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Validation of MODIS derived aerosol optical depth over Western India

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[1] MODIS (Moderate Resolution Imaging Spectroradiometer) derived aerosol optical depths (AODs) were compared against the ground based observations from Microtops sunphotometer over Ahmedabad (72.5°E, 23.03°N) in Western India. The region is semi-arid and poses challenge for the satellite remote sensing of aerosols. Besides comparing the ground truth with the Collection Version 4 of MODIS aerosol product, the paper reports the first ever validation of the updated Collection Version 5 of the MODIS aerosol product over India. The AOD data from Aqua platform is averaged over $0.5° \times 0.5°$ centered at Ahmedabad and compared with the sunphotometer observation taken within half an hour to the satellite overpass time. The Version 4 data comparison showed a large scatter. Further, the comparison for 470 nm and 660 nm behave differently over different years. Overall, the comparison shows considerable improvement in the Collection Version 5 aerosol product. Among seasons, Pre-Monsoon (April to May) has the best correlation and Dry season (December to March) the least. The updated product has scope for further improvement as the correlations are less than unity, and the extent of underestimation for 470 nm is more during Dry and Post-Monsoon seasons whereas that for 660 nm is more during Pre-Monsoon and Monsoon seasons which are dominated by fine and coarse particles respectively. The results show a better surface reflectance parameterization by the MODIS Collection Version 5 algorithm as compared to Version 4 but the aerosol model used in the retrieval algorithm is still not adequate.

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1. Introduction

[2] Aerosols are in the forefront of climate studies since last two decades owing to the role they play in the Earth-Atmosphere system by absorbing or scattering the incoming solar radiation thus warming or cooling the atmosphere [*Bellouin et al.*, 2005]. Their optical properties which depend on their chemical composition, size and shape, determine their radiative behavior which in turn determines the overall effect they will have on the Earth radiation budget [*Charlson et al.*, 1992; *Chung et al.*, 2005]. The major problem in their characterization is on account of their short lifetime because of which they have high spatial and temporal variability [*Seinfeld and Pandis*, 1998]. Besides, the transport processes may bring in aerosols from other locations and affect the local climate there. These factors reinforce the necessity of aerosol monitoring on a larger spatial scale than can be provided by the ground based measurements [*IPCC*, 2001].

[3] Satellite based observations can provide detailed knowledge in this regard on a long timescale covering a large spatial area [*Kaufman et al.*, 2002a]. They have an additional advantage, compared to conventional ground based observations, in that since the same instrument is making observation globally, the aerosol concentration at different locations can be compared which will not be affected by the calibration errors of the instrument. Aerosol monitoring from space based instruments consists in extracting the atmospheric contribution from the total signal measured by the satellite sensor. Aerosol monitoring from previous sensors was limited to studies over oceans which have a distinct advantage in that the total measured signal is not much affected by reflectance from ocean surface away from sun-glint area [*King et al.*, 1999]. Aerosol retrieval over oceans is thus more accurate and reliable. Studies over land are comparatively more challenging because of the large surface reflectance which may introduce considerable errors in the retrieved results.

[4] The initial attempts for aerosol retrieval over land were made with the launch of the POLDER instrument [*Deschamps et al.*, 1994] which utilized the information regarding the polarization state of the radiation for the purpose [*Leroy et al.*, 1997] but had limitations with onboard calibration. It lasted for only 8 months due to technical problems in the spacecraft. Aerosol monitoring over land entered a new era with the launch of the MODIS instrument [*Barnes et al.*, 1998] onboard the NASA satellites Terra and Aqua in 1999 and 2002 respectively. It measures the Earth leaving radiances in 36 high resolution

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bands from 0.4 to 14.0 microns with a spatial resolution of 250 m, 500 m and 1 km depending on the wavelength. Its large swath of 2330 km allows the nearly global coverage within 1 or 2 days. The wide spectral coverage has advantage in deriving aerosol size distribution information and hence in uncoupling the total aerosol amount into contribution from natural and anthropogenic parts [*Kaufman et al.*, 2005]. Parallel measurement in visible and IR channels has also helped in overcoming the biggest obstacle in the aerosol retrieval over land viz, the separation of the surface reflectance part from the total measured signal [*King et al.*, 1992, 1999, 2003].

[5] In spite of these advantages, the space based measurements from MODIS, like any other sensor, suffer from various drawbacks. These include possibility of cloud contamination and errors arising due to various assumptions in the retrieval algorithm principally about the aerosol type and surface reflectance. To circumvent the uncertainties pertaining to these parameters, the procedure relies on the ground based observations which provide the exhaustive database of the aerosol microphysical properties [*D' Almeida et al.*, 1991; *Holben et al.*, 1998]. Even after the retrieval has been accomplished, the satellite retrieved data has to be validated against the ground truth data. Being based on the measurement of attenuation in direct solar radiation, data from ground based observations are not limited by the aerosol type and surface reflectance related constraints. Hence they represent the benchmark against which to verify the accuracy and validity of satellite based retrievals. An extensive validation exercise tests the efficacy of the retrieval algorithm, conditions under which it works satisfactorily and cases where further improvement is needed. Further, the validation exercise helps to quantify the improvements to the algorithm which are made from time to time. Validation of MODIS aerosol optical depth data started and is in progress nearly since the data from the sensor started coming in. *Chu et al.* [2002, 2003], *Ichoku et al.* [2002, 2003], *Remer et al.* [2002, 2005], *Levy et al.* [2005] and several other groups working on the validation efforts report their results based on the extensive validation of the aerosol product at its different stages of development. However, a detailed and extensive validation of the MODIS Level 2 data over the Indian subcontinent is still lacking. For example, *Tripathi et al.* [2005] studied 1 year of Level 2 data whereas *Jethva et al.* [2005] and *Prasad and Singh* [2007] used Level 3 gridded data for their comparisons. More details on their results will be discussed in the Results and Discussion section. The present paper discusses the validation of 4 years of the Level 2 MODIS retrieved aerosol optical depth product over Ahmedabad, an urban location in western India. Both versions of the aerosol product are considered so as to be able to assess the improvement in accuracy with transition from collection version 4 to version 5. In the present validation study, the aerosol product data from only the Aqua platform is used. To the best of our knowledge, this is the first time that the validation results from collection version C005 of MODIS aerosol optical depth data over India are being reported.

[6] Section 2 provides a brief overview of the MODIS retrieval algorithm for version 4 and upgrades to version 5. Only the algorithm over land will be discussed. Section 3 discusses the study location and local meteorology which is important while discussing the differences in the ground truth values and the MODIS retrieved values of the aerosol optical depth. Details of data analysis are given in section 4. Results and discussion of the validation effort are presented in section 5.

2. Overview of the MODIS Algorithm for Aerosol Optical Depth Retrieval Over Land

[7] The retrieval philosophy of MODIS is based on the transparency of aerosols in the mid-IR wavelengths. The algorithm proceeds with the identification of dark targets in the satellite image which are essentially the regions of low surface reflectance as obtained from the mid-IR channel reflectance. The surface reflectance in visible wavelengths is obtained from the corresponding values in the mid-IR using the empirical relations [*Kaufman et al.*, 1997b, 2002b]:

$$R_{470} = R_{2130}/4; \quad R_{660} = R_{2130}/2 \tag{1}$$

[8] These relations were derived based on the atmospheric correction of the AVIRIS and Landsat Thematic Mapper data during SCAR-A experiment and represent the parallel processes affecting the surface reflectance in visible and mid-IR wavelengths [*Kaufman et al.*, 1997b, 2002b]. These values along with the satellite and solar geometries are input to the radiative transfer equation to derive the value of aerosol optical depth. The operational procedure for the retrieval process is the so-called Look-Up Table approach wherein the satellite measured radiances in the blue and red channels are matched against the simulated values of the top-of-atmosphere reflectance. The cloud mask and gaseous absorption is applied at the pre-processing stage. The decision about aerosol model is taken based on the ratio of path radiance in red and blue channels and the geographical location of the study area. Further details about the algorithm are discussed by *Remer et al.* [2005] and *Kaufman et al.* [1997a].

[9] The previous MODIS algorithm (Collection version C004) has recently been updated [*Levy et al.*, 2007b] to improve its performance after the initial validation results showed scope for further improvement when compared with the ground based observations [*Chu et al.*, 2002, 2003; *Ichoku et al.*, 2002, 2003; *Remer et al.*, 2005; *Levy et al.*, 2005]. The modifications correspond to the inclusion of polarization in the radiative transfer calculation [*Levy et al.*, 2004], the angular dependence of surface reflectance ratios [*Remer et al.*, 2001; *Gatebe et al.*, 2001] and the update of the aerosol models based on the aerosol climatology derived from the worldwide AERONET observations [*Dubovik et al.*, 2002].

[10] The negligence of polarization in the radiative transfer calculation at the computational stage may lead to artificial errors in the results. *Levy et al.* [2004] performed model studies to find how much effect the neglect of polarization in the radiative transfer calculation will have on the overall accuracy of the MODIS retrieved aerosol optical depth. They found the difference to be positive or negative depending on the scattering angle whereas the magnitude of difference was dependent principally on the sun and satellite geometry. Further, they foresee the differ-

ence to have impact on the individual retrievals though the long time global averages, like the ones used in the radiative forcing studies, will not be affected. The look-up tables in the version 4 algorithm were evaluated using the scalar version of the Dave SPD code [*Dave*, 1970]. The updated version 5 uses the radiative transfer code RT3 [*Evans and Stephens*, 1991] for the purpose which performs the radiative transfer calculations taking polarization into account. The aerosol optical properties required by RT3 are calculated using the MieV code [*Wiscombe*, 1981].

[11] The surface reflectance ratios in equation (1) were derived by nadir observations by the Landsat TM and AVIRIS data and thus does not include any possible angular dependence of the ratio. As explained by *Remer et al.* [2001], the surface reflectance ratios may have angular dependence mainly due to the absence of spectral signature of underlying surface in the specularly reflected radiation. Since the specular reflection takes place at the target surface and does not interact with the liquid water or chlorophyll content of the vegetation, the spectral signatures of the surface are absent in the reflected radiation so that the ratio of surface reflectance in the visible to mid-IR bands approaches unity. Further, specular reflection having special preference in the forward scattering direction, the retrieval made under such geometry is more affected than the backscatter direction. Besides, the surface reflectance ratio was found to have seasonal dependence and related to the NDVI of the surface. In the updated version, the surface reflectance at red is parameterized in terms of the surface reflectance at 2130 nm and is a function of scattering angle and NDVI of the target [*Levy et al.*, 2007b]. The surface reflectance value at blue wavelength is found from the value at red.

[12] The aerosol models in the version 4 algorithm were inferred based on the information regarding aerosol climatology available at that time. With the deployment of worldwide AERONET network, detailed information about the aerosol properties are available at more geographic locations [*Holben et al.*, 1998]. The updated MODIS algorithm uses the aerosol models classified using all the AERONET data processed as of February 2005. The procedure includes the cluster analysis of the AOD data from AERONET divided into different optical depth bins and sorted according to their single scattering albedo. Such analysis classified the AERONET data into different aerosol models viz., spheroid and three fine aerosol models- absorbing (ω = 0.85), moderately absorbing (ω = 0.90) and non-absorbing (ω = 0.95) aerosol types [*Levy et al.*, 2007a].

[13] Other special features of the updated MODIS aerosol product include the adjustment of the cloud mask, mass concentration, subpixel snow mask and approval of negative aerosol optical depths. In addition, the look-up table is examined through the AOD at 550nm as against the independent retrievals in 470 and 660 nm channels in the version 4 algorithm [*Remer et al.*, 2006; *Levy et al.*, 2007b].

3. Study Location and Local Meteorology

[14] The location under study is Ahmedabad (72.53°E, 23.03°N) in the western Indian state of Gujarat. The entire region is semi arid and is influenced by the Thar Desert in the North and Arabian Sea in the south-west. The local meteorology is summer from March to May, monsoon during June to September and winter from October to February.

[15] In the present study, the annual data set has been divided in four major seasons, viz, Dry (December to March), Pre-Monsoon (April and May), Monsoon(June to September) and Post-Monsoon (October and November) based on the variation of various meteorological parameters like wind speed and direction, temperature and relative humidity.

[16] The relative humidity is usually less than 30% during Dry months and between 30–40% during Pre-Monsoon and Post-Monsoon months. Monsoon season exhibits the highest value among all the seasons with RH crossing 70%. The average mean daily temperature during Dry season lies in the range of 22–24°C whereas during Pre-Monsoon season it is around 32°C [*Ganguly et al.*, 2006].

[17] Wind speed is highest (about 5 m/s) during Pre-Monsoon months closely followed by Monsoon months. It is lowest (about 2 m/s) during Post-Monsoon season and increases slightly during Dry season. Average value of wind speed showed a gradual decrease from 2002 to 2005. Amount of rainfall exhibited an increase during the study period. Thus the rainfall amount during 2002 was very less (400 mm). During 2003, Ahmedabad received comparatively more rainfall but with large variabilities. During 2005, the rainfall amount was the highest (about 1300 mm) among all the years and it was also uniformly distributed throughout the season (Figure 1).

[18] Figure 2 shows the overall pattern for aerosol optical depth distribution over Gujarat at 550 nm. It is derived by averaging the Level 2 aerosol data product from Terra platform on a 0.5°latitude × 0.5°longitude scale. While finding the monthly average, a particular grid box was chosen only if daily averaged data for at least 10 days was available for that particular box. The image shown is for November 2003 whereas the complete cycle of AOD variation can be seen at http://www.prl.res.in/~amisra/gujarat.html. The regions of highest AOD (greater than 0.6) are located over North-West Gujarat and over the Gulf of Khambhat whereas the AOD over North-East and South-West regions are comparatively low(less than 0.15). The overall pattern of distribution is similar over the years but the actual magnitude of the AOD value is different. The higher value of aerosol optical depth over the NW Gujarat is mainly due to the area being less vegetated. This is the region of the Rann of Kuchh, a marshy deposit of salt. Aerosol remote sensing from satellite means is specially challenging over this region because of the surface being highly reflecting. The higher wind speeds over the region further aid in lifting the salt particles into vertical column, increasing the aerosol content.

[19] Any study of the validation results has to be done taking into account the variation in the various meteorological parameters. Such a comparative study will aid not only in getting the overall view of the scenario during the study period but also in interpreting the various validation results in the light of various plausible causes. The main factors which govern the production and loss of the natural aerosol particles are wind, humidity and rainfall. For example, a higher wind speed aids in releasing more soil derived aerosol particles in the atmosphere resulting in an increased

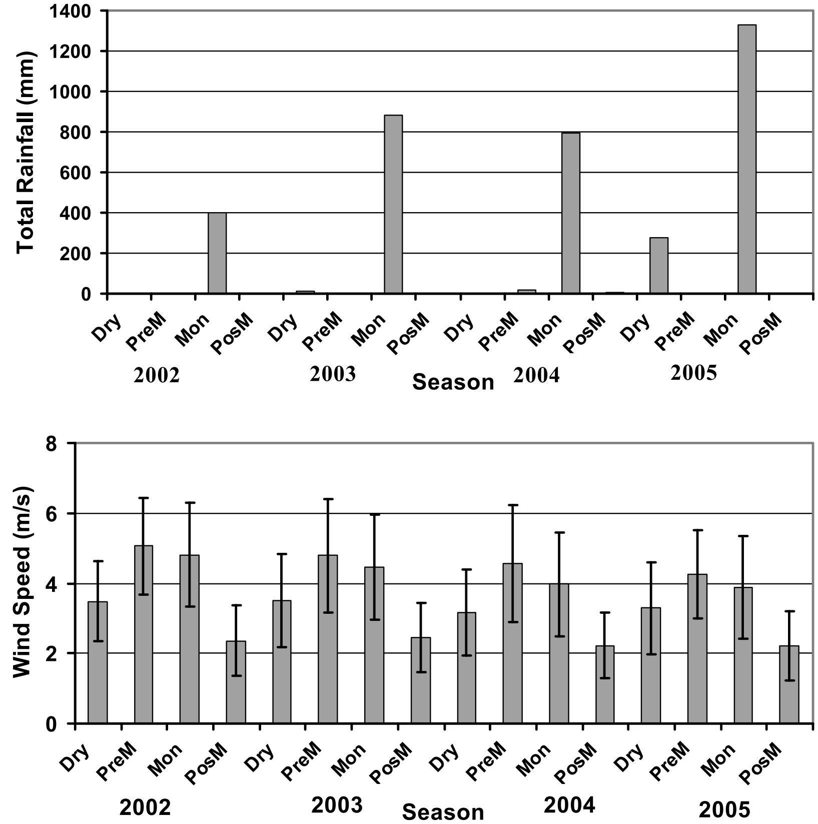

Figure 1. Variation of rainfall and wind speed during the study period, January 2002 to December 2005 over Ahmedabad, classified according to seasons, Dry(D, J, F, M), Pre-Monsoon(A, M), Monsoon(J, J, A, S) and Post-Monsoon(O, N).

columnar aerosol content. Increase in relative humidity results in hygroscopic growth of smaller particles thus increasing the integrated aerosol optical depth. Because of rainfall, the soil becomes damp restricting the possibility of soil derived particles being released. This, together with wet removal of aerosol particles leads to a reduction in AOD values. Dispersion of aerosol particles with wind is another loss process. The net amount of aerosol particles in the

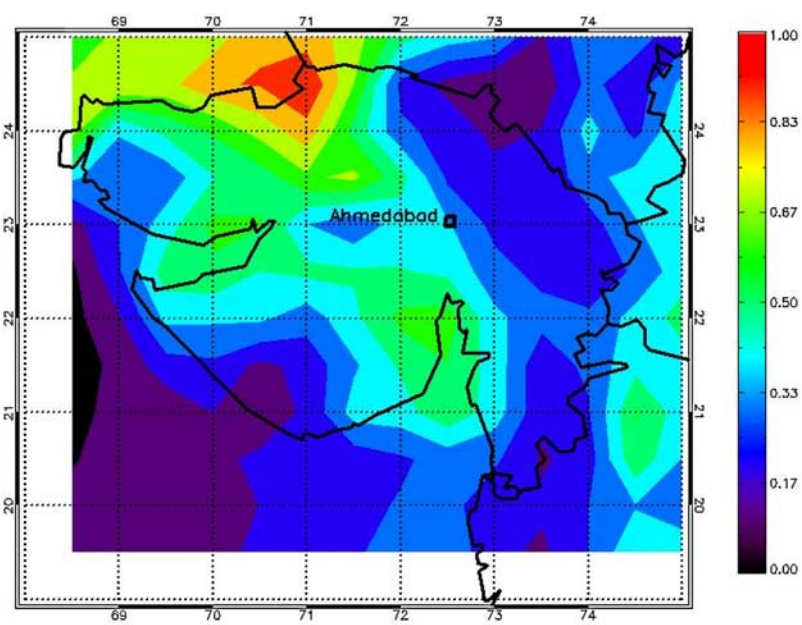

Figure 2. 0.5 Degree averaged map of Aerosol Optical Depth at 550 nm over Gujarat during November 2003. The complete data set can be accessed at http://www.prl.res.in/~amisra/gujarat.html.

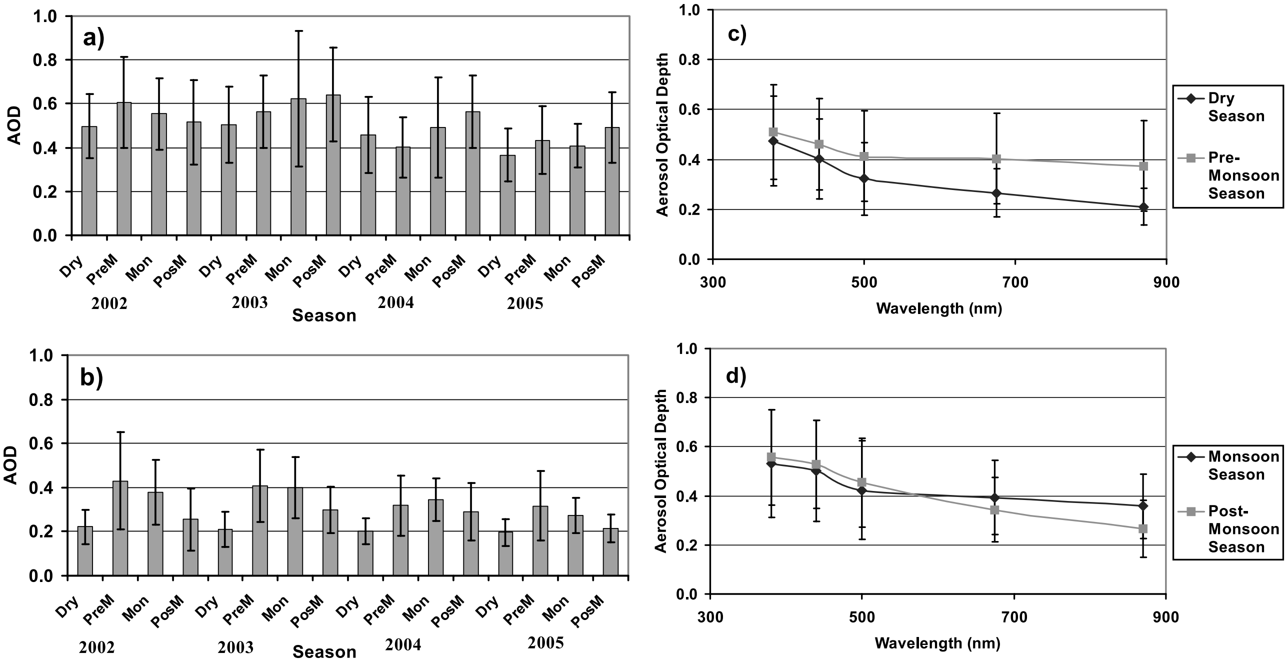

Figure 3. Observed variations in aerosol optical depth over Ahmedabad during the study period (2002–2005). (a) AOD at 380 nm (b) AOD at 870 nm (c) average AOD spectra for Dry and Pre-Monsoon seasons and (d) average AOD spectra for Monsoon and Post-Monsoon seasons [*Ganguly et al.*, 2006].

atmosphere depends on the dominant process and the size of the aerosol particles since different sized particles respond differently to the various meteorological changes. Thus soil derived dust particles are generated with higher wind speed and are settled with rain. As compared to the natural aerosols which have a large seasonal variation, the smaller anthropogenic aerosols have less seasonal variation. A moderate value of wind speed is sufficient for dispersal of these particles to the neighboring places.

[20] The variation in the ground based Sun photometer measured columnar aerosol optical depth over Ahmedabad [*Ganguly et al.*, 2006] at two representative wavelengths, disaggregated into different seasons are shown in the Figures 3a and 3b. Also shown is the behavior of the spectral aerosol optical depth for the different seasons (Figures 3c and 3d). These features can be grossly interpreted in terms of the meteorological variables esp, the wind speed and rainfall amount. The aerosol amount during Dry season is in general low at all wavelengths. During Pre-Monsoon season, the wind speed increases leading to an increase in the AOD value which is more pronounced at higher wavelengths due to the production of soil derived dust particles. During Monsoon months, as the wind speed is similar to that during Pre-Monsoon months, there is no considerable change in AOD at higher wavelengths. However, the AOD at lower wavelength show a marginal increase due to hygroscopic growth of particles as well as an increase in the boundary layer height which provides more accommodation space for the aerosols. The wind speed during Post-Monsoon season is the lowest and hence the production of soil derived dust particles becomes less. Also, the wet soil and increased vegetation after the monsoon reduce natural aerosol particles from being released from the surface. Thus the AOD at higher wavelengths is reduced due to a reduction in the dust derived aerosol component in the atmosphere. However, the AOD at lower wavelengths maintains its value since the boundary layer height is still large. The boundary layer height decreases during the Dry season so that the AOD values at all the wavelengths are lowest during this season [*Ganguly et al.*, 2006].

4. Data Analysis

[21] The MODIS level 2 aerosol data product from the Aqua platform is used in the present work. The data from both the collection version 4 [*Remer et al.*, 2005] and the updated version 5 [*Remer et al.*, 2006; *Levy et al.*, 2007b] are used. Even though the updated algorithm adds several more retrievals especially over brighter surfaces, only those data which are present in both versions are considered. Although this means a loss of about 10 data points, this was necessary to compare the retrievals from the two algorithms.

[22] The Microtops sunphotometer provides the ground truth data for the validation [*Morys et al.*, 2001]. Regular observations of columnar aerosol optical depth with the instrument are being carried out since 2002. The instrument provides the measurement of aerosol optical depth at 380, 440, 500, 675, and 870 nm wavelengths with uncertainty less than 0.03. A second Microtops sunphotometer is used to derive AOD at 1020 nm and total columnar ozone and water vapor concentrations. The derivation of aerosol optical depth is based on the attenuation of direct solar radiation by the atmospheric column and requires correction for gaseous absorption and Rayleigh scattering. Further details are given by *Ganguly et al.* [2006]. For the present study,

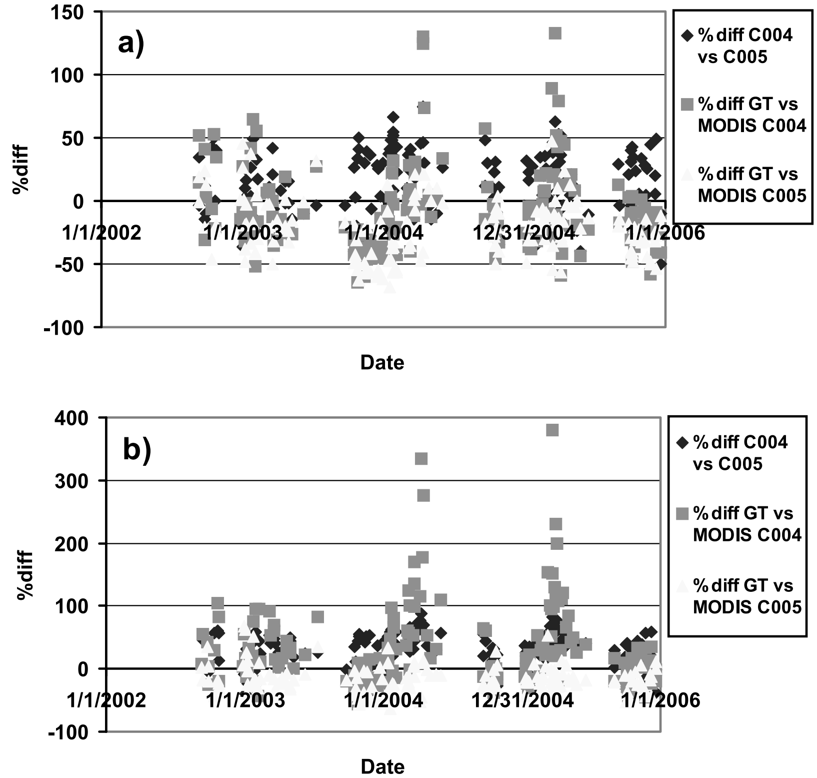

Figure 4. Time series of % difference (a) for 470 nm, (b) for 660 nm between different sets of data from both versions of MODIS algorithm and the Microtops Sunphotometer.

sunphotometer observations have been selected on the condition that the time difference between ground based observation and MODIS overpass time is less than or equal to half an hour. The MODIS derived AOD was averaged over 0.5° latitude × 0.5° longitude box centered over Ahmedabad. This is required to have a reasonable comparison between satellite derived values which are a spatially spread data with sunphotometer values which are point measurements. A larger box used for averaging will introduce aerosol type and topography related uncertainties whereas any smaller box will include very few data points used for the averaging [*Ichoku et al.*, 2002]. As MODIS provides AOD at 470 and 660 nm, none of which is present in the Microtops spectrum, the ground truth AODs at these wavelengths are found from the Angstrom Law fit [$AOD_\lambda = a\lambda^{-b}$] of the sunphotometer wavelengths. Apart from a combined comparison for the four years, the data have also been separated between individual years and also grouped into different seasons as per the criterion described in section 3 earlier.

5. Results and Discussion

[23] Before examining in detail the validation results over Ahmedabad, it is worth mentioning the results obtained by *Levy et al.* [2005] during the CLAMS experiment since the results obtained there provided the impetus for the latest update to the MODIS aerosol product. According to *Levy et al.* [2005], the offset in the correlation plot over land was more at blue than at red, while the slope was closer to unity at blue as compared to red and the correlation coefficient was also better at this wavelength. Further details in this regard along with the results from other validation groups are discussed later in this section.

5.1. AOD Validation Over Ahmedabad

[24] Results of MODIS AOD product validation over Ahmedabad have been shown in Figures 4 and 5 whereas Tables 1, 2 and 3 show the comparison of slope, intercept and R^2 values for different years and seasons as well as the combined data set.

[25] The time series of percentage difference in the MODIS retrieved and sunphotometer derived AOD is depicted in Figure 4, where,

$$\% \text{ difference } = \frac{\text{AOD}_{\text{MODIS}} - \text{AOD}_{\text{Sunphotometer}}}{\text{AOD}_{\text{Sunphotometer}}} \times 100 \qquad (2)$$

[26] A positive value of the percentage difference implies an overestimation by MODIS. It is observed that the magnitude of the percentage difference is minimum during post monsoon months which increases as summer approaches. During May/June owing to increased surface reflectance, the related errors increase. This feature is more pronounced during 2004 and 2005.

5.1.1. Comparison for Different Years

[27] Figures 5a and 5b depict the comparison of C004 MODIS aerosol optical depth with the Microtops sunphotometer data for the period 2002 to 2005. Figure 5a is for 470 nm while Figure 5b is for 660 nm. The deviation from unity of the slope of correlation plot represents systematic biases and are mainly due to aerosol model assumptions,

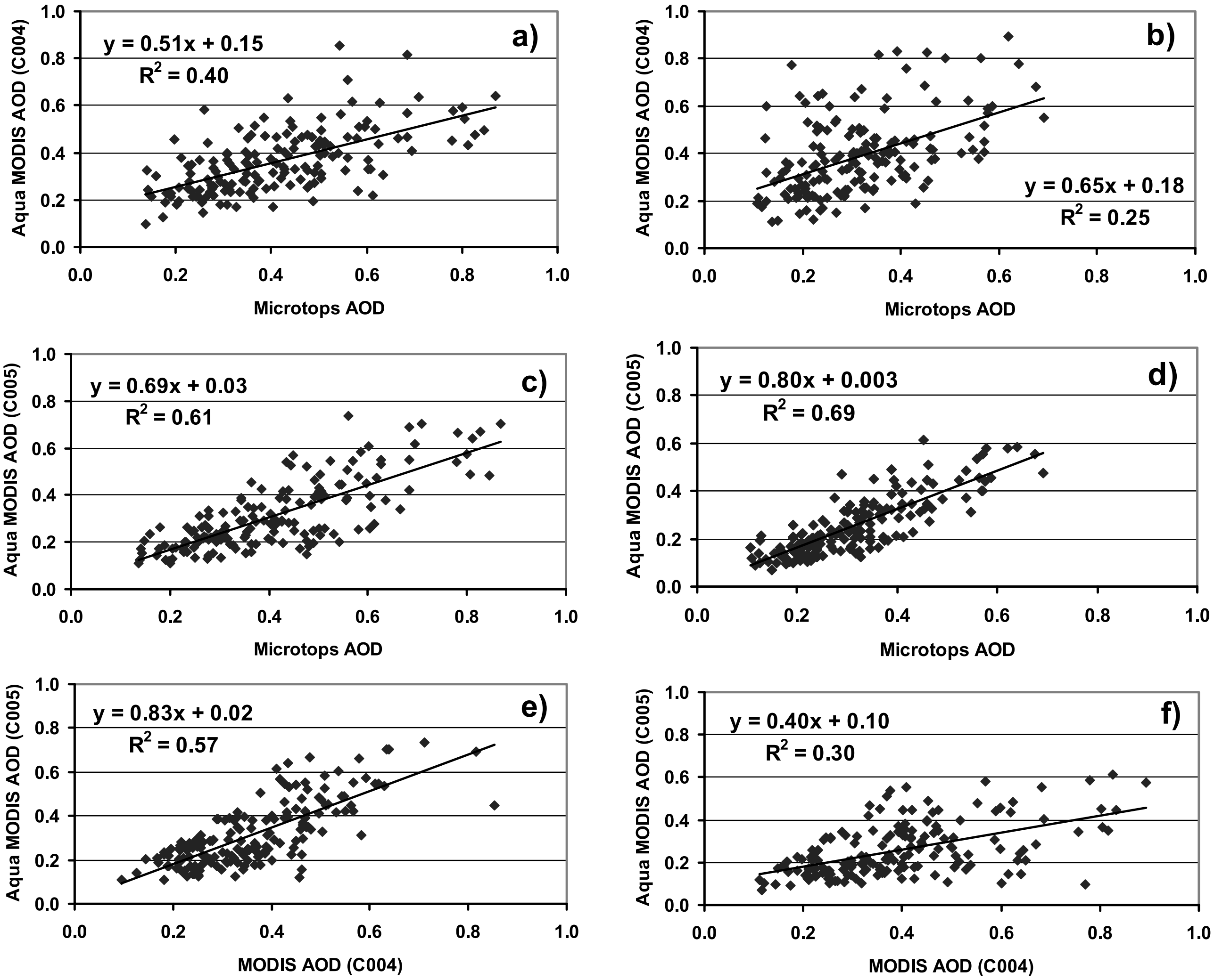

Figure 5. Validation results for the period 2002–2005; between Aqua MODIS (C-004) and Microtops for 470 nm (a) and 660 nm (b); between Aqua MODIS (C-005) and Microtops for 470 nm (c) and 660 nm (d); between Aqua MODIS C-004 and C-005 for 470 nm (e) and 660 nm (f).

instrument calibration or the choice of the lowest 20–50 percentile of the measurements [*Chu et al.*, 2002; *Chu et al.*, 2003; *Remer et al.*, 2005] whereas the intercept represents the errors due to surface reflectance assumptions. The large scatter seen in the plot is due to the comparison for 4 years of data which includes all seasons. Possibility of the comparison being better for some seasons than others can lead to large scatter. One of the ways in which it can affect the retrieval process is through the varying surface reflectance. It is seen that the spread in data was larger at red(R^2 = 0.25) or in other words, correlation was better for blue(R^2 = 0.40). Intercepts were nearly same in both cases (0.15 at blue and 0.18 at red) but slope was closer to unity for red(0.65) as compared to blue(0.51). This is in marked contrast to the result inferred by *Levy et al.* [2005] who found slope to be better at blue. The correlation coefficient results were consistent, however. In the updated product, for which the comparison plot has been shown in Figures 5c (for 470 nm) and 5d (for 660 nm), the improvement in the correlation coefficient (R^2) is conspicuous in this and all other plots. The R^2 value is similar for both wavelengths (0.61 at blue and 0.69 at red) in the updated product. Another drastic improvement pertains to the intercept value which has dropped to 0.03 at blue and 0.003 at red. As mentioned earlier, the intercept of the correlation plot denotes the errors due to inappropriate surface reflectance parameterization. Thus this improvement represents the

Table 1. The Slope, Intercept and R^2 for the Different Validation Cases at 470 nm

	C004			C005		
Case	Slope	Intercept	R^2	Slope	Intercept	R^2
Overall	0.51	0.15	0.40	0.69	0.03	0.61
2002	0.46	0.22	0.23	0.77	0.05	0.51
2003	0.53	0.12	0.45	0.68	0.03	0.52
2004	0.52	0.17	0.34	0.68	0.03	0.57
2005	0.57	0.12	0.40	0.78	−0.0002	0.71
Dry Season	0.51	0.14	0.47	0.65	0.04	0.60
Pre-Monsoon Season	0.55	0.18	0.33	0.84	0.01	0.73
Monsoon Season	0.84	0.10	0.45	0.87	0.03	0.65
Post-Monsoon Season	0.44	0.15	0.46	0.72	−0.03	0.66

Table 2. The Slope, Intercept and R^2 for the Different Validation Cases at 660 nm

Case	C004			C005		
	Slope	Intercept	R^2	Slope	Intercept	R^2
Overall	0.65	0.18	0.25	0.80	0.003	0.69
2002	0.39	0.24	0.21	0.70	0.05	0.56
2003	0.86	0.08	0.46	0.82	−0.003	0.62
2004	0.45	0.29	0.14	0.71	0.03	0.68
2005	0.82	0.14	0.22	0.90	−0.03	0.75
Dry Season	0.65	0.18	0.19	0.83	0.004	0.62
Pre-Monsoon Season	0.46	0.38	0.18	0.81	−0.0005	0.81
Monsoon Season	1.10	0.06	0.43	0.82	0.03	0.62
Post-Monsoon Season	0.63	0.11	0.49	0.86	−0.05	0.71

successful modification of the surface reflectance ratios. Slope of the correlation is still better at red (0.80) than at blue (0.69), a feature still in contrast to *Levy et al.* [2005]. Possibly it is because of the different aerosol types prevalent over the two study regions. However, the comparative results at the two wavelengths (such as here or in the work of *Levy et al.* [2005]) should be treated with caution and not generalized to all cases. This is clear from our other plots over Ahmedabad(results given in tabular form in Tables 1 to 3) where the combined data of Figure 5 has been disaggregated into separate years as well as different seasons as per the criteria discussed earlier. It is seen that the correlation of the two sets of data shows different behavior at these two wavelengths depending on the season. Figures 5e and 5f show the correlation between C004 and C005 AOD data from MODIS.

[28] Year 2002 had the least amount of data since MODIS onboard Aqua was launched during May this year which was immediately followed by the Monsoon months leading to a scarcity of data during this period. Still, some features observed during this data set show the correlation coefficient as well as intercept for C004 AOD data to be nearly same at both red (Intercept = 0.24, R^2 = 0.21) and blue (Intercept = 0.22, R^2 = 0.23) as shown in Tables 1 to 3. However, this time it was the slope at blue which had a better value ($Slope_{Blue}$ = 0.46, $Slope_{Red}$ = 0.39). The same pattern is observed in the updated aerosol product also (Tables 1 to 3) where slope at blue (0.77) is marginally higher than at red (0.70). However, in every way, the updated product has a better correlation than the previous version. This shows that the AOD retrieval by MODIS at the two wavelengths depends on the surface reflectance and the dominant aerosol species for the particular case. As noted previously, 2002 was the year receiving the least rainfall.

[29] The above case reverses in 2003 where the slopes for C004 data had higher value at red (0.86) as compared to at blue (0.53). Correlation coefficients were nearly same for both the wavelengths (R^2_{Blue} = 0.45, R^2_{Red} = 0.46) but intercept was larger for blue (0.12) than red (0.08). In the updated product also, slopes are higher and intercepts lower for red ($Slope_{Red}$ = 0.82, $Intercept_{Red}$ = −0.003, $Slope_{Blue}$ = 0.68, $Intercept_{Blue}$ = 0.03) whereas the correlation coefficient has shown more improvement at red (R^2_{Red} = 0.62, R^2_{Blue} = 0.52). The negative intercept at red denotes overcorrection for surface reflectance part.

[30] The pattern of correlation for C004 reversed again for the year 2004 when the slope was larger and intercept lower at blue wavelength (Slope = 0.52, Intercept = 0.17) as compared to red (Slope = 0.45, Intercept = 0.29). Correlation coefficient was considerably higher at blue (R^2_{Blue} = 0.34, R^2_{Red} = 0.14). This pattern changed in the updated product where the slope is marginally larger and correlation coefficient higher for red ($Slope_{Red}$ = 0.71, R^2_{Red} = 0.68, $Slope_{Blue}$ = 0.68, R^2_{Blue} = 0.57). However, intercepts are same at both the wavelengths ($Intercept_{Blue}$ = $Intercept_{Red}$ = 0.03).

[31] The slope pattern for C004 changed again during 2005 when the slope at red was larger than at blue whereas correlation coefficient was still quite larger at blue. Intercept at red was only marginally higher than at blue. The updated product (C005) for this year has the best correlation among all the comparisons. The slope at red (0.9) is the closest approach to unity. The slope at blue (0.78), though not at par with that at red, is still quite larger as compared to other years. The intercepts for this year are the lowest among all the cases though their negative values denote an overcorrection for the surface reflectance contribution. The correlation coefficients are also the best with its value at red (0.75) only marginally higher than at blue (0.71). 2005 was the year that received the highest amount of rainfall which increased the soil moisture content and greenness of surface thus reducing the surface reflectance part. This feature has been very well captured in the updated MODIS aerosol product. However, the negative intercepts denote the over-correction for surface reflectance.

[32] Overall, (**i**) In the version C004, correlation coefficient was better at blue than red for all years except for 2003 when they had nearly similar values. Intercepts were larger at red for all years except 2003 in which case intercept at blue was larger. Slopes of the correlation plot in this version did not show any particular pattern since for 2002 and 2004 slope at blue was more close to unity whereas for 2003 and 2005 as well as in the combined data set, it was the slope at red which was larger. (**ii**) For the updated product, except 2002, slopes are better at red than blue for all the years as well as the combined data. Correlation coefficient is better at red for all the years whereas the intercept is either lower at red than blue or equal at both the wavelengths. (**iii**) For the updated product (version C005), the best correlation is for 2005 with R^2 and slope highest and intercept lowest. This was the year receiving the maximum rainfall so that soil moisture and increased vegetation led to reduced surface reflectance and hence to lower errors due to surface reflectance.

Table 3. The Slope, Intercept and R^2 of C004 and C005 Intercomparison for the Different Cases at 470 nm and 660 nm

Case	470 nm			660 nm		
	Slope	Intercept	R^2	Slope	Intercept	R^2
Overall	0.83	0.02	0.57	0.40	0.10	0.30
2002	0.75	0.04	0.43	0.39	0.13	0.13
2003	0.96	−0.003	0.67	0.57	0.08	0.48
2004	0.65	0.06	0.41	0.27	0.13	0.14
2005	0.79	0.02	0.61	0.33	0.10	0.31
Dry Season	0.80	0.01	0.51	0.29	0.12	0.16
Pre-Monsoon Season	0.79	0.04	0.60	0.47	0.03	0.33
Monsoon Season	0.61	0.13	0.50	0.45	0.13	0.53
Post-Monsoon Season	1.00	−0.04	0.53	0.73	0.02	0.42

5.1.2. Comparison for Different Seasons

[33] The comparison between MODIS and Microtops data has been disaggregated among different seasons according to the criteria described earlier.

[34] During dry season, for the C004 data set, the correlation was much better at blue (R^2 = 0.47) than at red (R^2 = 0.19), while the slope as well as intercept were lower at blue. With the updated product, correlation shows substantial improvement at both the wavelengths and the new values of R^2 are nearly equal at both wavelengths (0.60 at blue and 0.62 at red). The slope, though much closer to unity than the previous version, is lower at blue than at red in the updated product also. Another noticeable feature is the reduction in the intercept values at both wavelengths being closer to zero at red than blue.

[35] In the Pre-Monsoon C004 data set also, the correlation was very poor at red(R^2 = 0.18) as against that at blue (R^2 = 0.33). However, this time slope at blue was closer to unity than at red. The intercepts are large at both wavelengths- being much higher at red (0.38) than at blue (0.18). With the update to the C005 data set, we see a great improvement in all the parameters. Slopes at both wavelengths are nearly equal with that at blue (0.84) only slightly higher than at red (0.81). Correlation coefficient is also highest during this season as compared to all other seasons, its value being 0.73 at blue and 0.81 at red. The extremely low values of intercept are also noteworthy (0.01 at blue and −0.0005 at red). In every regard, the updated MODIS aerosol product shows extremely good behavior during Pre-Monsoon months as compared to other seasons.

[36] Monsoon season suffers from the lowest number of data points used in the comparison because of generally overcast conditions during most of the days during this season. For the C004 version, slopes were quite large and much closer to unity (0.84 at blue and 1.1 at red) and intercepts were also lower (0.1 at blue and 0.06 at red) as compared to Dry and Pre-Monsoon months. The correlation coefficient was almost similar at both the wavelengths (0.45 at blue and 0.43 at red). Upgrade to the C005 version improved the correlation coefficient though its value at both wavelengths is still equal (0.65 at blue and 0.62 at red). Intercepts in the new product are exactly equal at both wavelengths (0.03) and are higher than the Pre-Monsoon values. The slope at blue (0.87) and red (0.82) are very close to their Pre-Monsoon values.

[37] With the C004 version for the Post Monsoon months also, the correlation (R^2 = 0.46 at blue and 0.49 at red) was nearly similar to that for Monsoon months and much better than for Dry and Pre-Monsoon season. Slope was not satisfactory (0.44 at blue and 0.63 at red) and intercept was also large (0.15 at blue and 0.11 at red). In the updated product, the intercepts have negative values at both wavelengths (−0.03 at blue and −0.05 at red) representing an over-correction for the surface reflectance. The slope as well as correlation coefficient is higher at red (slope = 0.86, R^2 = 0.71) than at blue (slope = 0.72, R^2 = 0.66).

[38] Tables 1 to 3 give the slopes, intercepts and correlation coefficients for all the cases discussed so far. From this and from all the previous plots, a few points can be noted:

[39] (**i**) Except monsoon season, the pattern of slope is preserved with the transition from C004 to C005 product viz, whenever the slope at blue was higher than at red for C004, it is the same case with C005 also and vice versa.

[40] (**ii**) Interestingly, a comparative view of the slopes in the validation results (of the updated product) for different seasons at the two wavelengths reveals that the AOD is underestimated at 470 nm to a greater extent than 660 nm during Dry and Post Monsoon seasons. It may be recalled that during these seasons, the total aerosol content in the atmosphere is dominated by fine particles. The number concentration of the fine particles used in the look-up tables for aerosol retrieval by MODIS is lower than the actual content in the atmosphere during this season. Similarly, as noted earlier, during Pre-Monsoon and Monsoon months, the total aerosol content is dominated by coarse mode particles. During these months, it is observed that the AOD at 660 nm is more underestimated, though marginally, than at 470 nm. The number concentration of coarse particles during these seasons is not properly accounted for in the MODIS aerosol models and the actual coarse aerosol content is higher. Overall, the slopes differing from unity reflect the discrepancy between the aerosol models used in the MODIS aerosol retrieval scheme and the actual aerosol model. Further, the variation of slopes with season at the two wavelengths, especially corresponding to the dominant species present (smaller particles during Dry and Post Monsoon months and coarse particles during Pre-Monsoon and Monsoon months) implies that the aerosol model used by MODIS algorithm is not able to account for the seasonal variations in the aerosol type. This aspect forms the most important conclusion of our work.

[41] (**iii**) The intercepts in the updated product for all seasons are less than 0.04 which is a great improvement over the previous version(C004) of the MODIS aerosol product and denotes a much better account of surface reflectance parameterization. The negative intercepts during Post Monsoon season, when the surface reflectance value itself is low, imply an over-correction for surface reflectance contribution.

[42] (**iv**) Overall, the updated product has the best correlation for Pre-Monsoon among all seasons and Dry season the least.

5.2. Discussion of Results by Other Groups

[43] It is worthwhile to mention here the validation efforts at other locations by different groups and compare them with the results we have obtained. The major source providing the ground truth data for validation efforts elsewhere comes from the AERONET [*Holben et al.*, 1998]. The procedure followed is the so-called 'spatiotemporal approach' put forwarded by *Ichoku et al.* [2002]. There, the spatial average of MODIS derived AOD found from 50 × 50 km centered over the validation site is compared with the temporal average of AERONET AOD data taken within 1 h of MODIS overpass. A further condition is imposed that there must be at least 5 pixels from MODIS data and 2 data points from AERONET for the validation to be valid.

[44] The initial validation results of MODIS aerosol retrieval were provided by *Chu et al.* [2002] who used the 315 co-located measurements from AERONET sunphotometers and MODIS for the comparison. They found intercept of 0.06 and 0.02 at 470 and 660 nm respectively whereas

the slope of the correlation plot was 0.86 at both the wavelengths. The correlation coefficient R at 470 and 660 nm was 0.91 and 0.85 respectively[*Chu et al.*, 2002].

[45] *Ichoku et al.* [2003] used the ground based observations of aerosol properties made during the SAFARI 2000 experiment to make an extensive investigation of behavior of MODIS aerosol product especially in regard to the smoke aerosols produced as a result of biomass burning. They observed that during the biomass burning period, the AOT values predicted by MODIS were lower than AERONET especially at higher aerosol optical depth. They attributed this to the application of the same value of single scattering albedo (ω = 0.90) for smoke aerosols globally and suggested lower values for southern African region [*Ichoku et al.*, 2003]. This modification was implemented in the later version of the MODIS aerosol retrieval algorithm.

[46] *Chu et al.* [2003] used collocated AERONET data and version 2 and version 3 MODIS aerosol data from August 2000 to July 2002 for the validation purpose thus encompassing a larger database of 3384 datapoint from worldwide observations. Their study revealed the slope of correlation plot to be 0.84 and 0.82 at 470 nm and 660 nm and intercepts to be 0.07 and 0.04 at the aforesaid two wavelengths respectively. The correlation coefficient R was 0.91 and 0.82 respectively. These results were nearly similar to their earlier work [*Chu et al.*, 2002]. In the same work, they reported the validation result of MODIS aerosol optical depth as compared against the handheld sunphotometer observation at Peking University, Beijing, China. In this case, they compared the sunphotometer measurements at 550 nm averaged over ±1 h of MODIS overpass against the MODIS derived AOD value within 10 km of the ground based observation site [*Chu et al.*, 2003]. This comparison showed a slope of 0.86 and intercept of 0.08 with R value of 0.85.

[47] *Remer et al.* [2005] used two years(August 2000 to August 2002) of Terra Collections 003 and 004 AOD data from MODIS to validate against the collocated AERONET aerosol optical depth values over land thus including 5906 data points representing approximately the data from all over the globe. Their validation effort showed a slope of 0.83 and 0.70 at 470 nm and 660 nm respectively. The intercepts at these two wavelengths were 0.09 and 0.059 whereas the corresponding R values were 0.83 and 0.68 respectively. They cite a possible calibration problem or improper representation of surface reflectance in some cases to be probable reasons for a positive bias seen at low optical thickness values.

[48] *Levy et al.* [2005] carried out an extensive validation of the Level 2 MODIS aerosol product over both ocean as well as land during the CLAMS experiment of 2001 over the US east coast. This region had shown large discrepancy during the validation effort by *Remer et al.* [2005]. During this monthlong campaign (from 10 July 2001 to 2 August 2001), MODIS derived aerosol optical depth product was compared against a large database of ground based sunphotometers formed from AERONET, Microtops, LARC and AATS-14 sunphotometers. Their methodology was based on the spatiotemporal approach developed by *Ichoku et al.* [2002]. These comparisons revealed that although the MODIS retrievals were consistent with ground based data over oceans, there were substantial differences over land especially at blue wavelength. Only the validation results of aerosol optical depth over land are discussed here. Their results showed offsets of the correlation plots to be larger at 470 nm (0.26) as compared to that at 660 nm (0.17) but slopes were closer to unity at 470 nm (0.76) than 660 nm (0.46). Further, correlation was also found to be better at blue (R^2 = 0.5) than at red (R^2 = 0.17). Corresponding values at green wavelength were intermediate to that for blue and red [*Levy et al.*, 2005]. This was a detailed study in the sense that besides performing an exhaustive validation of MODIS aerosol products, *Levy et al.* [2005] also looked for possible sources of error and tried to perform corrections for the same. Thus in order to take into account the errors arising due to possibility of inappropriate aerosol model, they changed the aerosol model to *Dubovik et al.* [2002] model instead of the *Remer and Kaufman* [1998] urban/industrial model used in the aerosol retrieval. Similarly, in order to look into the possibility of improper surface reflectance parameterization, they performed atmospheric correction using the CLAMS experiment data and used the resulting VIS/mid-IR surface reflectance ratios for modified AOD retrievals. Both these processes were followed separately in order to assess the individual impact due to each of them. In this way, they found that the aerosol model modification and surface reflectance update improved the slopes and intercepts respectively of the correlation plots. Their results and work has been discussed here in detail since it forms the starting point as well as the framework for the updated MODIS aerosol product (C-005). Therefore any results obtained from the validation of this product should be interpreted in this light.

[49] Among the Indian context elsewhere, validation of MODIS derived AOD has also been attempted by *Tripathi et al.* [2005]. Using MODIS Level 2 AOD data from collection 4 and AERONET data(interpolated at 550 nm) for 2004, they found an overestimation by MODIS during dust and an underestimation during non-dust seasons with slopes and intercepts in the two cases 2.46, −0.63 and 0.69, 0.12 respectively. The R^2 values in both the cases (0.72 and 0.71 respectively) were nearly same.

[50] In the context of studying the aerosol properties and their variation along the Indo-Gangetic basin, *Jethva et al.* [2005] compared the monthly mean AOD at 550 nm computed from MODIS Level 3 daily gridded data with the AERONET sunphotometer derived monthly mean AOD values from Kanpur, India for the period January 2001 to July 2003. They found a systematic overestimation by MODIS during summer and an underestimation during winter [*Jethva et al.*, 2005].

[51] *Prasad and Singh* [2007] validated the MODIS monthly averaged Level 3 data against the Level 2 data from AERONET at 550 nm (interpolated from AERONET wavelengths) for a 4 year period from January 2001 to December 2004. They found MODIS overestimating the AOD values during summer and underestimating during winter with slope and intercept in the two cases 0.512, 0.5229 and 0.4843, 0.1522 respectively. The R^2 values in the two cases were 0.2937 and 0.4715 respectively [*Prasad and Singh*, 2007].

[52] These points have been summarized in Table 4. One noticeable feature is the obvious dependence of the correlation on the study location. This highlights the importance

Table 4. A Comparison of the Validation Results Obtained by Different Groups Quoted in This Paper[a]

	Details of Study			Correlation Coefficients					
				470 nm		550 nm		660 nm	
Group	Ver	Lev	Location	Sl	In	Sl	In	Sl	In
Chu et al. [2002]		2	global	0.86	0.06			0.86	0.02
Chu et al. [2003]	2, 3	2	global	0.84	0.07			0.82	0.04
Chu et al. [2003b]	2, 3	2	Beijing			0.86	0.08		
Remer et al. [2005]	3, 4	2	global	0.83	0.09	0.78	0.068	0.7	0.059
Levy et al. [2005]	4	2	US East Coast	0.76	0.26	0.64	0.21	0.46	0.17
Tripathi et al. [2005]	4	2	Kanpur(ND) Kanpur(D)			0.69 2.46	0.12 −0.63		
Prasad and Singh [2007]		3	Kanpur(S) Kanpur(W)			0.51 0.48	0.52 0.15		
Present study[a]	4	2	Ahmedabad	0.51	0.15			0.65	0.18
Present study[b]	5	2	Ahmedabad	0.69	0.03			0.80	0.003

[a]Version and level of MODIS aerosol product, region of study and slope and intercepts at 470, 550, 660 nm are given. Kanpur (D) and Kanpur (ND) represent Dust and Non-Dust period for Kanpur respectively. Similarly Kanpur(S) and Kanpur(W) represent Summer and Winter period validation data over Kanpur. Two other studies by *Ichoku et al.* [2003] and *Jethva et al.* [2005] have not been shown since they do not quote coefficients of the correlation. *Ichoku et al.* [2003] found underestimation by MODIS over Southern Africa attributed to insufficient absorption by MODIS aerosol model. *Jethva et al.* [2005] found overestimation by MODIS during summer and underestimation during winter over Kanpur.

of the detailed validation of MODIS aerosol product for different geographical regions. Another feature worth mentioning is the different values of the slopes and intercepts at different wavelengths, especially in the work of *Remer et al.* [2005], *Levy et al.* [2005] and our work. Since the dominance of particles of a particular size is best reflected at a particular wavelength and also because of surface reflectance dependence on wavelengths, validation carried out at more than one wavelength provides more details regarding possible improvements to aerosol model, surface reflectance etc. Further, a classification of the correlation in terms of seasonal variation, as in our study, will reflect the precise cases where account of seasonal changes in the aerosol type and surface features are needed.

6. Conclusion

[53] Behavior of two versions (collection C004 and C005) of MODIS aerosol product is studied over Ahmedabad, a semi-arid urban location in western India. On the basis of meteorology, the annual cycle is divided into Dry, Pre-Monsoon, Monsoon and Post-Monsoon seasons. Pre-Monsoon and Monsoon months are dominated by coarse mode aerosols whereas the Post-Monsoon and Dry months are characterized by fine mode particles.

[54] The collection version C004 of the MODIS aerosol product showed a large scatter in the correlation plot with the Microtops sunphotometer derived AOD values. The correlation plots were marked by slopes deviating from unity and large intercepts.

[55] The updated MODIS aerosol product (C005) with better surface reflectance parameterization, updated aerosol models and other modifications to the retrieval procedure, shows a tremendous improvement in all the parameters of the correlation plot. The intercepts for all years and all seasons are less than 0.05 at both 470 and 660 nm. Among all the years, 2005 shows the best correlation with R^2_{Blue} = 0.71 and R^2_{Red} = 0.75. $Slope_{Blue}$ = 0.78 and $Slope_{Red}$ = 0.90 are closest to unity and intercepts are lowest for this year as compared to other years- a feature related to the highest rainfall received during this year as compared to others which reduces the surface reflectance. Pre-Monsoon season shows the best correlation among all the seasons with R^2_{Blue} = 0.73, R^2_{Red} = 0.81, $Slope_{Blue}$ = 0.84, $Slope_{Red}$ = 0.81, $Intercept_{Blue}$ = 0.01 and $Intercept_{Red}$ = −0.0005. Further, this season shows the maximum improvement in correlation from the C004 data which is attributed to the better parameterization of surface reflectance in the updated product which is usually high during this season.

[56] Still, the updated product also has slope of correlation plots less than unity denoting need of further improvement in the aerosol model. It is also noted that the underestimation is large at 470 nm during Dry and Post-Monsoon months and at 660 nm during Pre-Monsoon and Monsoon months which implies that the aerosol model used by MODIS underestimates fine mode particle number during Dry and Post-Monsoon months and coarse mode particle number during Pre-Monsoon and Monsoon months.

[57] Overall behavior of the updated product is much better than collection version C004 especially in regard to surface reflectance related uncertainties. The errors related to the aerosol model uncertainties will also be reduced with better and more data getting available.

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