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Global evaluation of the Collection 5 MODIS dark-target aerosol products over land

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Abstract

NASA's MODIS sensors have been observing the Earth from polar orbit, from *Terra* since early 2000 and from *Aqua* since mid 2002. We have applied a consistent retrieval and processing algorithm to both sensors to derive the Collection 5 (C005) dark-target aerosol products over land. Here, we co-locate the MODIS field of view aerosol retrievals with Level 2 AERONET sunphotometer measurements at over 300 sites, and find 85 000 matched pairs that represent mutually cloud-free conditions. From these collocations, we validate the total aerosol optical depth (AOD or τ) product, and define the expected error (EE) as $\pm(0.05+0.15\tau)$. Since we find that >66% (one standard deviation) of MODIS AOD values compare to AERONET within EE, we can consider global AOD to be validated. However, MODIS does not compare as well to AERONET at particular sites and seasons. There are residual biases that are correlated with Ångstrom exponent, scattering angles, and scene reflectance conditions, resulting from assumptions about the aerosol optical properties and surface conditions that are not accurate everywhere. Although we conclude that the AOD over land is globally quantitative, MODIS-derived parameters of aerosol size over land (Ångström exponent, fine AOD) are not. When separating data into those derived from Terra versus those from Aqua, scatterplots to AERONET are nearly indistinguishable. However, while Aqua is stable, Terra shows a slight trend in its bias with respect to AERONET; overestimating (by ~0.005) before 2004, and underestimating by similar magnitude after. This suggests small, but significant calibration uncertainties of <2%, which could lead to spurious long-term aerosol trends.

1 Introduction

As components in Earth's global climate system, global aerosol distribution and loading must be characterized in order to understand their impacts. The climate and aerosol communities are increasingly relying on satellite-derived aerosol data, for research as

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well as for monitoring. Aerosol products from NASA's Moderate Imaging Spectrometer (MODIS; Salomonson et al., 1989) sensor were utilized in the latest IPCC (4th) assessment of climate (IPCC, 2007), and are being assimilated into chemical transport models (e.g. Zhang and Reid, 2006). Satellite aerosol products, including those from MODIS, are also being used for estimating and monitoring ground-level particulate matter (PM) at regional and local scales (e.g., Al-Saadi et al., 2005; van Donkelaar et al., 2010).

There are two MODIS sensors (King et al., 2003), observing Earth from polar orbit aboard NASA's *Terra* (since February 2000) and *Aqua* satellites (since June 2002). MODIS is uniquely suited for characterization of aerosols, combining swath size (~2330 km), spectral resolution (36 wavelength bands, spanning from 0.415 µm to 14.5 µm) and spatial resolution (1 km, 0.5 km, or 0.25 km, depending on band). Orbit stability and calibration are both rigorously maintained by the MODIS Characterization Support Team (MCST), to within ±2–3% at typical situations (Xiong et al., 2005, 2007). To take advantage of MODIS's sensitivity to aerosol signals, efficient retrieval algorithms have been developed, maintained, and consistently applied to the entire time series. These algorithms operate by matching observed spectral reflectance (statistics of non-cloudy pixels) to lookup tables (LUT) that simulate spectral reflectance for expected aerosol conditions. Each retrieved value represents the aerosol conditions in non-cloudy skies, within some expected error interval. The current suite of MODIS aerosol products are derived separately over three environments: 1) dark-surface (far from sun glint) ocean targets (Remer et al., 2005), 2) dark-surface (vegetation; soils) land targets (Levy et al., 2007b), and 3) bright surface (deserts) land targets (e.g, Hsu et al., 2004).

In this paper, we assess the performance of the aerosol products over dark-land targets (environment 2). These products include total *aerosol optical depth* (τ or AOD) at 0.55 µm, *spectral* AOD at 0.47 and 0.65 µm, *the aerosol model weighting factor* (η or ETA) at 0.55 µm, *fine-model* AOD (τ_f or fAOD) and *Ångstrom exponent* (α) defined using 0.47 and 0.65 µm,. Retrievals of the AOD and size parameters, plus diagnostic

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parameters and retrieval *Quality Assurance* (QA), comprise the set of *Level 2* (L2) aerosol products. These L2 products are retrieved at 10 km resolution globally, and are contained in data product files, which we denote as M*D04 (MOD04 for Terra and MYD04 for Aqua). These M*D04 files are processed and archived by the MODIS Adaptive Processing System (MODAPS) at NASA's Goddard Space Flight Center, in Hierarchal Data Format (HDF) with parameters stored as Scientific Data Sets (SDS). The most recent dark-target aerosol data are being processed as Collection 5, or C005 for Terra and Collection 51 or C051 for Aqua.

Prior to Terra launch, Kaufman et al. (1997a) estimated the *expected error* (EE) for MODIS-retrieved AOD. Since then, many studies (e.g. Chu et al., 2002; Remer et al., 2005), have attempted to *validate* the MODIS products with respect to EE, most recently for the dataset known as Collection 4 (C004). The C004 MODIS-derived aerosol products were compared to global sunphotometer data, and shown to compare within EE on a global scale (Remer et al., 2005). However this and other studies (e.g. Levy et al., 2005) demonstrated that there were locations and conditions where the C004 errors were systematically larger. These errors were of a magnitude that the C004 products were not accurate enough for use in global model assimilation (e.g. Hyer and Reid, 2009).

Levy et al. (2007a, b) characterized some of the limitations of the C004 algorithm, and introduced the "second-generation" dark target algorithm that was used to process C005. Although there have been studies using C005 dark-target products both globally (e.g. Remer et al., 2008), and regionally (e.g. Mi et al., 2007), this paper is a more in-depth evaluation. Here, we compare the entire MODIS time series (from both Terra and Aqua) to global AERONET data, thus quantifying global EE, and identifying where and under what conditions the C005 products may still be falling short. In Sect. 2, we briefly summarize the C005 dark-target aerosol retrieval and products, and define the concept of EE. We compare the MODIS-derived aerosol products with measurements by ground-based sunphotometers, for spectral AOD in Sect. 3, and for aerosol size parameters (including Ångström exponent and fine AOD) in Sect. 4. We use the

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spatial-temporal collocation method that was introduced by Ichoku et al. (2002), and used previously by Remer et al. (2005) and others. In Sect. 5, we summarize our validation results and suggest steps necessary to reduce the remaining systematic discrepancies. Section 6 offers some discussion of the significance of the results and conclusions.

2 The MODIS aerosol retrieval over land

The MODIS "dark-target" aerosol retrieval algorithm is optimized for land surfaces that are "dark" in parts of the visible (VIS) and shortwave infrared (SWIR) spectrum. Generally, vegetated and dark soil regions are examples of such dark targets. Although the algorithm's details have evolved since inception (Kaufman et al., 1997a), the fundamental logic remains the same. Specifically, the algorithm uses two visible (VIS) and one shortwave IR (SWIR) bands (centered about 0.47, 0.65 and 2.1 µm) (Kaufman et al., 1997a; Levy et al., 2007b), which a) are nearly transparent to CO_2, H_2O and other gaseous absorption, and b) demonstrate a spectral relationship that constrains the reflectance properties of vegetated land surfaces (Kaufman et al., 1997b). Additional wavelengths in other parts of the spectrum are used to mask out clouds, deserts, snow, and ice – non dark-target conditions (Ackerman et al., 1998; Martins et al., 2002; Li et al., 2003). Although the nominal resolution of MODIS is 500 m in most wavelength bands, the MODIS aerosol retrieval is performed at 10 km. The 10 km retrieval allows us to improve the signal to noise ratio since we can throw out many pixels (clouds, cloud shadows, snow, surface inhomogeneities) and still have sufficient information for doing the retrieval.

The heart of the algorithm is a lookup table (LUT), containing radiative transfer (RT) simulations of the top-of-atmosphere (TOA) spectral reflectance field for typical aerosol scenarios over land. The algorithm tries to match the LUT to the observed radiation field, and deduce the properties of the aerosol in that scene. The solution includes the total AOD at 0.55 µm and a weighting factor (ETA or η) that represents the fraction

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of the total AOD contributed by fine-sized aerosol. A small fitting error (ε) indicates that the solution from the LUT closely matches the observations. The AOD is the vertical integration of aerosol extinction, a physical property of the aerosol field. ETA is essentially the algorithm's fitting parameter, providing flexibility for mixing aerosol types to match to observed spectral reflectance. ETA does not represent a physical aerosol quantity.

While the *retrieved* parameters (AOD, ETA) are the solution to the algorithm, they also depend on assumptions. Knowledge of the assumptions in the LUT, including the shape, size distributions and refractive indices of the aerosol models, leads to calculation of additional parameters. These *derived* parameters include spectral AOD, Ångstrom exponent (AE or α), and fine AOD (fAOD or τ_f). Specifically, the AE is a one-parameter description of the spectral AOD dependence, which can be related to relative aerosol size (e.g. Eck et al., 1999). Larger values of AE (steeper spectral dependence) indicate smaller column-effective particle size, and conversely. The fine-model AOD (fAOD or τ_f) is the product of AOD and ETA at 0.55 µm. We refer to this quantity as the fine-model AOD because one of the multi-modal models is dominated by the fine mode. (The other, the dust model, is dominated by the coarse mode.) Although there can be correlation between this fine-model AOD and common definitions of fine-*mode* AOD (like that derived from MODIS over ocean), we emphasize that over land, it is not a physical retrieval of aerosol particle size.

Finally, the MODIS algorithm reports a number of *diagnostic* products, including an estimate of the "quality" of the retrieval. The *Quality Assurance* (QA) plan (e.g. Hubanks, 2007) is a series of tests that indicates whether certain conditions are met during the course of the retrieval. At the end of the retrieval process, a summary QA Confidence (QAC) flag summarizes the results of all QA tests, and indicates a relative "confidence" in the retrieved product. We expect that data having larger QAC values will be more accurate, and therefore more useful for quantitative applications (e.g. Kahn et al., 2009).

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2.1 Expected error

Because the MODIS algorithms are designed to infer aerosol properties from the radiation field, uncertainties in the retrieval assumptions and retrieval methodology lead to uncertainties in the retrieved products. Prior to Terra launch, Kaufman et al. (1997b) used sensitivity studies to estimate the *expected error* (EE) of the MODIS-retrieved AOD. Estimated as $\pm(0.05+0.20\tau)$, the MODIS EE represented the fusion of absolute (0.05) and relative (20%) uncertainties that would arise from combined errors in assumed boundary conditions (e.g. surface reflectance, instrument calibration) and errors in aerosol model type (such as in single scattering albedo).

After the launch of Terra (and later Aqua), the actual MODIS-derived AOD was repeatedly collocated with, and compared to global sunphotometer data, which is used as ground-truth (e.g. Chu et al., 2002; Remer et al., 2005). Good matches were reported wherever the MODIS-retrieved AOD, τ_{MODIS}, fell within the envelope defined by

$$\tau - |\mathrm{EE}| \leq \tau_{\mathrm{MODIS}} \leq \tau + |\mathrm{EE}|. \quad (1)$$

Validation referred to the process of quantifying the EE, so that at least 66% (or one standard deviation) of matches would fall within this envelope. Through validation, Chu et al. (2002) suggested that the EE could be reduced to

$$\mathrm{EE} = \pm(0.05 + 0.15\tau), \quad (2)$$

which was later confirmed by Remer et al. (2005) for a large dataset (Collection 4; 5906 collocations).

However, these and other studies (e.g. Levy et al., 2005; Hyer and Reid, 2009) noted conditions and locations where the errors were larger. For example, Remer et al. (2005) demonstrated that on average, the C004 algorithm tended to overestimate AOD, especially in conditions of low aerosol loading (i.e., τ<0.1). Other systematic biases were noted in some regions, which included both under and overestimates, all indicating insufficient constraints on surface and/or aerosol properties in the retrieval. Levy et

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al. (2005) looked at a specific region of MODIS/sunphotometer disagreement, the US East Coast, and found ways to update both the surface and aerosol optical assumptions to provide better agreement with sunphotometer observations. Levy et al. (2004) also indicated how the neglect of polarization in the radiative transfer simulations could introduce errors.

2.2 The C005 algorithm and products

Based on the lessons learned from systematic C004 evaluation, Levy et al. (2007a) created the "second-generation" over-land retrieval algorithm, which was then implemented for C005 processing (starting in early 2006). Although in general, the dark-target concept (Kaufman et al., 1997a; Remer et al., 2005) was retained, there were major modifications for C005 (Levy et al., 2007a, b), including:

- The global aerosol is represented by three spherical, fine (sized)-dominated aerosol types, distinguished by their single scattering albedo at 0.55 µm (SSA=0.86, 0.91 and 0.95), as well as a single, spheroidal, coarse (sized)-dominated, dust aerosol type (SSA=0.95). Each aerosol model has two lognormal modes. Seasonal, gridded maps ($1^\circ \times 1^\circ$) assign the fine-dominated type to constrain the LUT search.

- Instead of neglecting polarization in the atmospheric simulations (Levy et al., 2004), the LUT was created with vector RT code (Evans and Stephens, 1991). Modified T-matrix code (Dubovik et al., 2006) was used to calculate spheroid, dust type scattering, whereas Mie code (Wiscombe, 1980) was used for the other types.

- Instead of fixed ratios, the VIS/SWIR surface reflectance parameterization includes y-offsets, and varies by SWIR vegetation index and scattering angle.

- Instead of the two-channel VIS retrieval with transparent 2.1 µm assumptions, the retrieval is a three-channel inversion (0.47, 0.65 and 2.1 µm) that allows for

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the possibility of non-transparent dust in all channels. The VIS/SWIR surface reflectance relationships are used to constrain the solution.

- Instead of simple reduction of Rayleigh AOD over elevated targets, the phase function dependency of Rayleigh/aerosol interaction is included.
- To reduce statistical biases in low-AOD conditions (AOD<0.05), negative AOD values down to −0.05 are permitted.
- The improved snow/ice mask of Li et al. (2003) is implemented.

Other than implementing the snow mask of Li et al. (2003) into the C005 algorithm, the pixel selection technique remained the same. The 3×3 visible reflectance variability test (e.g. Martins et al., 2002) provides the primary cloud screening, and of the remaining pixels, 20% of the darkest and 50% of the brightest pixels are discarded. The C005 processing also included major changes to the *Quality Assurance* (QA; Hubanks, 2007) plan. The new QA plan included information characterizing the type, quality and confidence of the input MODIS reflectance data, ancillary datasets (e.g. meteorology or ozone ancillary data; Levy et al., 2009b), as well as some of the intermediate and output products.

2.3 Preliminary validation

Levy et al. (2007a) collected a test-bed (6000 granules) of archived MODIS-C004 radiance files, and compared results of the second-generation algorithm with those obtained by the previous one. For the test-bed, the overall, mean AOD decreased from ~0.28 (C004-like) to ~0.19 (C005-like). They found that the comparison of total AOD with collocated, global, AERONET (Holben et al., 1998) sunphotometer measurements (>1200 cases) was improved, as demonstrated by the correlation coefficient (R) increasing from 0.85 to 0.89, and the y-offset decreasing from 0.097 to 0.029. For the test-bed, 67% of the MODIS/AERONET AOD collocations fell within the EE envelope (Eqs. 1, 2), indicating preliminarily validation. Levy et al. (2007a) also noted minor

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improvements in the correlation of MODIS/AERONET size parameters, however there was no indication they were globally quantitative.

Although the new aerosol retrieval algorithm passed the preliminary validation tests using the archived C004 radiances, new calibration coefficients were introduced by MCST for C005 processing (http://mcst.gsfc.nasa.gov/uploads/files/c5_luts_update/L1B_Aqua_LUT_History.txt and http://mcst.gsfc.nasa.gov/uploads/files/c5_luts_update/L1B_Terra_LUT_History.txt). This means that the preliminary validation performed by Levy et al. (2007a) may not apply to actual C005 products. In fact, Remer et al. (2008) identified differences between the C004 and C005 datasets over ocean that could be attributed to the calibration changes. Thus, evaluation of actual C005 is necessary.

3 Global evaluation of C005 products

The algorithm's *retrieved* parameters are solutions to the lookup table matching. These are AOD and ETA (at 0.55 µm), and are reported as SDSs in the M*D04 file as "Corrected_Optical_Depth_Land" and "Optical_Depth_Ratio_Small_Land", respectively. The fAOD is simply the product of the solution (AOD×ETA) and is reported as "Optical_Depth_Small_Land". Calculation of additional parameters requires the information embedded in the LUT. For example, based on assignment of aerosol model type, which is in turn associated with assumed aerosol optical properties (e.g., spectral extinction), we compute such parameters as spectral AOD (0.47 and 0.65 µm; "Corrected_Optical_Depth_Land" SDS) and the AE ("Angstrom_Exponent_Land"). Although these are derived parameters, they are essentially *algorithm diagnostics* (Kahn et al., 2009).

The Quality Assurance (QA) information, including the summary QAC, is true diagnostic information, reported using the "Quality_Assurance_Land" SDS. Tables of the QA tests are found in Levy et al. (2009b) and Hubanks (2007). Another source of QA interpretation is found in Kahn et al. (2009); and we note that QAC (this study) and their QC flag are the same. The QA Usefulness (QAU) flag (1st bit) is necessary for level

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3 processing (e.g., Hubanks et al., 2007). Depending on which tests pass or fail, the algorithm may report fill (i.e., missing) values for all, some, or none of the parameters. For example, if the scene reflectance is brighter than 0.25 at 2.1 µm, only the spectral AOD is reported. All the other parameters are set to fill values and QAC is set to zero. Independent of the QAC, if the retrieved AOD is less than 0.2, the derived fAOD value is reported, but not ETA. If retrieved AOD is reported but negative (i.e., $0>AOD>-0.05$), then size apportionment is meaningless, so fAOD, ETA, and AE are all reported as fill values. Thus, there are high confidence (QAC=3) pixels that report AOD, but not size parameters. The QAC is the *algorithm* confidence in the product, yet we expect that data having QAC=3 will be more accurate, and therefore more useful for quantitative applications (e.g. Kahn et al., 2009).

3.1 Collocation with AERONET

Here, we collocate the entire set of C005 Terra/Aqua-MODIS aerosol retrievals with the AERONET Version 2.0, Level 2 Quality Assured (cloud screened and calibrated) direct-sun measurements of spectral AOD (Holben et al., 1998; Smirnov et al., 2000). Although the AERONET AOD uncertainties are on the order of 0.01–0.02 (Eck et al., 1999), we consider them as "ground truth" for satellite product validation. Using quadratic fits on a log-log scale (Eck et al., 1999), we interpolate the AERONET data to MODIS band-effective wavelengths (i.e., 0.47, 0.55 and 0.65 µm bands), and calculate the 0.47/0.65 µm Ångstrom exponent to match that reported in the MODIS product. Finally, we use the spectral de-convolution technique of O'Neill et al. (2003) to derive AERONET fine mode fraction and fine-mode AOD. Again, note that the AERONET fine-mode fractions and fine-mode AOD are not the same as the MODIS estimates of ETA and fine-dominated AOD, but we can check for respective correlation.

We employ the spatio-temporal technique of Ichoku et al. (2002), which creates a grid of 5 by 5 MODIS aerosol retrievals, with the AERONET station within the middle pixel. Since each MODIS aerosol pixel represents approximately a 10 km area, the subsetted area is approximately 50 km by 50 km. Spatial statistics for the MODIS subset are cal-

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culated and compared to the temporal statistics of the AERONET observations taken within ±30 min of MODIS overpass. At least 5 of the possible 25 MODIS retrievals, and 2 of the possible 4 or 5 AERONET observations, are required to include a collocation in our statistics. This means that the collocation might not include the exact 10 km MODIS aerosol retrieval region in which the AERONET station resides, and could include retrievals from pixels that are 20–25 km away. For a collocation to be included, both MODIS and AERONET require sampling that is sufficiently free of clouds, based on their respective cloud-masking algorithms. This precludes evaluation of MODIS products in conditions of overcast or some partial cloud situations.

As of September 2008, our database included collocations with 328 AERONET sites, of which 32 were island sites that could not be used for over-land comparison. Of the remainder, 203 sites were inland, and the rest located at or near shoreline. Some sites offer long time series of measurements, whereas others have measurements only during particular seasons or field experiments. We exclude sites where the elevation of the AERONET instrument and the average of the 50 km×50 km surrounding region differ by >300 m; in these locations AERONET does not represent the surrounding scene. The result is 85 463 matches for the combined Terra/Aqua dataset. For discussion in this paper, we will label sites by the names given by the AERONET team (http://aeronet.gsfc.nasa.gov).

3.2 Global AOD

Figure 1 is a frequency scatterplot of the over-land comparison of total AOD at 0.55 µm, for the combined Terra and Aqua datasets. The data are not filtered by QAC. The color of each ordered pair (0.025×0.025 increment) represents the number of such matchups. The dashed, dotted and solid lines are the 1-1 line, defined EE for land AOD (Eq. 2), and the linear regression of the pre-sorted scatterplot, respectively. Table 1 gives some of the regression statistics. Sixty-nine percent of the MODIS retrievals of the comprehensive data set of 85 463 collocations lie within the EE defined by Eq. (2). In addition, as compared to C004 (Remer et al., 2005), the C005 AOD (at 0.55 µm)

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shows much closer match to the 1-1 line (y=0.95x+0.005 versus y=0.78x+0.068), and a higher correlation (R=0.88 versus R=0.80). Validation is also achieved for the 0.65 and 0.47 channels (also in Table 1).

3.3 Global aerosol particle size

Each of the four aerosol types used in the retrieval are bi-lognormal, having both fine and coarse modes (e.g. Levy et al., 2007a). Three of the models are fine-mode dominated and the fourth (the dust model) is coarse-mode dominated. This means that the algorithm's solution is a fine/coarse mixture having four lognormal modes (two fine and two coarse). The weighting of the fine-dominated model (to the total) is the ETA parameter, which is also the non-dust weighting. Unlike the η parameter, which is derived by the aerosol retrieval over ocean (Tanré et al., 1997) or the deconvolution of AERONET-observed AOD (e.g. O'Neill et al., 2003), the MODIS-derived, over-land ETA parameter is NOT "fine-mode weighting" and does not represent aerosol size distribution. ETA is simply a way to fit the MODIS-observed spectral dependence and our preliminary validation exercises (Levy et al., 2007a) did not indicate correlation between the MODIS ETA parameter and AERONET retrieved η. Our current study does not indicate significant correlation, either.

Having slightly better correlation compared to AERONET, the preliminary validation (Levy et al., 2007a) suggested that perhaps the Ångstrom exponent (AE) calculated from AOD at 0.47 and 0.65 µm or the fine AOD (AOD×ETA) demonstrates some skill. Figure 2 shows the scatterplots of MODIS-derived AE (top) and fine AOD (bottom) against their respective AERONET quantities. Containing one standard deviation of the collocated points, the expected errors (EE) for AE and fAOD are plotted as ±0.4 and $\pm(0.05+0.20\tau_f)$, respectively.

Taken together, these size plots indicate that in order to match the TOA spectral observations, the MODIS retrieval is often choosing the dust model even when the actual aerosol particles may be small. This occurs because of the bimodal nature of each model and the limited sensitivity to particle size in the over-land algorithm. The retrieved AE is forced along the lower edge of the dynamic range, sometimes even in situations that are known to be smoke or pollution. This clearly indicates that the retrieved AE should not be confused with reality.

In general, except for cases where MODIS wrongly favors the dust model (appearing as the red arm along the *x*-axis), there is better correlation of MODIS-derived fAOD (AOD×ETA) with that derived by AERONET. Thus, it appears that fAOD offers greater sensitivity to particle size. However, this apparent correlation is driven by the strong dependence on total AOD (Fig. 1), which is generally well retrieved by MODIS. However, because ETA is such a weak parameter, fAOD does not provide any new information on particle size. There is no physical information contained in the C005 aerosol size parameters, whether retrieved as a solution to the inversion (e.g. ETA) or derived downstream (fAOD or AE).

In future collections of MODIS data, we suggest that derived (or assumed) parameters such as fAOD and AE should be removed. ETA must be retained because it provides vital information for evaluating the performance of the algorithm. Due to their lack of quantitative usefulness, there will be no additional discussion of the aerosol size parameters in this paper.

3.4 QAC filtering

As mentioned previously, each set of retrieved products is accompanied by an estimate of the QAC. Table 2 presents the information contained in the 0.55 µm row of Table 1, but separated by QAC value. We see that the quality of the MODIS/AERONET comparison is strongly dependent on QAC. For the retrievals with QAC=0, there is significant deviation from the 1-1 line. Although the global averages of both datasets are similar, MODIS retrieves only 50.34% of the cases to within EE for QAC=0. However, as we increase our QAC value, the regression become more symmetric to the 1-1 line and the percentage within EE increases to 66.10%, 67.75%, and 72.60% for QAC=1, 2 and 3, respectively. In general, retrievals with QAC=3 provide the best matches to AERONET, so all further analyses in this paper will be performed for those 58 526

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points. Note that a user may choose to use data with lower QAC, but is strongly advised not to use retrievals with QAC=0 for any quantitative purpose. The choice depends on the application's tolerance for uncertainty versus the need for spatial coverage.

3.5 AOD filtering

For C004 validation, Remer et al. (2005) found that >66% or 1-standard deviation of the 5906 over-land collocation points were contained within the EE envelope. However, the standard deviations were not smaller than EE for all values of AOD, indicating that the stated EE (Eq. 2) was not entirely correct.

Here, Fig. 3 presents the 58 586 QAC=3 cases of C005, binned by AERONET AOD. On the *x*-axis, there are 50 equal sized bins (~1200 observations per bin). However, instead of the MODIS AOD, the *y*-axis is the absolute difference between MODIS and AERONET AOD (MODIS-AERONET). The statistics are presented as box-whisker plots, where the horizontal centers and half-widths of the red boxes represent the means and the standard deviations of the AERONET AOD in each bin. In the vertical, the centers and the tops/bottoms represent the medians and the middle 66% (1σ) intervals of the MODIS-AERONET differences for each bin. The black squares are the mean of the MODIS-AERONET differences (usually close to the median). The red dashed-dot lines are linear best fits to the bottoms and tops of the boxes, which can be compared with the green dashed lines encompassing the EE envelope. Finally, the blue whiskers represent the 96% (2σ) intervals of the MODIS-AERONET differences.

From Fig. 3, we see across the entire AOD range that: a) the mean bias of the MODIS retrieval is near zero, and b) the 66% interval and the green EE envelope are nearly identical. This means that the EE is a reasonable assessment of C005's AOD error across the entire range of AOD, indicating a more robust validation of the product. We note that the 2-σ bars represent AOD error approximately double of the 1σ (and EE) envelopes.

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4 Local C005 validation

Although we have robustly validated the *global* C005 AOD within EE, we know from the literature (e.g. Jethva et al., 2008; Kahn et al., 2009) that there are *regions* where MODIS has systematic problems retrieving AOD. MODIS may systematically overestimate or underestimate AOD for one reason or another, and the errors might be offsetting (Kahn et al., 2007). In this section, we examine the performance of the MODIS algorithm for retrieving AOD at individual AERONET sites. By separating into cases with light aerosol loadings (τ<0.15) and heavy aerosol loadings (τ>0.4), we can suggest whether systematic errors result from poor surface assumptions or poor aerosol model assumptions.

4.1 Site by site: overall

Our dataset includes collocations from different sites and different seasons. These sites represent a variety of surface types (forests, savanna, urban, soils, etc), and a variety of expected aerosol types. Although we have demonstrated that on average, the retrieval algorithm has made the correct assumptions as to surface and aerosol characteristics, we know that there are sites where MODIS shows systematic errors.

Let us consider the *fraction* of the MODIS-retrieved AOD values that fall within EE at each site during a given season, as well as the sign of the mean bias. Where we see at least 2/3 (66% or 1-σ), we consider this to have "good" matching. If fewer than half lie within EE, this is a "poor" match, and we determine whether MODIS tends to retrieve too low or too high. Figure 4 provides visual assessment of both matching quality and MODIS bias, during the summer months (June, July, and August). Symbols are plotted at AERONET sites having at least ten collocations for the season, and are color-coded based on the fraction of MODIS data that matches within EE. Green symbols are plotted where ≥66% match ("good") within EE (e.g. GSFC). Red represents sites (e.g., Dalanzadgad) where <50% match within EE coupled with a MODIS high bias. There are no cases for this season, but if plotted, purple would refer to sites with <50%

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match and a MODIS low bias. Alta Floresta is marked by yellow because the fraction is between 50% and 66%, with a high bias. Jabiru is marked blue to refer to similar fraction, but a low MODIS bias. Scatterplots for four example sites (GSFC (38° N, 76° W), Alta Floresta (9° S, 56° W), Dalanzadgad (43° N, 104° E), and Jabiru (12° S, 132° E)) are displayed at the bottom, indicating why the site received a certain color symbol.

For the summer months, much of the US East Coast shows very good agreement at 0.55 µm. An exception is New York City (the CCNY and GISS sites, both near (40° N, 73° W)), where the urban surface is poorly represented by MODIS's surface reflectance parameterization (Oo et al., 2010). Most sites in Western Europe also compare well, except for Venise (45° N, 12° E), which is actually an oceanographic platform, 15 km into the Adriatic Sea. Essentially, since the MODIS C005 algorithm was developed based on MODIS/AERONET collocations and AERONET sky retrievals available through 2005 (Levy et al., 2007a, b), the US East Coast and Western Europe dominated the database. Except for the urban and offshore sites, the surface is generally at least partially vegetated, and the aerosol is characterized by fine particles and a high single scattering albedo. Thus, it is not surprising that the products generally compare well in these regions.

Good comparisons are seen over southern Africa (e.g., Mongu (15° S, 23° E)) and parts of the Amazon for this season, which are both dark surface regions and were well sampled by AERONET prior to C005. Even though Japan and Korea were not well sampled prior to C005 development, and the aerosol tends to be more absorbing than that over the Eastern US and Western Europe, good agreement is seen there because the surfaces are not too different. Good agreement is also seen at the Chinese sites of Taihu (31° N, 120° E) and Xianghe (39° N, 116° E) (Mi et al., 2007). Interestingly, while the region surrounding Kanpur, India (26° N, 80° E) is relatively bright, the sunphotometer site is located in a small pocket of vegetation. For the summer season, the agreement is good (e.g. Jethva et al., 2007).

In addition to the urban surfaces mentioned above, MODIS compares poorly over

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brighter and elevated targets. For example, Palencia, Spain, is on a plateau, has a relatively brighter surface where the aerosol signal is comparatively weak for a dark-target retrieval. Poor comparisons are also noted at sites over the western US, (e.g. BSRN-Boulder (40° N, 105° W) and Sevilleta (34° N, 106° W)), the Patagonian region of Argentina (e.g., Trelew (43° S, 65° W)), and the steppe and near desert plateaus of Russia and China (e.g., Irkutsk (51° N, 103° E) and Dalanzadgad). While these scenes do not exceed the brightness criteria test for dark target scenes (2.1 µm reflectance greater than 0.25), they may be too bright for optimal use of the dark target algorithm. In addition, these regions may be dominated by aerosol types that would not have been characterized by the clustering of AERONET data available in 2005 and assumed for the dark-target algorithm. These regions may be better suited for retrieval with the Deep Blue algorithm (Hsu et al., 2004), but testing this hypothesis is beyond the scope of this paper.

Although most of the darker-target sites compare to within global EE as expected, we find sites that compare less well. For examples, Alta Floresta and Cuiaba (15° S, 56° W) are both in Brazil, one near the border of the Amazon forest, the other located further south in the cerrado (savanna-like vegetation). These two sites have been collecting data for a long time, and were used when developing C005. Yet, for both sites, AOD tends to be overestimated in heavy aerosol conditions, and underestimated (consistently negative) in light loading conditions. These differing biases result from poor assumptions in both the aerosol model and the surface reflectance. During the development of the C005 aerosol models, Levy et al. (2007b) found that the aerosol type in the region sometimes had lower single scattering albedo (SSA~0.86 at 0.55 µm), and sometimes higher (SSA~0.91), and had a tendency to have lower SSA towards the southeast. A box was drawn on a map to signify where the stronger absorbing type should be preferred, but the borders were arbitrary due to lack of information. The box designating absorbing aerosol type was drawn too far west, which led to a systematic overestimate in heavy aerosol conditions, especially at Cuiaba. Analysis of version 2 sun retrievals (http://aeronet.gsfc.nasa.gov) suggested that, in fact, SSA over Cuiaba

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is normally closer to 0.9 than to 0.86 during the dry season. At Alta Floresta (farther west), where the C005 moderately absorbing aerosol type (SSA~0.91) is assigned, the true SSA is closer to 0.92–0.93 (Schafer et al., 2008). Therefore, both sites would experience similar systematic bias. A correction to the aerosol model assignments in Brazil is required, in some ways opposite to the correction that was implemented over Southern Africa (Ichoku et al., 2003) for C004.

As for the consistent retrieval of negative AOD in light loading conditions, these two Brazilian sites may suffer from similar problems as noted at Jabiru (northern Australia). This systematic bias for low AOD results from overestimating the surface reflectance in the visible channels. Since the C005 algorithm was optimized for the set of global collocations that favored sites in the Eastern US and Western Europe, the surface reflectance parameterization was biased toward these sites and their NDVI characteristics. The vegetation in the Amazon rainforest has smaller visible/SWIR ratios than the presumed global average. In addition, parts of the Amazon (as well as Australia) are known to have red soils, which may not display the same surface reflectance relationships as modeled with the C005 parameterization.

4.2 Separating surface assumption and aerosol assumption errors

At Cuiaba and Alta Floresta, the MODIS-derived AOD are overall within EE, but that general assessment hides offsetting biases related to surface and aerosol assumptions. To evaluate these issues we separate the MODIS/AERONET comparisons into three groups, based on the AOD (at 0.55 µm) observed by AERONET. Collocations where $\tau<0.15$ are "light" aerosol loading conditions, for which MODIS errors would be strongly related to errors in surface reflectance assumptions. Cases where $\tau>0.4$ are "heavy" aerosol loadings, which we use to evaluate the reliability of the aerosol model assumptions. The cases of $0.15\leq\tau\leq0.4$ likely are influenced by both surface and aerosol errors, so further analysis will not assist in evaluating either issue.

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Here we can compute an *error ratio* (ER),

$$ER = (\tau_{MODIS} - \tau)/EE, \quad (3)$$

which compares the actual error to the expected error (e.g. Mi et al., 2007). Where $-1 \leq ER \leq 1$, the actual error is smaller than EE, indicating a "good" match. Where $|ER| > 1$, it is a "poor" match. MODIS underestimation and overestimation are represented by $ER < 0$ and $ER > 0$, respectively.

For each group (light and heavy loadings) separately, we calculate the *mean* ER of the MODIS/AERONET matches (minimum of ten) at each site and season, and use these values to characterize the relative quality of the MODIS product. Figure 5 is a color-coded map of the mean ER at each site during summer months, for the light ($\tau < 0.15$; top panel) and heavy ($\tau > 0.4$; bottom panel) aerosol cases. The greenish colors (cyan and lime) are sites where $|ER| \leq 1$, meaning that the systematic bias is less than the EE for the particular AOD group. Cooler colors indicate $ER < 0$ (MODIS underestimation) whereas warmer colors represent $ER > 0$ (overestimation), and those colors farther from green (e.g., purple, red) represent increasingly severe average bias. Unlike single collocation estimates of ER, sites where average $|ER| > 0$ indicate systematic bias to the MODIS retrieval.

Separation by aerosol regime helps to provide confirmation of our hypotheses in the previous section. For example, in the Amazon, MODIS clearly underestimates AOD in light loading conditions, and overestimates in more polluted conditions, indicating both that the surface is darker (in the visible) than the VIS/SWIR relationship suggests, and that the particles are brighter than that assumed for the region. In urban or oceanic platform areas (e.g. CCNY or Venise) and brighter elevated surfaces (e.g. US Southwest) the MODIS overestimations are generally confined to the low AOD conditions, indicating that the surface assumptions are the dominant source of errors. For the polluted conditions during the summer months, MODIS underestimates AOD in the biomass burning regions of the African Sahel (Dakar (14° N, 16° W) and Ouagadougou (12° N, 1° W)), which we believe is a result of not enough absorption for the assigned aerosol model, and not due to surface assumptions.

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We find it interesting that the AOD at Bonanza Creek (64° N, 148° W) is severely overestimated in polluted conditions, which suggests that our assumed aerosol model (SSA∼0.91) is too absorbing to represent the dense smoke (SSA∼0.97) observed at the site (Eck et al., 2009), possibly due in part to significant burning of peat fuels in the region.

In general, except for sites such as Kanpur or Mongu, that experience widely variable seasonal vegetation states, the characteristics of the MODIS retrieval quality do not vary much from season to season, so the summer month map provides the general global picture. Note that only a few sites meet the minimum ten collocations in heavy loading conditions.

5 Systematic errors

From Sect. 4 and the literature, we know that significant retrieval biases are tied to particular locations. Many authors have found ways to improve MODIS retrievals at particular sites (e.g. Mi et al., 2007; Oo et al., 2009; Jethva et al., 2008), but we have not implemented them into the global algorithm. Others have used data assimilation to systematically "correct" the MODIS data in poorly performing areas, but may not always get to the root cause of the problem in the first place. Here we determine whether there are residual errors due to such conditions, including cloud fraction, assumed surface type characteristics, or geometry. Of course, there can be multiple reasons for poorer than average retrieval in a particular scene. For example, coarse-dominated dust aerosol type will be more common over more arid, brighter surfaces. Both characteristics would hinder the accuracy of the retrieved AOD.

5.1 Ångstrom exponent

Figure 3 indicated that we have correctly defined the EE (Eq. 2) of the MODIS AOD for the global aggregate, however Figs. 4 and 5 show that the accuracy varies by lo-

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cation. What are the conditions that are related to the quality of the comparison? Figure 6 plots the differences between MODIS and AERONET as a function of the Ångstrom exponent, AE, defined by AERONET AOD interpolated to the MODIS wavelengths of 0.47 µm and 0.65 µm, as described in Sect. 3.3. Data are sorted by AE and grouped into 50 equally populated bins. Each box represents the statistics of the MODIS-AERONET differences in the bin. The means and standard deviations of the AE (for each bin) are the centers and half widths in the horizontal. The mean, medians, and 66% ($1-\sigma$) interval of the MODIS-AERONET differences are the squares, the center, and top-bottom intervals in the vertical. The dashed curves represent the over-land EE envelope for total AOD ($\pm(0.05+0.15\tau)$; Eq. 2), where EE is calculated based on the mean AERONET AOD within the bin (diamonds; right axis). From this plot, one can assess the average absolute error (and sign), the relative error, as well as the average error in comparison to EE that varies with AE. One also can see whether 66% of the collocations fall within EE for a given bin. Note that the EE envelope is larger for coarse-dominated cases, indicating that our sample of coarse-dominated aerosol cases (presumably dust) has larger AOD than our sample of fine-dominated cases.

Figure 6 shows that for the MODIS/AERONET collocations with QAC=3, MODIS-retrieved AOD is generally accurate where AE is within the algorithm's assumed AE parameter space ($0.8<\alpha<1.6$). Within this AE interval, there is very little variability of AERONET AOD, such that each bin's average AOD is approximately 0.2, with EE of ±0.08. The absolute and relative errors, as well as the ER are all close to zero. For the bins with AE>1.6 (fine-dominated), AERONET observed-AOD is lower, so that the corresponding EE has a smaller envelope. Yet MODIS tends to overestimate by ~0.02 (relative error of 20–30%), which in EE-space is ER~0.3–0.4. For coarse-dominated aerosol ($\alpha<0.6$) scenes, where the AERONET AOD is generally larger, MODIS tends to underestimate AOD by 0.03–0.04. While this is a somewhat smaller relative error of 15–20%, in EE-space, the average ER is similar in magnitude.

Let us further study the dependence of AOD error and AE, by separating the 58 526 cases into three groups based on AERONET observed AOD. Figure 7 plots the 33 794

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cases of light aerosol loading (τ<0.15) in the top panel, and the 6621 cases of heavy loading (τ>0.4) in the bottom panel. The remaining cases, having moderate aerosol loadings, are not plotted. For low aerosol loading, the MODIS retrieval of AOD has negligible bias on average, and >66% are within EE, regardless of the scene's AE. There is a small, but systematic MODIS overestimation (~0.01) for the highest AE cases (α>2.0). On the other hand, MODIS retrieval of high AOD (τ>0.4) can have significant errors, especially for the lowest AE cases (α<0.8). For these coarse-dominated conditions, MODIS underestimates AOD by 0.2 or 20%, leading to poor retrievals compared to EE (ER~1.0). MODIS underestimation is largest in heavy, dusty conditions. In heavy fine-dominated situations the tendency is towards an overestimation of ~0.05 or 6%.

5.2 Cloud fraction

Although the MODIS cloud-clearing algorithm aims to remove clouds from the scene, many studies have reported a positive correlation between AOD retrieval error and cloud fraction, suggesting residual cloud contamination in the MODIS aerosol retrieval (Kaufman et al., 2005; Marshak et al., 2006; Zhang et al., 2005). The MODIS-aerosol-product cloud fraction is calculated from the 500 m resolution pixels (Levy et al., 2009) that were removed during the cloud masking of the aerosol algorithm (Martins et al., 2002). Figure 8 plots the MODIS-AERONET differences as a function of MODIS-aerosol-product cloud fraction over land. The great majority of cases have low cloud fraction (<5%) and there is no significant bias, such that validation (within global EE) is achieved for scenes with cloud fraction less than 5%. Yet, Fig. 8 also shows that MODIS overestimates AOD when cloud fraction is higher, and the error increases with increasing cloud fraction. As cloud fraction goes above 20%, the mean MODIS error approaches 0.03–0.04 or 15–20% in relative AOD units. Average ER~0.3–0.4. For the larger cloud fractions (>13%), fewer than 66% are within EE.

The collocation data set that produced Fig. 8 is inherently biased towards low cloud fraction because of the requirement that both AERONET and MODIS report aerosol retrievals at the same time. Globally, the MODIS retrieval will encounter higher cloud fractions than seen in this data set. Thus, the biases seen in Fig. 8 for cloud fraction above 20% will have a greater effect on aerosol statistics calculated from the MODIS retrieval than is apparent from the figure, though "ground-truth" data to assess this situation statistically is lacking.

There are many reasons for AOD dependence on cloud fraction, as well as many possible factors that could increase retrieval error with cloud fraction, such as cloud contamination in the retrieved product. The differences between MODIS and AERONET, however, might not be due entirely to MODIS cloud screening blunders. In fact, they can arise from different strategies for sampling. The AERONET sun mode's cloud screening algorithm tests temporal variability (e.g., Smirnov et al., 2002), whereas MODIS's cloud screening algorithm operates on spatial variability. It is easy to visualize a scenario where the sunphotometer's view of the sun is unobstructed, yet there are clouds along the horizon. The AERONET view will be biased towards the clear sky, whereas the MODIS view will include some pixels that are sampled within cloud fields. We know that non-cloudy holes within cloud fields are physically different from the non-cloudy atmosphere far from clouds (Charlson et al., 2007; Koren et al., 2007, 2009). Higher humidity in cloud fields contribute to aerosol swelling close to the clouds (e.g. Twohy et al., 2009), and stray light from 3-D effects (e.g. Wen et al., 2007), remnants of decaying clouds and other cloud-related issues (e.g. Koren et al., 2009) all contribute to increasing the AOD retrieved in the cloud field. Note that some factors that enhance satellite-retrieved AOD in cloud fields should be included in the result (swelling) whereas others represent AOD-retrieval artifacts (3-D effects), but all are physical phenomena that cannot be avoided by cloud masking, unless aerosol retrievals are excluded over the entire cloud field. The paradigm that MODIS does not avoid cloud fields as strictly as AERONET, contributes to the MODIS-AERONET differences in Fig. 8.

We split the cloud fraction cases into three groups based on the AERONET AOD, including those with light (τ<0.15) and heavy (τ>0.4) aerosol loadings. We do not plot the results here, but for the light loading cases, the residual cloud fraction bias con-

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tinues even to lower cloud fraction cases (>2%). For the heavy loading cases on the other hand, the differences between MODIS and AERONET are nearly *independent* of cloud fraction. This suggests that enhanced AOD associated with cloud fields saturates for higher aerosol loading situations, or that heavy aerosol is not significantly increased in cloud fields. We must remember that although the MODIS validation is constrained by AERONET data and its cloud screening, MODIS may be retrieving in different conditions than AERONET is observing.

5.3 Scene and surface reflectance properties

The MODIS second-generation algorithm makes two major assumptions about the surface optical characteristics. The full inversion expects the scene to be "dark" (observed reflectance at 2.1 µm must be less than 0.25), and that there are constraints on surface spectral reflectance properties. Specifically, it is assumed that there is a relationship between the visible (VIS: 0.47, 0.65 µm) and shortwave-infrared (SWIR: 2.1 µm) surface reflectance, that also depends on scattering angle and surface "greenness" (Levy et al., 2007b). The surface greenness, parameterized by the NDVI_swir (Karneili et al., 2002), is similar to the standard Normalized Difference Vegetation Index (Tucker et al., 1979), but based on two SWIR channels (1.6 and 2.1 µm). Except for extremely dusty cases, the use of the SWIR channels was expected to help minimize aerosol contamination. When developing the C005 algorithm, Levy et al. (2007b) relied on a MODIS granule test-bed, which resulted in a decision to optimize the retrieval to cases with scene reflectance between 0.01 and 0.25, and the NDVI_swir dependency to between 0.25 and 0.6. While not explicitly noted previously, this test-bed was dominated by data from the US East Coast and Western Europe, where the observed 2.1 µm reflectance is ~0.10, and the NDVI_swir is ~0.4. Although there were scenes that demonstrated a larger range of surface conditions in the testbed, their influence on the global surface parameterization was small.

Figure 5 (top) showed that there are many locations over the globe where MODIS and AERONET do not agree, even in light loading conditions. We can examine the

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impact of scene and surface assumptions by concentrating on these cases. Figure 9 plots MODIS-AERONET differences in light loading conditions (τ<0.15), as a function of MODIS-observed scene brightness (reflectance in 2.1 µm; top) and scene greenness (NDVI_swir; bottom). Differences between MODIS and AERONET are smallest in the mid-range, when the scene reflectance is 0.12, and/or the NDVI_swir is 0.4. MODIS is biased high (by 0.02 or 20%) when the scene reflectance is >0.17 and biased low by similar amount when the scene reflectance is <0.07. The scene's NDVI_swir demonstrates a larger influence on the MODIS bias, such that errors are >0.03 (30%) when NDVI_swir <0.2 and <−0.03 (30%) when NDVI_swir >0.6.

However, even though there are systematic biases, there are only a few conditions for which <66% of the MODIS/AERONET collocations match within EE. These occur when scene reflectance is >0.20 and/or NDVI_swir <0.2, which represents less than 10% of the global dataset. In other words, MODIS tends to overestimate over surfaces that are brighter and less green than optimal, and to underestimate when they are darker and greener. However, for the most part, over the middle of the range optimal for MODIS retrieval, there is very little systematic bias. In order to make MODIS retrieval more accurate over the entire range of surfaces, the assumptions of surface reflectance relationships, surface darkness and surface greenness will need to be reevaluated for future MODIS retrievals. From Fig. 9, it appears that a simple linear factor could correct most of the observed bias.

5.4 Observation geometry

An ideal aerosol algorithm would retrieve AOD of equal quality, independent of solar and observing geometry. However, factors other than algorithm performance can also cause covariance between MODIS AOD retrieval error and observing geometry. For example, many heavy aerosol events (dust, smoke, pollution) occur in mid-latitude and tropical regions during summer. These events tend to coincide with specific scattering geometry. The solar zenith angle (θ_0) is small in these circumstances, and scattering angle, Θ, is related to solar zenith angle as well as target view zenith θ and relative

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solar/sensor azimuth ϕ angles:

$$\Theta = \cos^{-1}(-\cos\theta_0\cos\theta + \sin\theta_0\sin\theta\cos\phi), \tag{4}$$

These factors create natural correlations between observed AOD and scattering angle. Because absolute AOD error increases with AOD (e.g., Fig. 3), correlations between absolute AOD error and scattering angle also occur. However, the relative or fractional error is much less dependent on AOD, so this metric should be relatively independent of geometry.

Figure 10 presents the statistics of the MODIS-AERONET differences as a function of sensor view zenith angle. Angles are negative or positive, depending on whether they are to the "left" or "right" of nadir along the path of the orbit. For example, the left side of the orbit corresponds to the eastern side for Terra (descending across equator), and the western side for Aqua (ascending). The sun is on the western side for Terra and eastern side for Aqua, so there is symmetry to glint and hotspot patterns.

We see from Fig. 10 that although in general, >66% of MODIS-AERONET collocations are within EE, MODIS tends to overestimate AOD by ~0.01 (5% relative error) on the sun-glint (left) side and to underestimate by similar magnitude on the sun-shadow (right) side of the swath. If split into light (τ<0.15) and heavy (τ>0.4) aerosol loadings, we would see that a) the view angle dependence is limited to low AOD conditions, and that b) the errors are independent of angle in heavy aerosol conditions. Yet, 66% of the collocations fall within the EE envelope, indicating that the EE an accurate assessment, regardless of view zenith angle.

Scattering angle dependence is more difficult to decipher, and is presented for the global aggregate in Fig. 11. Again, the average absolute errors of MODIS are small (<0.01) across the entire range of scattering angle, and for the most part, >66% of collocations in every bin match within EE. However, *observed* AERONET AOD increases with scattering angle in three discrete groups: low AOD (<0.15) for smallest angles, medium AOD (~0.2) for angles between 100°–140° and largest AOD (>0.25) for largest angles (>160°). Because what we are reporting is based on MODIS/AERONET collocations, the true AOD is correlated with *where* MODIS is sampling with *which* angles.

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High values for AOD are more common in the tropics than near the poles, and conditions of near-nadir solar zenith angles and larger scattering angles are also more common in the tropics than near the poles. This means that larger AOD is associated with larger scattering angle, which is seen in Fig. 11. MODIS tends to overestimates AOD near 120°, and slightly underestimate between 140° and 160°.

The magnitudes of the high and low MODIS biases in these plots are generally negligible, but to avoid misinterpretation due to possible cancellation of errors, we again separate our collocations into light (τ<0.15) and heavy (τ>0.4) aerosol loading cases (Fig. 12). For the light loading cases, the angular dependence of the AERONET AOD is reduced, but the pattern of MODIS-AERONET differences is retained from Fig. 11. For the heavy aerosol cases, although in general the relative bias of MODIS is low, there is large negative bias (0.08 or 10%) in the 140°–160° angle range. The AERONET AOD is higher (~0.8) in this range than for smaller angles (~0.7).

We slice our dataset once more, this time separating the heavy aerosol loading cases (τ>0.4) by AERONET-observed AE. Figure 13 displays MODIS-AERONET errors for cases of low AE (α<0.8; top) and high AE (α>1.2; bottom). The statistics are too sparse to make conclusions about the angular dependence, however, it is clear that there are compensating errors from different aerosol regimes. The presumably dust cases (α<0.8) are generally underestimated by 0.1 (15–20%), with largest bias of 0.2 (~25%) in the 140°–160° range. For the high AE cases, presumably dominated by fine-mode aerosol, MODIS consistently overestimates AOD, especially in the range 120°–130° where the bias is ~0.1 (15%). This points to possible issues with the assumed particle scattering phase functions for both coarse and fine modes.

Finally, returning to the light loading dataset (τ<0.15), we assess only the cases where 0.3≤NDVI_swir≤0.4, where we expect minimal bias due to the surface (e.g., Fig. 9). We plot the scattering angle dependence of these 7510 collocations as Fig. 14, and see that the angular pattern of Figs. 11 and 12 (top) remains. Because the AOD is so small, the angular dependence suggests residual BRF (bidirectional reflectance function) dependence in the surface properties that are not captured in the retrieval

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assumptions (e.g. Gatebe et al., 2001). In fact, when we constrain to only cases where AERONET-measured AOD<0.1, the pattern still remains.

6 Terra versus Aqua

Until now, the validation effort in this paper has been based on the union of the Terra and Aqua collocations. For C004, Remer et al. (2005) compared Terra and Aqua AOD data separately to AERONET, and found no significant differences between their uncertainties. During the development of C005, Levy et al. (2007a) performed preliminary evaluation for the C005 algorithms (using C004 radiance as inputs) and reached the same conclusion. Here, we separate C005 MODIS AOD products into Terra and Aqua cases (QAC=3), and compare with AERONET separately, in more detail. The results are shown in Table 4, and there is no significant indication that one instrument compares better to AERONET than the other. It is interesting that there is some suggestion that collocated AOD is higher in the afternoon (Aqua; $\tau \sim 0.201$) than in the morning (Terra; $\tau \sim 0.195$), but it may be only a sampling issue; Terra's time series is 2.4 yr longer than Aqua's, and both include some incomplete years.

6.1 Validation time series

In recent years, there has been some effort to use satellite data to examine aerosol trends (e.g. Mishchenko et al., 2007; Karneili et al., 2009). In these studies, the magnitude of trends is on the order of 0.01–0.02 per decade, and it has been suggested to search for similar trends in the MODIS data record. However, before concluding that trends in the MODIS data record are significant, we must rule out the possibility that they are caused by artifacts, such as instrument calibration drift.

Even with known sensor degradation, the MODIS channels used in the aerosol retrieval are maintained by the MCST to within 2% of typical reflectance levels (for example, 0.002 of 0.1 reflectance units) (Xiong et al., 2005). Sensitivity tests with the MODIS

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algorithm (e.g. Levy et al., 2007b) suggest that such small calibration errors can still result in AOD errors of ∼0.01–0.02. For C005-derived AOD over ocean, Remer et al. (2008) reported a rather large offset of ∼0.015 (10%) between the global means of Terra and Aqua, and suggested the discrepancy was due to calibration differences between the two sensors. For the same study, they concluded there was no significant difference between Terra and Aqua over land. However, if one zooms in on the plots, there is some indication that Terra's AOD is decreasing, whereas Aqua's is increasing over time.

From the time-aggregated validation exercises we have performed so far, we do not see significant differences between Terra and Aqua "quality". However, our aggregation may be hiding a systematic *change* in quality for one or both sensors that results in canceling errors. If not characterized properly, such systematic change might appear as an artificial global AOD trend.

Let us compare Terra and Aqua separately to AERONET, but as a function of time, and for complete years only. For this purpose, we require AERONET sites that are long-term, and assume that their post-processing (to level 2) removes artificial trends in the AERONET data time series. Table 5 lists selected AERONET sites with a seven-year or longer record.

Figure 15 plots the Error Ratio (ER) for 0.55 µm AOD (Eq. 3) calculated for every MODIS/AERONET collocation in our multi-station, seven-year record. We see no trend for Aqua, yet a downward trend for Terra. The trend in ER for Terra is statistically significant, as measured by a T-test with 6512 points and correlation of R=0.215. Terra-MODIS seems to be biased high by 0.01 (10%) early in the mission, flipping to a low bias of similar magnitude sometime after 2004. This indicates an artificial drift in Terra's AOD time series, although it is within the validated EE.

To explain the drift, we recall that the over-land retrieval inverts reflectance in three channels (0.47, 0.65 and 2.1 µm). The 0.47 µm channel, like the other MODIS blue and deep blue channels at 0.412 and 0.443 µm, is affected by polarization and directional signal issues. This is especially true for Terra, which suffers from more significant opti-

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cal sensor degradation than does Aqua (X. Xiong, personal communication). However, unlike the 0.412 and 0.443 µm channels, which are closely monitored by the ocean color team (http://oceancolor.gsfc.nasa.gov/VALIDATION/operational_gains.html) and tuned for the bio-optical retrieval algorithms, the 0.47 µm channel may have residual calibration error. Sensitivity tests show that a systematic change in the 0.47 µm channel, capable of driving the trend seen in MODIS-Terra's ER record, is entirely possible. Preliminary analysis of the 0.47 µm reflectance suggests that there is such a residual time-dependent trend. We can see how the process of MODIS validation can help reveal hidden biases or uncertainties in the calibration algorithms. Certainly, calibration has been an important consideration in other data validation efforts (e.g. Lyapustin et al., 2007; Kahn et al., 2005; Lallart et al., 2008).

7 Conclusions

As a result of deficiencies observed for previous versions/collections of MODIS aerosol products over dark-land targets (e.g., Remer et al., 2005; Levy et al., 2005), a new version of the MODIS dark-target algorithm was developed (Levy et al., 2007a, b, 2009), and used for deriving Collection 5 (C005). Here, we used sunphotometer (AERONET) data as ground truth, to evaluate eight-plus years (2000–2008) of the MODIS-derived total AOD and aerosol size products, from both Terra and Aqua.

Of 85 463 valid MODIS/AERONET collocations (at 0.55 µm), 68.8% demonstrated AOD matching that fell within expected error (EE) bounds of ±(0.05+15%), a criterion for MODIS-C005 AOD product validation. When separated by QAC, only 50% of the collocations having low confidence (QAC=0; N=10 743) matched within EE, whereas 72% of those with high confidence (QAC=3; N=58 726) matched within EE. Those collocations having QAC=3 also demonstrated regression fits extremely close to 1-1. This means that stratifying by QAC can be significant for some applications, and suggests that whenever possible, *users should rely on the highest confidence data for quantitative studies*. The use of lower confidence data should depend on the trade-off between

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an application's tolerance for uncertainty and the spatial coverage requirements.

Even when constrained to the highest confidence data, comparison of MODIS-derived Ångstrom Exponent and fine AOD showed that *MODIS does not provide quantitative information about aerosol size over land*. Thus, we strongly recommend that users NOT use size products quantitatively. In response to community needs and confusion, we plan to remove AE and fine AOD parameters from future product lists. The ETA (model weighting) parameter will be retained for its diagnostic value.

Although we consider the MODIS-derived AOD to be a globally validated product, the literature clearly points out regional and systematic errors. Many of these errors can be traced to inapplicable assumptions about surface reflectance and/or assigned aerosol optical properties.

By considering only cases with light aerosol loading (τ<0.15, N=33 794), we focused on issues related to the assumed surface reflectance. We characterized the MODIS-AERONET differences as functions of observed NDVI_swir and 2.1 µm scene reflectance.

- MODIS compares best (negligible bias and good correlation) over sites that are both moderately "dark" (2.1 µm reflectance ~0.10–0.15) and moderately "green" (NDVI_swir ~0.30–0.40). Such generally vegetated sites occur over the Eastern United States, Western Europe and Southern Africa.
- MODIS overestimates AOD (by 0.02 or more), where surfaces are brighter (2.1 µm reflectance approaching 0.25) and less green (NDVI_swir<0.2). This includes the western US and Central Asia.
- MODIS underestimates AOD (by 0.02 or more) where the surface is unusually dark (2.1 µm reflectance <0.05) or green (NDVI_swir>0.6). These conditions are seen in parts of the Amazon forest, as well as Northern Australia and areas known for reddish color soils.

By considering only cases of heavy aerosol loading (τ>0.4; N=6621), we focused on issues related to assumed assigned aerosol properties.

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- MODIS-derived AOD compares best to AERONET where the observed aerosol is fine-mode dominated, and the algorithm-assigned model's single scattering albedo is appropriate. These conditions are met over the East Coast of the US, Western Europe, and parts of Asia.
- MODIS overestimates in fine-dominated cases where the observed SSA is greater than that assumed. For example, for the Brazilian Cerrado, the assumed SSA=0.86 whereas more recent AERONET data suggests SSA=0.91.
- MODIS underestimates in cases where observed SSA is less than that assumed for the fine-mode model, and/or that dust is mixed in. This is noted in Southern Africa, and along the Sahel and Indian semi-arid zones.

As a result of these findings, we suggest that maps of aerosol model type assignments be modified for future versions of the aerosol algorithm.

Although they are clearly tied to specific regions, systematic biases were found to be dependent on a variety of assumed and observed conditions. In general, MODIS underestimated AOD for low AE ($\alpha<0.8$), and overestimated for high AE ($\alpha>1.6$). The low AE cases tend to be characterized by larger total AOD, and the underestimation is more significant for heavy aerosol loading. Clearly, the MODIS algorithm does not work well for dust. There was no systematic bias for the range of AE ($0.8<\alpha<1.6$), which suggested that the MODIS algorithm performed appropriately when the ambient conditions were similar to the algorithm's expected AE range.

The MODIS bias is positively correlated with observed cloud fraction. As cloud fraction increased from 10% to 60%, the average MODIS-AERONET differences increased to 0.03 (~15% relative error). The MODIS bias is not significantly correlated with cloud fraction for conditions of heavy aerosol loadings.

The MODIS-AERONET differences are correlated with scattering angle. However, part of this dependence is clearly related to MODIS's *sampling* dependence on scattering angle. Dust and absorbing aerosol types dominate tropical regions, which coincidently are the *only* regions that MODIS can observe with large scattering angle.

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Separation by aerosol conditions, by AOD and/or AE, demonstrates where there are also true artifacts in the retrieval. For example, when constrained to cases of light aerosol loading and optimal NDVI_swir conditions, we still find that MODIS-AERONET differences depend on scattering angle. This suggests that our assumed surface reflectance may be missing some BRF factor, and should be studied further.

We found no significant differences in retrieval biases between Terra and Aqua. However, there is a statistically significant *change* in the *Terra*-MODIS/AERONET comparison. Although insignificant for most purposes, Terra-MODIS tends to overestimate by 0.01 before 2004, and underestimate by similar magnitude thereafter. The likely cause is degradation of Terra's optical response in the 0.47 µm channel (used in the land algorithm only) that results in very small errors to the sensor's calibration over time. This effect is not found with Aqua data. The calibration issues should be updated in a future reprocessing of MODIS data.

In this paper, we performed overall assessment of the MODIS AOD relative to AERONET, and identified and quantified systematic biases that are functions of Angstrom exponent, cloud fraction, surface scene conditions, and time. Other parameters were also examined, including retrieval fitting error and precipitable water vapor, but these exhibited no systematic biases. The observed biases may be positive or negative, and could be large in either absolute or relative senses. Despite these systematic biases, nearly 80% of the retrievals fall into a parameter range where AOD errors were less than 0.01. The biases discussed above and displayed in the figures should be acknowledged and considered when using MODIS land AOD retrievals in cloudy scenes, in heavy dust or heavy smoke, in dense vegetation or over bare soils. Alternatively, these situations could be avoided.

Here, we also assessed the performance of the MODIS aerosol (AOD and size parameters) compared to AERONET observations. We have not attempted to characterize MODIS data that is not collocated with AERONET. However, we now have defined a quantitative EE for the MODIS dark target aerosol products over land, and have exposed biases in the retrieval products. We encourage users to take these biases into

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account as they use the Collection 005 products. The results presented here will provide a solid base from which to adjust the algorithm and prepare for future Collections of the MODIS products.

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Table 1. Statistics of the comparison between MODIS and AERONET total spectral AOD over land. N=85 463.

Wave (µm)	Mean AOD AERONET	Mean AOD MODIS	Regression equation	R	RMS	% in EE
0.65	0.162	0.174	$y=0.969x+0.007$	0.872	0.103	71.21
0.55	0.198	0.203	$y=0.952x+0.005$	0.882	0.116	68.78
0.47	0.243	0.245	$y=0.967x+-0.001$	0.896	0.131	66.44

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Table 2. Statistics of the comparison between MODIS and AERONET total AOD at 0.55 µm over land, as a function of QAC.

QAC value	N	Mean AOD AERO	Mean AOD MODIS	Regression equation	*R*	RMS	% in EE
0	10 743	0.220	0.222	$y=0.698x+0.049$	0.794	0.146	50.34
1	5484	0.177	0.207	$y=0.990x+0.020$	0.860	0.114	66.10
2	10 710	0.183	0.211	$y=1.005x+0.015$	0.872	0.116	67.75
3	58 526	0.199	0.198	$y=0.988x+-0.004$	0.905	0.106	72.60
≥ 1	74 720	0.195	0.201	$y=0.989x+-0.000$	0.896	0.109	71.43
≥ 0	85 463	0.198	0.203	$y=0.952x+0.005$	0.882	0.116	68.78

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Table 3. AERONET sites with long-term records used for time series assessment.

Site Name	(Lat, Long)
Alta Floresta	(9° S, 56° W)
Banizoumbou	(13° N, 2° E)
BONDVILLE	(40° N, 88° W)
Cart Site	(36° N, 97° W)
Dakar	(14° N, 16° W)
Dalanzadgad	(43° N, 104° E)
El Arenosillo	(37° N, 6° W)
GSFC	(38° N, 76° W)
Ispra	(45° N, 8° E)
Mongu	(15° S, 23° E)
Ouagadougou	(12° N, 1° W)
Sevilleta	(34° N, 106° W)
Skukuza	(24° S, 31° E)
Venise	(45° N, 12° E)

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Table 4. Statistics of the comparison between MODIS and AERONET total AOD at 0.55 µm over land, (QAC=3) for Terra and Aqua.

Satellite	N	Mean AOD AERONET	Mean AOD MODIS	Regression equation	R	RMS	% in EE
Both	58 526	0.199	0.198	$y=0.988x+-0.004$	0.905	0.106	72.60
Terra	35 753	0.195	0.193	$y=0.987x+-0.003$	0.909	0.105	73.01
Aqua	22 773	0.201	0.202	$y=0.992x+-0.007$	0.898	0.108	71.96

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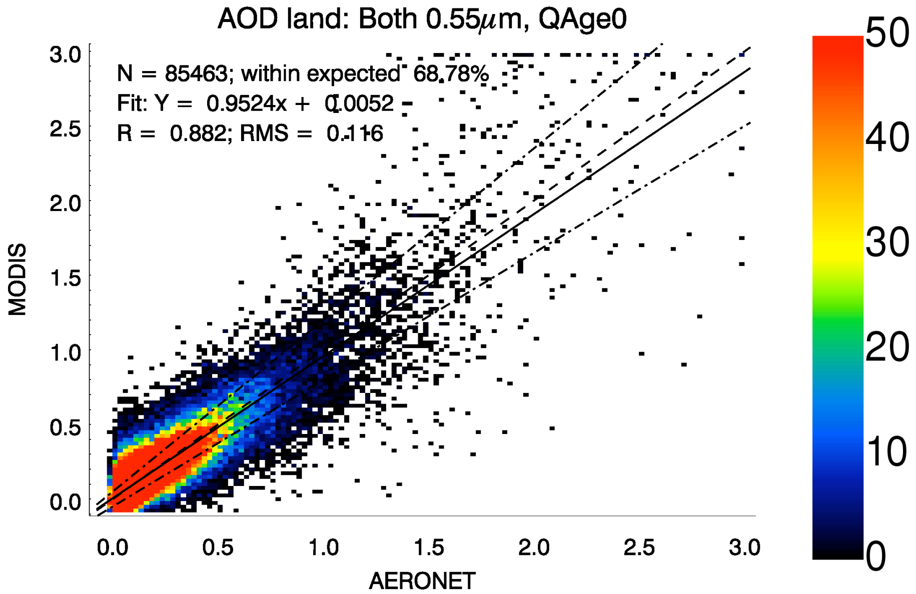

Fig. 1. MODIS C005 AOD at 0.55 µm over dark land (QAC≥0) collocated with AERONET (quadratically interpolated) to the same wavelength, for combined Terra and Aqua datasets. Data are sorted according to ordered pairs (AERONET, MODIS) of AOD in 0.025 intervals, so that color represents the number of cases (color bar) having that particular ordered pair value. The dashed, dotted and solid lines are the 1-1 line, EE for land AOD ($\pm(0.05+0.15\tau)$), and the linear regression of the pre-sorted scatterplot, respectively. Text at the top describes: the number of collocations (N), the percent within expected error, the regression curve, correlation (R), and the RMS error of the fit.

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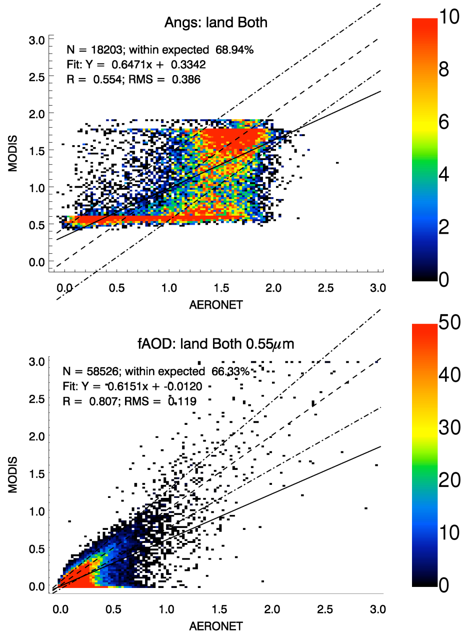

Fig. 2. MODIS-derived 0.47/0.65 µm AE (top) and 0.55 µm fAOD (bottom) collocated with analogous AERONET parameters. Data are sorted according to ordered pairs (AERONET, MODIS) of AOD in 0.025 intervals, so that color represents the number of cases (color bars) having that particular ordered pair value. For each panel, the dashed, dotted and solid lines are the 1-1 line, EE, and the linear regression of the pre-sorted scatterplot, respectively. Text at the top describes the number of collocations (N), the percent within expected error, the regression curve, correlation (R), and the RMS error of the fit. The AERONET AE is derived from AOD that has been interpolated (quadratic) to MODIS wavelengths, whereas the AERONET fAOD was derived with the O'Neill et al. (2003) deconvolution technique. EE for AE is ±0.4. EE for fAOD is $\pm(0.05+0.20\tau)$.

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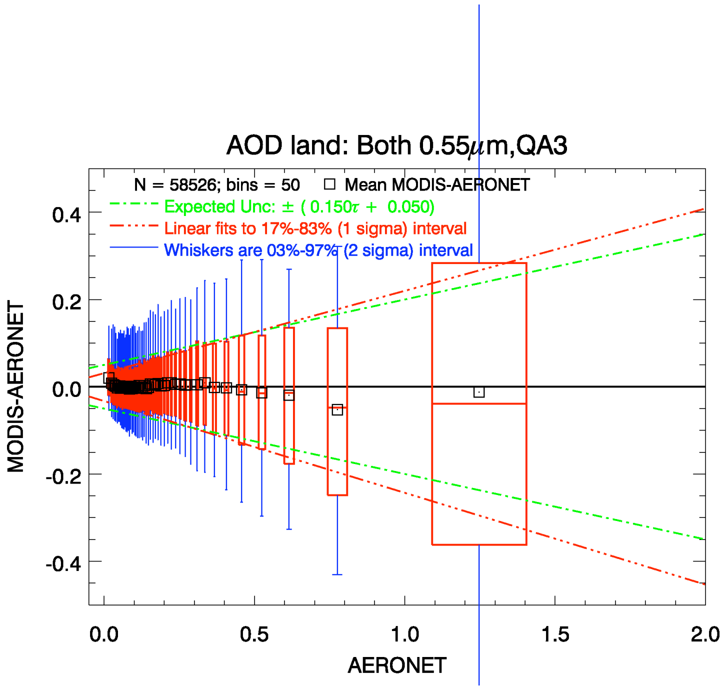

Fig. 3. Absolute error of AOD (MODIS-AERONET) at 0.55 µm versus AERONET-derived AOD at 0.55 µm, for QAC=3. The *x*-axis is the AERONET derived AOD, and the *y*-axis is the absolute MODIS-AERONET AOD difference. Data are sorted by AERONET AOD and grouped into 50 equal bins. Each boxplot represents the statistics of the MODIS-AERONET differences in the bin. The means and standard deviations of the AERONET AOD are the centers and half widths in the horizontal (red). The mean, medians, and 66% (1-σ) interval of the MODIS-AERONET differences are the black squares, the center, and top-bottom red intervals in the vertical (also red). The blue whiskers are the 96% (2-σ) intervals. The red dashed curves are linear best fits to the 66% interval, whereas the green dashed curves represent the over-land EE for total AOD ($\pm(0.05+0.15\tau)$).

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Evaluation of Collection 5 MODIS aerosol over land

R. C. Levy et al.

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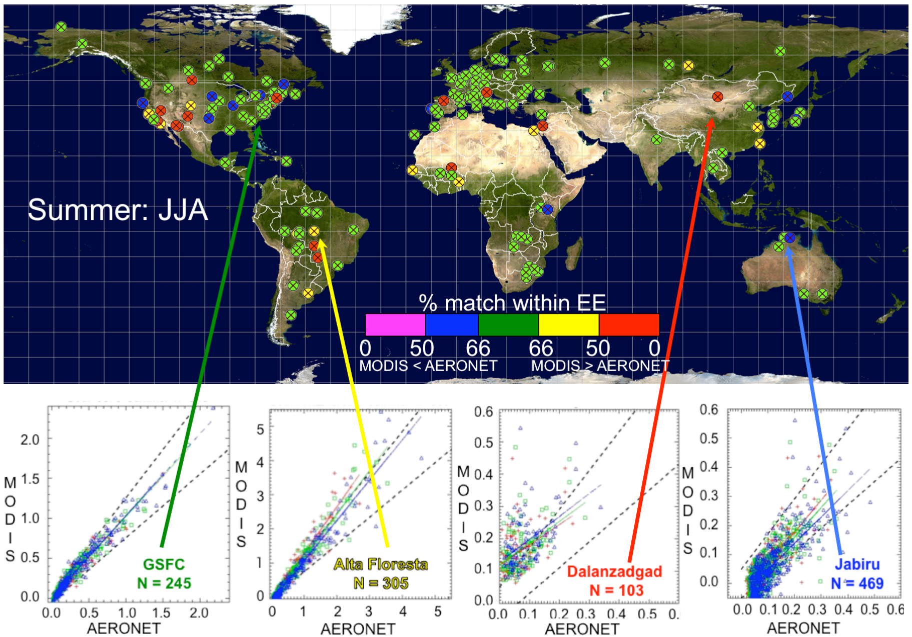

Fig. 4. "Quality" of Terra-MODIS/AERONET comparisons of total AOD over land at each site, from Terra, during June-July-August. The color at each represents the "quality" of the comparison, designated as the percentage of the collocations that fall within EE (Table 3). The comparisons of spectral AOD (different symbols: blue – 0.47 µm, green – 0.55 µm, red – 0.65 µm) at four sites are plotted, including: GSFC (38° N, 76° W), Alta Floresta (9° S, 56° W), Dalanzadgad (43° N, 104° E) and Jabiru (12° S, 132° E). The dotted lines for each scatterplot are the EE ($\pm(0.05+0.15\tau)$) over land.

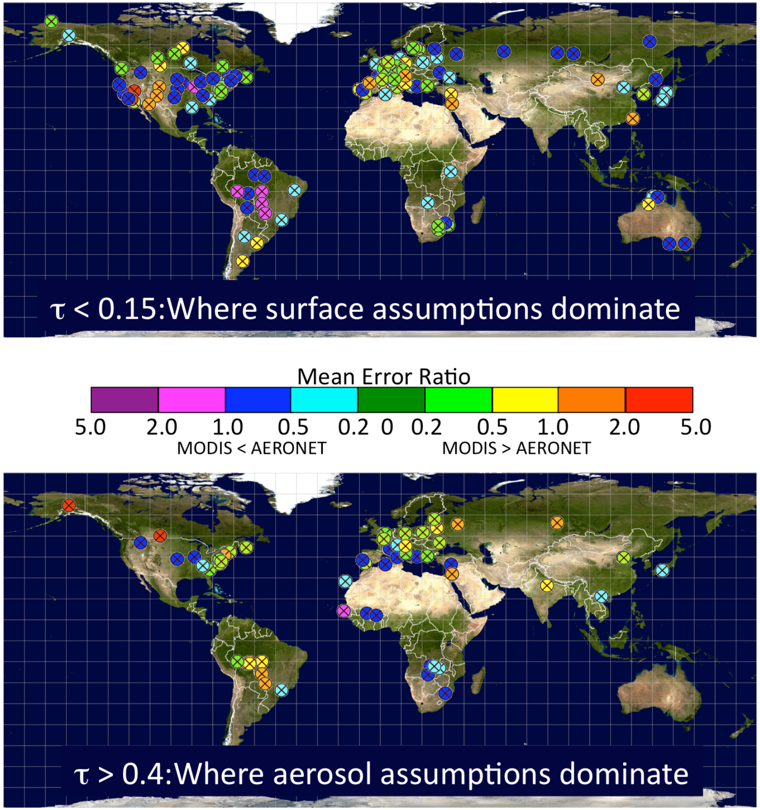

Fig. 5. "Quality" of MODIS/AERONET 0.55 µm AOD comparison at each AERONET site during June-July-August, for cases where AERONET AOD <0.15 (top) and AERONET AOD>0.4 (bottom). Sites are color-coded based on the average error ratio (Error/EE). Greenish colors (cyan and lime) are sites where the average of the MODIS and AERONET-derived AOD values differ by less than half of EE. Colder (warmer) colors represent cases where MODIS, on average, significantly underestimates (overestimates) AOD.

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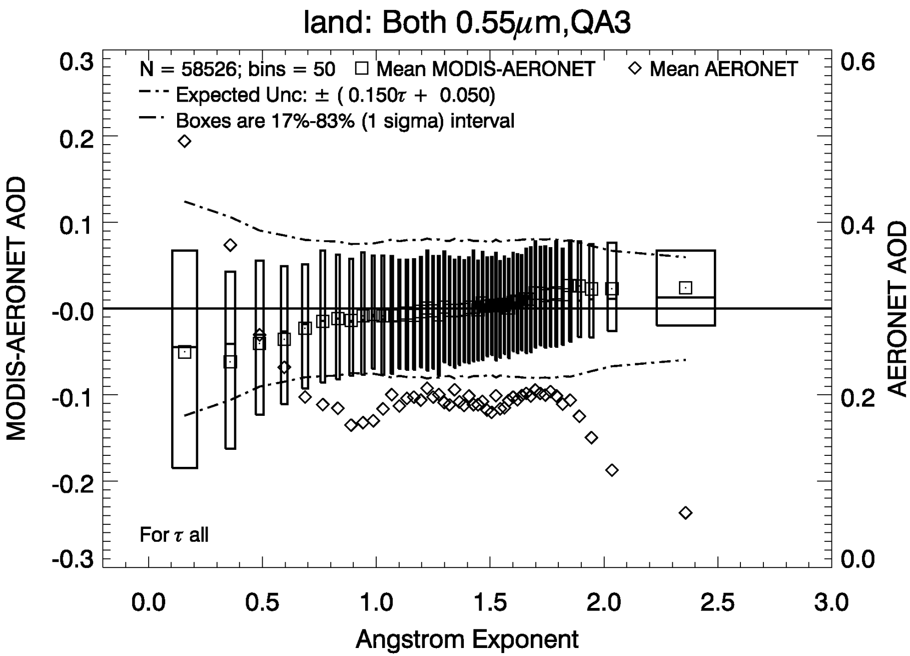

Fig. 6. Differences between MODIS and AERONET-reported AOD at 0.55 µm (MODIS-AERONET) versus AERONET–observed AE, for QAC=3. Data are sorted by the AE and grouped into 50 equal bins. Each box represents the statistics of the MODIS-AERONET differences in the bin. The means and standard deviations of the AE (each bin) are the centers and half widths in the horizontal. The mean, medians, and 66% (1-σ) interval of the MODIS-AERONET differences are the squares, the center, and top-bottom intervals of the boxes. The dashed curves represent the over-land EE envelope for total AOD ($\pm(0.05+0.15\tau)$), where EE is calculated based on the mean AERONET AOD within the bin (diamonds; right axis).

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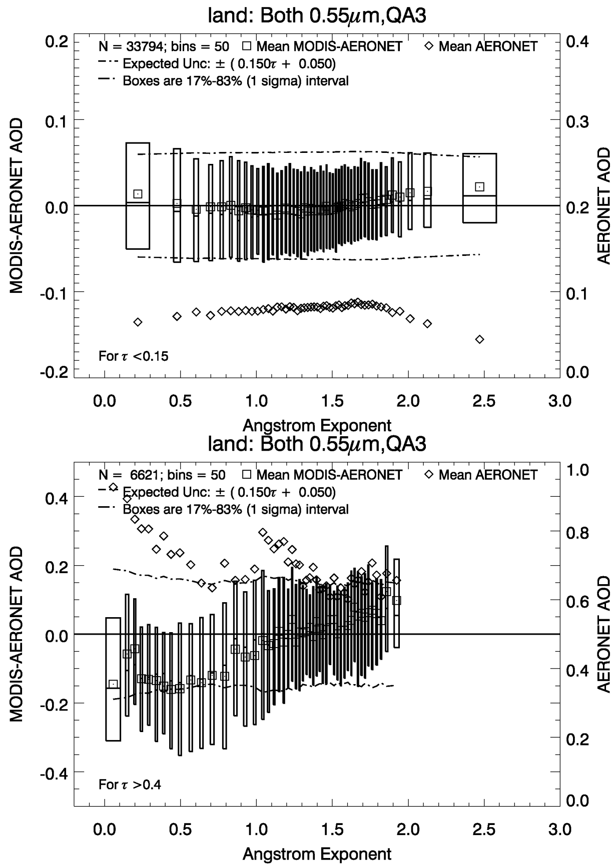

Fig. 7. Same as Fig. 6, but divieded into "light" (τ<0.15) and "heavy" (τ>0.4) aerosol loading cases. Note differences in y-axis scales.

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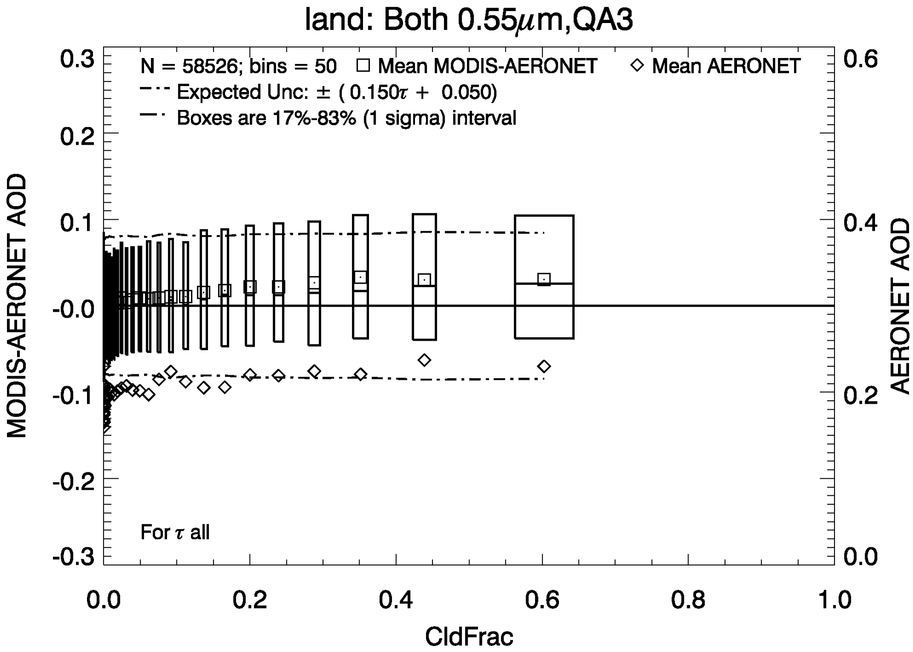

Fig. 8. Differences between MODIS and AERONET-reported AOD at 0.55 µm (MODIS-AERONET) versus MODIS-retrieved cloud fraction, for QAC=3. Explanation of symbols is same as for Fig. 6.

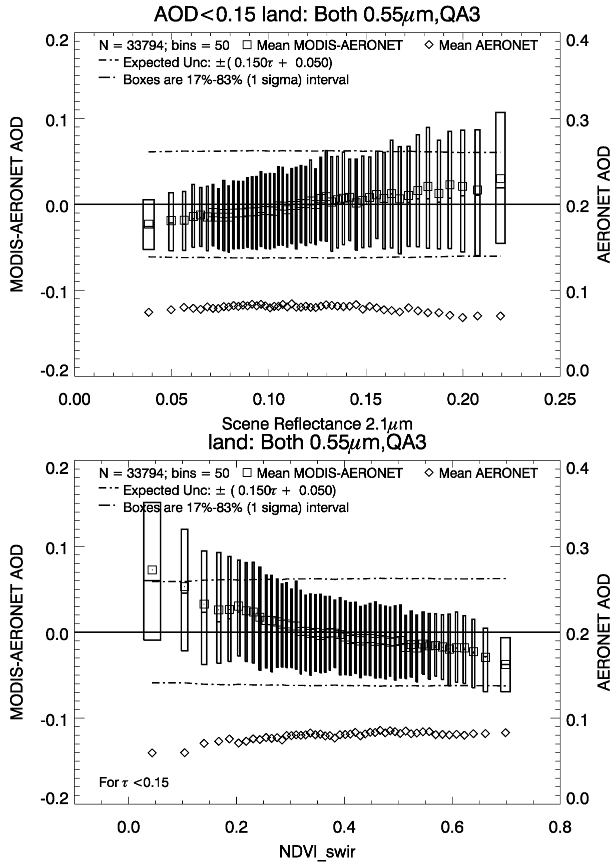

Fig. 9. Differences between MODIS and AERONET-reported AOD at 0.55 µm (MODIS-AERONET) for "light" (τ<0.15) loading cases with QAC=3. Plotted are differences as function of 2.1 µm scene reflectance (top) and NDVI_swir. Explanation of symbols is same as for Fig. 6.

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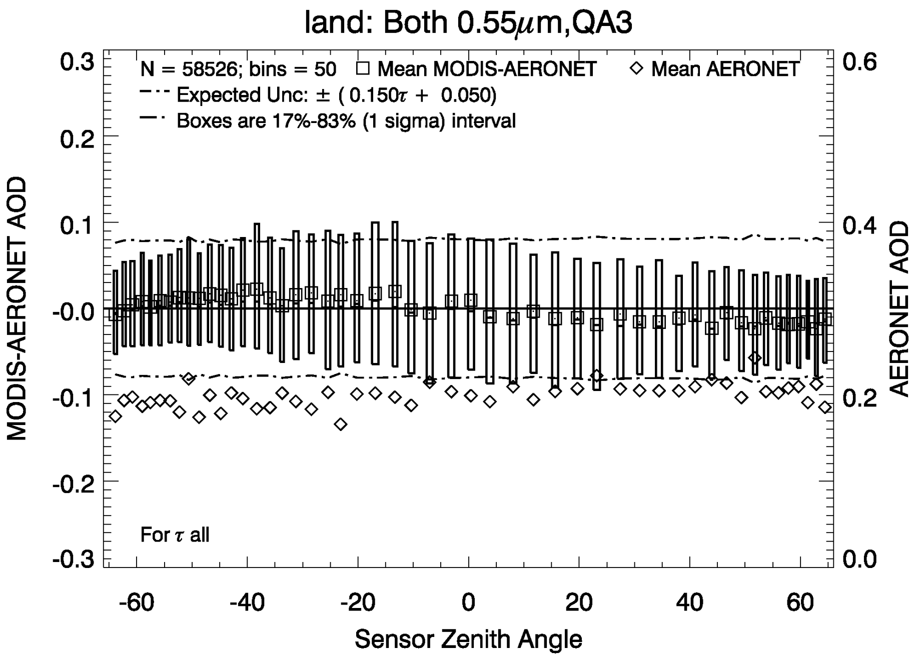

Fig. 10. Differences between MODIS and AERONET-reported AOD at 0.55 µm (MODIS-AERONET) versus MODIS-observed sensor zenith angle, for QAC=3 over land. Explanation of symbols is same as for Fig. 6. Note that the negative values of sensor zenith angle refer to the "left" of the MODIS swath along the track (west side for Aqua, east side for Terra).

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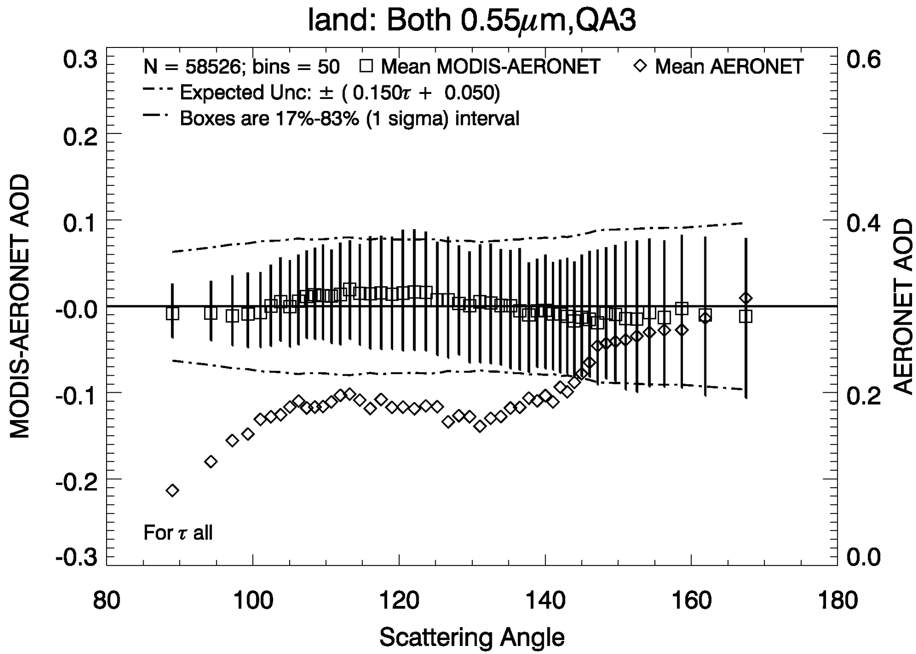

Fig. 11. Differences between MODIS and AERONET-reported AOD at 0.55 µm (MODIS-AERONET) versus MODIS-observed scattering angle, for QAC=3. Explanation of symbols is same as for Fig. 6.

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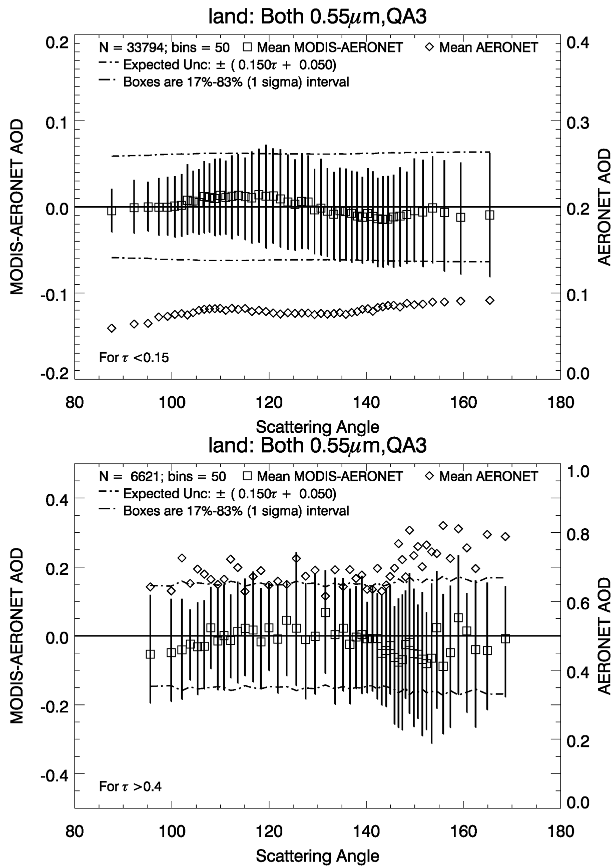

Fig. 12. Same as Fig. 11, but divided into "light" (τ<0.15) and "heavy" (τ>0.4) aerosol loading cases.

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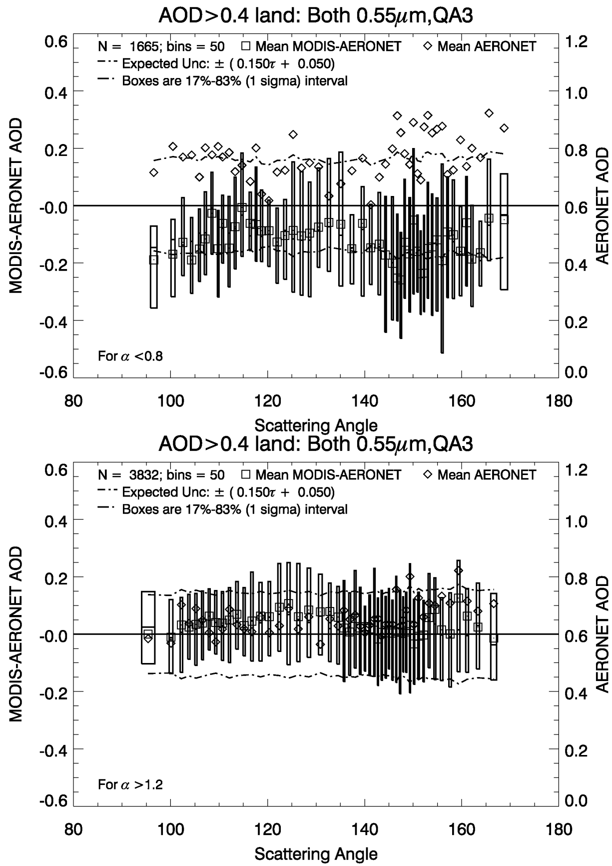

Fig. 13. Same as Fig. 12, but for heavy loadings (τ>0.4) only, divided into AERONET-reported Ångstrom exponent, into "large" (α<0.8) and "small" (α>1.8) aerosol cases.

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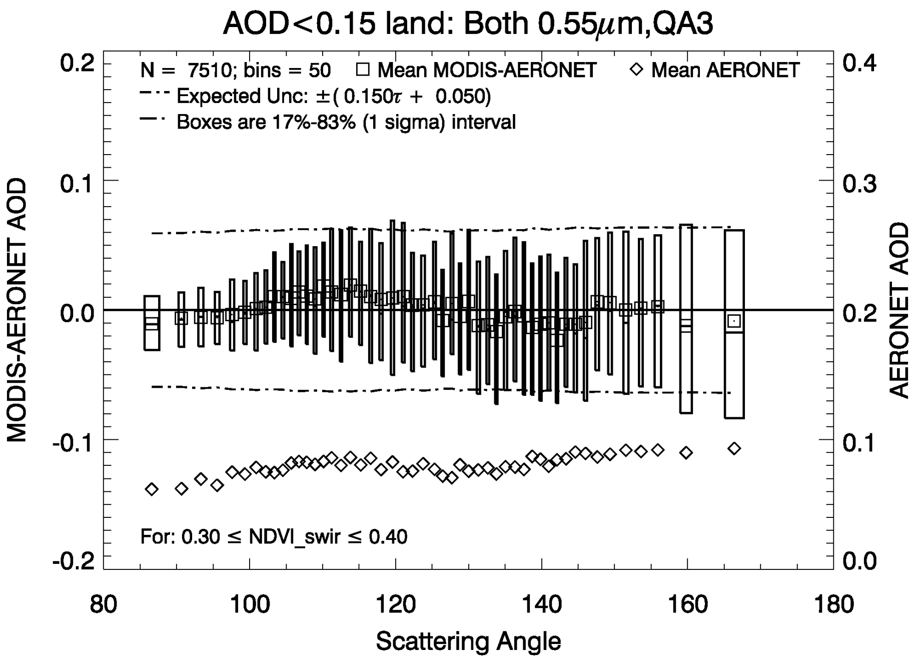

Fig. 14. Same as Fig. 12, but for light (τ<0.15) aerosol loadings only, for a small subset of the NDVI_swir range.

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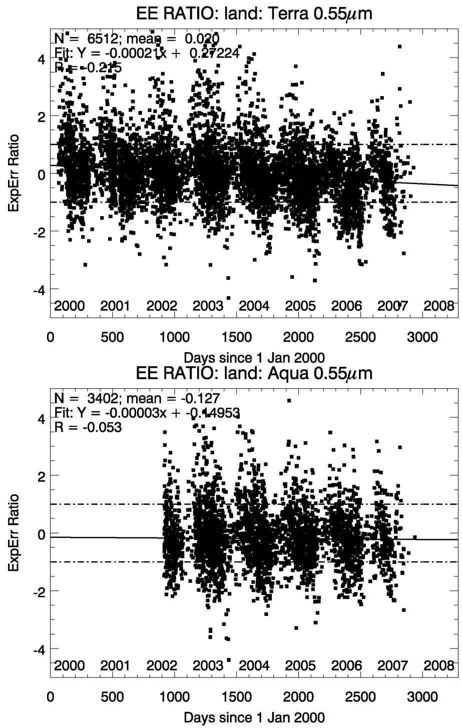

Fig. 15. Time series of Error Ratio (ER) of MODIS C005 0.55 µm AOD compared to seven long-term AERONET sites, for Terra (left) and Aqua (right). Points between the dashed lines (±1) are cases where MODIS matches AERONET within EE over land ($\pm 0.05 \pm 0.15\tau$). The solid line is the linear regression. At the top of the plot is text that describes: the number of collocations (N), the regression equation and correlation (R).

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