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Comparison of coincident Multiangle Imaging Spectroradiometer and Moderate Resolution Imaging Spectroradiometer aerosol optical depths over land and ocean scenes containing Aerosol Robotic Network sites

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[1] The Multiangle Imaging Spectroradiometer (MISR) and the Moderate Resolution Imaging Spectroradiometer (MODIS), launched on 18 December 1999 aboard the Terra spacecraft, are making global observations of top-of-atmosphere (TOA) radiances. Aerosol optical depths and particle properties are independently retrieved from these radiances using methodologies and algorithms that make use of the instruments' corresponding designs. This paper compares instantaneous optical depths retrieved from simultaneous and collocated radiances measured by the two instruments at locations containing sites within the Aerosol Robotic Network (AERONET). A set of 318 MISR and MODIS images, obtained during the months of March, June, and September 2002 at 62 AERONET sites, were used in this study. The results show that over land, MODIS aerosol optical depths at 470 and 660 nm are larger than those retrieved from MISR by about 35% and 10% on average, respectively, when all land surface types are included in the regression. The differences decrease when coastal and desert areas are excluded. For optical depths retrieved over ocean, MISR is on average about 0.1 and 0.05 higher than MODIS in the 470 and 660 nm bands, respectively. Part of this difference is due to radiometric calibration and is reduced to about 0.01 and 0.03 when recently derived band-to-band adjustments in the MISR radiometry are incorporated. Comparisons with AERONET data show similar patterns.

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1. Introduction

[2] On 18 December 1999, NASA launched Terra, the first of a series of satellites within the Earth Observing System (EOS), a comprehensive program for monitoring the surface and atmosphere from remote sensing platforms and ground-based stations. Among the main objectives of EOS is improvement in our understanding of geophysical processes governing global changes in our planet's climate, including scattering and absorption of solar radiation by aerosols. Quantifying aerosol radiative forcing and its impact on the Earth radiative energy balance remains significantly uncertain without accurate long-term measurements of aerosol properties and their spatial and temporal variabilities. MISR and MODIS, two of five instruments aboard the Terra platform, measure aerosol optical depth, among other parameters [*Diner et al.*, 1998; *Kaufman et al.*, 1997a]. The Aerosol Robotic Network (AERONET), a ground-based aerosol monitoring network [*Holben et al.*, 1998], is an integral part of the EOS program that provides standardized aerosol products for validating the satellite data.

[3] The independent aerosol retrieval strategies and algorithms used by MISR and MODIS exploit the complementary multiangle (MISR) and multispectral (MODIS) nature of their measurements. Within a 7-min period, MISR observes the same point on Earth in nine different angles and four spectral bands. MODIS observes the same point in a single direction, but in 36 channels covering a wide spectral range. Of these, a subset of 7 channels is used for aerosol retrievals. The two instruments have stringent cal-

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ibration performance requirements that are validated periodically using the onboard calibrators and vicarious calibration experiments [*Bruegge et al.*, 2002; *Chrien et al.*, 2002; *Abdou et al.*, 2002; *Guenther et al.*, 1998]. Comparisons between their retrieved aerosol optical depths and with those obtained from AERONET provide an opportunity to explore the similarities and differences between MISR and MODIS products. A motivation of this study is to explore the unique strengths of these two approaches quantitatively, with the ultimate goal of capitalizing on their collocation on the same platform to improve the aerosol products retrieved from Terra.

2. Aerosol Retrieval Strategies

2.1. MISR

[4] MISR contains nine push-broom cameras that observe the same point on Earth at nine different angles: nadir, ±26.1°, ±45.6°, ±60.0°, and ±70.5° relative to nadir, both forward (+) and aft (−), and four spectral bands (446, 558, 672 and 866 nm). All routine operational processing of MISR is carried out at the NASA Langley Atmospheric Science Data Center (ASDC). Level 1 processing of MISR data produces radiometrically calibrated and georectified top-of-atmosphere (TOA) radiance data for all 36 channels (nine cameras $\times$ 4 spectral bands) of the instrument. At level 2, coregistered multiangle, multispectral data on a 1.1 km $\times$ 1.1 km Space Oblique Mercator grid are used in subsequent aerosol processing. Retrievals are performed over 16 $\times$ 16 arrays of these 1.1- km pixels, comprising 17.6 $\times$ 17.6 km "regions." It is assumed that the atmospheric aerosols are laterally homogeneous within each region. An important component of MISR aerosol retrieval strategy is a lookup table (LUT) of precalculated radiances associated with a preselected set of aerosol models representative of those expected to be found in nature. The LUT, known as the Simulated MISR Atmospheric Radiative Transfer (SMART) data set, includes atmospheric path radiances and other radiative transfer parameters for the viewing and illuminating geometries relevant to MISR observations. During the retrieval process, mixtures of aerosols contained within the SMART data set are generated and subjected to a variety of tests in order to establish which model or set of models fit the data. For any given aerosol retrieval, it is possible that more than one aerosol model gives a satisfactory fit to the observations. MISR optical depth retrievals are summarized in a parameter called the regional mean spectral optical depth, which is an unweighted average over all successful models, that is, models satisfying the established set of retrieval tests. It is the only summarized optical depth parameter in MISR products that entirely excludes unsuccessful models. No weighting is applied to the average in order to achieve an unbiased mean. The MISR team recommends the use of this optical depth to data users, and recent versions of the aerosol product also archive this parameter under the name regional best estimate spectral optical depth.

[5] A first step in the retrieval process is to evaluate the surface contribution to the measured TOA radiances. Accordingly, two distinct aerosol algorithms are used: one for retrieving aerosol over land and the other over ocean, or dark water. The dark water retrieval utilizes the red and near- infrared channels and assumes that the water-leaving radiance is negligible in these two bands. The surface model explicitly accounts for specular reflection and whitecap contributions, and measurements acquired within 40° of the specular reflection are not used. The contributions of these effects to the TOA radiances are precalculated for various wind speeds and observation geometries and stored in the SMART lookup table. A recent refinement to the algorithm is to include green band radiances in the retrieval when the optical depths (τ) exceed 0.5, and the blue band radiances when the optical depths exceed 0.75, with weighting proportional to the optical depth. The weights increase linearly from zero at these threshold optical depths to 1.0 at τ = 1.5 and 1.0 in the blue and green, respectively. The purpose of this refinement is to use as much available information as possible, but to minimize the effect of surface radiances on the results. This recent refinement is applied to MISR data version F05-0011 and above (in this work data version F05-0012 are used).

[6] For aerosol retrievals over land, all 36 channels are used (a minimum of 20 channels are required). The surface contribution to the TOA radiances are represented in the retrieval algorithm as the sum of empirical orthogonal functions (EOFs) that are determined from the measured data. This is done within each region by subtracting the multiangle radiances of the darkest pixel (in the nadir) from the radiances of other pixels, effectively removing the atmospheric path radiance from these pixels. The residual radiances are then decomposed into EOFs which are used to model the angular reflectance of the surface contribution to the TOA radiance. Region-averaged radiances are then compared, via least squares, to the sum of the surface component and the atmospheric path radiance, the latter computed from mixtures of aerosol components contained in the SMART data set. The residuals in the comparisons are assessed using χ^2 statistical tests and all the optical depths and the associated aerosol models that meet a set of specified criteria are reported as successful retrievals. A major attribute of this algorithm is that it requires no assumption about the absolute reflectance of the land surface, since the separation of surface-leaving and path radiance contributions is achieved by taking advantage of differences in their angular signatures. Therefore there are in principle no restrictions on the type of surface over which the algorithm can be applied, as long as contrast is present in the scene so that the EOFs can be determined. Detailed descriptions of the MISR aerosol retrieval and its evolution since the start of MISR operation are given in the work of *Martonchik et al.* [1998, 2002].

2.2. MODIS

[7] Like MISR, the MODIS aerosol retrievals are based on a lookup table procedure in which the satellite measured radiances are matched to precalculated values in the LUT and the values of the aerosol properties used to create the calculated radiances are retrieved. Also like MISR, the MODIS aerosol retrievals are performed using two separate algorithms, one for aerosols over land and the other for retrievals over ocean [*Remer et al.*, 2005].

[8] Over land, the retrieval is made at two wavelengths independently: 470 and 660 nm, using additional information from the 2130 nm channel [*Kaufman et al.*, 1997a].

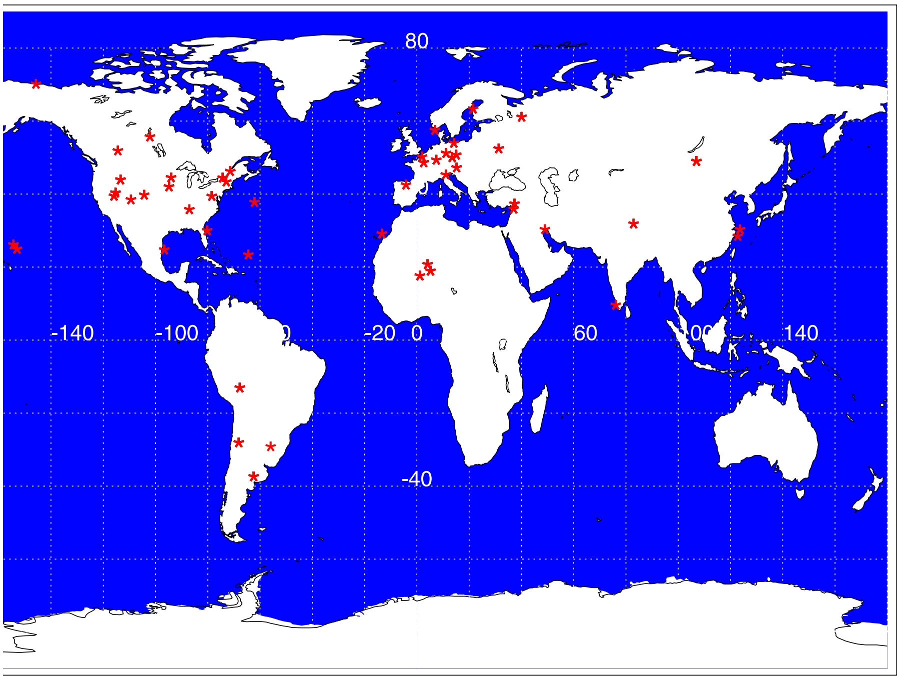

Figure 1. AERONET sites, a total of 62, used in this work.

Because MODIS does not have the benefit of MISR's multiangle information to determine the path radiance, separation of the surface and atmospheric components of the radiance reaching the satellite is achieved by estimating the spectral surface reflectance in each pixel. This is done by using the 2130 nm channel, which in most cases is unaffected by aerosol, to determine surface reflectance. The surface information is then transferred to the 470 nm and

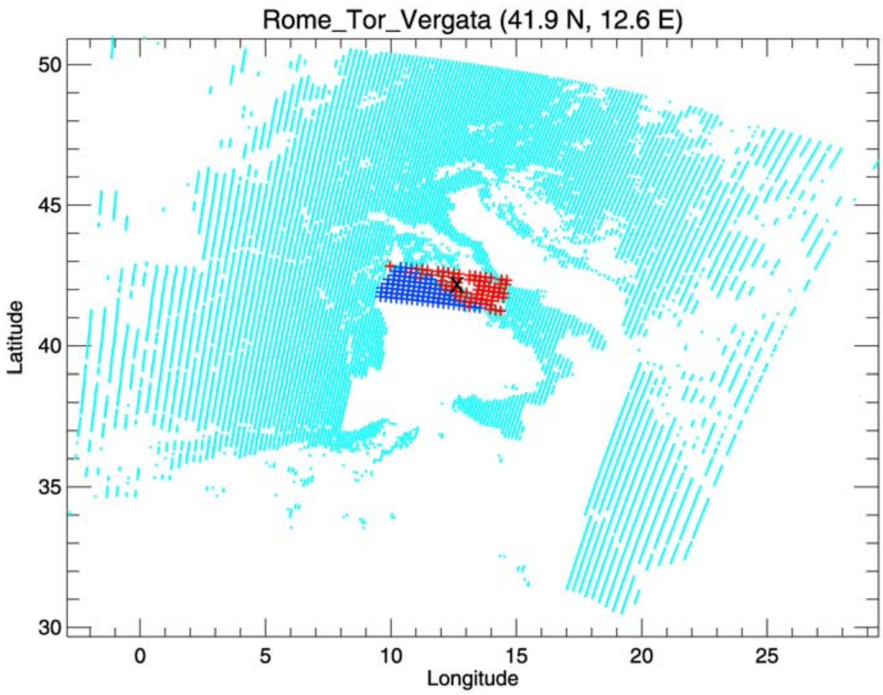

Figure 2. A sample of MISR (block) and MODIS (5-min granule) data and their overlap at the AERONET site. MISR data are shown in red and dark blue, for land and ocean retrievals, respectively. All MODIS data are shown in light blue. The white space show pixels with no retrievals (mostly over water due to Sun glint).

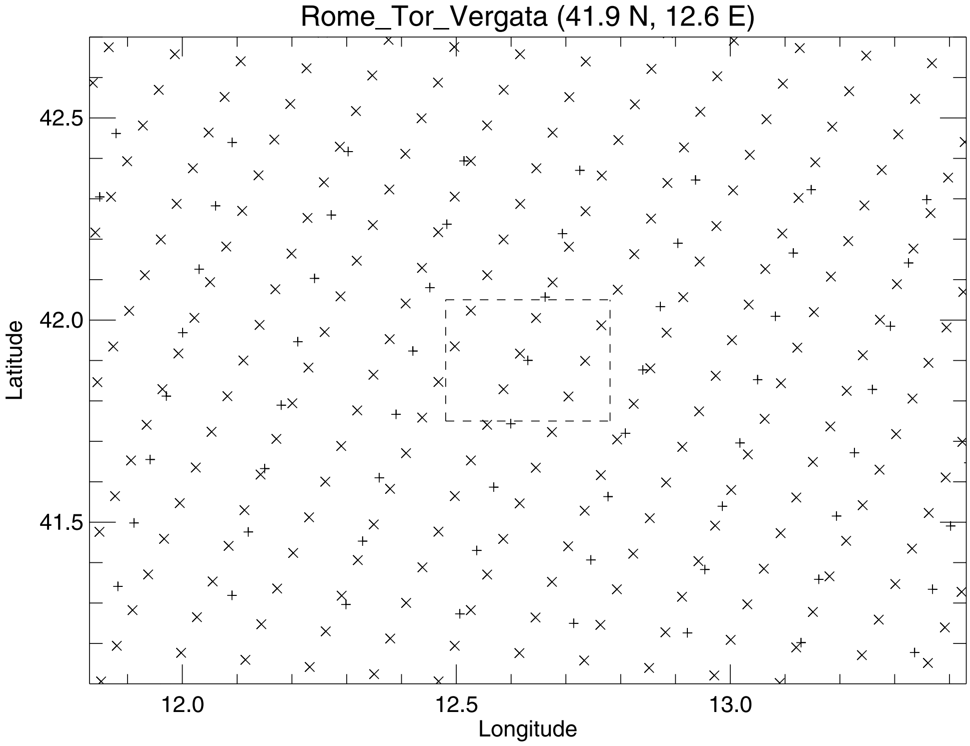

Figure 3. Illustration of the colocation of MISR (pluses) and MODIS (crosses) pixels. The averaging box covers an area of ±0.15° in latitude and longitude. The average of all (but no less than four) MODIS data (with QA ≥ 2) within this box is compared with MISR data at the center of the box.

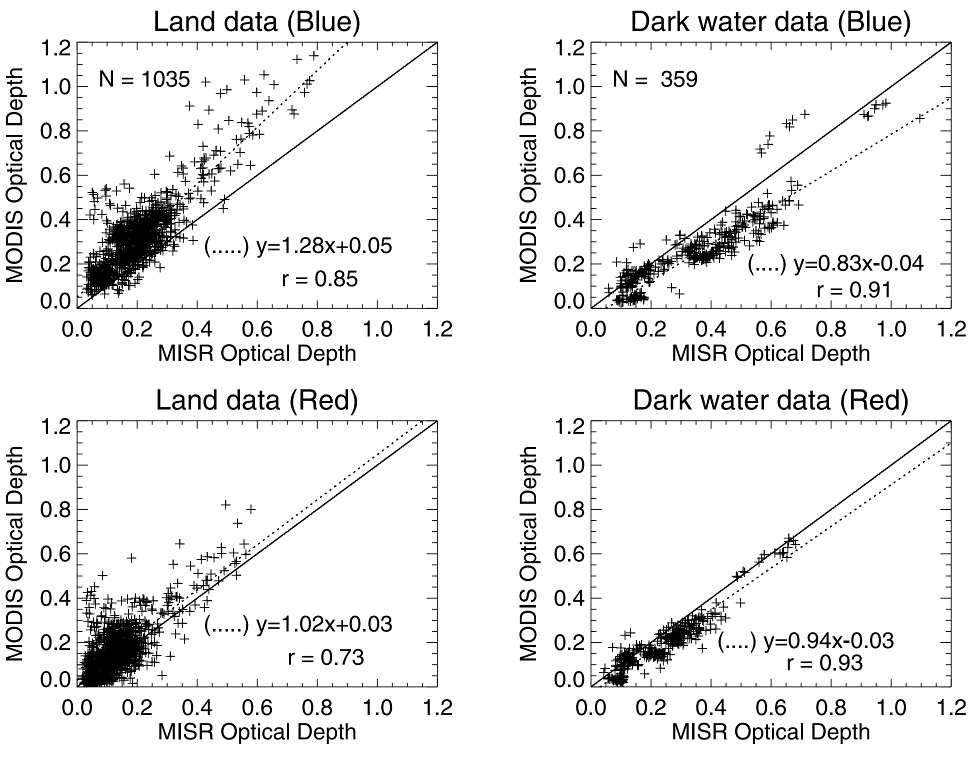

Figure 4. Comparison of the collocated MISR and MODIS optical depths retrieved at 470 nm (blue) and 660 nm (red) over land and ocean from observations over 62 AERONET sites during March 2002. The total number of points, N, available for the regression analyses are shown for each case. The dotted line is the linear least square fit, and r is the correlation coefficient of the regression.

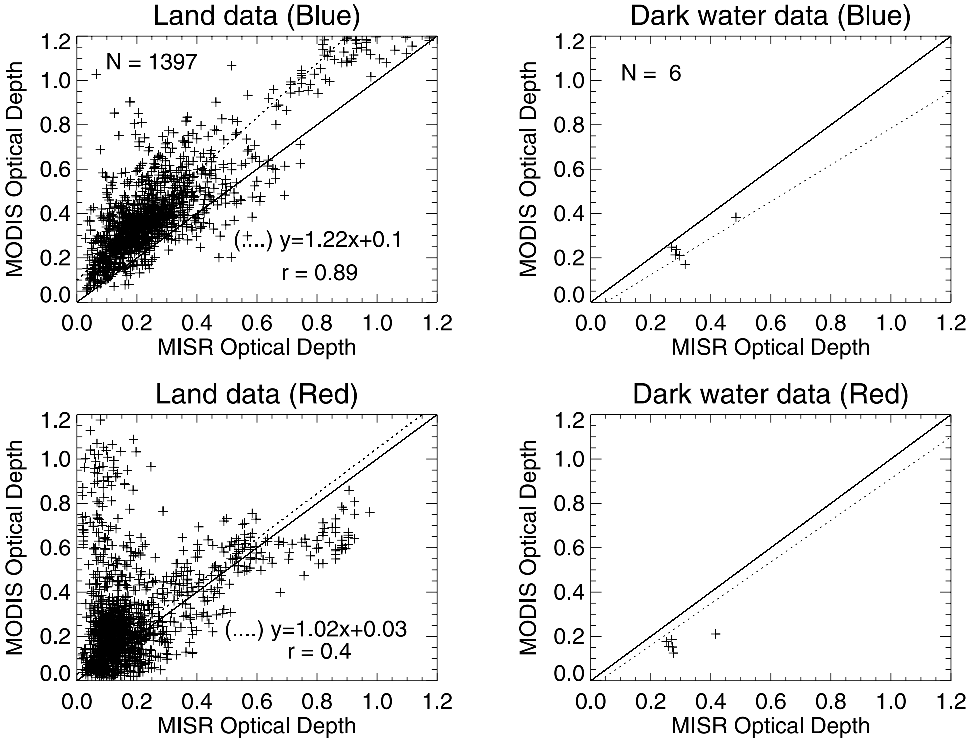

Figure 5. The same as in Figure 4, but for the data obtained in June 2002. Very few MODIS data with QA ≥ 2 were available over dark water in the June data set.

660 nm channels by using empirical relationships between the reflectances at these wavelengths [*Kaufman et al.*, 1997b, 2002]. The empirical relationship between visible and midinfrared surface reflectance holds for most dark vegetated surfaces. It breaks down for brighter surfaces and for situations with standing water and snow. A water and snow mask is employed to guard against contamination. Each retrieval is given a quality assessment (QA) flag, which is a number between 0 and 3, with 3 being the highest quality and 0 being the lowest. In this study only retrievals with QA ≥ 2 are used.

[9] Over ocean, the retrieval is made from simultaneously inverting six wavelengths (550, 660, 860, 1240, 1630, and 2130 nm) [*Tanré et al.*, 1997]. Note that the 470 nm channel is not included in the inversion and is never retrieved directly from the satellite measured radiances in that channel. Instead an optical thickness value at 470 nm is reported by extrapolating from the other six wavelengths. The inversion does not necessarily return a unique solution. Two solutions are reported for the ocean retrievals: the "best" solution, which is the solution with the least fitting error, and the "average" solution, which is the average of all solutions that meet the criterion of matching the observed radiances with less than 3% error. In this study, the "best" ocean aerosol solution is compared with MISR and AERONET. In many applications of the MODIS aerosol data, the "average" solution is the preferred parameter [*Remer et al.*, 2005]. As with MISR, the glint region is masked within 40° from specular reflection direction. Over the dark nonglint regions, the water-leaving radiance is assumed to be negligible except at 550 nm where it is assumed to be 0.005. The ocean retrievals are also given a QA flag, and only retrievals with QA ≥ 2 are used in this study.

2.3. AERONET

[10] AERONET is a globally distributed network of automated ground-based instruments and data archive system, developed to support the aerosol community. The instruments used are CIMEL spectral radiometers that measure direct Sun and diffuse sky radiance, in the almucantar and principal planes, acquiring data through a large range of scattering angles [*Holben et al.*, 1998]. The aerosol optical depths are determined from the spectral extinction of the direct Sun measurements, using the Beer-Bouguer Law, in seven spectral bands (340, 380, 440, 500, 670, 870, and 1020 nm). Sky radiance measurements are inverted with the Dubovik [*Dubovik and King*, 2000] and Nakajima [*Nakajima et al.*, 1983, 1996] inversions to provide aerosol properties of size distribution and phase function over the particle size range of 0.05 to 15 μm. The AERONET optical depths used in this study are level 1.5 values obtained from cloud-free observations. Level 2 optical depths are quality assured data retrieved from pre and post field calibrated measurements. However, these data were not always available and their differences from the level 1.5 data were mostly insignificant. The estimated uncertainty in the AERONET optical depth data is $\sim\pm 0.015$ at wavelengths >440 nm.

3. Data and Results

[11] The retrievals described here are based on data collected during the three months of March, June and September 2002. A total of 318 MISR and MODIS coincident scene images containing at least one AERONET site were used in the analyses. A total of 62 AERONET sites were covered by these data and, as shown in Figure 1, are mostly located on

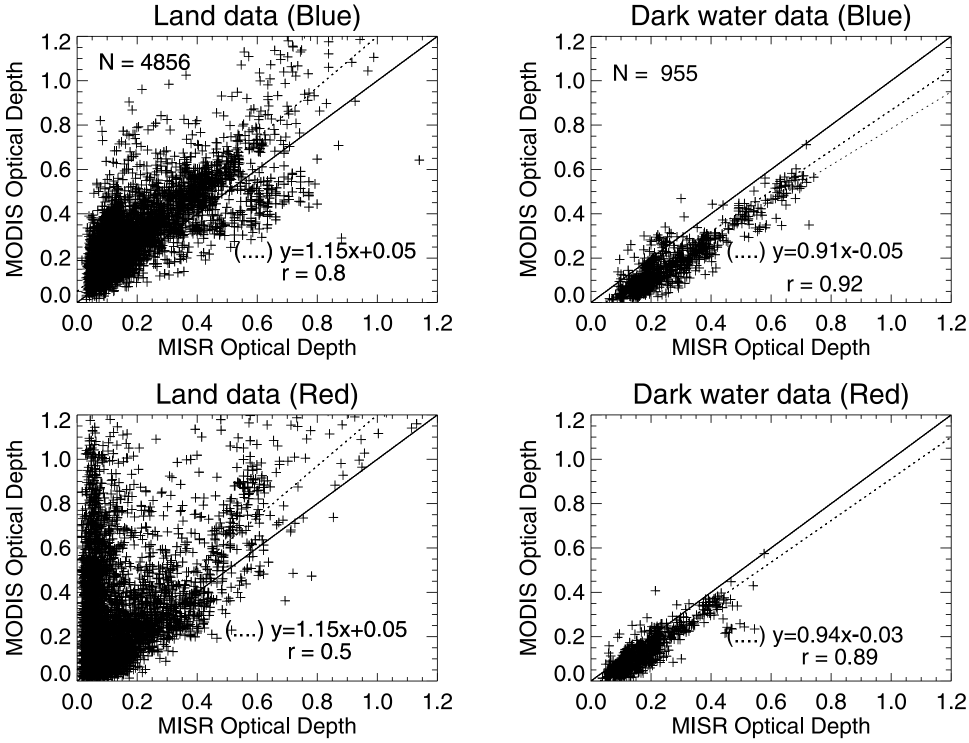

Figure 6. The same as in Figure 5 but for the data obtained in September 2002.

land with a few coastal and ocean sites. MISR data are drawn from blocks of 32 $\times$ 8 regions of 17.6 km $\times$ 17.6 km "regional mean spectral optical depth." The MODIS data (MOD04_L2) are obtained from 5-min granules of 135 $\times$ 203 pixels of 10 $\times$ 10 km resolution, and the optical depth data used are the "Corrected_Optical_Depth_Land" and the "Effective_Optical_Depth_Best_Ocean" for the land and ocean comparisons, respectively.

3.1. MISR/MODIS Comparison

[12] Figure 2 illustrates an example of MISR and MODIS images, at Rome-Tor Vergata, one of the AERONET sites (41.8° E, 12.65° N), showing the extents of their coverage. The comparisons are made only between valid collocated data, as illustrated in Figure 3, where each MISR regional optical depth is compared to the mean of all (but no less than four) MODIS values, with QA $\geq$ 2 (see section 2.2), that are available within ±0.15° in latitude and longitude from a MISR grid point, with values retrieved over land and ocean averaged separately. Figures 4, 5, and 6 show the comparison results for the months of March, June and September 2002, in the blue (470 nm) and red (660 nm) bands. Results from the four spectral bands of MISR are linearly interpolated to the MODIS wavelengths using an interactive data language (IDL) interpolation routine. Over land, optical depth values extend over the range 0.01 to 1.2, at both wavelengths, for most of the three months data sets. The majority of the data, however, have optical depths <0.5. Figures 4, 5, and 6 show that MODIS optical depths over land are typically larger than those retrieved from MISR. This difference is most pronounced at 470 nm where MODIS values are, on the average, $\sim$35% larger than MISR. For the dark water retrievals, as shown in the right-hand panels of Figures 4, 5, and 6, the optical depths in the March and September data sets are mostly in the range 0.1 to $\sim$0.7, in the blue channel, while very few data points with QA $\geq$ 2 were available in the data set of the month of June. In contrast to the land retrievals, MISR and MODIS optical depths over dark water show better correlation, with MISR data biased high with respect to MODIS. This bias is, on the average, $\sim$0.1 and 0.05 in the blue and red bands, respectively.

3.2. Comparison With AERONET

[13] To generate satellite data for comparison with AERONET, the averaging box is centered at each AERONET site that has a successful optical depth retrieval. All MISR and MODIS retrievals that are available within ±0.15° in latitude and longitude from that site are separately averaged and compared with the AERONET optical depth. The latter is the average of all the values obtained within ±30 min from the Terra overpass. For proper temporal collocation, at least two AERONET values were used in this averaging. The total number of AERONET data points is 318 but several of the sites have one or both of the Terra retrievals missing. Out of these 318 points, only 84 have valid, spatially and temporally collocated retrievals from AERONET, MISR and MODIS jointly. More data are available, however, if each instrument is separately compared with AERONET where 130 and 113 data points for MISR and MODIS land retrievals are available, respectively. Comparisons over land and ocean are shown in Figures 7 and 8, respectively. The dotted lines in these figures border the uncertainties derived from theoretical sensitivity studies for MISR (the larger of ±0.05 or ±0.2τ over ocean with similar uncertainties assumed for land) [*Kahn et al.*, 2001] and MODIS (±0.05 ± 0.2τ over land; ±0.03 ± 0.05τ over ocean) [*Kaufman et al.*, 1997a; *Tanré et*

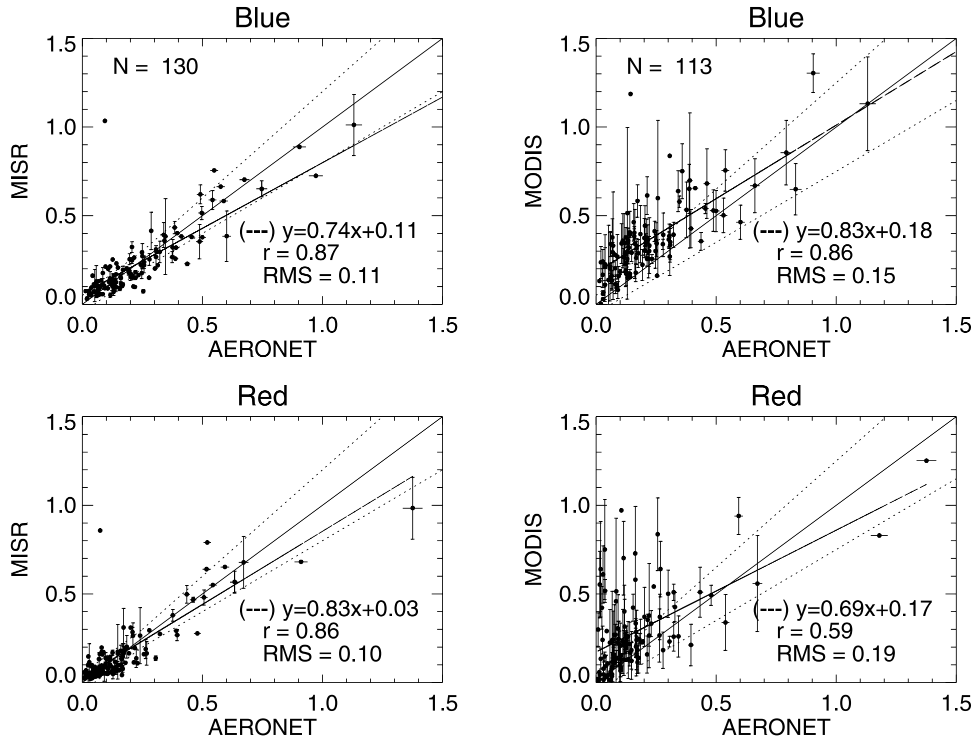

Figure 7. Comparison of MISR and MODIS land retrievals with the AERONET, at 470 nm (blue) and 660 nm (red), for all the three months (March, June, and September 2002) data sets. In this figure the number of AERONET points that have collocated data with MISR and MODIS are 130 and 113, respectively. The error bars represent the standard deviation in MISR and MODIS data available in the averaging box. For the AERONET, at least two data points were available in the temporal period of ±30 min from the Terra overpass. The temporal variability of the AERONET data was mostly very small (on the average <0.02), and therefore some of the error bars on the AERONET data do not show. The dotted lines border the uncertainties in MISR (the maximum of ±0.05 and ±0.2τ) and MODIS (±0.05 ± 0.2τ), and the dashed lines represent the least square linear fit with AERONET (y = m * x + b). The correlation coefficient, r, and errors (RMS) are shown for each regression.

al., 1997]. The error bars are the standard deviation for MISR and MODIS data that were available within the averaging box. No limit was set on the minimum number of data points that were averaged. For MODIS, except for five cases, there were always more than four valid data points available within the box. For cases where only a single data point is available in the averaging box, the standard deviation is set to 0.0. The standard deviation of the AERONET optical depths available within the ±30 min were usually very small (mostly <0.02) and, therefore, most of the error bars for the AERONET data do not show in Figures 7 and 8. Correlation coefficients, root mean square errors and best linear fit (dashed line) between the sensors' optical depths and the corresponding AERONET values are given on Figures 7 and 8. The regressions shown in these figures, show that relative to AERONET, MISR generally underestimates the optical depth retrieved over land while MODIS overestimates them. For the dark water retrievals, the number of data points available for the comparisons are statistically very small to reach a firm conclusion. However, for MISR, it is clear that optical depth retrieved over ocean are biased high compared to those retrieved from AERONET by an average of about 0.05 at 470 nm and 660 nm. Explanations for this bias are discussed in the next section. Further comparisons of MISR with AERONET, stratified by season and expected region, are presented in the work of *Kahn et al.* [2005a] and *Martonchik et al.* [2004].

4. Discussion

[14] Comparison of MISR and MODIS optical depths with each other and with AERONET demonstrate similar trends, with MODIS values biased high over land and MISR values biased high over ocean. We now discuss possible explanations for the observed differences.

4.1. Radiometric Calibration

[15] Recent calibration analyses based on three years of in-flight data, using the routine onboard calibrator, vicarious calibration, and the Terra lunar calibration experiment, have indicated that MISR red and near-infrared bands are consistently too bright by 3% and 1%, respectively, relative to independent standards [*Bruegge et al.*, 2003; *Kahn et al.*, 2005b]. Consequently, reprocessed data will incorporate a corresponding downward adjustment in the radiance scales for these two bands. However, the standard products used in this paper have not yet been reprocessed to include such adjustment. To explore the effect of adjusting the relative

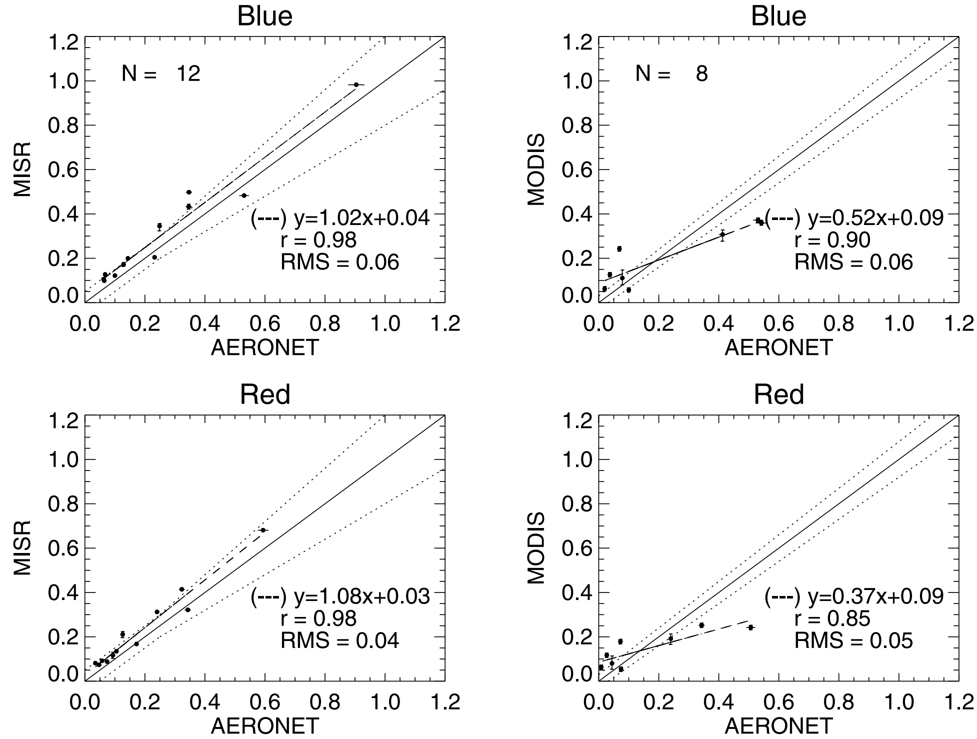

Figure 8. The same as in Figure 7, but for the retrievals over dark water. The number of AERONET points that have collocated data with MISR and MODIS are few in this case. The spatial variabilities in MISR and MODIS ocean data are either too small or only single data points were available in the averaging box, and therefore the error bars are either too small or of zero value.

spectral radiometric scale on the MISR aerosol retrievals, a correction was applied to the red and near-infrared radiances of the March data set. As shown in Figure 9, the calibration adjustments result in smaller optical depths over dark water with diminishing effect at larger wavelengths. This adjustment brings MISR and MODIS dark water retrievals into closer agreement without significantly affecting the mean values for the land retrievals. For example, the average effect in the case of March dark water retrievals is an averaged decrease of optical depth of ~0.09 and ~0.02 in the blue and red bands, respectively, while for land retrievals, the effect is within 0.01 in both bands. Figure 9 also shows a scatter in the difference between the optical depths retrieved before and after the calibration correction, on the order of ±0.05. This is because the relative spectral radiometric adjustment results not only in a change in optical depth for a given model, but also can result in a different set of models passing the goodness-of-fit tests within a given region.

[16] In addition to the relative spectral correction for MISR, there also exists an absolute radiometric-scale difference between MISR and MODIS [*Bruegge et al.*, 2003]. The MISR absolute scale is based upon comparisons to a multiyear set of vicarious calibration experiments performed over desert playas such as Railroad Valley, NV, whereas the MODIS scale is based on that instrument's onboard calibrator. When MISR radiances over land are compared to radiances in the MODIS land channels, MODIS radiances are approximately 3% lower. Similarly, when MISR radiances over ocean are compared to radiances in the MODIS ocean channels, MODIS radiances are again approximately 3% lower. However, the more relevant comparison may be between MISR radiances and the MODIS land band radiances over ocean, since the land bands are used in the MODIS aerosol retrievals over both ocean and land. When this comparison is made, the MODIS radiances are approximately 10% lower than the MISR values [*Bruegge et al.*, 2003]. Further work is in progress to understand the cause of this discrepancy, but is likely to be one contributor to the difference in MISR and MODIS optical depths retrieved over ocean.

4.2. Aerosol Models

[17] The above discussion emphasizes the importance of the choices of aerosol models in the lookup tables underpinning the retrievals. As illustrated in Figures 10a and 10b, most of the aerosol retrieved by AERONET during the three months of March, June, and September 2002, has optical depths less than ~0.5 and consists of particles with Angstrom exponent (AE) in the 1 to 2 range, with several instances of large particles (AE < 1) and very few of smaller particles (AE > 2). As noted before from Figure 7, and shown also in Figures 10c and 10d, relative to AERONET, MISR slightly underestimates the aerosol optical depths over land while MODIS generally overestimates them. To examine the effect of the aerosol models in the LUTs on the spectral shape of the retrieved optical depths, i.e., on the retrieved particle size, MISR and MODIS Angstrom exponents relative to the corresponding AERONET value, are displayed in Figures 10e, 10f, 10g, and 10h, as functions of

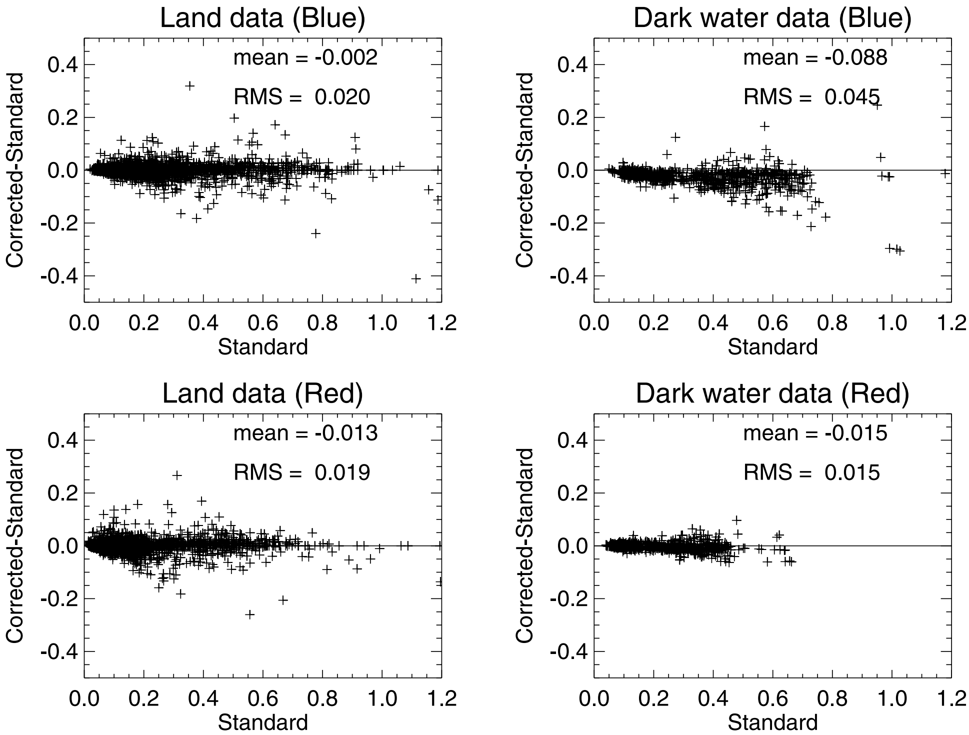

Figure 9. The difference between MISR optical depths (March data only) retrieved with the current retrieval algorithm (standard) and when the radiometric scale of the red and NIR bands are adjusted by −3% and −1%, respectively. These adjustments reduced the optical depth retrieved over ocean by a mean value of −0.09 in the blue band and −0.02 in the red. This brings MISR and MODIS ocean retrievals comparisons, shown in Figures 4, 5, and 6, into closer agreement. The effects on the land retrievals are within 0.01 for both bands. The scatter of the data indicates that these adjustments resulted also in retrieving different types of aerosol models (see discussion in section 4).

optical depth and AE, respectively. Although the pattern is not very clear, MISR optical depths and Angstrom exponents relative to AERONET seem to show opposite trends, whereby when MISR underestimates the optical depth it overestimates the AE values, i.e., underestimates the particles' size, and in the few cases when MISR overestimates the optical depth, as is the case below 0.05 for example, it underestimates the Angstrom exponent, i.e., overestimates the particle size. This behavior is consistent with the aerosol scattering properties in the scattering angles range typical for MISR (∼90° to 150°), where smaller particles scatter more light and, therefore, smaller optical depth are required to fit the observed TOA radiances. This correlation, however, may not be as simple when particle absorption is taken into consideration. Finally, when the difference in MISR and MODIS AE values from the corresponding AERONET values are displayed as a function of the latter, as shown in Figures 10g and 10h, a pattern emerges very clearly for MISR, where in the cases that AERONET AE < 1 it retrieves larger AE values (or smaller particles) and for AERONET AE > 2, MISR retrieves smaller AE values (or larger particles). These discrepancies in MISR and MODIS AE values relative to AERONET could also be attributed to errors in surface retrievals. Surface contributions are very small over ocean but, unfortunately, the number of data points available are statistically too small. However, the available AE values for particles retrieved over ocean, shown superimposed on the plots in Figures 10g and 10h, exhibit similar behavior as those retrieved over land. This suggests that the choice of aerosol models are most likely the source of the optical depth and AE discrepancies shown in Figure 10.

[18] Quantitative assessment of MISR aerosol retrieval that is based on the aerosol air mass types over a two-year period at several AERONET sites confirms this conclusion [*Kahn et al.*, 2005a]. The contents of LUT are currently under revision to improve MISR aerosol retrievals. For example, it is now understood that the dust models used in the MISR retrievals are too absorbing, and revised dust models are being generated [*Kalashnikova et al.*, 2005]. In addition a wider range of bimodal, nonabsorbing mixtures are being considered.

4.3. Surface Model Assumptions

[19] The largest differences between MISR and MODIS occur for the retrievals over land. As shown in Figure 7, MISR is generally in good agreement with AERONET within the expected uncertainty limits. For MODIS, however, at optical depths values smaller than ∼0.4, in the visible band, MODIS is biased high compared to the AERONET and show inhomogeneity within the pixels that surround the AERONET sites. The MODIS aerosol optical thickness retrievals over both land and ocean have been compared with collocated AERONET observations using a carefully designed spatiotemporal approach [*Ichoku et al.*, 2002] and reported in the work of *Chu et al.* [2002] and

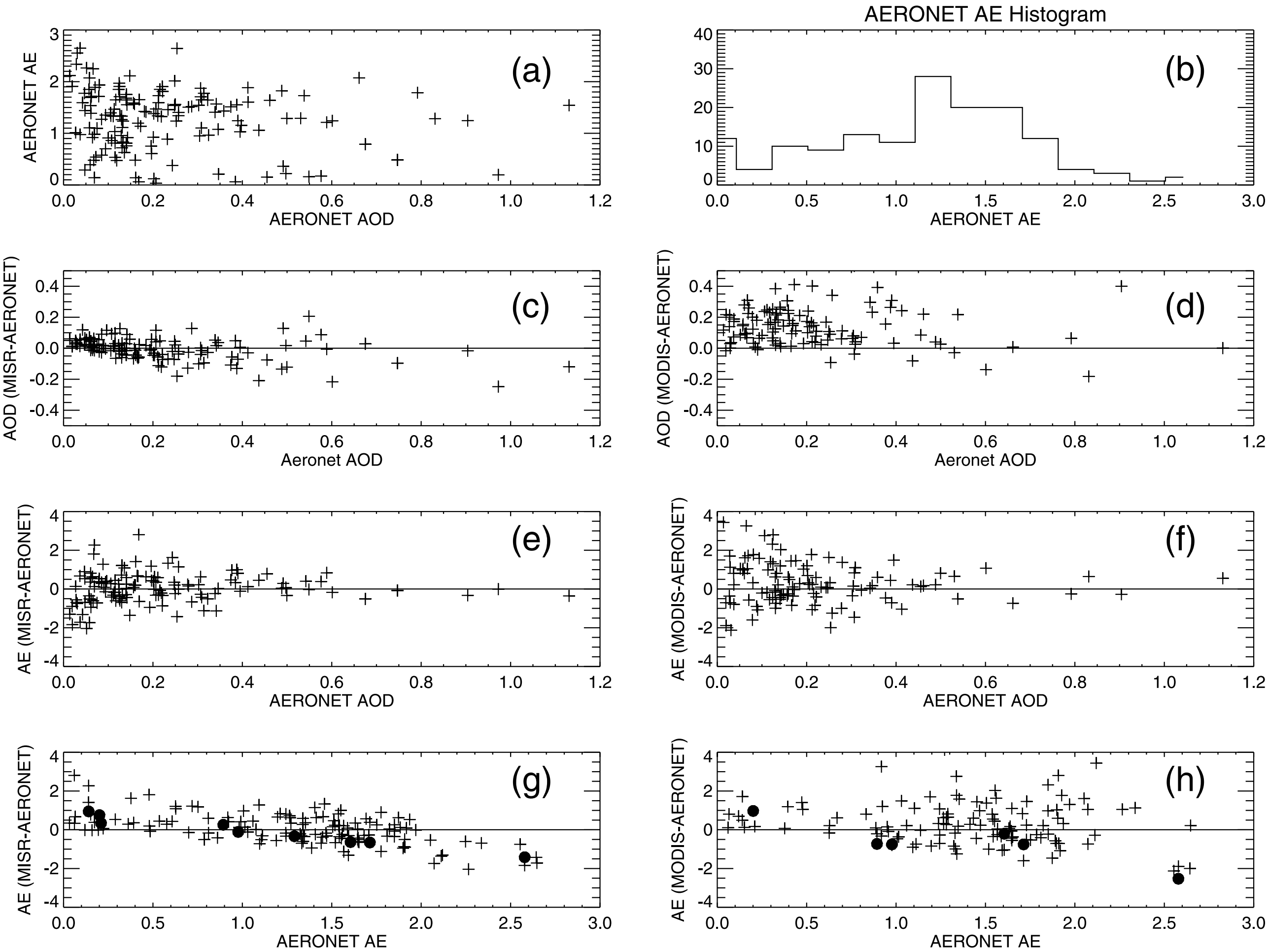

Figure 10. Comparison of MISR and MODIS aerosol optical depths (AOD), retrieved over land in the blue band, and the Angstrom exponents, AE (i.e., particle size), with the corresponding AERONET values. For proper comparison, all the AE values in this figure are estimated from the optical depths shown in Figures 7 and 8 in the blue and red spectral bands. The AE values estimated from the ocean retrievals are superimposed (filled circles) on the plots in Figures 10g and 10h.

Remer et al. [2002]. A more extensive comparison spanning a full two years of observations using 133 AERONET stations, resulted in nearly 2000 ocean collocations and 6000 land collocations [*Remer et al.*, 2005]. These studies indicate that MODIS aerosol optical thickness products over land are accurate to within $\pm 0.05 \pm 0.20\tau$, except in situations with possible cloud contamination, over surfaces with subpixel surface water such as coastal areas and marshes, and over surfaces with subpixel snow or ice cover. Contamination by subpixel snow, water, or desert can be expected to result in nonoptimal results for the MODIS land retrievals due to a departure in the spectral signature of these surfaces from the underlying assumption of the retrieval algorithm. To explore this further, Figures 11 and 12 show comparisons of MISR and MODIS optical depths, respectively, with AERONET at 660 nm, using separate color codes to identify desert and coastal sites from the rest of the inland sites. As shown in these figures, MISR retrievals are mostly within their expected uncertainties irrespective of surface type, as expected for the multiangle algorithm. However, MODIS retrievals at desert sites, where surfaces are bright, and coastal sites, where subpixel water contamination is expected, are biased high compared to AERONET. Previous studies [e.g., *Chu et al.*, 2002] report similar results. Excluding these desert and coastal sites, the MODIS land retrievals are in better agreement with the AERONET data.

5. Conclusions

[20] MISR and MODIS optical depth retrieved from 318 scenes that contain AERONET sites were compared. The results show that, over land, MODIS is biased high compared to MISR while the opposite is true over ocean. Compared with AERONET, MISR is in good agreement within the maximum of ± 0.05 or $\pm 0.2\tau$ for both land and dark water retrievals. In case of the latter, however, MISR is, on the average, $\sim$0.05 and 0.025 higher than the AERONET in the blue and red bands, respectively, prior to application of a band-to-band radiometric calibration adjustment. The latest MISR radiometric calibration adjustments of the red and near-infrared bands by -3%

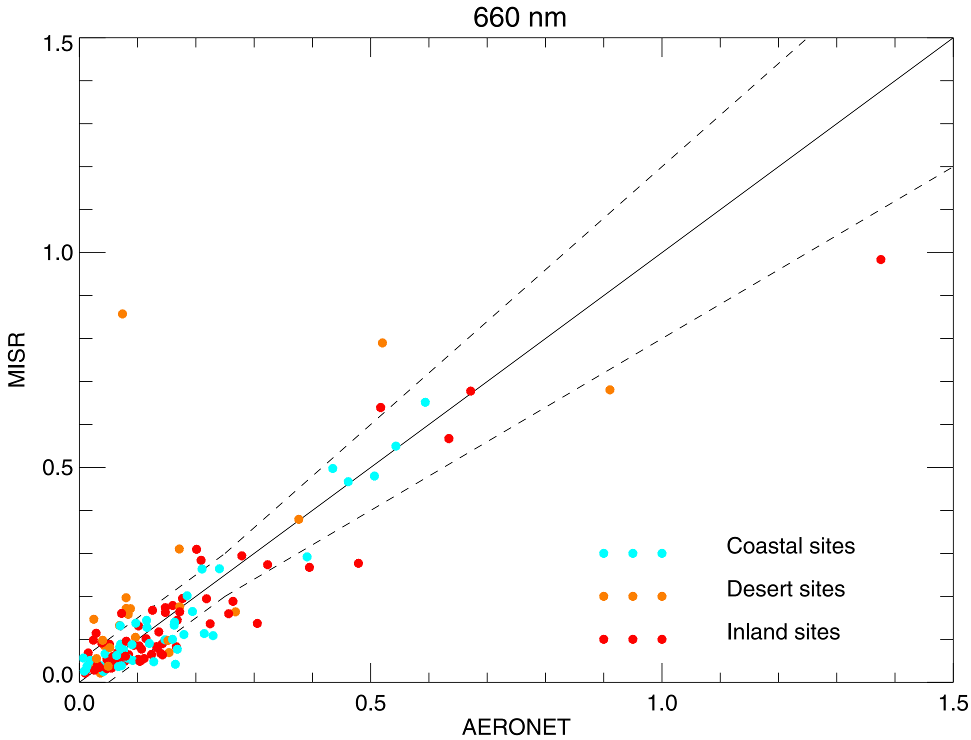

Figure 11. Comparison of MISR with AERONET land retrievals over inland, desert, and coastal sites at 660 nm. The dashed lines border the MISR uncertainties of the maximum of ±0.05 and ±0.2τ.

and −1%, respectively, partly resolve the discrepancies of the ocean retrievals. Revised dust models are being generated to replace the more absorbing ones used in MISR's LUT. Those are expected to further improve the agreement between MISR and AERONET retrievals.

[21] MODIS retrievals over desert and coastal sites, where surface brightness and subpixel water contamination cause large errors, are biased high compared to AERONET. Over other inland sites MODIS is in better agreement with AERONET and most of the retrievals fall within the

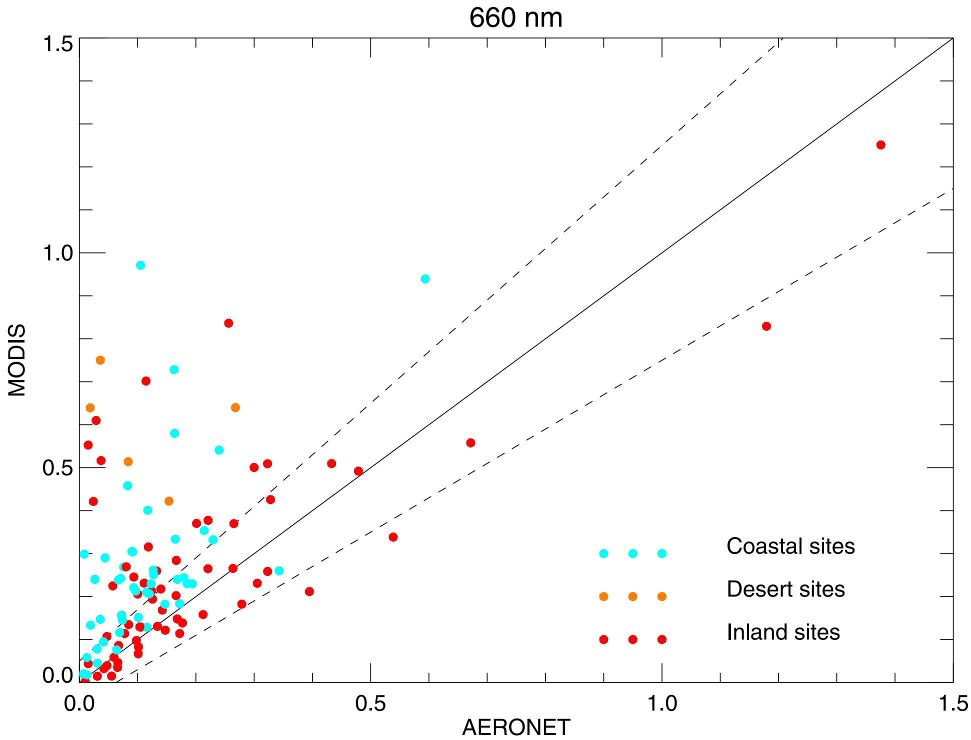

Figure 12. Similar to Figure 11 but for MODIS. The dashed lines in this case border the MODIS uncertainties estimated at ±0.05 ± 0.2τ.

calculated uncertainty of $\pm 0.05 \pm 0.2\tau$. The data points available for the MODIS and AERONET comparison over ocean were too few to reach a meaningful conclusion. Remaining discrepancies between MISR and MODIS may be attributed to differences in their calibration, algorithm assumptions, or the aerosol models in the lookup tables used in the retrieval algorithms.

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References

Abdou, W. A., C. J. Bruegge, M. C. Helmlinger, J. E. Conel, S. H. Pilorz, W. Ledeboer, B. J. Gaitley, and K. J. Thome (2002), Vicarious calibration experiment in support of the Multiangle Imaging Spectroradiometer (MISR), *IEEE Trans. Geosci. Remote Sens.*, *40*, 1500–1511.

Bruegge, C. J., N. L. Chrien, R. R. Ando, D. J. Diner, W. A. Abdou, M. C. Helmlinger, S. H. Pilorz, and K. J. Thome (2002), Early validation of the Multiangle Imaging Spectroradiometer (MISR) radiometric scale, *IEEE Trans. Geosci. Remote Sens.*, *40*, 1477–1492.

Bruegge, C. J., W. Abdou, D. J. Diner, B. J. Gaitley, M. Helmlinger, R. A. Kahn, and J. V. Martonchik (2003), Validating the MISR radiometric scale for the ocean aerosol science communities, in *Proceedings of the International Workshop on Radiometric and Geometric Calibration, December 2–5, 2003, Gulfport, Mississippi*, pp. 103–115, A. A. Balkema, Brookfield, Vt.

Chrien, N. L., C. J. Bruegge, and R. R. Ando (2002), Multiangle Imaging Spectroradiometer (MISR) on-board calibrator (OBC) in-flight performance studies, *IEEE Trans. Geosci. Remote Sens.*, *40*, 1493–1499.

Chu, D. A., Y. J. Kaufman, C. Ichoku, L. A. Remer, D. Tanré, and B. N. Holben (2002), Validation of MODIS aerosol optical depth retrieval over land, *Geophys. Res. Lett.*, *29*(12), 8007, doi:10.1029/2001GL013205.

Diner, D. J., et al. (1998), Multiangle Imaging Spectroradiometer (MISR) instrument description and experiment overview, *IEEE Trans. Geosci. Remote Sens.*, *36*, 1072–1087.

Dubovik, O., and M. D. King (2000), A flexible inversion algorithm for retrieval of aerosol optical properties from Sun and sky radiance measurements, *J. Geophys. Res.*, *105*, 1072–1087.

Guenther, B., G. D. Godden, X. Xiaoxiong, E. J. Knight, S. Qiu, H. Montgomery, M. M. Hopkins, M. G. Khayat, and Z. Hao (1998), Prelaunch algorithm and data format for the level1 calibration products for the EOS_AM1 Moderate Resolution Imaging Spectroradiometer (MODIS), *IEEE Trans. Geosci. Remote Sens.*, *36*, 1142–1151.

Holben, B. N., et al. (1998), AERONET—A federal instrument network and data archive for aerosol characterization, *Remote Sens. Environ.*, *66*, 1–16.

Ichoku, C., D. A. Chu, S. Mattoo, Y. J. Kaufman, L. A. Remer, D. Tanré, I. Slutsker, and B. N. Holben (2002), A spatiotemporal approach for global validation and analysis of MODIS aerosol products, *Geophys. Res. Lett.*, *29*(12), 8006, doi:10.1029/2001GL013206.

Kahn, R., P. Banerjee, and D. McDonald (2001), Sensitivity of multiangle imaging to natural mixtures of aerosols over ocean, *J. Geophys. Res.*, *106*, 18,219–18,238.

Kahn, R. A., B. J. Gaitley, J. V. Martonchik, D. J. Diner, K. A. Crean, and B. Holben (2005a), Multiangle Imaging Spectroradiometer (MISR) global aerosol optical depth validation based on 2 years of coincident Aerosol Robotic Network (AERONET) observations, *J. Geophys. Res*, doi:10.1029/2004JD004706, in press.

Kahn, R., et al. (2005b), MISR calibration, and implications for low-light-level aerosol retrieval over dark water, *J. Atmos. Sci.*, in press.

Kalashnikova, O. V., R. Kahn, I. N. Sokolik, and W.-H. Li (2005), Ability of multiangle remote-sensing observations to identify and distinguish mineral dust types: 1. Optical models and retrievals of optically thick plumes, *J. Geophys. Res.*, *110*, D18S14, doi:10.1029/2004JD004550.

Kaufman, Y. J., D. Tanré, L. A. Remer, E. Vermote, A. Chu, and B. N. Holben (1997a), Operational remote sensing of tropospheric aerosol over land from EOS Moderate Resolution Imaging Spectroradiometer, *J. Geophys. Res.*, *102*, 17,051–17,067.

Kaufman, Y. J., A. E. Wald, L. A. Remer, B.-C. Gao, R.-R. Li, and L. Flynn (1997b), The MODIS 2.1 μm channel correlation with visible reflectance for use in remote sensing of aerosol, *IEEE Trans. Geosci. Remote Sens.*, *35*, 1286–1298.

Kaufman, Y. J., N. Gobron, B. Pinty, J. Widlowski, and M. M. Verstraete (2002), Relationship between surface reflectance in the visible and mid-IR used in MODIS aerosol algorithm—Theory, *Geophys. Res. Lett.*, *29*(23), 2116, doi:10.1029/2001GL014492.

Martonchik, J. V., D. J. Diner, R. A. Kahn, T. P. Ackerman, M. M. Verstraete, B. Pinty, and H. R. Gordon (1998), Techniques for the retrieval of aerosol properties over land and ocean using multiangle imaging, *IEEE Trans. Geosci. Remote Sens.*, *36*, 1212–1227.

Martonchik, J. V., D. J. Diner, K. A. Crean, and M. A. Bull (2002), Regional aerosol retrieval results from MISR, *IEEE Trans. Geosci. Remote Sens.*, *40*, 1520–1531.

Martonchik, J. V., D. J. Diner, R. Kahn, B. Gaitley, and B. N. Holben (2004), Comparison of MISR and AERONET aerosol optical depths over desert sites, *Geophys. Res. Lett.*, *31*, L16102, doi:10.1029/2004GL019807.

Nakajima, T., M. Tanaka, and T. Yamauchi (1983), Retrieval of the optical properties of aerosols from aureole and extinction data, *Appl. Opt.*, *22*, 2951–2959.

Nakajima, T., G. Tonna, R. Rao, P. Boi, Y. Kaufman, and B. Holben (1996), Use of sky brightness measurements from ground for remote sensing of particulate polydispersions, *Appl. Opt.*, *35*, 2672–2686.

Remer, L. A., et al. (2002), Validation of MODIS aerosol retrieval over ocean, *Geophys. Res. Lett.*, *29*(12), 8008, doi:10.1029/2001GL013204.

Remer, L. A., et al. (2005), The MODIS aerosol algorithm, products and validation, *J. Atmos. Sci.*, in press.

Tanré, D., Y. J. Kaufman, M. Herman, and S. Mattoo (1997), Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiances, *J. Geophys. Res.*, *102*, 16,971–16,988.

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