångström Exponent) which is 1.34 for winter and 0.80 for pre-monsoon. Frequency distribution of α is mono-modal in winter and bi-modal in pre-monsoon. Winter modal value of α (= 1.4) implies the dominance of submicron aerosols originating from anthropogenic activity like fossil fuel combustion and biofuel burning (Venkataraman *et al.*, 2005; Pandithurai *et al.*, 2007). During pre-monsoon, α-frequency distribution has bi-modal character with primary and secondary α-modal values of 0.5 and 0.95, respectively. Even though the primary modal value is not so prominent, it is indicative of the bi-modal nature of frequency distribution of α which indicates dominance of both fine- and coarse-mode aerosols. This reveals that the aerosol system over Pune is controlled by different sources depending on the season. Monthly variation of AOD and Angstrom Exponent during 2008–10 is shown in Fig. 2. From the figure, it is seen that the high and low α - values during winter and pre-monsoon respectively corroborate the earlier observation (Fig. 1). It is also seen that AOD, in general, is low during winter and high during pre-monsoon.

Aerosol Columnar Volume Size Distribution

The atmospheric aerosols are produced from several natural and man-made sources which present a wide range of particle sizes and concentrations. Their behavior and the atmospheric effects produced by them also depend on their size. Thus, the aerosol size distribution can be an indicator of the type of aerosols. In the present work, aerosol columnar volume size spectra, determined by following the inversion algorithm developed by Dubovik and King (2000), have been used to study the characteristics of aerosol size distribution. The observed aerosol columnar volume size distribution is found to be bi-modal and can be represented by log normal distribution of the form:

$$\frac{dV}{d\ln r} = \frac{V_0}{\sigma\sqrt{2\pi}}\exp\left(-\frac{\ln\left[r/r_m\right]^2}{2\sigma^2}\right) \tag{1}$$

where, dV/dlnr is the aerosol volume size distribution, V_o is the column volume of particles per unit cross section of atmospheric column, r is the particle radius, r_m is the modal radius and σ is the standard deviation of the natural logarithm of particle radii. Bi-modal nature of the aerosol columnar 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 hetero-molecular nucleation and growth of larger particles by condensation of gas-phase reaction products (Singh *et al.*, 2004).

Results are given in Fig. 3, which exhibits the seasonal features of the aerosol columnar volume size distribution for the study period. From the figure, we perceive that the

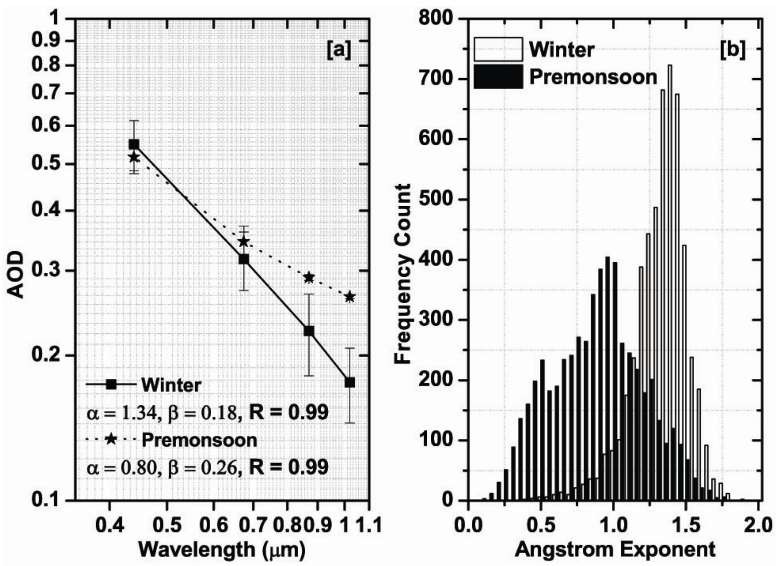

Fig. 1. Seasonal (a) spectral variation of AOD (550 nm) and (b) frequency distribution of Ångström Exponent over Pune using AERONET measurements for the period 2008–10.

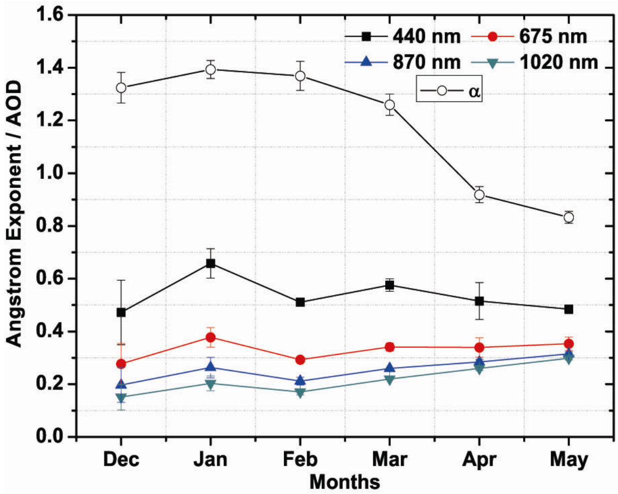

Fig. 2. Monthly variation of AERONET retrieved AODs and Ångström Exponent (α) during 2008–10.

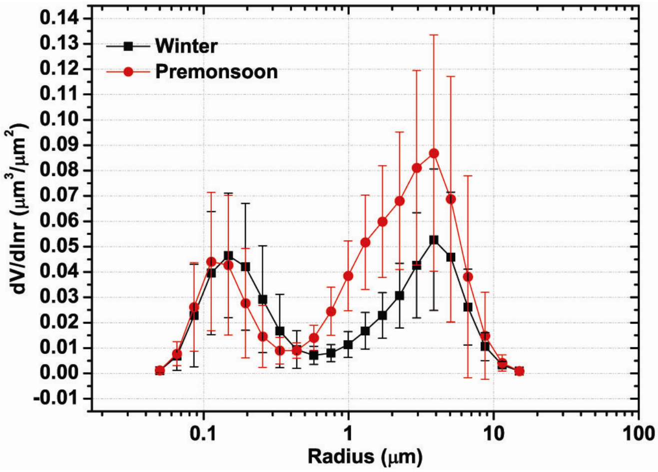

Fig. 3. Seasonal variation of aerosol columnar volume size distribution over Pune using AERONET measurements during the period 2008–10.

peak volume concentrations of both accumulation (< 1 µm) and coarse-mode (> 1 µm) aerosols are low during winter. More importantly, they are comparable in magnitudes with coarse-mode peak volume concentration slightly larger than fine-mode peak volume concentration. As compared to winter, during pre-monsoon there is no considerable change in accumulation-mode peak volume concentration but there is significant increase in peak volume concentration (about 1.5 times) for the coarse-mode aerosols. The parameters corresponding to the accumulation and coarse-mode radii of the aerosol columnar volume size distribution (Fig. 3) and values of the Angstrom Exponent are given in Table 1. From the table, it is seen that during winter, peak volume concentration of accumulation and coarse-mode are 0.047 (± 0.025) $\mu m^3/\mu m^2$ and 0.053 (± 0.028) $\mu m^3/\mu m^2$, respectively. During pre-monsoon, the corresponding values are 0.044 (± 0.027) $\mu m^3/\mu m^2$ and 0.087 (± 0.047) $\mu m^3/\mu m^2$. The dominance of coarse-mode particles is due to dust aerosols produced by strong winds (wind-blown dust) and strong surface heating. Surface heating results in strong heat flux between the surface and atmosphere which is associated with buoyancy. This buoyant force uplifts the dust particles in the atmosphere.

The Angstrom Exponent, in the range 0.5–0.95 (as quoted above), also supports the dominance of coarse-mode particles in pre-monsoon. The sources of fine-mode particles are fossil fuel combustion and industrial pollutants. It is also seen that the variation in coarse-mode is much larger than fine-mode, indicating that the loading of coarse-mode could be episodic.

Single Scattering Albedo (SSA)

The SSA is a common and fundamental 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). Increased absorption with wavelength is, generally, a typical sign of carbonaceous aerosols (Russell *et al.*, 2010). Gadhavi and Jayaraman (2010) observed that the spectral dependence of absorption coefficient is different for carbonaceous particles arising from vehicular pollution and biomass burning. Furthermore, they observed that the biomass burning has higher absorption at lower wavelength. SSA is a function of wavelength and

Table 1. Seasonal values of columnar volume size distribution parameters and Ångström Exponent (α).

Season	V_a ($\mu m^3/\mu m^2$)	R_a (μm)	σ_a	V_c ($\mu m^3/\mu m^2$)	R_c (μm)	σ_c	α
Winter	0.047	0.148	0.025	0.053	3.857	0.028	1.307 (± 0.189)
Premonsoon	0.044	0.113	0.027	0.087	3.857	0.047	0.851 (± 0.315)

V is the peak volume concentration of atmospheric aerosol particles per unit cross-section of the atmospheric column, R is the radius and σ is corresponding standard deviation of the natural logarithm of the radii (subscripts "a" and "c" stand for accumulation and coarse mode, respectively) and α is mean Ångström Exponent.

its value is mostly dependent on the composition and size distribution of aerosols. In the present paper, SSA having an accuracy of ± 0.03 (Holben *et al.*, 2006), is studied by using AERONET inversion products (level 2.0) derived from the direct sun and sky radiance measurements following retrieval algorithm of Dubovik and King (2000). Fig. 4 depicts the wavelength dependence of SSA during 2008–10. From the figure, it is seen that during winter SSA decreases with wavelength having a value 0.86 ± 0.03 at 440 nm and 0.82 ± 0.04 at 1020 nm. Lower SSA at longer wavelength shows dominance of absorbing aerosol over Pune, which is attributed to presence of a mixture of aerosols from multiple sources like vehicular pollution, industrial pollutants, and biomass burning in the field. However, in pre-monsoon, a reversal in the SSA variation is observed (SSA is 0.87 ± 0.02 at 440 nm; and 0.89 ± 0.04 at 1020 nm). This suggests that the dominance of coarse particles (mostly dust) during pre-monsoon, is either due to local activities like urbanization, industrialization and construction activities or wind-blown dust due to strong surface heating (Devara *et al.*, 2002; Devara *et al.*, 2005; Ramachandran and Rajesh, 2007; Bhawar, 2008; Babu *et al.*, 2010; Dani *et al.*, 2010; Kumar *et al.*, 2011). Additionally, long-range transport of dust may also play a role in this regard, for example, aerosols get transported from Saudi Arabia and Afghanistan to the study region (Pandithurai *et al.*, 2007). 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 the Europe and the Mediterranean region. However, Ganguly *et al.* (2005b) found an increasing trend in SSA from 0.75 to 0.90 which is ascribed to asymmetrical changes in the source potential and/or removal mechanism of absorbing aerosol over the locations in the central part of India. Monthly variation of the SSA (Fig. 5) reveals that during 2008–09, there is a sharp increase in the SSA from December to May indicating increase in scattering aerosols while the increase is moderate during 2009–10. The aerosol type changes sometime in March after which dust aerosols seem to dominate total mass.

So far, from the SSA analysis it is observed that spectral variation of SSA in winter and pre-monsoon months is more or less similar to urban and dust aerosol model types. Hence, we derive modeled SSAs for urban and dust aerosol models using "Optical Properties of Aerosol and Cloud" model viz., OPAC (Hess *et al.*, 1998) and compare the resulting values with measured SSAs (Fig. 4). There are ten

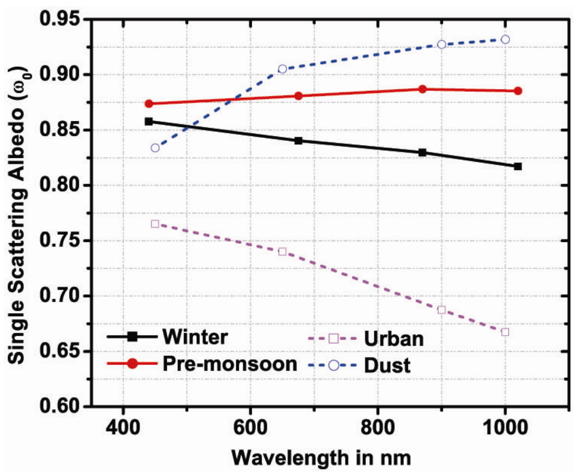

Fig. 4. Wavelength dependence of single scattering albedo [both modeled (OPAC) and measured (AERONET)] over Pune during 2008–10. (Dashed lines-open symbols represent modeled output and solid lines-solid symbols stand for measured values).

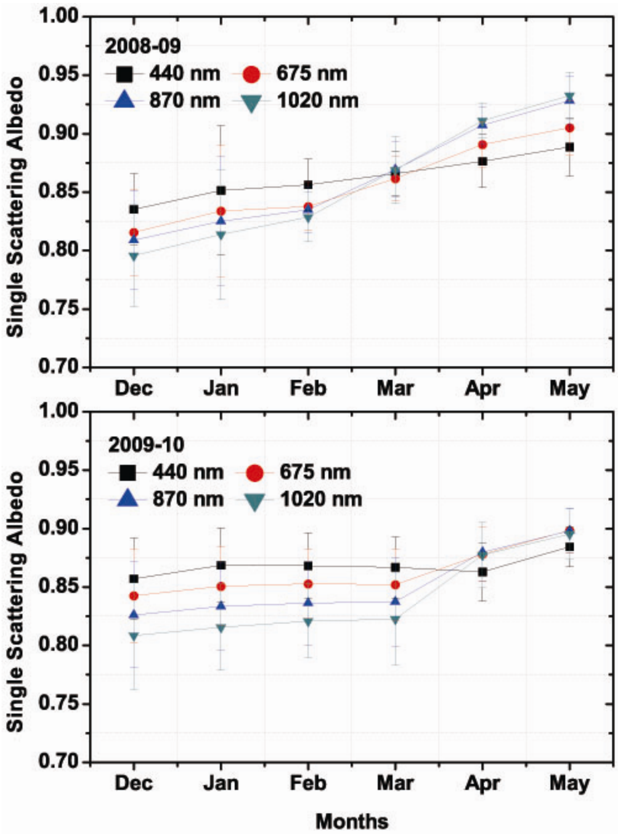

Fig. 5. Monthly variation of AERONET measured single scattering albedo over Pune.

different aerosol models available in OPAC. We employed urban aerosol model for winter SSA and desert (dust) aerosol model for pre-monsoon SSA. On the basis of 30 years of climatological mean of RH, we choose 50% of RH in the OPAC model. Comparison of modeled and measured SSAs (Fig. 4) depicts nearly similar spectral dependence of SSA for both the data sets. However, the rate of change is higher in modeled SSA values. Measured and modeled SSA curves are comparable in shape having slightly different magnitudes. For urban aerosol model SSAs range between 0.76 (for 450 nm) and 0.66 (for 1000 nm), while for dust aerosol model the SSAs lie in the range 0.83 and 0.93 for the respective wavelengths.

Inter-Comparison of Aerosol Optical Depth

In comparison studies, linear regression parameters (slope and intercept) of the correlation plot of the collocated data to be compared assume utmost importance (Misra *et al.*, 2008; Levy *et al.*, 2010). This is because of the deviation of slope of the correlation plot from unity which represents systematic biases in the MODIS retrievals. In the following sub-sections, we discuss the comparison between collocated MODIS – AERONET - MICROTOPS II sun-photometer measurements with relevant statistics involved.

MODIS and AERONET

Fig. 6 shows correlation plots of the MODIS AOD retrievals against AERONET derived AODs during winter and pre-monsoon for the period 2008–10. In the figure, the dashed, red and blue colored lines represent 1-1 line, the linear regression of the scatter plot, and defined EE for the AOD respectively. It is found that about 70%–80% of the MODIS retrievals of the comprehensive data sets of collocations lie within EE defined by relation: AOD – |EE| $\leq$ $AOD_{(MODIS)}$ $\leq$ AOD + |EE|. According to Levy *et al.* (2010), 70% of MODIS retrievals within expected errors are considered as validated and quantitative. In this case, the MODIS AODs over Pune are validated and acceptable. So, one may go forward and use the MODIS data for the regional and temporal analysis. It is seen that during winter, correlation coefficients are 0.79 and 0.62 for the Terra and Aqua respectively. While during pre-monsoon, corresponding coefficients are 0.78 and 0.74. All these correlation coefficients are significant at 0.01 level. The root mean squared error (RMSE) between the ground-based AERONET and the MODIS AODs lies in the range 0.09 to 0.10 for the data under study. In winter, slopes of the regressed lines are 0.63 and 0.74 for the Terra and Aqua respectively and in pre-monsoon, slopes are 0.97 (for Terra) and 0.94 (for Aqua).

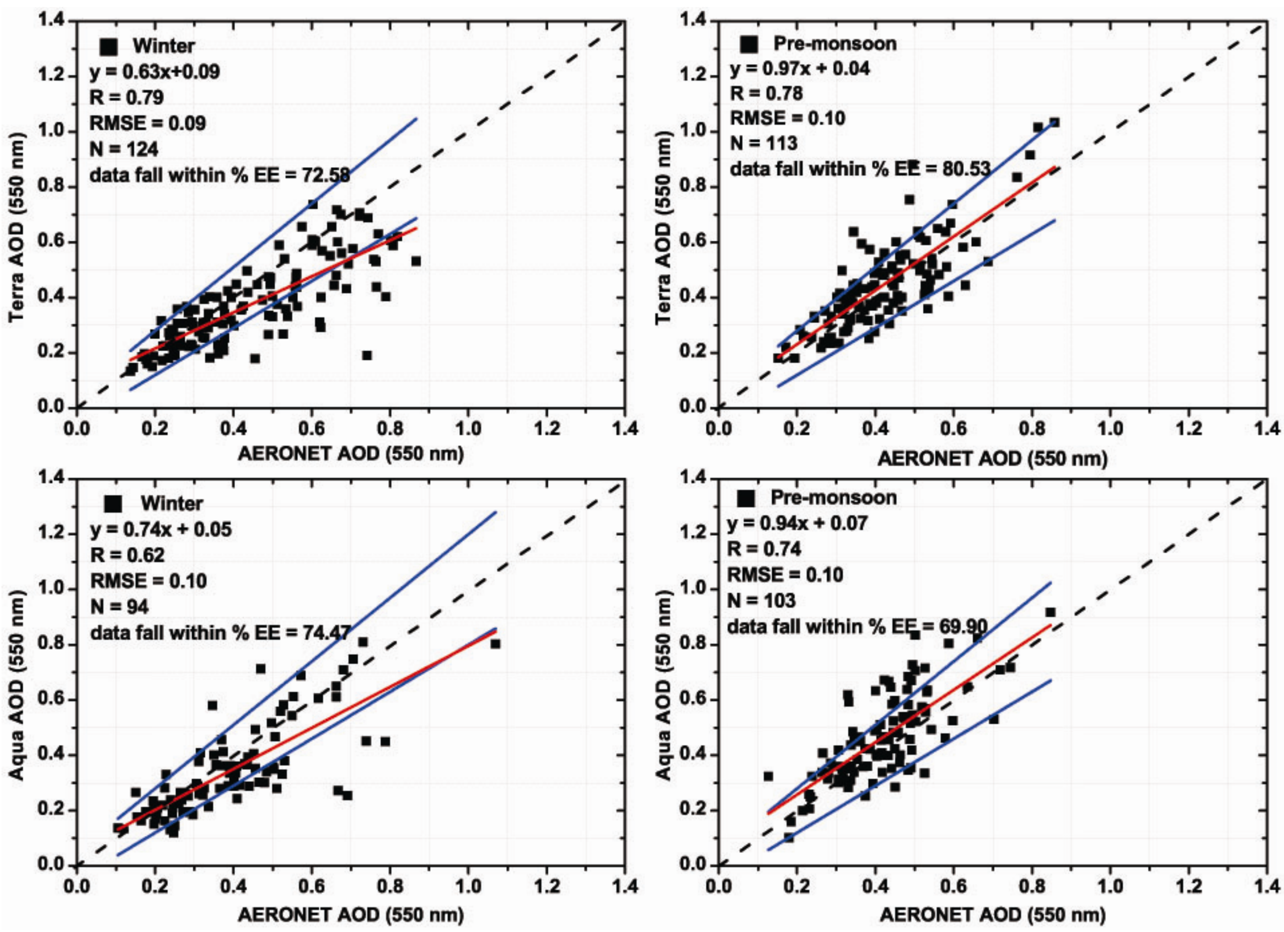

Fig. 6. Correlation plots of MODIS (Terra and Aqua) AOD retrievals against AERONET derived AODs, for winter and pre-monsoon seasons during 2008–10. (The red, blue solid lines and dashed black line represent linear regression, EE and 1:1 line, respectively).

Yearly comparisons of the MODIS retrievals against the AERONET measured AODs at 550 nm are also done and results are given in Table 2. It is seen that the MODIS retrievals fall within the range of 68% to 84% of the EE band and also bear a good correlation with the AERONET measurements (R in the range 0.7 to 0.8) for Terra and Aqua, respectively. In 2008–09, intercepts of linear regression fit are 0.05 and –0.01 for Terra and Aqua respectively and corresponding slopes are 0.86 and 1.05. However, in 2009–10, slopes of regression lines are 0.65 and 0.73 for Terra and Aqua respectively and corresponding intercept is 0.11 for both Terra and Aqua.

MODIS and MICROTOPS II sun-photometer

Fig. 7 shows correlation plots of the MODIS AOD retrievals against the MICROTOPS measured AODs during winter and pre-monsoon (2008–10). The MODIS AOD retrievals corroborate well with the MICROTOPS II sun-photometer measurements with correlation coefficients in the range 0.73 to 0.93 for Terra and Aqua and corresponding root mean square errors lie in the range 0.06–0.10 for winter and pre-monsoon. Intercepts of linear regression fit are 0.03 (Terra) and 0.04 (Aqua) during winter whereas for pre-monsoon, intercepts are 0.05 (Terra) and 0.09 (Aqua). The slopes of regressed lines are 0.54 and 0.70 during winter and 0.58 and 0.76 during pre-monsoon for Terra and Aqua respectively.

From Fig. 6 and Fig. 7 it is clear that at Pune the MODIS retrieved AODs systematically underestimate during winter and show good-match during pre-monsoon. The

Table 2. Results of regression analysis for MODIS (Terra and Aqua) derived AOD against AERONET measurements at 550 nm during 2008–09 and 2009–10.

Year		Slope	Intercept	R	RMSE	% in EE	N
2008–09	Terra	0.86	0.05	0.80	0.09	83.89	118
	Aqua	1.05	–0.01	0.78	0.10	73.26	101
2009–10	Terra	0.65	0.11	0.70	0.11	68.07	119
	Aqua	0.73	0.11	0.73	0.11	69.79	96

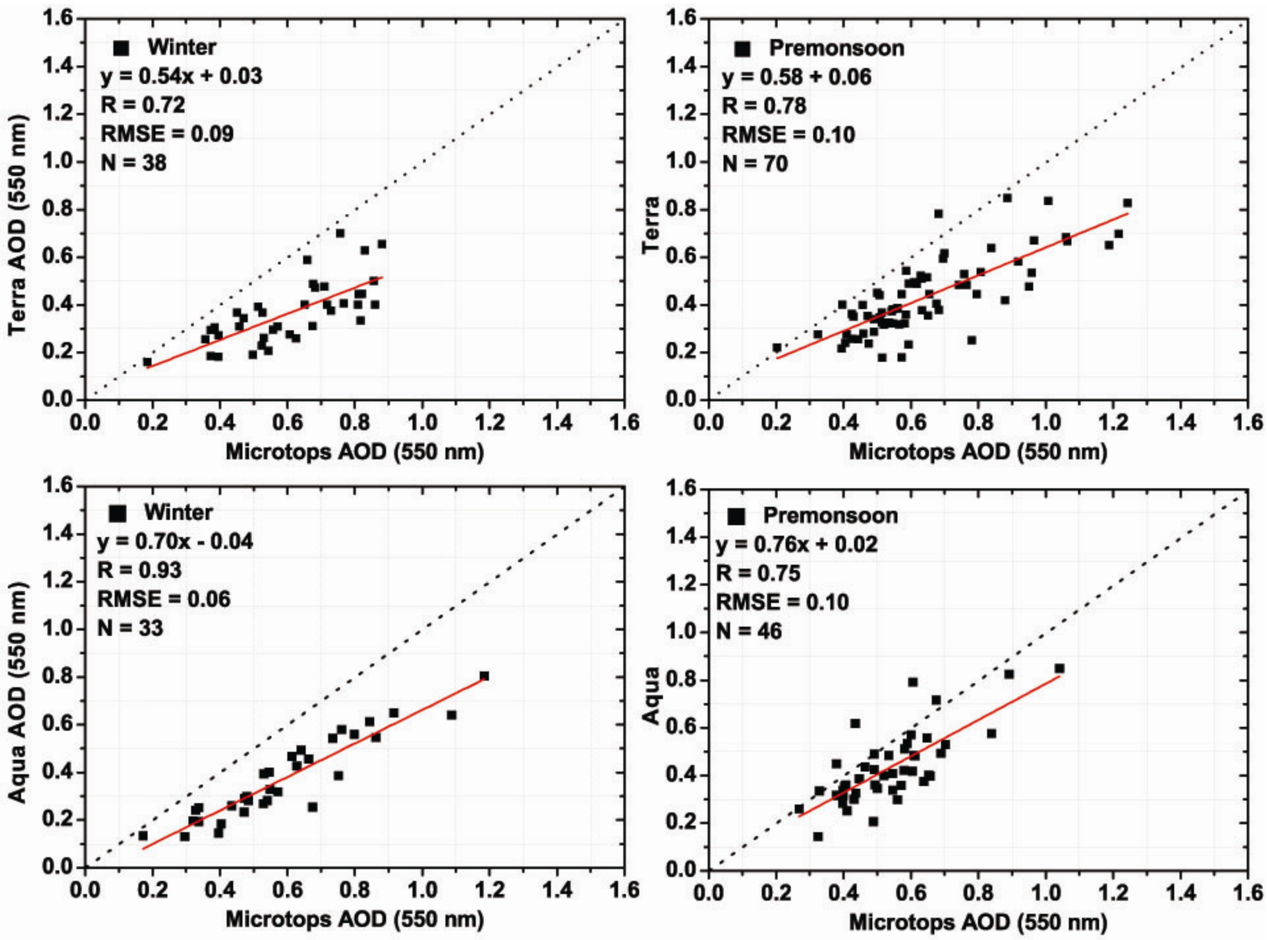

Fig. 7. Correlation plots of MODIS (Terra and Aqua) AOD retrievals against Microtops measured AODs for winter and pre-monsoon during 2008–10. (The red solid lines represent linear regression and dotted lines are 1:1 lines).

inconsistency between aerosol microphysical and optical properties and surface reflectance used in the MODIS are possible reasons for these differences during winter. The underestimation during winter and good-match during pre-monsoon is also confirmed in monthly variation plot of MODIS and AERONET AOD measurements as shown in Fig. 8. Similar results have been reported by Jethva *et al.* (2007a, b), Tripathi *et al.* (2005), Jethva *et al.* (2005) and Prasad and Singh (2007) over Kanpur and also by Yang (2010) over tropical coastal site in China. However, all these studies have got the MODIS overestimation during pre-monsoon. The occurrences of non-zero intercepts (Fig. 6, Fig. 7 and Table 2) indicate 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 (Zhao *et al.*, 2002; Tripathi *et al.*, 2005). Also, large errors in surface reflectance may lead to large intercepts (Chu *et al.*, 2002; Tripathi *et al.*, 2005). Moreover, deviation of the slope from unity (Fig. 6, Fig. 7 and Table 2) signify the inconsistency between the aerosol microphysical-optical properties and the surface reflectance used in the MODIS retrieval algorithm and that in the ground truth retrievals generated by AERONET and MICROTOPS (Zhao *et al.*, 2002; Tripathi *et al.*, 2005; Yang, 2010).

The effect of slope and intercept on correlation of the MODIS derived AODs with the AERONET and MICROTOPS measurements shown in Fig. 6 and Fig. 7, is well represented in average monthly variation (Fig. 8) and the frequency distribution (Fig. 9) of AODs derived from the MODIS and AERONET during the study period (2008–10). As shown in Fig. 8, error bars superimposed on each histogram represent standard deviation of ensemble mean AOD which generally ranges between 0.05 and 0.2. The number of days used in the analysis is also indicated on the bar chart. It is clear from the figure that the variation patterns of the MODIS and AERONET match well for both the years. It is seen that the MODIS AODs are relatively lower than those of AERONET in winter (i.e., during light aerosol loading). However, in pre-monsoon (i.e., during heavy aerosol loading), MODIS AODs are matching quite well with AERONET AODs. Seasonal frequency distribution for the collocated data sets of MODIS and AERONET measured AODs is shown in Fig. 9. It is seen that at the bin size group AOD < 0.3 and 0.3–0.4, the frequency of occurrence of the AOD is maximum (~22–28% in winter; ~10–32% in pre-monsoon). Also, for the bin size range AOD < 0.3–04, frequencies of MODIS AODs are slightly higher than those of AERONET AODs in winter while during pre-monsoon there is reversal in this trend. This behavior can be attributed to deviation of the slope from unity as is seen in correlation plot. Further, the frequencies of the MODIS AODs during pre-monsoon are found to be lower than those of AERONET AODs for the range AOD < 0.3–0.5. In the range of AOD > 0.5, MODIS AODs are consistently lower

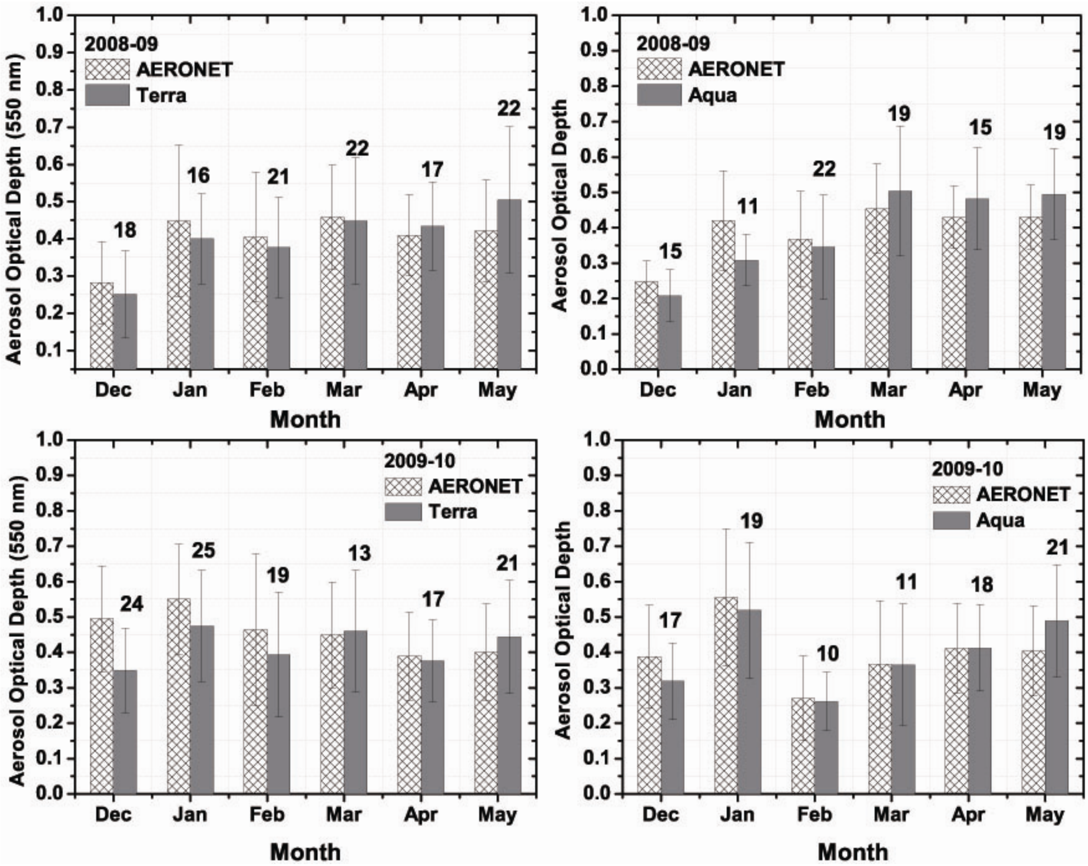

Fig. 8. Histograms of monthly AODs for MODIS and AERONET for 2008–09 and 2009–10 over Pune (numbers above histogram indicate the number of daily data sets used in the analysis).

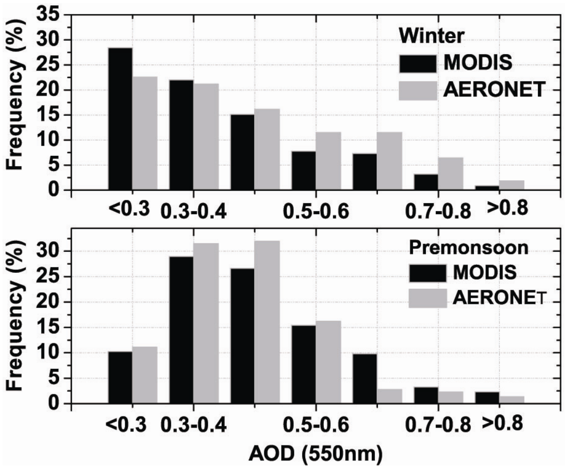

Fig. 9. Frequency distribution of MODIS and AERONET AODs during 2008–10.

than AERONET AODs during winter while in pre-monsoon in the AOD range > 0.6, MODIS AODs are consistently higher than AERONET AODs. Thus, the frequency distribution of MODIS and AERONET aerosol products also supports the underestimation of AOD by MODIS in winter and better match during pre-monsoon.

Separating the aerosol path reflectance from the total surface reflectance measured by satellite sensor at top of the atmosphere is very difficult in space-based aerosol remote sensing because the land reflectance is highly variable in space and time (Jethva *et al.*, 2007a). In Pune, generally the vegetation pattern (NDVI) varies from season to season and hence the surface reflectance. Therefore, the bias in MODIS retrievals during winter (underestimation) indicates the facts that the surface at study region is unusually dark (2.1 µm reflectance < 0.05) or green (NDVI_SWIR > 0.6), and/or the bias may also be due to the lower value of SSA (0.82–0.86) during winter than that of the assumed SSA value (0.90) in the MODIS algorithm (Levy *et al.*, 2010).

AERONET and MICROTOPS II Sun-Photometer

Fig. 10 reveals correlation plot of AERONET against MICROTOPS AODs at 675 nm for all collocated data points during 2008–10. Linear regression analysis (as applied to Fig. 10) shows that correlation coefficient is 0.81 and the slope and intercepts are 0.97 and 0.10, respectively. Seasonally averaged diurnal inter-comparison between AERONET and MICROTOPS AODs is shown in Fig. 11. It is clear from Fig. 10 and Fig. 11 that the MICROTOPS AODs consistently overestimate those of AERONET with mean bias of about 0.1 in AOD values. This discrepancy in the MICROTOPS can be caused by filter degradation, temperature effects and poor pointing at the sun besides calibration issues. The pointing accuracy of the optical filters towards the sun, during each measurement, is very crucial for accurate measurement of atmospheric constituents (Srivastava *et al.*, 2008). In the present study, MICROTOPS was operated with a precision elevation-azimuth assembly, so as to strictly maintain the stability of instrument and the pointing accuracy of each optical filter.

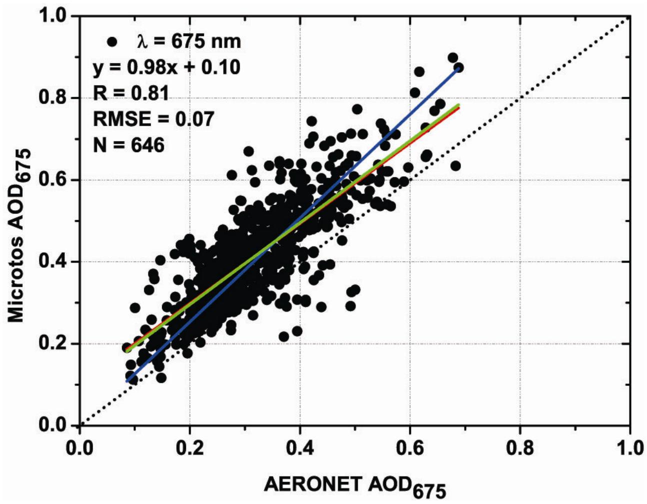

Fig. 10. Correlation plot of AERONET and Microtops derived AODs at 675 nm during 2008–10. (Red line is regression line, blue and green lines are forced lines at intercept = 0 and slope = 1 respectively; dotted black line is 1:1 line).

Spatial Distribution and Long-Term MODIS Aerosol Records

The MODIS aerosol optical depth retrieved at spatial resolution ranging from10 × 10 km^2 (nadir) to 50 × 50 km^2 (swath extremes) has been processed to analyze seasonal and annual spatial distribution for about 200 × 200 km^2 area centered on Pune city. Fig. 12 shows the seasonal spatial distribution for the years from 2001 to 2010. Seasonally, monsoon months (Jun-Jul-Aug) experienced highest aerosol loading followed by pre-monsoon (Mar-Apr-May). However, high AOD in monsoon could be due to cloud-contamination. Post-monsoon (Sept-Oct-Nov) and winter (Dec-Jan-Feb) months have similar aerosol loading over the region. Thus, there are no significant inter-annual changes in post-monsoon and winter seasons. The mean regional AOD values for the four seasons are 0.47, 0.38, 0.28, and 0.29 for Jun-Jul-Aug, Mar-Apr-May, Sept-Oct-Nov, and Dec-Jan-Feb months respectively. These year-to-year variations in AOD values are not large and do not show any linear trend. The lowest annual mean AOD value (0.32) was observed in 2005 whereas highest annual mean AOD value (0.58) was observed in 2002 which was a drought year. High aerosol loading during 2002 was due to less washout effect and wind-blown dust. The regional decadal mean AOD value with annual standard deviation was found to be 0.36 ± 0.09. The spatial distribution of AOD clearly divides the region into high AOD regime (eastern part) and low AOD regime (western part) and these differences are more prominent in pre-monsoon and monsoon months than the other two seasons. This typical spatial distribution of AOD may have its roots in topography, winds and aerosol source locations in the region. The study region Pune is leeward side of Western Ghats. Note here that Western Ghats is in North-South direction across the 200 × 200 km^2 grid box. The dynamics of air motion over and around the hill and/or mountain wave phenomena over the Western Ghats produce

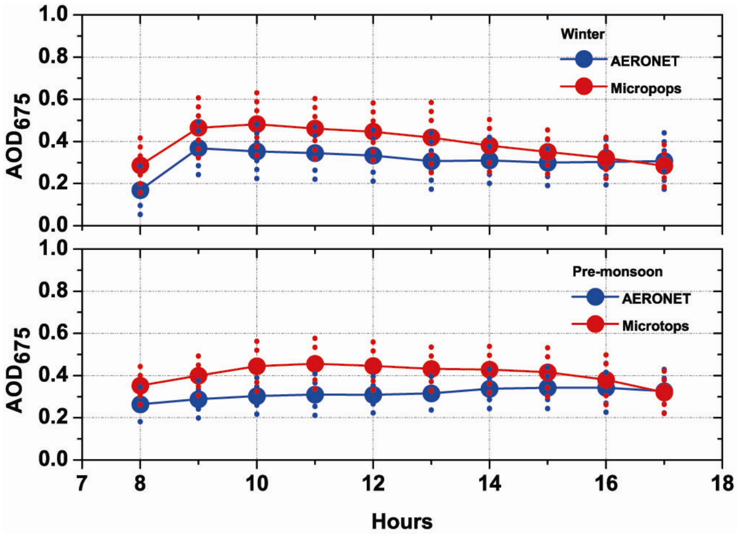

Fig. 11. Inter-comparison of seasonally averaged diurnal AERONET and Microtops AODs during 2008–10.

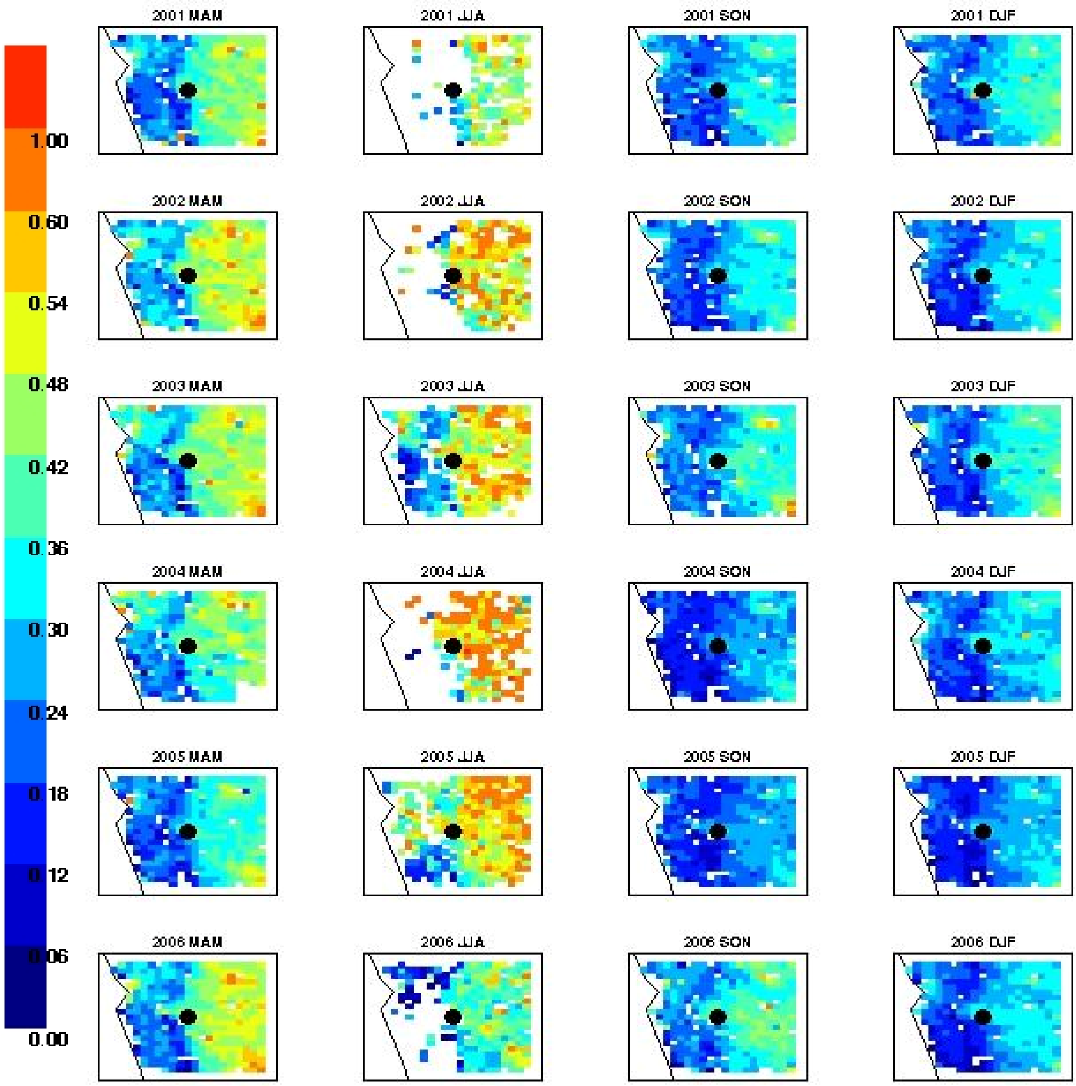

Fig. 12. Spatial distribution of MODIS AODs over Pune and surrounding area (≈ 200 × 200 km^2). Each map represents seasonal mean values in a particular year. Season changes from right (MAM) to the left (DJF) whereas year increases from 2001 (top) to 2010 (bottom).

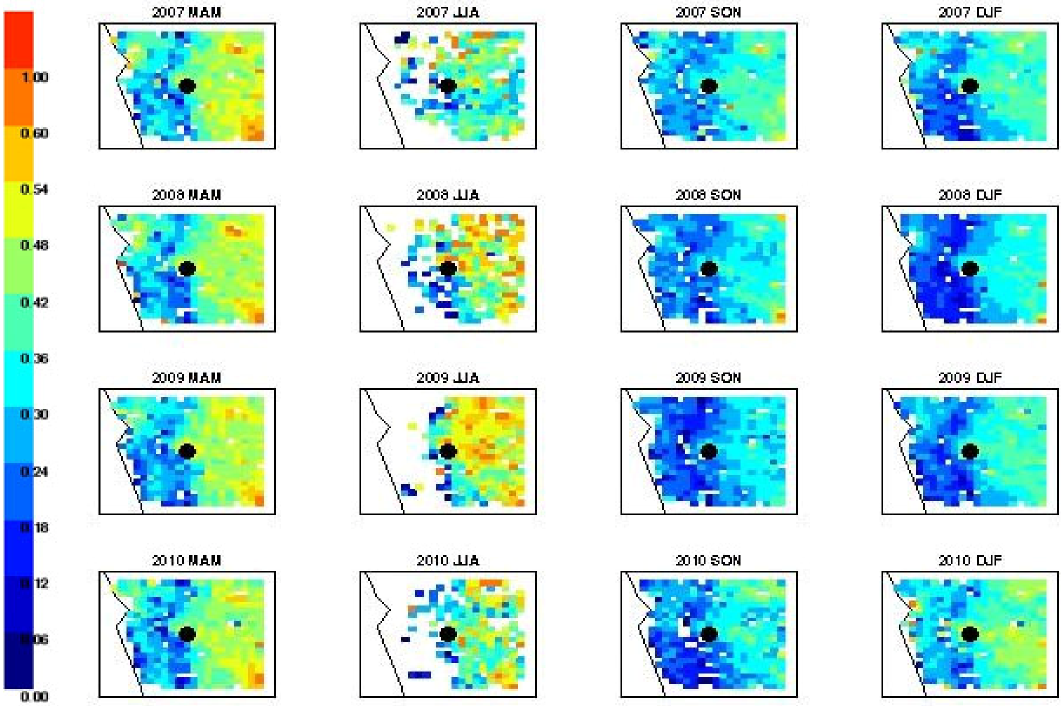

Fig. 12. *(continued).*

lee waves during winter (Sarker, 1966). Strong westerlies blow across the Western Ghats during pre-monsoon and monsoon which could possibly up-lift the marine aerosols. Thus, this is favorable for the advection of uplifted marine as well as anthropogenic aerosols from the western to eastern region. In addition, eastern part is mostly urban, semi-urban and has more land area than that of the western part. Thus, more aerosols are produced due to the anthropogenic activity and wind-blown dust. Altogether, due to this peculiar topography, aerosols set/accumulate in the Eastern part making it a high AOD regime.

SUMMARY

The paper presents aerosol properties measured from three different instruments. The main conclusions of the study are: Over Pune, aerosol physical and optical properties show strong seasonal variation. In winter, higher value of α is associated with low AODs (0.31 ± 0.1) and lower value of α is associated with high AODs (0.36 ± 0.1) during pre-monsoon. The variation in alpha is mostly because of variation in AOD at longer wavelengths whereas AOD at shorter wavelengths remains more or less constant. This indicates that the anthropogenic aerosols contribute substantially to AOD over Pune. Also, windblown dust and sea-salt particles might cause variation in AOD and alpha. The dust particles generated in construction activity (fugitive dust particles) are usually very big in size (bigger than 1 μm) and they rarely contribute to columnar AOD, at most they may contribute in surface particle concentration. Though the size distribution is bi-modal, the dominant component during pre-monsoon is dust. SSA is found to be highly wavelength dependent. The SSA (0.86 ± 0.03 at 440 nm and 0.82 ± 0.04 at 1020 nm) decreases in winter, indicating the dominance of absorbing aerosols, mainly arising from vehicular pollution, industrial pollutants and biomass burning. However, in pre-monsoon, increase of SSA (0.87 ± 0.02 at 440 nm and 0.89 ± 0.04 at 1020 nm) with wavelength shows the presence of coarse-mode particles which may be due to construction activity and wind-blown dust due to strong surface heating. The SSA values reported here during pre-monsoon and winter respectively are about 1.1 to 8.9% lower than the corresponding value assumed in MODIS algorithm. In addition to this, comparisons of measured SSAs with modeled (OPAC) SSAs shows that measured and modeled SSAs are comparable in shape with different magnitude. For urban aerosol model, SSA values are ranging between 0.76 (for 450 nm) to 0.66 (for 1000 nm) and for dust aerosol model, the corresponding values are ranging between 0.83 and 0.93.

Inter-comparison of MODIS AOD retrievals with respect to AERONET and MICROTOPS suggests that the MODIS AODs over Pune are validated and acceptable (about 70%–85% of MODIS retrievals fall within the expected error). During pre-monsoon, MODIS AODs are good matched with AERONET measurements (slope ≈ 1 and intercept ≈ 0). Despite the acceptable agreement, however, MODIS AODs underestimate in winter (slope lies between 0.63 and 0.73 with corresponding intercept ranging between 0.05 and 0.09). Additionally, average monthly variation of MODIS and AERONET AODs show similar pattern of variation with MODIS AOD values systematically less than those of AERONET AODs during winter and more or less similar during pre-monsoon. Improper assumption of surface reflectance and selection of aerosol type can be the possible factors contributing to these discrepancies. MICROTOPS

AODs are found to overestimate over those of the AERONET AODs. This discrepancy in the MICROTOPS can be caused by filter degradation, temperature effects and poor pointing at the sun during the course of manual operation of MICROTOPS besides calibration issues while AEROENT is remotely operated.

The spatial distribution of AOD clearly divides the region into high AOD regime (eastern part) and low AOD regime (western part) and these differences are more prominent in pre-monsoon and monsoon months than the other two seasons which may be due to the peculiar topography, winds and aerosol source locations.

The results presented in the present paper indicate that the Terra and Aqua MODIS retrievals are validated and acceptable with few exceptions as stated above. Nonetheless, the data is useful to characterize AOD distributions over tropical urban city, Pune. One may go forward and use the MODIS data over Pune for the temporal analysis. However, systematic errors in the MODIS products during winter need further investigation.

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