Improved retrieval of aerosol size-resolved properties from moderate resolution imaging spectroradiometer over India: Role of aerosol model and surface reflectance

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[1] We have compared the total as well as fine mode aerosol optical depth (τ and τ_{fine}) retrieved by Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra and Aqua (2001–2005) with the equivalent parameters derived by Aerosol Robotic Network (AERONET) at Kanpur (26.45°N, 80.35°E), northern India. MODIS Collection 005 (C005)–derived $\tau_{0.55}$ was found to be in good agreement with the AERONET measurements. The τ_{fine} and η (τ_{fine}/τ) were, however, biased low significantly in most matched cases. A new set of retrieval with the use of absorbing aerosol model (SSA ~ 0.87) with increased visible surface reflectance provided improved τ and τ_{fine} at Kanpur. The new derivation of η also compares well qualitatively with an independent set of in situ measurements of accumulation mass fraction over much of the southern India. This suggests that though MODIS land algorithm has limited information to derive size properties of aerosols over land, more accurate parameterization of aerosol and surface properties within the existing C005 algorithm may improve the accuracy of size-resolved aerosol optical properties. The results presented in this paper indicate that there is a need to reconsider the surface parameterization and assumed aerosol properties in MODIS C005 algorithm over the Indian region in order to retrieve more accurate aerosol optical and size properties, which are essential to quantify the impact of human-made aerosols on climate.

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1. Introduction

[2] The satellite-based remote sensing of tropospheric aerosols has become an essential tool to monitor aerosols globally. Since late 1970s, aerosol properties over oceans have been monitored by Advanced Very High-Resolution Radiometer (AVHRR) onboard NOAA series of satellites. Using the back-scattered ultraviolet (UV) radiation, the Total Ozone Mapping Spectrometer (TOMS) has provided the longest time series of information on elevated absorbing aerosols over land and ocean [*Herman et al.*, 1997; *Torres et al.*, 1998]. These information, however, were limited to mainly oceanic regions or provide a qualitative measure of aerosol loading over land and ocean. The retrieval of aerosol optical and size properties on operational basis with high spatial and temporal resolution is the prime requirement today to assess the impact of aerosols on the earth's climate. With the launch of Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra (18 December 1999) and Aqua (4 May 2002), the operational remote sensing of tropospheric aerosols over the globe on a daily basis has become possible. The high spatial and temporal resolution with desired accuracy of the retrieved aerosol properties by MODIS allow us to study aerosols on various scales. *Kaufman et al.* [1997] had developed the first over-land MODIS aerosol algorithm that was based on the look-up-table approach. The spectral reflectance measured by MODIS at the top of atmosphere are matched with the pre-calculated reflectance for a set of aerosol models and surface reflectance. Since its launch in year 2000, MODIS aerosol algorithm has been continually updated and evaluated with respect to ground-based measurements. The aerosol products derived from MODIS have been extensively used by the scientific community in variety of applications. MODIS has provided the first comprehensive aerosol database globally which has helped in understanding the global aerosol distribution. MODIS has an ability to separate aerosols by their size that aids in identifying the anthropogenic (mainly fine mode) and natural aerosols (mainly coarse mode) in total aerosol loading. Several validation studies have compared the MODIS aerosol products with those of ground-based

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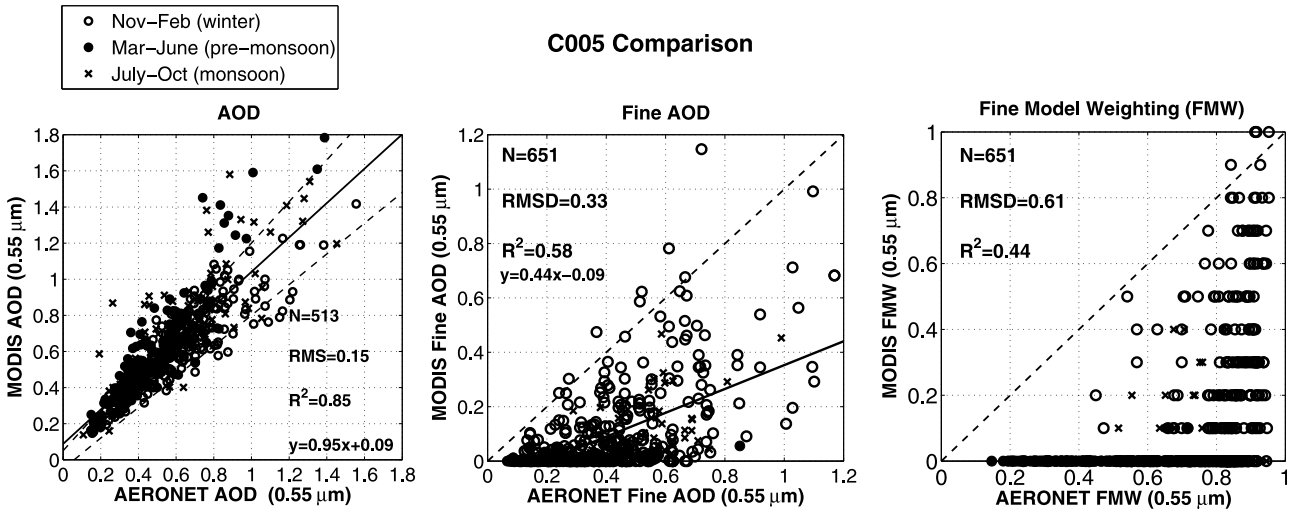

Figure 1. Scatterplot of (left) colocated aerosol optical depth, (middle) fine mode AOD, and (right) fine model weighting, at 0.55 μm, between MODIS (y axis) and AERONET (x axis) for data acquired from Terra and Aqua platforms during period 2001–2005 at Kanpur, India. The dashed lines (Figure 1, left) are predicted uncertainty of $\Delta\tau = \pm 0.05 \pm 0.15\tau$, where τ is aerosol optical depth, and solid line is linear regression fit. Root mean square difference (RMS) and correlations (R^2) are given within each subplot.

measurements (mainly AERONET) and shown that the aerosol optical depth (AOD or τ) retrieved by MODIS over ocean is well within the prelaunch uncertainty ($\Delta\tau = \pm 0.03 \pm 0.05\tau$). Over land, the accuracy of retrieved τ is limited ($\Delta\tau = \pm 0.05 \pm 0.15\tau$), primarily because of difficulty in handling heterogeneous and especially bright surface reflectance. Studies by *Chu et al.* [2002] and *Remer et al.* [2005] had demonstrated that MODIS C004 tended to underestimate at larger values of τ. Over bright surfaces and in dusty regions, τ of C004 was overestimated [*Kaufman et al.*, 2000; *Chin et al.*, 2004; *Jethva et al.*, 2007]. These and many other studies indicated that there was a need to improve the aerosol algorithm particularly over land.

[3] In order to reduce bias observed in the MODIS C004 aerosol products, *Levy et al.* [2007] have implemented the second-generation MODIS aerosol algorithm for the retrieval of aerosols over land. Keeping the basic philosophy of retrieval same, the old algorithm (C004) has been restructured to incorporate some major changes. A new set of fine and coarse mode aerosol models have been assigned to each region using the subjective cluster analysis applied to AERONET measurements worldwide. The reflectance relationships for deriving surface reflectance in the visible channels (0.47 μm and 0.66 μm) have been parameterized in which the reflectance ratio is now a function of "greenness" of target and scattering angle. The new algorithm no more assumes that the 2.1 μm channel is transparent to aerosols, rather it first determines the surface reflectance at 2.1 μm based on the measured reflectance and assumed aerosol properties at this wavelength. Look-up-table (LUT) calculations are based on the combination of MIEV code [*Wiscombe*, 1981] and RT3 radiative transfer code [*Evans and Stephens*, 1991] that accounts for the effects of polarization. Section 3 describe the aerosol retrieval procedure adopted in the C005 algorithm. The details of Collection 005 (C005) algorithm and aerosol products can be found in the theoretical basis document on MODIS web page.

[4] The economic development and greater population density over the northern India have led to the higher levels of pollution in this region [*Guttikunda et al.*, 2003]. Recent aerosol inventories [*Reddy and Venketaraman*, 2002a, 2002b] and measurements provided by the ground-based and satellite [*Di Girolamo et al.*, 2004; *Singh et al.*, 2004; *Jethva et al.*, 2005] show that the Indo-Gangetic Plane (IGP) is one of the highly aerosol loaded regions in India. The major sources of aerosols over this region are seasonal biomass-burning smoke, biofuel combustion [*Venkataraman et al.*, 2005] and dust [*Singh et al.*, 2004; *Jethva et al.*, 2005; *Sagnik et al.*, 2004]. Since year 2001, AERONET sunphotometer at Kanpur, India has provided remotely sensed high-quality data on spectral τ, single-scattering albedo ($\omega_0(\lambda)$), refractive index, and aerosol volume size distribution ($dV/dlnr$) from the spectral sun and sky measurements [*Holben et al.*, 1998; *Dubovik and King*, 2000]. The later inversion parameters are considered to be good when condition $\tau_{0.44} > 0.4$ is satisfied. All together, the seasonality of aerosols, variable surface properties, meteorology, and topography make this region a good test bed for evaluating the performance of MODIS aerosol algorithm.

2. Comparison of MODIS C005 Aerosol Retrieval With AERONET

[5] Figure 1 shows the scatterplot of colocated $\tau_{0.55}$ derived by Terra and Aqua MODIS C005 and AERONET for the period 2001–2005. The spatially averaged MODIS τ in a grid box of size 0.5° × 0.5° centered at AERONET site have been compared with the temporally averaged AERONET measurements within ±30 min of MODIS overpass over the sunphotometer site [*Ichoku et al.*, 2002]. MODIS-derived τ is found to be within the predicted uncertainty of

$\Delta\tau = 0.05 \pm 0.15\tau$ [*Remer et al.*, 2005; *Levy et al.*, 2007] for most matched cases. The slope of linear regression to be close to one and high correlation ($R^2 \sim 0.85$) between MODIS and AERONET show good agreement between the two independently derived τ. MODIS aerosol algorithm derives size-discriminated τ over ocean [*Tanré et al.*, 1997] as well as over land [*Kaufman et al.*, 1997; *Remer et al.*, 2005]. The concept of aerosol fine mode fraction (C004 terminology) or fine model weighting (C005 terminology) has been introduced in the algorithm which quantifies the fractional contribution of fine-dominated model in the total τ. In both versions of aerosol algorithm, each aerosol model contains fine and coarse mode and therefore, fine mode fraction value of 1 means the total τ is contributed by the fine-dominated model only and value of 0 means total τ is contributed by the coarse-dominated model only. A sensitivity analysis of aerosol retrieval carried out by *Tanré et al.* [1997] showed that the fine mode fraction ($\eta = \tau_{fine}/\tau_{total}$) can be derived with an absolute uncertainty of ±0.25 over ocean. *Kleidman et al.* [2005] have found good agreement between MODIS-derived η and equivalent AERONET inversion over ocean. Thus, the retrieval is better constrained over ocean. Over land, η may have greater uncertainty and has not been validated extensively. *Remer et al.* [2005] suggested that η carries qualitative meaning on a monthly scale and no claim has been made yet on its accuracy over land. Since η is an important parameter retrieved by MODIS that carries information on the anthropogenic and natural fraction of total τ, it should be evaluated against equivalent ground-based retrieval.

[6] Figure 1 compares MODIS-derived τ_{fine} (middle) and η (right) with equivalent parameters derived by AERONET at Kanpur. Note that both parameters are not physically identical. τ_{fine} derived by MODIS is the contribution of fine-dominated model in the total τ, whereas AERONET sky retrievals designate fine mode τ to be the volume contribution of aerosols below a radius <0.6 μm. The τ_{fine} derived by AERONET using Dubovik algorithm is uncertain within the range 0.015–0.03 (Dr. Oleg Dubovik, personal communication). At $\tau = 1$, this yields error in η of 15%–30% for lower values of τ_{fine} (<0.2), and less than 5% for moderate to high τ_{fine} (>0.5). Since both quantities are defined in similar ways and indicate relative dominance of fine and coarse particles in total aerosol loading, a good correlation between them is expected here. In most colocated cases, MODIS-derived τ_{fine} and η were found to be underestimated significantly. In many cases τ_{fine} and η were zero or close to zero, suggesting the use of dust model in the retrieval at Kanpur. Several studies [*Di Girolamo et al.*, 2004; *Singh et al.*, 2004; *Jethva et al.*, 2005] have shown that fine mode particles are dominant in total aerosol loading over the Indo-Gangetic basin region including Kanpur during winter (November to February). Hence, at least during winter, it was expected that MODIS should retrieve larger values of τ_{fine} and η that are consistent with those derived by AERONET. Before the launch of C005 aerosol algorithm, *Levy et al.* [2007] had studied the sensitivity of C005 retrieval to the likely uncertainty in parameters. The total τ was found to be stable under minor calibration and random errors as well as choice of model. The retrieval of η however, showed greater sensitivity to the choice of aerosol model and visible surface reflectance.

[7] The issue here is that C005 aerosol algorithm accurately derives total midvisible τ but the mixture of aerosol models used to derive τ seems to be inappropriate. This indicates that the inversion of MODIS measurements is probably nonunique in which different assumptions about aerosol and surface properties would retrieve same columnar τ. In the present study, we attempt to address this problem through the sensitivity of the retrieval to the change in the aerosol model and surface reflectance. The uncertainty in the estimation of these parameters can have significant impact on the accuracy of aerosol retrieval. The objective of this study was to find a right combination of aerosol model and surface parameterization that should retrieve accurate total as well as size-segregated aerosol properties over the Indian region. Section 3 describes the aerosol retrieval procedure. Section 4 presents the results of the aerosol retrieval sensitivity and its validation against AERONET. An independent comparison of the new MODIS retrieval with in situ measurements over southern India is presented in section 5. The work is summarized and concluded in the section 6.

3. Aerosol Retrieval Procedure

[8] The retrieval of aerosol properties from MODIS spectral measurements involves the assumption on the state of atmosphere as well as on the surface optical properties. The MODIS aerosol algorithm developed by *Kaufman et al.* [1997] and *Levy et al.* [2007] model the aerosol component as mixtures of fine and coarse mode particles with varying optical and size properties. The surface reflectance in the visible channels are estimated using SWIR-VIS relationships. As seen in Figure 1, C005 algorithm selects too much coarse mode in most cases, it was thought that the assumed fine model (moderately absorbing over Indian subcontinent) may be inappropriate over this region. Therefore, the focus here was to select a new aerosol model for the region which can replace the existing fine-dominated aerosol model in the retrieval. Using a reasonably long record of AERONET QA data (about 5 years), a new fine-dominated model has been derived using the procedure described by *Levy et al.* [2007]. Table 1 lists the aerosol size and optical properties of the "Kanpur" and MODIS C005 aerosol models. The Kanpur model differs from the Neutral/Generic model in terms of single-scattering albedo. The SSA (0.55 μm) of Kanpur model is ~0.86, suggesting absorbing aerosols, whereas that of Neutral/Generic model is ~0.92, suggesting scattering type of aerosols. Notably, the refractive index and SSA of the Kanpur model are close to that of the Absorbing/Smoke model which is not assigned as a fine-dominated model over the Indian region. The MIEV code [*Wiscombe*, 1981] was used to generate scattering and extinction properties for C005 aerosol models. The output of MIEV code were then used as input to the RT3 radiative transfer model [*Evans and Stephens*, 1991] to compute the TOA reflectance for the seven values of τ at 0.55 μm (0, 0.25 0.5, 1.0, 2.0, 3.0, 5.0), 9 solar zenith angles (0.0, 6.0, 12.0, 24.0, 36.0, 48.0, 54.0, 60.0 and 66.0), 16 sensor zenith angles (0 to 66 in step of 6), and relative azimuth angles (0 to 180 in step of 12). In the present study, the same procedure was followed as described by *Levy et al.* [2007] for the new retrieval except that the aerosol model and the visible surface reflectance were changed from

Table 1. Aerosol Optical and Size Distribution Properties Derived From AERONET Wintertime (November and December) Inversion Data at Kanpur, India[a]

Model	Mode	r_v (μm)	σ	V_0 ($\mu m^3/\mu m^2$)	Refractive Index	ω
Kanpur						0.86
	Accum	$0.153+0.04\tau$	0.46	$0.021+0.102\tau$	1.52-0.02i	
	Coarse	2.77	0.61	$0.012+0.131\tau$	1.52-0.02i	
Levy et al. [2007]						
Absorbing/Smoke						0.87
	Accum	$0.0096\tau + 0.1335$	$0.0794\tau + 0.3834$	$0.1748\tau^{0.8914}$	1.51-0.02i	
	Coarse	$0.9489\tau + 3.4479$	$0.0409\tau + 0.7433$	$0.1043\tau^{0.6824}$	1.51-0.02i	
Neutral/Generic						0.92
	Accum	$0.0203\tau + 0.145$	$0.1365\tau + 0.3738$	$0.1642\tau^{0.7747}$	$1.43-(-0.002\tau + 0.008)$i	
	Coarse	$0.3364\tau + 3.101$	$0.098\tau + 0.7292$	$0.1482\tau^{0.684}$	$1.43-(-0.002\tau + 0.008)$i	
Spheroid/Dust						0.95
	Accum	$0.1416\tau^{-0.0519}$	$0.7561\tau^{0.148}$	$0.0871\tau^{1.026}$	$1.48\tau^{-0.021}$ 0.002i	
	Coarse	2.2	$0.554\tau^{-0.0519}$	$0.6786\tau^{1.0569}$	$1.48\tau^{-0.021}$ 0.002i	

[a]The "Absorbing," "Neutral," and "Spheroid" are the global aerosol models used by the MODIS Version 5 or Collection 005 aerosol algorithm. Each model has two modes, i.e., accumulation and coarse. τ is aerosol optical depth at 0.55 μm. Abbreviations: r_v, mean radius; σ, standard deviation of volume distribution; ω, single-scattering albedo at 0.5 μm.

their original state derived in the C005 algorithm. The spectral reflectance data from MODIS Level 2 database were extracted from both Terra and Aqua platforms over Kanpur region for the period 2001–2005. For each Level 2 granule, the extracted reflectance and geometrical parameters (Sun-sensor viewing angles) were averaged in a grid box of size 0.5° by 0.5° centered at AERONET site (26.45°N, 80.35°E) at Kanpur. Then averaged reflectance were used as input to the aerosol retrieval code which then computes total TOA reflectance for the thirteen mixtures of fine and coarse aerosol models reflectance ($\eta = -0.1, 0.0, 0.1, \ldots, 1.1$) such that, $\rho\lambda^{TOA} = \eta\rho\lambda^{fine} + (1 - \eta)\rho\lambda^{coarse}$ where $\rho\lambda^{TOA}$ is the total reflectance at TOA for wavelength λ, η is the weight given to LUT fine model reflectance ($\rho\lambda^{fine}$). The algorithm then finds a value of τ at 0.55 μm and surface reflectance at 2.1 μm for a combination of fine and coarse model reflectance that provides zero error in the spectral fit between the MODIS-measured and LUT reflectance at 0.47 μm with minimum error ε at 0.66 μm. Thus, the output parameters are τ and η at 0.55 μm, and surface reflectance at 2.1 μm. In order to perform the sensitivity analysis, fine-dominated model and surface reflectance in the visible channels were allowed to change. All other parameters were retained at their original states defined in the C005 algorithm.

4. Results

4.1. New Aerosol Retrieval With Absorbing/Smoke Model

[9] The Absorbing/Smoke model of C005 is a fine-dominated model having SSA of ~0.87 at 0.55 μm. This model has been assigned over biomass burning regions of South America and Central Africa in the MODIS C005 algorithm. The subjective cluster analysis of AERONET data led to a neutral aerosol model having SSA~0.92 over the southeast Asia region including India. Figure 2 depicts the time series of monthly mean SSA at 0.44 μm and 0.675 μm derived by AERONET at Kanpur. The SSA at either wavelengths show seasonality in aerosol absorbing characteristic where SSA was less than 0.88 during November–December, indicating presence of absorbing aerosols over the site, and then steadily increases up to ~0.95 (scattering type aerosols) till the arrival of Indian Summer Monsoon in June–July. The SSA at 0.47 μm of moderately absorbing and dust model of MODIS are 0.93 and 0.94, respectively, which is higher than

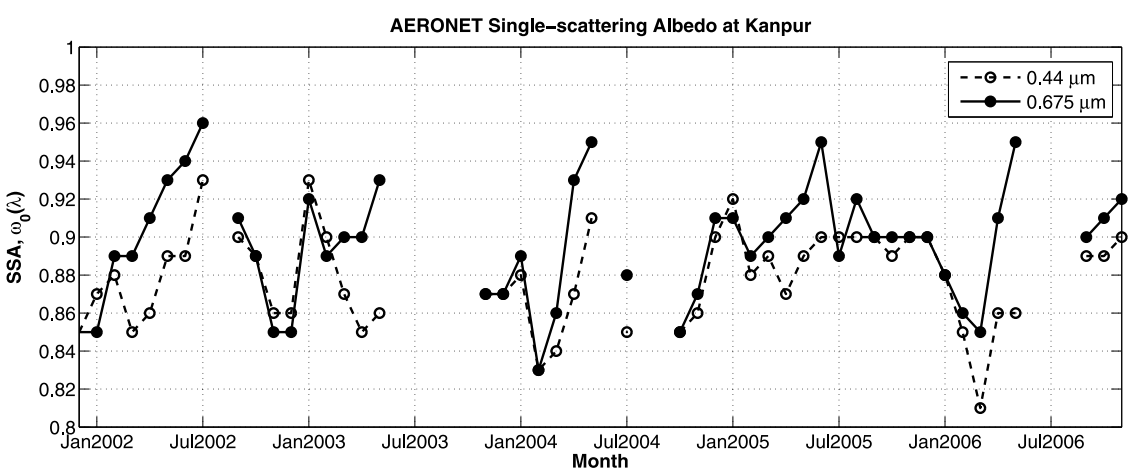

Figure 2. Time series of monthly mean single-scattering albedo at 0.44 and 0.675 μm derived by AERONET at Kanpur.

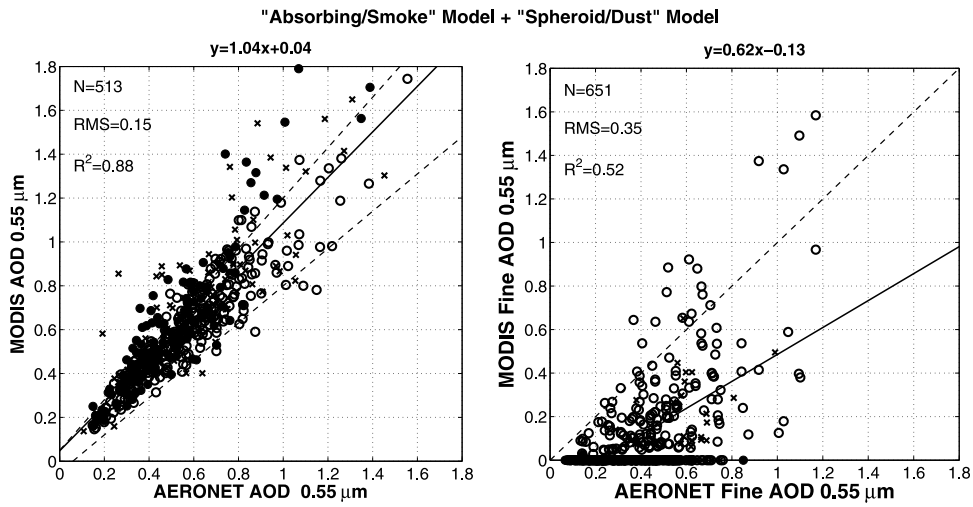

Figure 3. Comparison of (left) aerosol optical depth and (right) fine mode AOD derived from using the absorbing/smoke model of MODIS with that of AERONET at Kanpur. The legends used in Figure 1 are also applicable here. The dashed lines in Figure 3 (left) are predicted uncertainty of $\Delta\tau = \pm 0.05 \pm 0.15\tau$, and solid lines are linear regression fits with equations given at the top of each plot. Root mean square difference (RMS) and correlations (R^2) are given within the plot.

the SSA derived by AERONET. The SSA of absorbing model, however, is close to the AERONET-retrieved values for the winter period at Kanpur. Thus, absorbing model of MODIS may represent the aerosol optical properties at Kanpur and therefore expected to retrieve more accurate aerosol properties. Figure 3 shows the comparison of AOD (left) and τ_{fine} (right) at 0.55 μm retrieved using the absorbing model with that of AERONET. The τ retrieval was found to be slightly overestimated with respect to that of AERONET, however, with marginal increase in correlation. The new retrieval of τ_{fine} is, however, still biased low (toward coarse mode) much like C005. The use of the absorbing aerosol model produces result that are almost similar to the C005 retrieval.

4.2. Sensitivity of Aerosol Retrieval to Change in Surface Reflectance

[10] The estimation of the surface reflectance is a crucial step in deriving the aerosol properties over land. Its signal is comparable to that of aerosols and also can dominate the total signal. The uncertainty in estimating the surface reflectance can lead to erroneous retrieval of τ which can be as much as ten times the uncertainty in the surface reflectance [*Kaufman et al.*, 1997]. In the previous section, it was shown that the change in the fine aerosol model seems to be ineffective in retrieving consistent size-resolved properties (τ_{fine} and η). This left us with a choice to change the surface parameterization in the retrieval algorithm. For estimation of the surface reflectance in the visible channels, MODIS uses parameterized surface reflectance relationships between the SWIR and visible wavelengths that include the dependence on the surface type and scattering angle [*Levy et al.*, 2007]. The colocated MODIS C004-Land and AERONET data used in the atmospheric correction to derive the parameterized surface reflectance relationships was restricted to the conditions of τ (0.50 μm) less than 0.2. This is to minimize the errors arising from multiple scattering at higher AOD. The AERONET aerosol data collected at Kanpur over the period 2001–2005 suggests that only ~3% of the total data represents the low aerosol loading ($\tau_{0.50} < 0.2$). It means that the input from the Kanpur-AERONET data to the MODIS atmospheric correction was not significant. This may be the one reason why the parameterized surface reflectance relationships used in the MODIS algorithm may not hold good for this region.

[11] Despite the parameterization of surface reflectance, several factors can introduce error in the estimation of visible surface reflectance. For instance, an improper choice of aerosol model in the atmospheric correction can lead to error in the surface reflectance relationships. The uncertainty in the assumed slope and intercept of relationships can result in erroneous surface reflectance. As stated earlier, the 2.1 μm channel is no longer assumed to be transparent to aerosols and therefore, the surface reflectance in this channel have to be estimated first. Based on the assumed optical properties and radiative transfer calculations, MODIS C005 algorithm estimates the surface reflectance at 2.1 μm given the measured apparent reflectance at TOA. The uncertainty in the assumed properties at 2.1 μm therefore can also lead to incorrect visible surface reflectance. Since we do not have the exact information on the radiative properties of aerosols at 2.1 μm and also due to uncertainty associated with the SWIR-visible relationship, we change the surface reflectance at 0.66 μm directly in step of 0.005 from its base state derived by the C005 algorithm in both positive (up to $\Delta\rho^s_{0.66} = +0.025$) and negative (up to $\Delta\rho^s_{0.66} = -0.025$) directions. Note that the increment in surface reflectance is same for all data points irrespective of their absolute values. We also allow the corresponding change in surface reflectance at 0.47 μm in accordance with the reflectance relationship between 0.66 μm and 0.47 μm. The aerosol properties were derived for each step of the increased/decreased surface reflectance with two aerosol models analyzed here. The output of each experiment was then compared with the AERONET measurements. Figure 4 show the statistical results of comparison between the new retrieval of τ

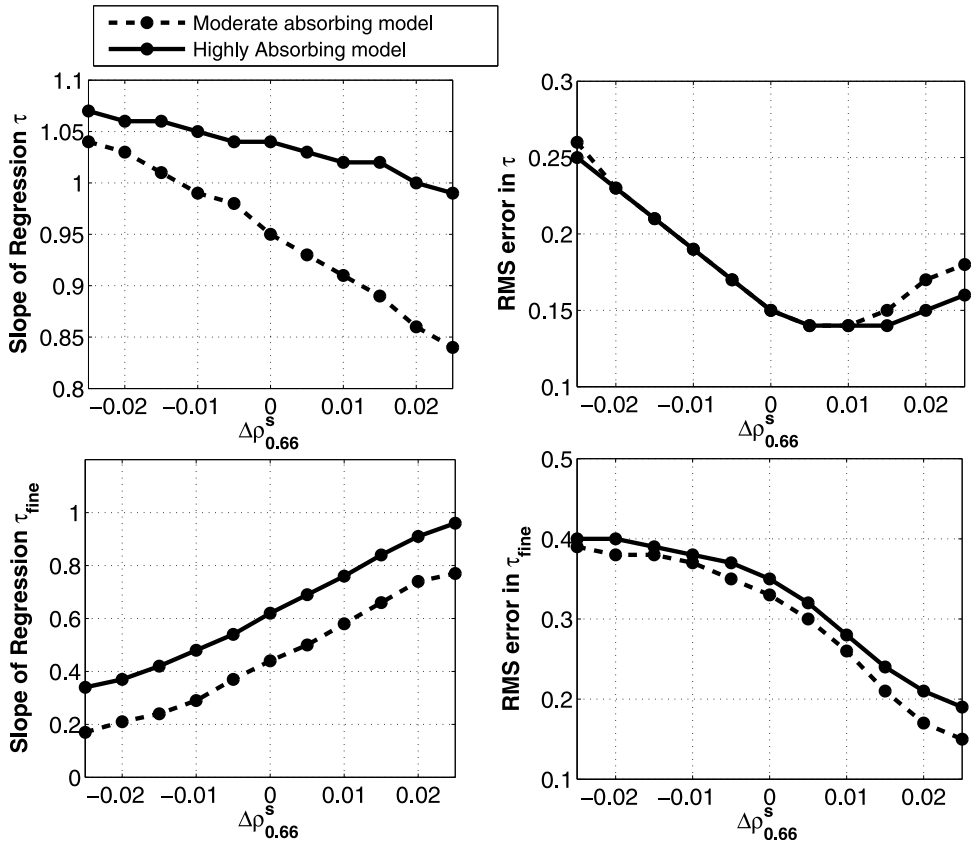

Figure 4. The slope of (left) linear regression and (right) root mean square error between new retrieval of τ and τ_{fine} and that of Kanpur-AERONET as a function of change in the surface reflectance for moderately and highly absorbing aerosol models.

and τ_{fine} with that of AERONET. The error has been quantified as "Root mean square Error" and "Linear Regression" is the linear fit between the new retrieval and AERONET measurements. In the case of MODIS C005 and absorbing models, the error in the retrieval of τ and τ_{fine} and also the slope and intercept of linear fits were increased monotonically when the surface reflectance at 0.66 μm was decreased. On the other hand, an increase in the surface reflectance resulted in lower error and better regression between the retrieved parameters and AERONET measurements.

[12] Figure 5 shows the comparison of τ, τ_{fine}, and η retrieved using the combination of absorbing aerosol model and increased surface reflectance ($\Delta\rho^{s}_{0.66}$ = +0.02) with colocated AERONET measurements at Kanpur. This particular combination of aerosol model and surface reflectance is found to be the best among all the cases analyzed here, which provides more accurate aerosol retrieval in all three parameters with least error and better correlation with AERONET. Note that the error in the new retrieval of τ is less than that seen in C005 products. The new τ_{fine} is now in good agreement with that of AERONET. A low bias in the τ_{fine} and η seen in the C005 data is largely removed. The new retrieval of η now show bimodality in contrast to unimodal (very low biased) C005 retrieval. Also, the intermediate values of η are now more frequent compared to that of C005.

[13] Figure 6 shows the distribution of error (new retrieval AERONET) in the retrieval of τ (top), τ_{fine} (middle) and η (bottom) at 0.55 μm for C005 and new retrieval. Clearly, the new retrieval of τ is less frequently overestimated compared to that of C005. However, as expected, many τ retrieval are underestimated a bit due to increased visible surface reflectance. Overall, the total error in the new τ retrieval is still lesser than the error encountered in C005 data. In the case of τ_{fine}, the difference between the new retrieval and C005 is significant. While the C005 retrieval is mostly underestimated (negative error), the error in the new retrieval of τ_{fine} is more frequent in the range ±0.2. The real improvement in the retrieval of τ_{fine} with the absorbing model and increased surface reflectance is on the negative side of errors where the large underestimation in the C005 retrieval is now largely reduced. Error in the new retrieval of η is distributed on either sides, i.e., overestimation and underestimation, whereas that of C005 was underestimated in almost all cases. Note that η is the ratio of τ_{fine} and τ, therefore given no error in the retrieval of τ, the percentage error in η equals that of τ_{fine}. In the present case, since the new retrieval of τ is underestimated a bit and magnitude of τ_{fine} is increased, the resultant error in η for many retrieval fall on the positive side (overestimation). Thus the accurate estimation of η depends on the accuracy of τ and τ_{fine}.

5. Testing New MODIS Aerosol Retrieval Over Southern India

[14] In February 2004, an intense land campaign was conducted over the peninsular India under the Indian Space

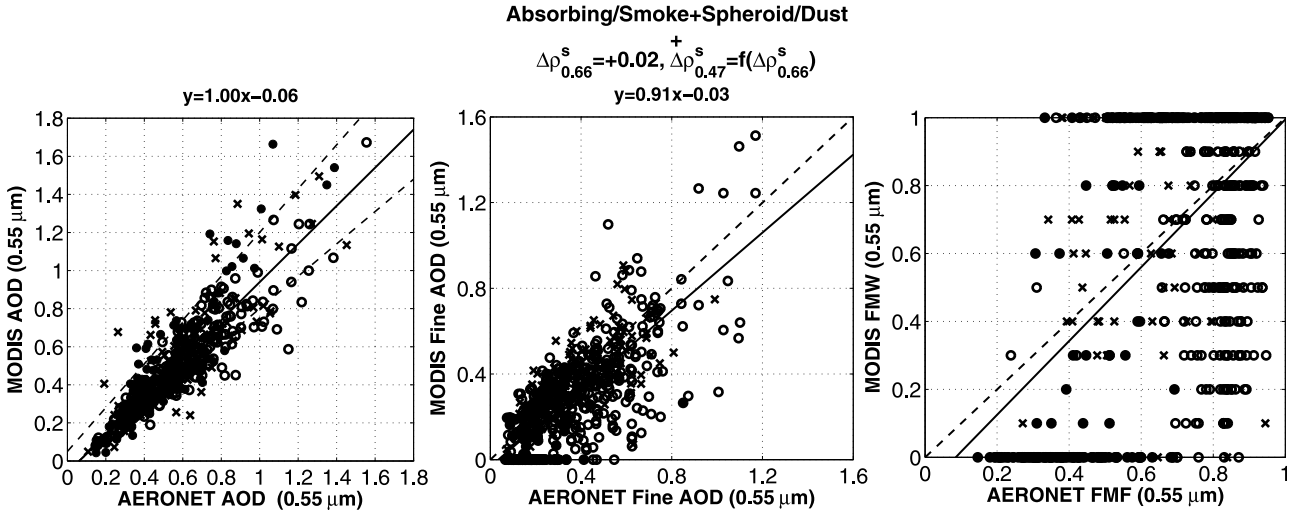

Figure 5. Comparison of (left) aerosol optical depth, (middle) fine mode aerosol optical depth, and (right) fine model weighting retrieved using absorbing aerosol model and with increased visible surface reflectance with colocated AERONET inversions at Kanpur, India. The solid black lines are linear regressions with equations given at the top of the plot.

Research Organization's Geosphere-Biosphere Program (ISRO-GBP) with the aim of mapping the spatial characteristics of aerosols [*Moorthy et al.*, 2005]. This was the first experiment in this region in which number of research teams had participated with instrumented vehicles along the road network covering different locations and almost entire south India (7°N–24°N, 72°E–84°E). The aerosol measurements made during the experiment include mass concentration and mass size distribution (in 10 discrete bins) in the size range 0.05–25 μm. The error in the measurements

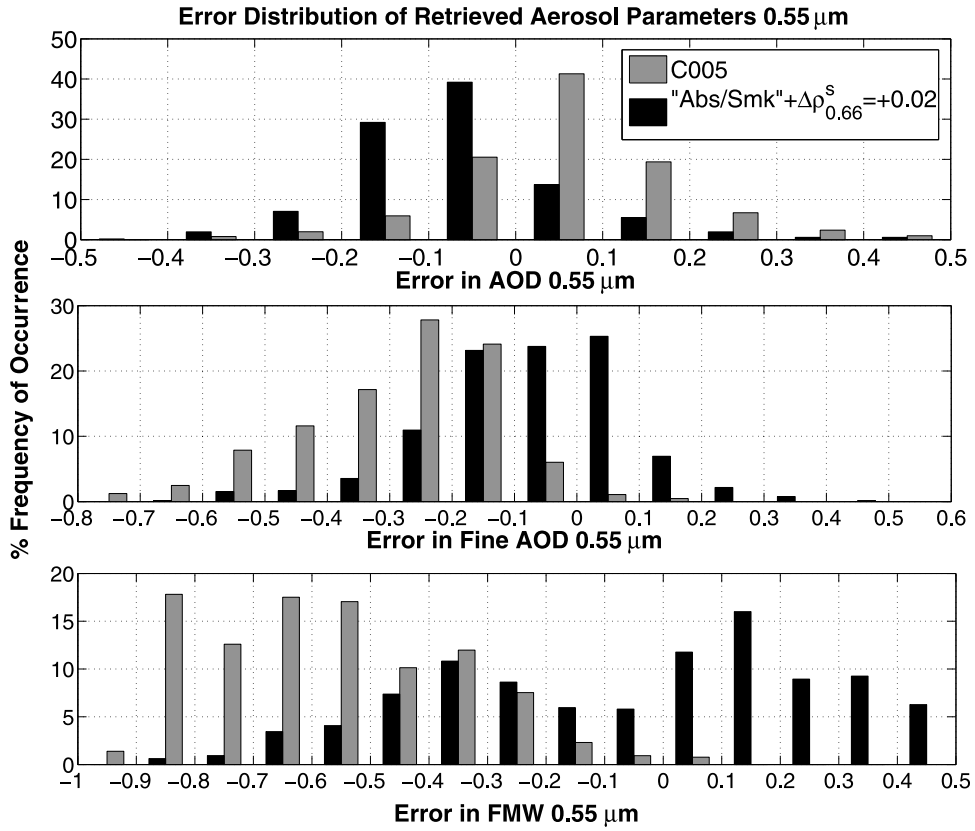

Figure 6. The distribution of error (new aerosol retrieval AERONET) in (top) aerosol optical depth, (middle) fine mode AOD, and (bottom) fine model weighting at 0.55 μm.

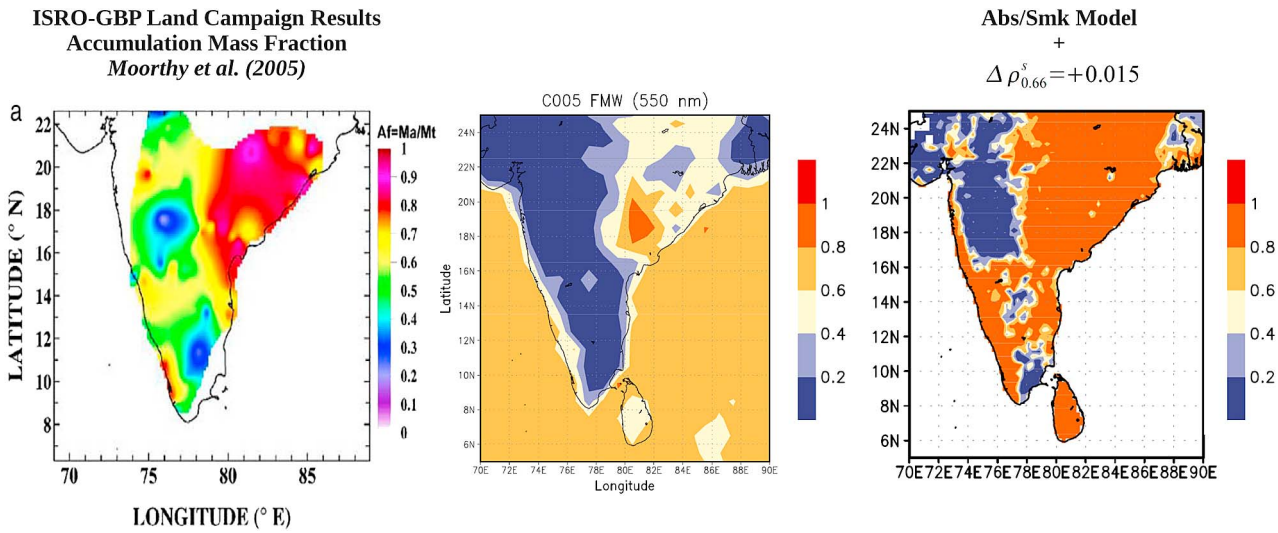

Figure 7. (left) Spatial distribution of monthly mean accumulation mass fraction for February 2004 obtained from *Moorthy et al.* [2005]. (middle) The fine model weighting η for the same period derived from MODIS C005 and (right) new retrieval using absorbing model with increased visible surface reflectance over the peninsular India are shown.

of mass concentration was expected to be between 3% to 20%. This study had also reported the accumulation aerosol mass fraction (A_f) as the ratio of accumulation mass concentration (radius <0.4 μm) to the total mass concentration. This work has been presented and summarized in a paper by *Moorthy et al.* [2005].

[15] The left frame of Figure 7 shows the spatial composite of A_f reported in a paper by *Moorthy et al.* [2005]. This paper compared the measured accumulation mass fraction with the aerosol fine mode fraction derived from MODIS C004 data for the same period. Note that the aerosol fine mode fraction derived by MODIS is the total column retrieval of the fractional contribution of fine mode particles in the total aerosol optical depth, whereas A_f estimated from the land campaign measurements represents in situ surface (not columnar) fractional mass contributed by the accumulation (fine) mode particles in the total mass concentration. They found a remarkable agreement between the spatial patterns of the two independently derived information on the fine mode particles over the peninsular India. Both showed large contribution of fine mode aerosols over the eastern and northern parts and pockets of low accumulation fraction over the central-western and peninsular region. The in situ surface measurements of A_f shown here provided a good opportunity to evaluate the MODIS C005 retrieval of fine model weighting η. The middle frame of Figure 7 shows the spatial pattern of monthly mean η derived from C005 data over the study region for February 2004. The spatial pattern of η of C005 over the study region differs significantly from that of in situ accumulation mass fraction. While the A_f and C004-derived η indicated highs over the eastern part of India, η of C005 is relatively lower over the same region. The pockets of low A_f and C004 η over the interior part of the peninsula were spatially well correlated, whereas η of C005 is low (<0.2) over most part of the western-central and peninsular India. These results again show that the η of C005 is low over large part of the southern India compared to the measured accumulation fraction during February 2004.

[16] The problem of low bias in the retrieval of η by MODIS may be again addressed through retrieval experiment as done in the case of Kanpur. The procedure for the new retrieval remains same which composed of extraction of Level 2 spectral apparent reflectance over the Indian region for February 2004 and use these measurements in the retrieval code with varying aerosol model and visible surface reflectance. In the case of aerosol model experiment, we notice that the new absorbing model of MODIS retrieves η that is similar in magnitude as well in spatial distribution to the existing C005 retrieval over the study region. The change in the fine-dominated aerosol models thus did not reproduce the observed pattern of accumulation fraction.

[17] The right frame of Figure 7 shows the spatial distribution of η (0.55 μm) retrieved using the absorbing model and increased surface reflectance ($\Delta\rho^{s}_{0.66}$ = +0.015). The surface reflectance at 0.47 μm was allowed to increase in accordance with the surface reflectance relationship between the 0.66 μm and 0.47 μm wavelengths. The spatial distribution of new retrieval of η were found to be in good agreement with the measured A_f over the peninsular India. The pockets of low accumulation fraction over the interior parts of peninsula and highs over eastern part are now well captured in the new set of retrieval. Moreover, the spatial continuity of η also improves with the implementation of the proposed changes. Note that since the accumulation mass fraction and η are not physically identical quantities, a good spatial correlation in terms of highs and lows over much of southern India strongly indicate that the new aerosol model and surface parameterization proposed here are more likely to be real. A paper by *Jethva et al.* [2009] reports probably the first measurements of actual spectral surface reflectance measured from an aircraft borne spectroradiometer over

Bangalore region (12.95°N, 77.57°E) in the southern India. This paper has shown that the measured visible surface reflectance is higher than that assumed by the current MODIS C005 algorithm. We need more measurements like this to verify the new surface parameterization proposed in the present study.

6. Conclusions

[18] The space-based remote sensing of aerosols over land from MODIS measurements requires accurate modeling of aerosols and surface optical properties. In the present study, we analyze the role of these two major assumptions in the derivation of aerosol properties. A large negative bias observed in the retrieval of size-segregated aerosol optical properties (τ_{fine} and η), though with accurate retrieval of total AOD, by MODIS against AERONET at Kanpur (26.45°N, 80.35°E), India served as an example of the nonuniqueness of the aerosol inversion. We have attempted to address this issue through the sensitivity analysis of the MODIS aerosol retrieval in which several combination of aerosol models and visible surface reflectance were tested over the Indian region. The use of absorbing aerosol model (SSA ~ 0.85, not assigned over the Indian region in the MODIS C005 aerosol algorithm) with increased surface reflectance in the visible channels provided improved retrieval of spectral τ as well as τ_{fine} and η which are more accurate than that provided by the C005 products at Kanpur. An independent comparison of the new retrieval of η over much of southern India showed improved agreement with the ground-based in situ measurements of accumulation aerosol mass fraction. Though, current MODIS aerosol algorithm has limited information over land to derive size-resolved aerosol properties, present study demonstrates that the accuracy of these retrievals can be improved through right parameterization of surface and aerosol properties. There seem to be clearly a need to reconsider the surface parameterization and aerosol model in the current MODIS algorithm over the Indian region for the accurate derivation of the total as well as size-segregated aerosol properties, both are essential in quantifying the impact of man-made and natural aerosols on climate.

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