Global evaluation of the Collection 5 MODIS aerosol products over land and ocean

Robert C. Levy[1,2], Lorraine A. Remer[2], Richard G. Kleidman[1,2], Shana Mattoo[1,2], Charles Ichoku[2], Thomas F. Eck[3,2]

[1]Science Systems and Applications Inc., Lanham, MD USA

[2]NASA/Goddard Space Flight Center, Greenbelt, MD USA

[3]Goddard Earth Science and Technology Center, Baltimore, MD USA

Corresponding author's address: Dr. Robert Levy
SSAI
Code 613.2
NASA/Goddard Space Flight Center
Greenbelt MD 20771
Email : robert.c.levy@nasa.gov

301-614-6123 (voice)
301-614-6307 (fax)

Submitted to ACPD
Mar 2009

Abstract

NASA's MODerate-resolution Imaging Spectroradiometers (MODIS) 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 the entire time series of both MODISs, deriving the Collection 5 (C005) dark-target aerosol products. Here, we co-locate the MODIS field of view aerosol retrievals (Level 2) with AERONET sunphotometer measurements at nearly 300 sites, resulting in over 100,000 matched pairs. Over land and ocean separately, we characterize the expected uncertainty (EU) for particular MODIS -derived aerosol parameters. We demonstrate that global EU for total and spectral aerosol optical depth (AOD or τ) is $\pm(0.05+0.15\tau)$ and $\pm(0.04+0.05\tau)$ over dark land and ocean respectively. We identify systematic errors at particular sites and seasons. In some cases AOD agreement is good at all wavelengths, in others the AOD is accurate at one wavelength, but spectral dependencies are not well captured. For yet others, AOD in all wavelengths compares poorly. We also assess MODIS-derived aerosol size parameters. With EU of ±0.45, MODIS has little skill at deriving Ångström exponent (α) over land, globally, but has qualitative accuracy over specific sites. Over the global ocean, α is much better constrained (EU = ±0.3), although there are clear biases for regions known for dust or higher aerosol absorption. A better alternative for estimating submicron-sized aerosol contribution is the fine aerosol AOD (fAOD), which is shown to have EU over land and ocean more similar to the total AOD. Finally, we define the Fraction of EU (FEU) for AOD, to characterize how the sensors may be changing over time. We find that the MODIS/AERONET comparison is

consistent throughout the entire mission for both Terra and Aqua over ocean, as well as for Aqua over land. There is a systematic change for Terra over land that we believe to be a result of calibration uncertainty.

1. Introduction

As components in Earth's global climate system, characterizing aerosols' global distribution and loading are necessary for understanding their impacts. The climate and aerosol communities are increasingly relying on satellite-derived aerosol data, including products of passive remote sensing. Aerosol products from NASA's Moderate Imaging Spectrometer (MODIS) sensor were utilized in the latest IPCC (4th) assessment of climate [IPCC, 2007]. 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].

There are two MODIS sensors, observing Earth from polar orbit (705 km altitude) aboard NASA's *Terra* (since Feb 2000) and *Aqua* satellites (since June 2002). MODIS has an attractive combination of 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). For each instrument, spatial and spectral performance has been monitored and maintained by the MODIS Characterization Support Team (MCST), such that for typical situations, calibration error is within ±2-3%. Thus, MODIS has contributed over nine years of comprehensive, stable and dependable observations of

Earth's spectral radiance. The MODIS aerosol algorithm relies on these optimal observations, ensuring long term accuracy, stability and usefulness of the retrieved aerosol products.

To take advantage of MODIS's sensitivity to aerosol signals, efficient and accurate retrieval algorithms have been developed, maintained, and consistently applied to the observations. Generally, the 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 uncertainty. The current suite of MODIS aerosol products are derived by separate algorithms that retrieve aerosol properties over three separate environments: 1) dark-surface (far from sun glint) ocean targets [*Remer et al.,* 2005], 2) dark-surface (vegetation and bare soils) land targets [*Levy et al.,* 2007b], and 3) bright surface (deserts) land targets [*Hsu et al.,* 2004]. In this paper, we assess the performance of the aerosol products over the dark-targets (environments 1 and 2), where MODIS retrieves total *aerosol optical depth* (*AOD* or τ) at 0.55 μm, as well as other wavelengths in the visible (VIS) and Near-IR (NIR) spectrum. The dark target algorithms are also designed to retrieve some characteristics of submicron-sized aerosols (having radius less than approximately 1.0 μm). These size products include the *fine aerosol fraction* (*FF* or η), the *Ångström exponent* (α) and the *fine mode AOD* (*fAOD* or τ_f). Retrievals of the total AOD and size parameters, including diagnostic 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 processed by the MODIS Adaptive Processing System (MODAPS) at NASA's Goddard Space Flight Center. The most recent data (known as Collection 5, or C005) are freely available via the MODAPS web site.

The last comprehensive evaluation of regional and global MODIS aerosol products was performed for Collection 4 (C004) [*Remer et al.,* 2005]. Since then, the over land portion of the algorithm received a complete overhaul, (*Levy et al.,* 2007a, 2007b) whereas the over-ocean portion was more conservatively updated (*Remer et al.,* 2006). The Deep Blue algorithm [e.g., *Hsu et al.,* 2004] was added for bright surfaces, but its products are available for only a subset of Aqua data. A detailed global evaluation of Deep Blue products requires a separate paper, so it is not presented here. Although there has been some evaluation of C005 dark-target products both globally [e.g. *Remer et al.,* 2008], and regionally [e.g. *Mi et al.,* 2007], these references do not perform the in depth study we show here. Here, we "validate" total spectral AOD as well as particular aerosol size products, globally, regionally, and seasonally. We quantify the expected uncertainty (EU) of the MODIS products, by comparing with similar parameters derived from the sun/sky radiometers of the global Aerosol Robotic Network (AERONET, [*Holben et al.,* 1998]).

In Section 2, we briefly introduce the recent changes to the dark-target aerosol retrieval and products that are relevant for C005, and define the concept of "validation." We compare the MODIS –derived aerosol products to measurements by ground-based sunphotometers, for spectral AOD in Section 3, and for aerosol size parameters (including Ångström exponent and fine AOD) in Section 4. We use the spatial-temporal collocation method that was introduced by *Ichoku et al.,* [2002], and used previously by *Remer et al.,* [2005] and others. In section 5, we summarize our validation results and suggest steps necessary to reduce systematic discrepancies. Section 6 offers some discussion of the significance of the results and conclusions.

2. The MODIS aerosol retrieval

The MODIS dark-target aerosol retrieval uses portions of the visible (VIS), near-IR (NIR), and shortwave IR (SWIR) spectrum, specifically two 250 m resolution bands (centered about 0.66 and 0.86 μm), and five 500 m resolution bands (centered about 0.47, 0.55, 1.2, 1.6 and 2.1 μm). These bands are all in gas-absorption window regions, so that when constrained properly, they provide a clear signal of aerosol effects in atmospheric radiative transfer. The algorithm uses additional wavelengths in other parts of the spectrum to identify and mask out clouds and suspended river sediments [*Ackerman et al.,* 1998, *Gao et al.,* 2002; *Martins et al.,* 2002; *Li et al.,* 2003]. Based on studies of MODIS's spectral signal-to-noise properties, and the relationships of surface and aerosol optical properties, MODIS is capable of retrieving global aerosol properties at 10 km x 10 km resolution [e.g. *Levy et al.,* 2009b]. Both aerosol algorithms utilize pre-computed lookup tables (LUT) that simulate spectral reflectance from a number of probable aerosol scenarios.

By assuming properties of the surface reflectance, each dark-target algorithm uses the LUT to determine which aerosol scenario best "matches" the observations of spectral reflectance. Although the mechanisms of each algorithm are different, their solutions include a measure of total aerosol loading known as the aerosol optical depth (AOD, or τ) and a measure of the fraction of the optical depth attributed to fine-sized particles, known as the fine aerosol fraction (FF or η). Total AOD is a straightforward measure of column-integrated extinction, and is directly retrieved at 0.55 μm. Over the ocean, where the algorithm combines lognormal modes, the FF is the fraction of the AOD contributed by the fine-mode (aerosol modes with effective radius less than 1.0 μm). Over land, where bi-lognormal models take the place of single modes in the algorithm, the FF is the fraction of the AOD contributed by the fine-dominated model. Because the FF is defined differently over land and ocean, and is defined differently by AERONET [*O'Neill et al.,* 2003; *Kleidman et al.,* 2005], it is very difficult to evaluate. Instead, we look to the combination of AOD and FF, plus knowledge of which modes (ocean) or models (land) were used for the solution, to lead to aerosol size parameters that are easier to compare and evaluate. We define the spectral AOD, Ångström exponent (α), and fine AOD (fAOD or τ_F) below.

The MODIS algorithm derives AOD in all seven channels (0.47-2.12 μm) over ocean and at the three VIS channels over land (0.47, 0.55, and 0.66 μm). The *Ångström exponent* (α) describes the spectral dependence of the AOD in natural log space, and is a proxy for aerosol size distribution [e.g. *Eck et al.,* 1999]. It is defined in its simplest form as

$$\alpha_{\lambda 1,\lambda 2} = -\frac{\ln(\tau_{\lambda 1}/\tau_{\lambda 2})}{\ln(\lambda 1/\lambda 2)}, \qquad \mathbf{(1)}$$

where *λ1* and *λ2* are any two wavelengths, usually in the visible or near IR spectrum. Larger Ångström exponent values indicate dominance of smaller particles, and vice versa. The combination of wavelengths is defined differently over ocean and land. Over ocean, MODIS derives two Ångström exponents, one derived from 0.55 μm / 0.86 μm ($\alpha_{O,1}$), and the other from 0.86 μm / 2.1 μm ($\alpha_{O,2}$). The use of two values across this wavelength range help to detect spectral curvature, and aid in differentiating particle sizes and types [*Eck et al.,* 1999]. However, since AERONET does not measure far into the SWIR, for this paper, we compare only the values for $\alpha_O=\alpha_{O,1}$. Over land, only one value is derived, for 0.47 μm /0.66 μm and is denoted as α_L.

Since the FF is difficult to evaluate (differences in definitions) and quantify (unstable to inputs and assumptions; e.g. [*Levy et al.,* 2007b]) we shall calculate the fine aerosol optical depth (fAOD) by multiplying FF and AOD (i.e., $\tau_F = \eta\tau$), defined at 0.55 μm. The fAOD represents the aerosol optical depth attributed to fine-sized particles, and should be less sensitive to whether fine refers to "fine-mode" (over ocean) or "fine-dominated model" (over land). Since fine-sized (accumulation mode) particles often originate from anthropogenic combustion processes, such as urban pollution or biomass burning. The fAOD can help to identify aerosols of anthropogenic origin, even if fAOD is not the same as anthropogenic AOD [e.g. *Kaufman et al.,* 2003].

In addition to retrieving the spectral AOD and several aerosol size parameters, the algorithm assesses the confidence of a given retrieval, using a logic known as the *Quality Assurance* (*QA*) plan. Quality Assurance represents a series of tests that are applied during the retrieval process, in order to characterize the expected confidence of the retrieved product. QA assesses the quality and confidence of the input MODIS reflectance data, ancillary datasets [e.g. meteorology or ozone ancillary data; *Levy et al.,* 2009b], and/or output products. For example, one might ask, "after cloud screening and data selection, how many pixels are left to make a retrieval?" Given two retrievals of the same AOD, a solution that utilized more pixels may be expected to have higher confidence than one made from fewer pixels. Or one may ask, "How well does the best aerosol solution fit to the observed spectral reflectance?" A poor fit could be cause for lower confidence in the solution, and the QA would be adjusted accordingly. At the conclusion of the entire retrieval process, a final summary *Quality Confidence* (*QC*) flag is assigned to represent the aggregation of the QA tests. QC ranges from 0 to 3, indicating low, marginal, medium or high confidence in the solution. While the QC has no inherent relationship to whether a given MODIS AOD is comparable to a given AERONET AOD, higher confidence solutions tend to show better agreement. Thus, we limit our validation exercise to the best data only, which is defined in the later sections.

2.1 The MODIS aerosol algorithm through Collection 4

The MODIS dark-target retrieval concept was conceived prior to *Terra* launch, based on *Kaufman et al.,* [1997] over land, and *Tanré et al.,* [1996; 1997] over ocean. Their versions of the algorithms were implemented at first light and have evolved continuously, based on acquiring new scientific knowledge as well as new processing needs. Based on groupings of similar algorithms and data processing, there have been have been sets of products, known as "Collections". Early evaluation of Collection 2 and 3 MODIS products [e.g. *Chu et al.,* 2002; *Remer et al.,* 2002], showed remarkable agreement in retrieved AOD, but also suggested how the algorithms could be improved. The last comprehensive global evaluation was performed for Collection 4 (C004) [*Remer et al.,* 2005].

The C004 evaluation [*Remer et al.,* 2005] compared MODIS L2 AOD products (10 km x 10 km resolution) with measurements from 132 globally distributed ground stations of the Aerosol Robotic Network (AERONET; *Holben et al.,* 1998). This paper "validated" the MODIS-derived spectral AOD, meaning that one standard deviation (~66%) of the MODIS points fell within some expected uncertainty (*EU*) interval of the ground truth measurements. The EU for AOD (τ_{EU}) was defined as

$$\tau_{EU} = \pm(A + B\tau), \qquad \textbf{(2)}$$

where A and B are coefficients, and $\tau = \tau_{AERONET}$ (AOD measured by AERONET). These EU were previously defined as $\tau_{EU} = \pm(0.03+0.05\tau)$ over ocean [*Remer et al.,* 2002] and $\tau_{EU} = \pm(0.05+0.15\tau)$ over land [*Chu et al.,* 2002]. Although the paper concluded that the MODIS total and spectral AOD could be considered validated, certain systematic biases were also noted. Over ocean, there was minor under-prediction of high AOD (slope = 0.94 at 0.55 μm), which was more significant for land (slope = 0.78). Over ocean, retrieval of low AOD was generally quantitative as demonstrated by the minimal y-offset (+0.005). There was, however, a significant offset over land (+0.068).

Remer et al., [2005] also evaluated some aspects of the global aerosol size retrievals in C004. Over land, they indicated that averages of retrieved FF might be reasonable, but that scatter plots (not shown in their paper) suggested little or no skill at retrieving FF in a given scene. Over ocean, although they found a general underestimation of FF, it was often overestimated in heavy dust loadings. They also found that the FF retrieval over ocean could be heavily impacted by calibration. Further study by *Kleidman et al.* [2005] showed that FF could be even more significantly underestimated in conditions of heavy smoke or pollution loadings, and confirmed the overestimate (by 0.1-0.2) in dusty scenes. In another study, however, which compared MODIS data to airborne sunphotometer measurements, MODIS overestimated FF by 0.2 even when dust was not observed [*Anderson et al.,* 2005].

In addition to the conclusions of *Remer et al.,* [2005] for global data, there were a number of regional studies (e.g. [*Levy et al.,* 2005; *Jethva et al.,* 2007a; *Mi et al.,* 2007] that demonstrated that the total AOD over-land was even more significantly biased in certain regions. Also, since the retrieval of FF was essentially meaningless over land, it became apparent that a complete overhaul of the over-land algorithm was necessary. Over ocean, while there was little bias in the total AOD retrieval, there was still the offset in derived spectral dependence and FF (e.g. *Remer et al.,* [2005], *Kleidman et al.,* [2005] and *Anderson et al.,* [2005]) to consider. Therefore, refinements were also proposed for the over-ocean algorithm.

An unexpected problem with the C004 processing effort was that both the aerosol retrieval algorithm and the input radiances were allowed to evolve all using the C004 label. It was known that the aerosol algorithm was sensitive to the instrument calibration [e.g. *Tanré et al.,* 1997; *Levy et al.,* 2007], as well as to upstream products (e.g., cloud mask, water vapor retrieval). However, during the processing of the C004 MODIS aerosol algorithm, the upstream products and the calibration coefficients both underwent refinements (bug fixes, lookup table coefficients, etc) during the lifetime of the Collection. This meant that the combination of "forward" processing in real time (from 2004 onward) and "re-processing" of archived data (prior to 2004) was not performed consistently. Although in most cases these changes did not significantly impact the results, detailed analysis of certain data products showed trends or spikes associated with one or more of the changes. Thus, it was clear that it was necessary to reprocess the entire MODIS mission, using consistent calibration coefficients, upstream algorithms and aerosol retrieval. MODAPS began both forward processing and re-processing in early 2006, thus deriving the C005 aerosol products evaluated in this paper. A summary of the aerosol retrieval process is in the following subsections.

2.2 Collection 5 land algorithm

Based on the global and regional assessments of C004 (and prior) aerosol products over land, it was seen that while mostly within expected uncertainty, there was a tendency for biases both in low and high AOD conditions. *Levy et al.,* [2005] studied both offset and slope issues over land, and concluded that a combination of refined surface reflectance assumptions and aerosol optical assumptions could help to reduce biases in specific regions or seasons. Some errors could also be pegged to the neglect of polarization in the C004 radiative transfer calculations [*Levy et al.,* 2004]. As a result, the "second-generation" algorithm was developed [*Levy et al.,* 2007a; 2007b; *Remer et al.*, 2006], and was implemented operationally in early 2006 to derive the C005 products.

Essentially, the second-generation algorithm over land was a complete overhaul. All assumptions about aerosol optical properties were modified [*Levy et al.,* 2007b], as were surface assumptions [*Levy et al.,* 2007b] and snow masking [*Li et al.,* 2003]. To reduce statistical biases in clean aerosol ($\tau<0.05$) conditions, small negative AOD values were permitted, archived and assigned a high QC rating. Furthermore, the treatment of Rayleigh/aerosol interaction over elevated targets was changed. A vector radiative transfer code replaced the scalar code used in Collection 4, and the overall inversion scheme was changed to reflect the possibility of dust aerosol signal in the SWIR wavelength region. Using a substantial test-bed of C004 radiance data [*Levy et al.,* 2007a], the overall mean AOD of the test-bed retrievals went from ~0.28 (using the C004 algorithm) to ~0.19 (using the C005 algorithm). Comparison of total AOD with AERONET measurements (>1200 cases) was improved significantly, as demonstrated by higher correlation (R increasing from 0.847 to 0.894), and smaller y-offset (from 0.097 to 0.029). Nearly 67% of MODIS AOD retrievals compared to AERONET within the EU of $\pm(0.15+0.05\tau)$, indicating that the C005 algorithm could be validated, at least for the test-bed. Furthermore, there were minor improvements observed for retrievals of FF, Ångström exponent, and fAOD over land, using the new algorithm [*Levy et al.,* 2007a].

In addition to revised assumptions and mathematical fitting, the second-generation algorithm also included major changes to its Quality Assurance (QA) plan. Explanation of the QA tests and assigned QC summary flags can be found in *Levy et al.,* [2009b]. Depending on which tests pass or fail, the algorithm may report non-fill (missing) values for all, none or some of the parameters. For example, if the retrieved AOD is less than 0.2, the derived fAOD value will be reported, but not the FF. If retrieved AOD is reported but negative (e.g. > -0.05), then neither fAOD nor FF have meaning, and both would be reported as fill-value. Thus, there are fewer pixels with FF and fAOD reported than for total AOD. Yet, if all other QA tests pass, then the reported small AOD value may still receive high confidence (i.e., QC=3). While the QC has no inherent relationship to whether a given MODIS AOD is comparable to a given AERONET AOD, we find that data with QC<3 do not compare well. Therefore, for this work, we limit our validation effort to the set of high confidence (QC=3) data, about 60% of the reported (non-fill value) AOD retrievals [*Levy et al.,* 2009a].

2.2 Collection 5 ocean algorithm

Between C004 and C005, the only difference in the over-ocean algorithm was an adjustment to sea-salt aerosol refractive index, that better matches more recent observations [*Remer et al.,* 2006]. Although there were large error bars reported, AERONET retrievals of aerosol optical properties over ocean (available only after Terra-MODIS launch) suggested that the real part of the refractive index for sea salt was smaller than the 1.43 used for C004, and more like 1.35 (*Dubovik et al.,* [2002]). Using a test-bed of C004 radiance data [e.g. *Remer et al.,* 2006], and applying the reduced real part of the refractive index, it was found that much of the FF bias observed by *Kleidman et al.,* [2005] could be removed without impacting the total AOD retrieval. The mean AOD using either software remained at 0.15, but mean FF was reduced from 0.47 to 0.39. Comparison of MODIS with AERONET for 162 collocations demonstrated that retrieval of AOD was unchanged but that correlation (R), slope, and y-intercept were all improved for retrievals of FF [*Remer et al.,* 2006]. Thus, based on our preliminary study, compared to the C004 algorithm we expected C005 to report smaller fine fraction without changing the statistics of the total AOD.

Analogous to that described for over land, there is a QA plan for assessing retrieval confidence over ocean [*Levy et al.,* 2009b]. Like over land, the QA logic derives a final QC value for each retrieved 10 km x 10 km pixel, ranging from 0 (low confidence) to 3 (high confidence). Certain tests are stricter for ocean than for land, such that only 25% of the pixels over ocean receive QC=3 [*Levy et al.,* 2009a]. However, preliminary efforts showed that even "marginal" confidence data (i.e. QC=1) compared well with AERONET. Thus, for this paper, we have included all ocean data with QC≥1, thereby including 98% of the reported (non-fill) AOD values over ocean.

2.4 Notes on collection 5 products

Although the preliminary testing of the C005 algorithms [*Levy et al.,* 2007a; *Remer et al.,* 2006] showed improvements over the C004 algorithm, the exercise was based on using a database of archived reflectance data. While there were many MODIS/AERONET collocations (nearly 1400 combined over land and ocean), the test bed was limited in time and space. Furthermore, this test bed was made up of archived C004 reflectance data. However, when C005 was actually processed (and re-processed for data prior to 2006), the MCST introduced revised calibration coefficients. Thus, actual C005 input reflectances are different from the C005-like inputs of the test-bed. When we compare our products to AERONET data, we are testing both the validity of the new algorithms, as well as the validity of the C005 calibration.

In a recent paper, *Remer et al.,* [2008] found that in fact, the products derived from the C005 calibration differed significantly from those that might have been produced via the C004 calibration. Whereas the time series of global monthly AOD values over ocean were nearly exactly the same for Terra and Aqua for C004 [Remer et al. 2006], and were not expected (based on the test-bed) to change for C005, analysis of actual C005 data showed that Terra's global monthly mean AOD had increased by nearly 0.015. This increase was seen in all months, including the months prior to 2006 that were reprocessed. Aqua data products did not seem to be affected by revised calibration coefficients. Over land, although *Remer et al.,* [2008] noted difficulties in separating calibration and algorithm effects, it is clear that the products were impacted by the revised calibration.

3. Comparison of total AOD

Remer et al., [2008] began the process of validating the C005 aerosol products, using collocated AERONET data. Their purpose was to ensure that the MODIS products were trustworthy enough to begin to characterize global AOD climatology from the monthly products. In this paper, we concentrate on detailed study of the MODIS L2 products, compared to AERONET, over both land and ocean, and for individual sites. Our purpose is to show where the C005 algorithm works and where it does not.

Here, we collocate MODIS data with the AERONET Version 2.0, Level 2 Quality Assured (cloud screened and calibrated) sun measurements of spectral AOD [http://aeronet.gsfc.nasa.gov/new_web/Documents/version2_table.pdf] that have 0.01-0.02 uncertainties for all wavelength bands. Using quadratic fits on a log-log scale (e.g., *Eck et al.,* 1999]), we interpolate the AERONET data to exact MODIS wavelengths (i.e., 0.466, 0.553, 0.644, and 0.865 μm; [*Remer et al.,* 2006]). We use the spectral de-convolution technique of *O'Neill et al.,* [2003] to derive estimates of FF and fAOD. We employ the spatio-temporal technique of *Ichoku et al.,* [2002], which creates a grid of 5 by 5 aerosol MODIS retrievals, with the AERONET station inside the middle pixel. Since each MODIS aerosol pixel represents approximately a 10 km area, the subsetted area is approximately 50 km by 50 km. The spatial statistics of the MODIS retrievals in the 5 by 5 subset are calculated and compared to the temporal statistics of the AERONET observations taken ±30 minutes 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 the collocation in our statistics. This means that the collocation may not include the exact 10 km MODIS aerosol retrieval in which the AERONET station resides, and could include retrievals from pixels that are 20-25 km away. Although all AERONET sites are land-based (i.e. on continents, on coasts or on islands in ocean basins), assumption of aerosol spatial homogeneity over 50 km (e.g. *Anderson et al.,* [2003]) allows us to assess over-ocean aerosol products as well. Using this technique, a coastal AERONET site can be used simultaneously as ground-truth for both land and ocean MODIS aerosol retrievals. It is pertinent to note that for a valid match, both MODIS and AERONET must view conditions sufficiently free of clouds.

As of September 2008, our database includes collocations over 328 AERONET sites. 203 sites are inland, and used exclusively for comparison with the MODIS land products, whereas 32 are island sites used exclusively for over ocean. The rest are located on land near the shoreline so that they can be used for both comparisons. Some sites have been nearly "permanent" and offer a long time series of measurements, whereas other sites may only have measured during a particular season or field experiment. The result is 57,796 (39,994) matches for Terra (Aqua) over land and 14,817 (11,392) matches for Terra (Aqua) over ocean. We filter for recommended QC (QC=3 over land; QC≥1 over ocean), and remove the locations where the elevation of the AERONET site does not represent the surrounding scene. For example, Mauna Loa (elevation 3397 m) should not be used to evaluate aerosol properties over the nearby ocean (elevation 0 m). If the elevations of the AERONET site and the average of the 50 km x 50 km region surrounding it are different by >300 m, then the site is excluded. This also means that coastal AERONET sites may be excluded from comparison with ocean pixels. Still, after QC and elevation filtering, we are left with 35,753 (22,773) collocations for Terra (Aqua) over land and 13,733 (10,407) over ocean.

3.1 Total AOD over land

Fig. 1 displays the results of the collocation (filtered for QC=3 and elevation differences less than 300 m), for total AOD (at 0.55 μm) over land, for Terra (left) and Aqua (right). This is a density scatterplot, such that the color of each ordered pair (0.025 x 0.025 increment) represents the number of such matchups. The dashed, dotted and solid lines are the 1-1 line, defined EU for land AOD ($\tau_{EU} = \pm(0.05+0.15\tau)$), and the linear regression of the pre-sorted scatterplot, respectively. Also given for each plot are number of collocations (N), the percent within EU, the regression curve, correlation (R), and the RMS error of the fit. The plots show the quality of the matching, as both Terra and Aqua regressions hug the 1-1 line, have slopes near 1, y-intercepts near zero, and R>0.9. One can also see the relative dominance of AOD < 0.25, with decreasing numbers of points towards the axes limits. Table 1 provides the comparisons for all three wavelengths, including the means of the AOD from both MODIS and AERONET. There is little statistical difference between the overall fits of Terra and Aqua. For both instruments, at least 72% of the points lie within the dotted EU lines (at 0.55 μm), and at least 69% at the other two channels. This suggests that total AOD over land can be considered a "validated" quantity, at least globally within the EU defined by

$$\tau_{EU} = \pm(0.05 + 0.15\tau). \qquad \mathbf{(3)}$$

Lorraine Remer 3/24/09 7:27 AM
Comment: Do you know why the sharp cut-off at AOD ~ 0.03 in both MODIS and AERONET?

Table 1: Statistics of the comparison between MODIS (Terra and Aqua) and AERONET total spectral AOD over land. The number of points (N) is 35,753 (22,773) for Terra (Aqua).

Sat	Wave (μm)	Mean AOD AERO	Mean AOD MODIS	Regression equation	R	RMS	% in A
Terra	0.47	0.165	0.171	y = 0.984x + 0.001	0.892	0.097	74.40
Terra	0.55	0.201	0.202	y = 0.987x + -0.003	0.909	0.105	73.01
Terra	0.66	0.250	0.244	y = 0.985x + -0.009	0.920	0.120	70.46
Aqua	0.47	0.161	0.164	y = 0.986x + -0.002	0.883	0.099	73.55
Aqua	0.55	0.195	0.193	y = 0.992x + -0.007	0.898	0.108	71.96
Aqua	0.66	0.242	0.233	y = 0.991x + -0.013	0.908	0.123	69.17

A: EU = $\tau_{EU} = \pm(0.05+0.15\tau)$

However, global scatterplots like Fig. 1 can hide details. MODIS data may have systematic biases due to specific conditions (e.g., unique aerosol type, or surface conditions) encountered at certain sites or during certain seasons. Some sites may be biased high and others low, and will cancel each other in the global scatterplot. Given our expected uncertainty of the total AOD at 0.55 μm, we would like to characterize how well the algorithm is performing at a given site, for a given season. For example, if the statistics of the AOD comparison shows that MODIS and AERONET are well matched (66% within EU interval), we might call this a good comparison at the site. If they do not match, say less than 50% within the EU interval, then this is a poor comparison. We can extend these conditions to describing the comparison of the total AOD for the other VIS wavelengths (i.e., 0.47 and 0.66 μm). A condition of retrieving reasonable estimates of the aerosol size parameters is reasonable characterization of the AOD spectral dependence. If all channels match within EU, then we can consider it a good all around comparison. Likewise if all do not match, then this is a poor comparison. However, there are sites or seasons where the AOD at 0.55 μm compares well, but AOD at one or more of the other channels do not, or vice versa.

Fig. 2 provides a color wheel for subjective characterization of matching quality. Each color represents measures of two semi-independent MODIS/AERONET comparison tests (A and B), for a given MODIS-derived parameter. The first test quantifies the number of matched pairs that fit within a defined measure of EU. These matched pairs are assumed to be for the nominal product (e.g., at 0.55 μm for the MODIS AOD product). The second test may refer to a comparison at other wavelengths (for the AOD product) or a different measure entirely (e.g., correlation coefficients instead of number of matched pairs). Table 2 lists the details of comparison tests A and B for a different MODIS derived parameters, and the results that are associated with a given color.

For example, Fig. 2 may be used to qualify the degree of comparison for the MODIS total AOD product over land, for a given site, for a given season. Test A computes the number of matched pairs (at 0.55 μm) that fall within a defined estimate of EU. Test B computes the number of matched pairs at other channels (0.47 and 0.66 μm) that fall within EU. When referring to total AOD over land, green color (at the top) represents collocations where >66% of the MODIS-derived in all three VIS channels match AOD from AERONET within EU. Red color (at the bottom) represents the condition of <50% match for all three channels. Going counterclockwise (through cold colors) represent cases where the 0.55 μm values continue to match, but less match to one or more of the other VIS channels. Going clockwise (warm colors) represent increasing mismatch at 0.55 μm, but possibly better comparison at one or more of the other channels.

Table 2: Conditions A and B to designate symbol color for different MODIS parameters.

Color	AOD ocean [1]	AOD land [2]	fAOD ocean [3] / land [4]
Green	$\tau_{0.55}\% \geq 66$	$\tau_{0.55}\% \geq 66$	$\tau_F\% \geq 66$
	$\tau_{0.87}\% \geq 66$	$\tau_{0.47}\% \geq 66$ and $\tau_{0.67}\% \geq 66$	$R \geq 0.8$
Cyan	$\tau_{0.55}\% \geq 66$	$\tau_{0.55}\% \geq 66$	$\tau_F\% \geq 66$
	$50 \leq \tau_{0.87}\% < 66$	$\tau_{0.47}\% \geq 50$ and $\tau_{0.67}\% \geq 50$	$0.4 \leq R < 0.8$
Blue	$\tau_{0.55}\% \geq 66$	$\tau_{0.55}\% \geq 66$	$\tau_F\% \geq 66$
	$\tau_{0.87}\% < 50$	$\tau_{0.47}\% < 50$ or $\tau_{0.67}\% < 50$	$R < 0.4$
Purple	$50 \leq \tau_{0.55}\% < 66$	$50 \leq \tau_{0.55}\% < 66$	$50 \leq \tau_F\% < 66$
	$\tau_{0.87}\% < 50$	$\tau_{0.47}\% < 50$ or $\tau_{0.67}\% < 50$	$R < 0.4$
Red	$\tau_{0.55}\% < 50$	$\tau_{0.55}\% < 50$	$\tau_F\% < 50$
	$\tau_{0.87}\% < 50$	$\tau_{0.47}\% < 50$ or $\tau_{0.67}\% < 50$	$R < 0.4$
Orange	$\tau_{0.55}\% < 50$	$\tau_{0.55}\% < 50$	$\tau_F\% < 50$
	$\tau_{0.87}\% \geq 50$	$\tau_{0.47}\% \geq 50$ and $\tau_{0.67}\% \geq 50$	$R \geq 0.4$
Yellow	$50 \leq \tau_{0.55}\% < 66$	$50 \leq \tau_{0.55}\% < 66$	$50 \leq \tau_F\% < 66$
	$50 \leq \tau_{0.87}\% < 66$	$\tau_{0.47}\% \geq 50$ and $\tau_{0.67}\% \geq 50$	$0.4 \leq R < 0.8$
Lime	$50 \leq \tau_{0.55}\% < 66$	$50 \leq \tau_{0.55}\% < 66$	$50 \leq \tau_F\% < 66$
	$\tau_{0.87}\% \geq 66$	$\tau_{0.47}\% \geq 66$ or $\tau_{0.67}\% \geq 66$	$R \geq 0.8$

1: A) % of $\tau_{0.55}$ matches within EU, B) % of $\tau_{0.87}$ matches within EU; EU = $\pm(0.04+0.05\tau)$
2: A) % of $\tau_{0.55}$ matches within EU, B) % of $\tau_{0.47}$ matches within EU and/or % of $\tau_{0.67}$ matches within EU; EU = $\pm(0.05+0.15\tau)$
3: A) % of τ_{Φ} matches within EU, B) Correlation of τ_F ; EU = $\pm(0.05+0.05\tau)$
4: A) % of τ_{Φ} matches within EU, B) Correlation of τ_F ; EU = $\pm(0.05+0.20\tau)$

Fig. 3 shows quality of site-by-site comparison of total and spectral AOD over land during the summer from *Terra*, according to the color wheel of Fig. 2. To be included in this figure, a site has at least 10 matches during a given season across all years. The background image is a global surface reflectance (red, green and blue visible channels) browse image pulled from the MODIS land team website (http://landweb.nascom.nasa.gov/cgi-bin/browse/browse.cgi). Highlighted in Fig. 3 are scatterplots at four sites (GSFC, Alta Floresta, Dalanzadgad, and Jabiru), demonstrating why the site received a certain color symbol. AOD at GSFC (Maryland) is marked by green because >66% match within EU in all three channels, whereas Alta Floresta (Brazil) is marked by yellow because >50% but less than 66% match in all channels. At Dalanzadgad (Mongolia), AOD at all channels compare poorly, and is given a red symbol. Finally, Jabiru is given a blue symbol, because while AOD at 0.55 μm compares favorably within EU, at 0.47 μm it does not. Also, at Dalanzadgad, MODIS tends to overestimate AOD in clean conditions, whereas at Jabiru, MODIS tends to underestimate in clean conditions, deriving negative values of AOD.

Fig. 4 shows the quality of the site-by-site comparison by season (Winter, Spring, Summer, Fall), for *Terra*, superimposed on the global surface browse image (same as used for Fig. 3). To be included on a panel, a site should have at least 10 matches during a given season across all years. Because of seasonal changes in the surface or cloudiness, or the ephemeral nature of certain AERONET sites, not all sites are represented for all seasons. Although we plot results from Terra only, the maps (and discussions) are valid for both instruments.

By looking at the collection of panels, one can visually assess where the MODIS retrieval is performing well and also where is it not. Specific sites will be designated here (in the text) by the names given by the AERONET web site (http://aeronet.gsfc.nasa.gov). Much of the U.S. East Coast is plotted with green symbols over most seasons from both instruments, signifying very good agreement. An exception is over New York City (the CCNY and GISS sites, both near (40N, 73W)), where presumably, the urban surface is poorly represented by MODIS's surface reflectance parameterization. Many sites in Western Europe also compare well in all seasons, except for Venise (45N, 12E), a highly urbanized coastal site with inland water. Essentially, the MODIS C005 was developed based on the density of MODIS/AERONET collocations and AERONET sky retrievals available through 2005. The U.S. East Coast and Western Europe were already well sampled by AERONET, so that a robust characterization of both the aerosol (weakly absorbing; *Levy et al.,* [2007b]) and surface properties (generally vegetated; *Levy et al.,* [2007a]) were derived there. Therefore, it is not surprising that C005 products compare well in these regions. It is also not surprising that the sites with consistently poor comparisons are either heavily urbanized (CCNY, GISS and Venise) or have unique surface characteristics (Palencia, in Spain, is on a plateau, and characterized by relatively brighter surface, where the aerosol signal is comparatively weak for a dark-target retrieval. Other regions that are generally well retrieved by MODIS include southern Africa (e.g. Mongu (15S, 23E)), and the dark dense forests of the Amazon. These regions were also marked by relatively dense AERONET sampling (prior to C005) and relatively darker surfaces. We realize that the MODIS algorithm was well tuned for these regions. There, however, are locations where the results compare well, even where there were few or no AERONET measurements prior to C005. For example, sites over Japan and Korea compare 66% within expected uncertainty. *Mi et al.,* [2007] demonstrated good agreement for the Chinese sites of Taihu (31N, 120E) and Xianghe (39N, 116E). *Jethva et al.,* [2007] found similar agreement over Kanpur (26N, 80E), India, which while the general region is relatively bright, the immediate ~1km area around the sunphotometer is anomalously densely vegetated.

Although showing where the MODIS algorithm is performing well is useful, Figs. 3 and 4 are also designed to discover regions and sites where the MODIS products do not compare so well. In addition to some of the urban surfaces mentioned above, MODIS compares poorly over brighter and elevated targets. These areas include the western U.S., (e.g. BSRN-Boulder (40N, 105W) and Sevilleta (34N, 106W)) the Patagonian region of Argentina (e.g. Trelew (43S, 65W)), and the steppe and near desert plateaus of Russia and China (e.g. Irkutsk (51N, 103E) and Dalanzadgad). These scenes are too bright for optimal dark target algorithm performance, but do not exceed a brightness threshold test that would result in lowered QC (scene reflectance > 0.25 at 2.1 μm; [*Levy et al.,* 2007b]). These regions may be better suited for retrieval with the Deep Blue algorithm [Hsu et al., 2004]. Some of these regions are also marked by aerosol type that would not have been characterized by the clustering of AERONET data available in 2005.

We also find regions where we had expected better comparison - because the particular AERONET sites were available during the processing of C004, and thus used for developing C005. For example, Alta_Floresta (9S, 56W) and CUIABA-MIRANDA (15S, 56W) are located in Brazil, one near the border of the Amazon forest, the other located further south in the cerrado (savanna-like vegetation). Alta_Floresta is marked by green in some seasons (winter and fall), and yellow or red in the others. Cuiaba is generally marked red in all seasons. The scatter plots associated with these sites suggest that AOD is generally overestimated, especially as the loading increases. This is consistent with a scenario in which the assumed aerosol type has too much absorption in the optical model [e.g. *Ichoku et al.,* 2003]. In other words, in this region the *single scattering albedo*, or *SSA* is assumed too low. During the development of the C005 aerosol models, *Levy et al.,* [2007b] found that the aerosol type in the region would sometimes tend toward more absorbing particles (SSA~0.86 at 0.55 μm), or toward more moderate absorption (SSA~0.91), with a tendency to be more absorbing towards the southeast. Boxes were drawn on a map to signify where and when the stronger absorbing type should be preferred, and these borders were somewhat arbitrary. We believe that the box designating absorbing aerosol type was drawn too far west, which caused some of the systematic bias in high AOD conditions over Cuiaba. For example, AERONET Version 2 sun retrievals (http://aeronet.gsfc.nasa.gov) suggest that SSA over Cuiaba is closer to 0.9 during the dry season. Even the C005 moderately absorbing aerosol type may be too strong for characterizing Alta_Floresta, where SSA~0.91-0.92 would be more appropriate [Schafer et al. (2008; JGR)].

The last site we will explore here is Jabiru (12S, 132E) in northern Australia. This site has generally low AOD, and MODIS tends to derive negative AOD in these conditions [*Remer et al.,* 2008]. This is a systematic bias that results from overestimating surface reflectance in the visible channels. One possible reason is the presence of red soil, which may not display the same surface reflectance relationships as modeled with the C005 parameterization. Other regions, such as Brazil (including Alta_Floresta) during the rainy season, also show MODIS underestimation in clean conditions that may be a result of some other surface issue. Exploring and correcting for this negative bias is a subject of future study.

3.2 Total AOD over ocean

Fig. 5 displays the results of our collocation (including filtering for QC≥1 and AERONET site elevations less than 250 m above sea level), for total AOD (at 0.55 μm) over ocean, for Terra (left) and Aqua (right). Like Fig. 1, the color for each ordered pair represents the number of such matchups. The dashed, dotted and solid lines are the 1-1 line, EU for ocean AOD ($\tau_{EU} = \pm(0.03+0.05\tau)$, and the linear regression of the pre-sorted scatterplot, respectively. Also given for each plot are number of collocations (N), the percent within EU, the regression curve, correlation (R), and the RMS error of the fit. The plots show the quality of the matching, as both Terra and Aqua regressions hug the 1-1 line through the majority of the data, have slopes near 1, y-intercepts near zero, and R>0.9. One can see the relative dominance of AOD < 0.15, with decreasing numbers of points towards the axes limits. There is little statistical difference between the overall fits of Terra and Aqua, although Aqua's slope is further from 1.0 (0.91) than Terra's (0.97). For both instruments, less than 59% of the points lie within the dotted lines representing EU. Table 2 provides some statistics of the comparison for 0.55 μm, as well as the comparison at 0.86 μm. At 0.86 μm, the percent within EU is slightly better, but still not at the required 66% level required for validation. By slightly relaxing our EU bars to $\pm(0.04+0.05\tau)$, we can get to the >66% level (last column in Table 2). Nearly 75% fall within the interval $\pm(0.05+0.05\tau)$ originally defined by *Tanré et al*., [1997]. In keeping with our requirement of 66%, we claim over-ocean EU for C005 AOD to be

$$\tau_{EU} = \pm(0.04+0.05\tau). \qquad \mathbf{(4)}$$

We denote this revised EU interval by the term "new" (as compared to the "old" defined by Remer et al., 2005 for C004). In some sense, since >66% of C004 dataset fell within the old EU, C005 seems not as good as C004. We note, however, that some of the difference is due to slight changes in MODIS calibration of C005 radiances [e.g., Redemann et al., 2009].

Table 3: Statistics of the comparison between MODIS (Terra and Aqua) and AERONET total spectral AOD over ocean. The number of points (N) is 13,773 (10,407) for Terra (Aqua). The last two columns represent the % within EU at the old and new intervals.

Sat	Wave (μm)	Mean AOD AERO	Mean AOD MODIS	Regression equation	R	RMS	% in old	% in new
Terra	0.87	0.166	0.183	y = 0.976x + 0.015	0.913	0.077	59.99	69.74
Terra	0.55	0.192	0.210	y = 0.976x + 0.018	0.912	0.083	57.03	66.20
Aqua	0.87	0.174	0.177	y = 0.903x + 0.015	0.916	0.070	62.43	72.04
Aqua	0.55	0.201	0.205	y = 0.910x + 0.017	0.911	0.078	58.59	68.01

old: $\tau_{EU} = \pm(0.03+0.05\tau)$; new: $\tau_{EU} = \pm(0.04+0.05\tau)$

Table 3 points out an interesting difference between Terra and Aqua. Although the regression slopes for Terra are close to 1.0 in both wavelengths, the mean AOD for MODIS is 0.02 higher than for AERONET. The Aqua mean AOD is much closer to AERONET. To examine this issue, we perform another regression, this time excluding the extreme AOD events (7%) where AOD > 0.5 (according to AERONET). The results are presented in Table 4. Without the extreme events, Terra's mean bias, is still 0.017, which is more than 10% error. This discrepancy is consistent with that found by *Remer et al.,* [2008] as a difference between Terra and Aqua time series. We believe that this is bias of Terra (but not of Aqua).

Table 4: Statistics of the comparison between MODIS (Terra and Aqua) and AERONET total spectral AOD over ocean, limited to AERONET AOD < 0.5. The number of points (N) is 12,914 (9704) for Terra (Aqua). The last column is the % within EU (new) interval.

Sat	Wave (μm)	Mean AOD AERO	Mean AOD MODIS	Regression equation	R	RMS	% in new
Terra	0.87	0.134	0.151	y = 0.973x + 0.015	0.859	0.060	71.76
Terra	0.55	0.157	0.175	y = 0.972x + 0.018	0.867	0.064	68.11
Aqua	0.87	0.140	0.146	y = 0.901x + 0.015	0.885	0.050	74.64

Aqua	0.55	0.164	0.171	y = 0.901x + 0.018	0.884	0.056	70.52

New EU: $\tau_{EU} = \pm(0.04+0.05\tau)$

As we performed for over-land validation, we can create scatterplots to study the quality of the MODIS/AERONET comparison site-by-site over ocean. We summarize the results of the scatterplots on a global map, using the color wheel shown in Fig. 2, and the column from Table 2 for 'AOD ocean'. Since the comparison is for two wavelengths (0.55 and 0.86 μm) rather than three, the conditions for each color are different than for over land. A "good" site (green) is one where MODIS/AERONET AOD in both channels show 66% match within the new EU bars. A "bad" site (red) is where both channels show <50% match. Circling from green to red counterclockwise (colder colors) represents sites where the 0.55 μm channel compares favorably, but 0.86 μm compares increasingly poorly. Clockwise (warmer colors) represents sites that have poor comparison at 0.55 μm, but better comparison at 0.86 μm.

Like Fig. 3 over land, Fig. 6 displays the quality of MODIS (Terra) versus AERONET comparison for the sites used for evaluating over-ocean pixels during the summer. Also displayed are scatterplots from four sites, as examples of the different matchup characteristics (colors). It is interesting that while the collection of all comparisons looks extremely good in the global scatterplot (Fig. 5) the site-by-site comparisons do not look as consistently good. Fig. 7 displays comparisons of MODIS-Terra and AERONET for all seasons. Although, there is some difference between the distribution of colors between the Terra and Aqua maps, in general they are consistent, so only Terra is plotted here. Coastal sites along the U.S. East Coast (e.g., COVE (36N, 75W)) and Western

Europe (e.g. Venise (45N, 12E)) compare very well in both channels, during the winter and fall seasons. Over these regions, the comparison is worse in the spring and summer, especially for the 0.86 μm (blue and purple colors). During the summer, AOD derived over Saharan and Asian dust belts (e.g., Capo_Verde (16N, 22W), La_Parguera (17N, 67W), Shirahama (33N, 135E)), has errors at 0.55 μm, but most significantly at 0.86 μm (red and purple). This behavior is consistent with the sort of dust non-sphericity induced error suggested by *Levy et al.,* [2003]. MODIS retrievals near remote ocean island sites (e.g. Lanai (20N, 156W), Tahiti (17S, 149W), Guam (13N, 144E)) seem reasonable, although there are relatively few collocations, due to the temporary nature of these sites coupled with persistent cloudiness. Due to lack of financial support, the Lanai site was abandoned after 2003, and the Tahiti site has maintenance issues.

Ascension_Island (7S, 14W) provides long-term collocation, but has varied quality of spectral AOD comparison over both instruments and all seasons. All individual scatterplots, however, (not plotted) indicate significant y-offset (>0.1) and slope less than one (<0.8) at all wavelengths. Ascension_Island is an interesting site, because it is remote, yet is influenced by long-range transport of a variety of aerosol types during different seasons, such as Saharan dust and West African biomass-burning smoke in Winter, and Brazilian and southern African smoke in Summer.

4.0 Comparison of aerosol size parameters

Good or bad, we desire to characterize the EU for the aerosol size information (i.e. α and fAOD) over both land and ocean. We apply the same MODIS/AERONET matching strategy as for the total AOD, filtering by the number of valid pixels for MODIS ($\geq$5 out of 25) and valid measurements per hour ($\geq$2) for AERONET. We filter by QC threshold (QC=3 for land and QC$\geq$1 for ocean). We filter for scenes with low variability of elevation. We note, however, that according to the QA plan, the operational retrieval will not report valid size parameters for all retrieved pixels. For example, over land, the retrieval reports Ångström exponent only when the retrieved total AOD is positive (τ>0). Reporting FF requires even larger aerosol signal (τ>0.2 at 0.55 μm). The fAOD, however, is reported for all retrieved values of AOD (if AOD is negative, fAOD is given the value of zero). Over ocean, although there is no operational filtering of size products based on retrieved total AOD or QA results, we choose to further filter during our collocation process, thus ensuring sufficient aerosol signal.

4.1 Ångström Exponent and fAOD over land

The fundamental retrieved products of the C005 over-land algorithm are the total AOD at 0.55 μm, the fine mode fraction (FF), and the surface reflectance at 2.1 μm. The FF is incremented by 0.1 (from -0.1 to 1.1), and the other two parameters are fitted to the observed spectral reflectance, given the constraints of VIS/SWIR surface reflectance parameterization and seasonally/regionally defined fine dominated aerosol type. Note, that in the case of non-physical FF retrieval (-0.1 or 1.1), the FF would be adjusted to 0.0 or 1.0, and other parameters adjusted accordingly. Based on the C005 development test-bed [*Levy et al.,* 2007b], about 10% of cases resulted in non-physical FF. From sensitivity tests [*Levy et al.,* 2007b], we expected robust retrieval of total AOD, which was confirmed in section 3.1. Although the sensitivity tests and preliminary validation did not suggest significant improvement for C005 size parameters, we use this opportunity to characterize the products.

The Ångström exponent over land (α_L), derived by MODIS, relates the AOD at 0.47 and 0.66 μm (Eq 1). Since AERONET-derived AOD can be interpolated to MODIS wavelengths by quadratic interpolation [Eck et al., 1999], a comparable AERONET α_L can easily be derived. Although the operational algorithm requires only positive AOD, we shall require here that $\tau>0.2$. Thus, there are 11,184 (7019) collocations for Terra (Aqua) over land, which are plotted as density scatterplots in Fig. 8, with statistics described in Table 5.

Table 5 Statistics of the comparison between MODIS (Terra and Aqua) and AERONET Ångström exponent over land. The number of points (N) is 11,184 (7019) for Terra (Aqua).

Sat	Mean α_L AERO	Mean α_L MODIS	Regression Eq	R	rms of fit	% within ±0.45
Terra	1.295	1.145	y = 0.656x + 0.334	0.554	0.390	68.95
Aqua	1.265	1.125	y = 0.629x + 0.339	0.555	0.380	68.94

Although the mean values of Ångström exponent provided by either MODIS are both similar to AERONET (α_L~1.2), it is clear that MODIS has little skill at deriving it. The dynamic range derived from MODIS ($0.5< \alpha_L<1.8$), limited by the choice of MODIS aerosol models, is smaller than that derived by AERONET (generally $0.0<\alpha_L<2.2$). The correlations for α_L are much lower (R~0.55) than for the total AOD or even the spectral

AOD. In addition, the slopes are much less than one (~0.63) and the y-offsets are much larger than zero (~0.33). Yet we can assign EU for Ångström exponent over land ($\alpha_{L,EU}$),

$$\alpha_{L,EU} = \pm 0.45 \qquad \textbf{(6)}$$

so that 66% of the MODIS/AERONET matches are contained within them. These are placed on Fig 8 as the dashed lines. Of course, our eyes are drawn to the many points at the boundaries of MODIS retrieval space (e.g. α_L~0.6 for dust model or ~1.8 for fine-dominated models) regardless of what is derived by AERONET. Other than the extremely dense line of points where MODIS retrieves α_L~0.6, the blue colors suggest that MODIS and AERONET agree for some scenes with fine-dominated aerosols (α_L>1.5). There are many points, however, where alpha ~1.2-1.7 from AERONET paired with 0.6-1.2 for MODIS.

Note that due to the small separation between the two wavelengths (0.47 and 0.66 μm), measurement uncertainties in either channel can lead to large errors in deriving α. For example, we can envision a scene with modest signal (say τ=0.28, 0.20 and 0.16 at 0.47, 0.55 and 0.66 μm, respectively). Even if spectral AOD can be measured within ±0.01 (e.g. by AERONET), the "true" 0.47/0.66 Ångström exponent value (α_L=1.58) could be reported within ±0.28 (between 1.30 and 1.85). Therefore, while MODIS/AERONET matching is poor (±0.45), it is not unexpectedly poor. Further restricting AOD to (τ>0.4) leads to better correlation (R=0.68) and smaller EU (±0.4), but still, we cannot claim the over-land Ångström exponent to be a quantitative measure.

Although MODIS estimates of Angstrom exponent are clearly not useful globally, we can try to identify where it has some value. We again look at individual scatterplots, for specific sites and season. Fig. 9 shows MODIS versus AERONET derived Ångström exponent at GSFC (39N, 77W) during the summertime. Here, there is qualitative success of retrieving the appropriate dynamic range covered by AERONET. Although the slope is not one to one, the correlation is reasonable (R=0.71), 73% fit within ±0.45, and 66% fit within ±0.3.

The Ångström exponent is poorly derived because it is limited to the set of C005 aerosol models, which are in turn limited in dynamic range. We might consider whether there is instead a better constraint on fAOD. From AERONET, we compute fAOD from the sun-measured spectral AOD, following version 4 of the spectral deconvolution algorithm [*O'Neill et al.,* 2003] and assuming the 'Continental' aerosol model. The fAOD is defined regardless of total AOD, so we do not need to constrain to $\tau>0.2$ to have low uncertainty in its magnitude. Thus we can assess the full number of collocations (37,553 and 22,773 for Terra and Aqua). The scatterplot is presented as Fig. 10, with statistics listed in Table 6.

Table 6 Statistics of the comparison between MODIS (Terra and Aqua) and AERONET derived fAOD over land. The number of points (N) is 37,553 (22,773) for Terra (Aqua).

Sat	Mean fAOD AERO	Mean fAOD MODIS	Regression Eq	R	rms of fit	% within $\pm(0.05+0.20\tau)$
Terra	0.151	0.090	y = 0.644x + -0.013	0.817	0.120	66.15
Aqua	0.144	0.082	y = 0.577x + -0.010	0.787	0.118	66.62

The fAOD scatterplot (Fig. 10) shows many points near the one-to-one line. However, there are also a significant number of cases where MODIS is retrieving fAOD = 0.0 (approximately 10%), resulting in large differences between mean values (~0.08 for MODIS, ~0.151 for AERONET). Nonetheless, by setting EU bars for the fAOD over land as

$$\tau_{f,EU} = \pm(0.05+0.20\tau) \quad (7)$$

we can contain that 66% of the matched pairs, globally

Like we did for total AOD, we use the color wheel of Fig. 2 and Table 2, to assess the quality of the seasonal site by site comparisons. Instead of test B being based on EU for a different wavelength, the test B considers the magnitude of the correlation at the given site. In other words, "good" means correlation (R > 0.8) whereas "bad" means correlation (R < 0.4). The joint results of both tests A and B determine the color of the symbol designated at the site. For Terra, the results for each site, for each season are displayed by Fig. 11.

Overall, the best overall matches are for the eastern half of the U.S. during the summer. Both the correlation and number of matches within EU are high. This is not surprising given the plethora of AERONET information obtained for this region during C005 development. The worst performance (red colors) is seen at the semi-bright sites that surround the deserts of the world. Of course this is also expected.

We can only begin to assess the quality of the fAOD at the other sites. The U.S. East Coast during the winter and spring consistently shows cyan or blue colors, indicating good matching within EU, but with low correlation. This may indicate that, although the MODIS assumptions are generally correct for these regions/seasons with low signal, there is low sensitivity to small perturbations.

Given the dominance of green and bluish colors throughout the globe, we believe that the "true" conditions are generally well captured by the C005 LUT and surface parameterizations. Still, however, the MODIS estimates of fAOD are clearly wrong in some areas, even when there should be sufficient aerosol signal. For example, although AOD from MODIS compares well to AERONET at Kanpur, India, *Jethva et al.,* [2007] pointed out that C005 will almost exclusively retrieve dust (coarse-dominated aerosol), during the fall and winter, when pollution (fine aerosol) should have been dominant. Similar behavior is demonstrated in Fig 11, as indicated by the purple and red symbols. We performed a sensitivity study that suggested that if the assumed seasonal aerosol type was highly absorbing (SSA~0.86) instead of the (default) moderately absorbing model (SSA~0.91), the number of false dust retrievals would be reduced. A slight revision of surface reflectance parameterization would also help. Evaluation of revised AERONET data (known as Version 2; http://aeronet.gsfc.nasa.gov) confirms that the aerosol at Kanpur during the fall and winter may be more absorbing (~0.87-0.88) than previously believed.

For sites, such Kanpur, the aerosol signal is so strong there that better constrained surface and aerosol models will help. Over the bulk of the globe, however, the MODIS observations are likely to be insufficient for retrieving aerosol size parameters over land, meaning that external and/or additional constraint information (say from a model or another satellite product) may be required.

4.2 Ångström Exponent and fAOD over ocean

Although MODIS was not expected to, and does not, derive accurate aerosol size properties over all land surfaces, it was expected that it would do better over ocean. Fig. 12 and Table 7 compare the over water Ångström exponent (α_O), defined using 0.55 and 0.86 μm, constrained where total AOD > 0.15. Although this constraint is inconsistent with over land (AOD > 0.2), we use it because we expect better sensitivity over ocean, and it is consistent with a constraint used by Remer et al., [2005]. Fig. 13 and Table 8 assess derived fAOD for all collocations (not filtered by AOD).

Table 7 Statistics of the comparison between MODIS (Terra and Aqua) and AERONET Ångström exponent over ocean ($\tau > 0.15$). The number of points (N) is 4259 (3287) for Terra (Aqua).

Sat	Mean α_O AERO	Mean α_O MODIS	Regression Eq	R	rms of fit	% within ±0.3
Terra	0.943	0.867	y = 0.685x + 0.211	0.873	0.227	69.88
Aqua	0.880	0.864	y = 0.630x + 0.311	0.833	0.233	64.47

Table 8 Statistics of the comparison between MODIS (Terra and Aqua) and AERONET fAOD over ocean. The number of points (N) is 13,773 (10,407) for Terra (Aqua).

Sat	Mean fAOD AERO	Mean fAOD MODIS	Regression Eq	R	rms of fit	% within $\pm(0.04+0.05\tau_f)$
Terra	0.118	0.125	y = 0.809x + 0.023	0.846	0.059	67.12
Aqua	0.120	0.122	y = 0.718x + 0.028	0.799	0.061	64.79

Over ocean, the mean values of Ångström exponent derived by MODIS and AERONET are similar (α_O~0.9), and both MODIS instruments show skill at deriving it. Over ocean, the dynamic range derived from MODIS ($-0.2<\alpha_O<3.0$) seems sufficient at capturing the range of AERONET. Although the correlations for α_O are not much lower (R = 0.873 and 0.833 for Terra and Aqua, respectively) than for the total AOD, their slopes are much less than one (=0.685 and 0.630) with y-offsets much larger than zero (=0.21 and 0.31). Whereas both instruments showed nearly identical regressions over land, there are differences to the MODIS/AERONET Ångström exponent comparisons between Terra and Aqua. It is interesting that although the AERONET mean during Aqua overpass is lower (α_O=0.88 than that for Terra (α_O=0.94), both MODIS instruments derive α_O~0.865. The difference in AERONET means may be in part due to different sites representing different years for Terra and Aqua, which is not equally captured by the two satellites. While both satellite instruments underestimate their respective means, Terra's bias is even more pronounced. However, the regression coefficients for Terra are generally better than those for Aqua. Here, we assign EU of ocean Ångström exponent as

$$\alpha_{O,EU} = \pm 0.3, \quad \textbf{(8)}$$

so that approximately 66% of the MODIS/AERONET matches are contained within them. These are placed on Fig. 12 as the dashed lines.

The mean values of the fAOD (~0.12) are very similar for MODIS and AERONET, as well as similar for both MODIS overpasses. However, we note that both regressions show less than one slope (<0.81) and positive y-offsets (>0.02). Like shown for α_O, the mean fAOD seems to match somewhat less for Terra than Aqua, although the regression coefficients are stronger. We set EU for fAOD (τ_{fEU}) over ocean as

$$\tau_{fEU} = \pm(0.04+0.05\tau_f). \qquad \textbf{(9)}$$

to contain approximately 66% of the points of Fig. 13 (dashed lines). Most of the collocations are clustered at low AOD (measured by AERONET), however there are a few points at higher fAOD. These high fAOD points are generally underestimated by MODIS. We realize, although we successfully defined EU for fAOD over ocean, that it does not fully characterize the distribution of the biases displayed by Fig 13.

Essentially, we believe the discrepancies between MODIS and AERONET over ocean are mainly a result of discrepancies in assumed versus real aerosol optical properties. Because of retrieval artifacts seen in dust environments (because of dust non-sphericity), MODIS will compensate by using larger amounts of fine mode to fit the spectral reflectance. Thus, it tends to overestimate Ångström exponent and underestimate aerosol size in dusty conditions. The fAOD may be overestimated. Because the C005 aerosol models [*Remer et al.,* 2006] over ocean do not include much absorption, cases of pollution with significant black carbon content and certain biomass burning cannot be correctly fitted to the spectral reflectance. The MODIS algorithm will compensate by using a larger particle, and thus underestimate Ångström exponent and overestimate aerosol size. The fAOD will be underestimated in these conditions.

Once more, we describe a color wheel (Fig. 2 plus Table 2) to indicate, site-by-site and seasonally, the quality of fAOD comparison with AERONET. We represent the quality of comparison , in both expected uncertainty and correlation space. We set a “good” comparison (green) where >66% of collocations fall with expected uncertainty ($\pm(0.05+0.05\tau)$) and have correlation coefficients (R>0.8). A “bad” comparison (red) describes a comparison where <50% fall within uncertainty bars, and have R<0.4. Going counterclockwise (cooler colors) are cases with higher %, but lower correlation, whereas going clockwise (warmer colors) represents the opposite. The results are presented as Fig. 14.

Generally, Fig. 14 shows that in much of the globe, fAOD compares within EU (green, cyan and blue colors). However, at most sites, the correlation is lower than the global value of 0.8. Most of these points indicate that neither dust nor biomass burning are dominant.. The worst overall comparisons are seen at sites in the path of Asian aerosol transport (expected mix of pollution and dust), especially during the spring maximums. The correlation is almost always low (R<0.4) in the paths of Atlantic and Pacific dust, and higher in Europe. Although we do not display the plot for Aqua, we note that the symbols have similar color distributions. An interested exception is over the dust belts, where there are more blue symbols, suggesting more matches within EU, but still with low correlation.

5.0 Changes of AOD comparison over time

If we desire to use the MODIS data record for assessment of aerosol trend, we must demonstrate that there is no trend inherent in the MODIS instruments. We have already seen that there is a ~0.015 offset between Terra and Aqua over ocean (*Remer et al.,* [2008]) with no such offset over land. This, we understand is a result of absolute calibration differences (of less than the required 2%) in one or more channels used for the over ocean retrieval, that may not be used for retrieving over land. To believe in any MODIS derived aerosol trend, we must also demonstrate that the MODIS aerosol products are not changing in time.

We know that the MODIS calibrations are continuously being updated due to systematic degradation in sensor optics and electronics (e.g. Xiong et al., 2008). We would like to know whether these continuous updates have successfully maintained the accuracy of the MODIS observed spectral reflectances over time. We, however, do not have a known "truth" for assessing observed (top of atmosphere) spectral radiance, everywhere and throughout time. For successful retrieval of ocean color products, the MODIS ocean color team (http://oceancolor.gsfc.nasa.gov) requires better than 2% accuracy for measured radiance in low light. To attain that accuracy, they continuously perform *vicarious* calibration, meaning that they adjust the MODIS calibration coefficients so that a retrieved product will match a ground truth measurement of a particular ocean color parameter [*Franz et al.,* 2007]. This sort of tuning keeps the MODIS record consistent with surface measurements and measurements of previous ocean color measurement missions. However, 1) the vicarious calibration is over one site only, 2) it is intended for very low light conditions over the ocean (far from glint, clouds, land, and thick aerosol), and 3) the ocean color channels do not include the NIR and SWIR channels used for the dark target aerosol retrieval. The aerosol retrieval is not limited to the conditions at one site, and must work over medium and brighter surfaces over land and in heavy aerosol loadings.

We have the advantage of being able to evaluate the MODIS aerosol retrieval at multiple AERONET sites, including some that have operated throughout a long duration of the MODIS observing period. Table 9 lists selected AERONET sites with a seven-year or longer record, identifying which are used to evaluate over land and/or ocean aerosol retrievals.

Table 9: AERONET sites with long-term records used for time series assessment

Site Name	**(Lat, Long)**	**Land and/or Ocean**
Alta_Floresta	(9S,56W)	L
Ascension_Island	(7S,14W)	O
Banizoumbou	(13N,2E)	L
BONDVILLE	(40N,88W)	L
Capo_Verde	(16N,22W)	O
Cart_Site	(36N,97W)	L
Dakar	(14N,16W)	L, O
Dalanzadgad	(43N,104E)	L
El_Arenosillo	(37N,6W)	L, O
GSFC	(38N,76W)	L
Ispra	(45N,8E)	L
Mongu	(15S,23E)	L
Ouagadougou	(12N,1W)	L
Sevilleta	(34N,106W)	L
Skukuza	(24S,31E)	L
Venise	(45N,12E)	L, O

Like *Mi et al* [2007], we define the *Fraction of Expected Uncertainty* (*FEU*) for AOD as

$$FEU = \frac{\tau_{MODIS} - \tau_{AERONET}}{|\tau_{EU}|}, \quad \textbf{(10)}$$

where the || is the magnitude of the EU for the matched parameter (e.g. (A+Bτ) as defined in Eq. 2). Thus, $|FEU| \leq 1$ represents the case where MODIS agrees with AERONET within EU (a “good” match), and $|FEU| > 1$ represents a case where it does not (a “bad” match). In addition, the signed value of the FEU denotes whether MODIS is biased high (positive) or low (negative) compared to AERONET.

We assume that the measurement errors from the collection of AERONET instruments are random, so that we can plot the time series of the FEU. A change in FEU (MODIS/AERONET comparison) over time would indicate that MODIS is changing over time. Fig. 15 plots the time series of FEU for Terra (left) and Aqua (right) over land, where the EU is defined by Eq. 3. We use all collocations from the over-land sites listed in Table 9, providing 6512 for Terra and 3402 for Aqua.

For Aqua, (from 2002 through 2008), there is no clear or significant trend in the FEU. Overall, there is a slight negative bias shown by MODIS, which is consistent to that suggested by Table 1 (for all MODIS/AERONET collocations). For Terra, however, there is a statistically significant trend, as measured by a T-test with 6512 points and correlation of R=0.215. Early in the Terra mission, MODIS is biased high, which becomes a low bias sometime after 2004 (near day 1500). Averaged over the entire time series (as in Table 1 for all collocations), however, MODIS-Terra shows no bias.

Over ocean, we define the AOD EU by Eq. 4. We use all collocations for the over-ocean sites listed in Table 9, providing 2055 points for Terra and 1767 for Aqua. Fig. 16 shows that there is no significant trend for FEU for either Terra or Aqua over ocean. There is a small positive bias to Terra with an even smaller negative bias to Aqua. Again, these results are consistent with those of Table 3, for all collocations over ocean.

Based on Figs. 15 and 16, we do not have enough information to explain why only Terra's over land retrieval is changing. Analysis of spectral AOD show that all channels show a similar trend. Except for a few sites, most of the long-term AERONET stations are characterized by discrete episodes of high AOD. Thus, when we try to filter by the additional criteria of sufficient AOD signal (e.g. $\tau \geq 0.2$ over land or $\tau \geq 0.15$ over ocean), the statistics of fAOD and Ångström exponent become rather sparse. Time series of size parameter FEU are not as easy to interpret, and therefore are beyond the scope of this paper.

However, we recall that the over land retrieval inverts reflectance in three channels (0.47, 0.66 and 2.1 μm), whereas the over ocean aerosol retrieval inverts in six channels (0.55, 0.66, 0.86, 1.24, 1.64 and 2.12 μm). The 0.47 μm channel is used for land and not for ocean aerosol retrieval, and like other blue and deep blue channels (e.g. 0.412 and 0.443 μm) aboard MODIS, it is affected by polarization and directional signal issues. This is especially true for Terra, which suffers from more significant optical 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 it is entirely possible that a systematic change in the 0.47 μm channel is capable of driving the trend seen in MODIS-Terra's FEU record. Preliminary analysis of the 0.47 μm reflectance, included with our MODIS/AERONET collocations over ocean (which has no trend in AOD FEU), suggest that there is such a residual time dependent trend. Although it is beyond the scope of this paper to analyze for statistical significance and other details, we can see how the process of MODIS validation can help reveal hidden biases or uncertainties in the calibration algorithms.

6.0 Conclusions

As a result of deficiencies observed for previous versions/collections of MODIS aerosol products over ocean and 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; 2007b; *Remer et al.,* 2006], and used for deriving Collection 5 (C005). Here, we used ground truth sunphotometer (AERONET) data to evaluate eight years of the MODIS dark-target products, including the total AOD and several aerosol size products. We defined an expected uncertainty (EU) for a given parameter, which is an envelope that contains at least 66% of the matched pairs (MODIS versus AERONET). Some of the products we consider to be *validated* within their expected EU, although it is up to data users to decide whether our defined EU is small enough for a particular application.

Over dark-land targets, more than 69% of MODIS total AOD at several wavelengths (nominally 0.55 μm) matched those of AERONET within the EU defined by previous studies (i.e., $\tau_{EU} = \pm(0.05+0.15\tau)$). This satisfied our validation criteria. Over ocean, we found that the EU defined by previous evaluations was too restrictive. However, by slightly relaxing the EU to $\pm(0.04\pm0.05\tau)$ satisfied the 66% matching requirement for validation.

Although we demonstrated *global* validation of total AOD over each surface type, we expected that there might be systematic discrepancies over certain regions and/or seasons. We created a metric to assess the quality of the comparison, site by site, season by season, and separated by land and ocean as well as by Terra and Aqua. We defined a "good" comparison to be one where >66% of MODIS/AERONET pairs matched within EU at a particular site and season, and a "bad" comparison to be one where <50% were matched within EU. In general, over-land AOD was well matched in regions that were both vegetated (dark targets optimal for the MODIS algorithm), and also extensively sampled by AERONET prior to the development of the algorithm. These included the eastern United States, Western Europe and Southern Africa. Some regions, like southeastern Asia, were not previously sampled by AERONET, but compared well because they have similar surface properties. Although expected for a dark-target algorithm, poor comparisons were seen over brighter and elevated targets, such as the western United States and central Asia. Discrepancies were also seen over northern Australia and other areas known for reddish color soils. Yet, despite prior AERONET sampling and generally dark enough surface, we found poor comparison over the

Brazilian savanna that implied that the aerosol model assumed for MODIS had a single scattering albedo that was too low. Over ocean, the poorest comparisons were either in the known dust transport pathways (e.g. off Africa and East Asia), or where the aerosols are believed to have strong absorption (e.g. off Southern Africa or southern Asia). Since the current suite of C005 aerosol models are spherical and weakly absorbing, it was consistent that the comparison would be better over the open ocean or downwind of the developed nations (e.g., off the US East Coast). In general the comparisons were similar for both Terra and Aqua.

In response to community needs and concerns, we calculated EU for size parameters, in particular the Ångström exponent and fine AOD. Globally, we found that Ångström exponent over land (α_L) and ocean (α_O) agreed with AERONET values to within ±0.45 and ±0.3, respectively. Due to the lack of the full range of aerosol model choices, the dynamic range of MODIS's α_L (over land) was insufficient to capture the true range observed by AERONET. MODIS's Angstrom exponent also was not well correlated with AERONET values over land (R~0.55), suggesting that it cannot be considered a quantitative product, globally. There are regions, however, such as the eastern United States (e.g. GSFC site), where α_L displays some skill. Over ocean, α_O showed good correlation (R~0.8), although with slope less than unity. We believe the over ocean discrepancies are due to a combination of too little absorption and too much sphericity in the models to accurately retrieve large amounts of very small (absorbing biomass burning) and large (dust) aerosols. Analyses of retrieved fine AOD over both land and ocean showed that their discrepancies were consistent with those demonstrated by the Ångström exponent comparisons.

Finally, we derived the fraction of expected uncertainty (FEU) to characterize how the comparison of total AOD may be changing over time. From MODIS/AERONET comparisons at several long-term sites, we found that compared to AERONET, there is no systematic change in the MODIS data over time over ocean for either MODIS sensor. Although one must remember that MODIS data and AERONET observations are not exactly collocated over the ocean, there is some evidence that Terra has been slightly overestimating, whereas Aqua may have been slightly underestimating the true AOD over ocean. Over land, Aqua comparisons do not show a change over time, and the mean values from both AERONET and MODIS are comparable. However, there is a statistically significant change in the MODIS/AERONET comparison for Terra over land, from MODIS overestimating early in the mission, to underestimating in the later period. We believe the issue is a degradation of Terra's optical response in the 0.47 um channel (used in the land algorithm only) that results in very small errors to the sensor's calibration over time. The calibration issues should be updated in a future reprocessing of MODIS data.

In this paper, we have assessed the performance of the MODIS aerosol (AOD and size parameters) compared to AERONET observations. We have not attempted to characterize the MODIS data that is not collocated with AERONET. However, we now have defined a quantitative EU for some of the MODIS products. By learning where and when the MODIS algorithm appears to fall short of meeting expectations, we are performing necessary steps for future improvements. We now have a solid base in which to develop algorithms that may be used for deriving future collections of MODIS data.

Acknowledgements: We are deeply grateful to Wayne Newcomb, who was a vital member of the AERONET team from the genesis of the project until he sadly passed away in December 2008. We miss him, his dedication to details and his ability to talk a novice through a Cimel installation via a phone link across countless miles and time zones. Without Wayne and the many AERONET Principal Investigators and site managers, the data base used in this study would not be possible. This work has been funded by NASA research announcement NNH06ZDA001N-EOS, managed by Hal Maring.

References

Ackerman, S.A., K.I. Strabala, W.P. Menzel, R.A. Frey, C.C. Moeller and L.E. Gumley, 1998: Discriminating clear sky from clouds with MODIS. *J. Geophys. Res.*, **103**, 32139-32140.

Al-Saadi, J., J. Szykman, R. B. Pierce, C. Kittaka, D. Neil, D. A. Chu, L. Remer, L. Gumley, E. Prins, L.Weinstock, C. MacDonald, R. Wayland, F. Dimmick and J. Fishman, 2005: Improving National Air Quality Forecasts with Satellite Aerosol Observations. *Bull. Am. Met. Soc.* 86, 1249-1261.

Anderson T.L., R.J Charlson, D.M. Winker, J.A. Ogren and K. Holmen, 2003: Mesoscale variations of tropospheric aerosols, . *J. Atmos. Sci., **60**,* 119-136.

Franz, B. A. S. W. Bailey, P. J. Werdell, and C. R. McClain, "Sensor-independent approach to the vicarious calibration of satellite ocean color radiometry," Appl. Opt. 46, 5068-5082 (2007)

Chu, D. A., Y. J. Kaufman, C. Ichoku, L. A. Remer, D. Tanre, and B. N. Holben, 2002: Validation of MODIS aerosol optical depth retrieval over land. *Geophys. Res. Lett.*, **29**, doi: 10.1029/2001GLO13205.

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**, 20 673-20 696.

Dubovik, O., B.N.Holben, T.F.Eck, A.Smirnov, Y.J.Kaufman, M.D.King, D.Tanre, and I.Slutsker, 2002: Variability of absorption and optical properties of key aerosol types observed in worldwide locations, *J.Atm.Sci.,* **59**, 590-608 .

Eck, T.F., B.N.Holben, J.S.Reid, O.Dubovik, A.Smirnov, N.T.O'Neill, I.Slutsker, and S.Kinne, 1999: Wavelength dependence of the optical depth of biomass burning, urban and desert dust aerosols, *J. Geophys. Res.,* **104**, 31 333-31 350.

Franz, B. A. S. W. Bailey, P. J. Werdell, and C. R. McClain, 2007: Sensor-independent approach to the vicarious calibration of satellite ocean color radiometry, *Appl. Opt*. ***46***, 5068-5082.

Gao, B.-C., Y.J. Kaufman, D. Tanré and R.-R. Li, 2002: Distinguishing tropospheric aerosols from thin cirrus clouds for improved aerosol retrievals using the ratio of 1.38-µm and 1.24-µm channels. *Geophys. Res. Lett.*, **29**, 1890, doi:10.1029/2002GL015475.

Holben, B.N., T.F. Eck, I. Slutsker, D. Tanré, J.P. Buis, A. Setzer, E. Vermote, J.A. Reagan, Y.J. Kaufman, T. Nakajima, F. Lavenu, I. Jankowiak and A. Smirnov, 1998: AERONET--A federated instrument network and data archive for aerosol characterization. *Rem. Sens. Environ.*, **66**, 1-16.

Hubanks, P.A., 2007: MODIS Atmosphere QA Plan for Collection 005 Deep Blue Aerosol Update Version 3.5, available from http://modis-atmos.gsfc.nasa.gov/reference_atbd.php, 61 pps.
Hsu, N. C., S. C. Tsay, M. D. King, and J. R. Herman, 2004: Aerosol properties over bright-reflecting source regions. *IEEE Trans. Geosci. Remote Sens.*, **42**, 557-569.

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

Ichoku, C., L. A. Remer, Y. J. Kaufman, R. Levy, D. A. Chu, D. Tanre, and B. N. Holben, 2003: MODIS observation of aerosols and estimation of aerosol radiative forcing over southern Africa during SAFARI 2000. *J. Geophys. Res.*, **108** (D13), 8499, doi: 10.1029/2002JD002366.

Ichoku, C., L. A. Remer, and T. F. Eck, 2005: Quantitative evaluation and intercomparison of morning and afternoon MODIS aerosol measurements from Terra and Aqua. *J. Geophys. Res.* **110**, D10S03, doi: 10.1029/2004JD004987.

IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Jethva, H., S.K. Satheesh and J. Srinivasan, 2007: Assessment of second-generation MODIS aerosol retrieval (Colleciton 005) at Kanpur, India. Geophys. Res. Lett., 34, L19802, doi:10.1029/2007GL029647.

Kaufman, Y. J., and C. Sendra, 1988: Algorithm for atmospheric corrections of visible and Near IR satellite imagery. *Int. J. Rem. Sens.*, **9**, 1357-1381.

Kaufman, Y. J., D. Tanre, L. Remer, E. Vermote, A. Chu, and B. N. Holben, 1997: Operational remote sensing of tropospheric aerosol over land from EOS Moderate Resolution Imaging Spectroradiometer. *J. Geophys. Res.* (Atmos.), **102**, 17051-17067.

Kaufman, Y. J., O. Boucher, D. Tanre, M. Chin, L. A. Remer, and T. Takemura, 2005: Aerosol anthropogenic component estimated from satellite data. Geophys. Res. Lett. **32**, L17804, doi:10/1029/2005GL023125.

Kleidman, R.G., N.T. O'Neill, L.A. Remer, Y.J. Kaufman, T.F. Eck, D. Tanré, and B.N. Holben 2005: Comparison of moderate resolution Imaging spectroradiometer (MODIS) and aerosol robotic network (AERONET) remote-sensing retrievals of aerosol fine mode fraction over ocean. *J. Geophys. Res.*, **110** D22205, doi:10.1029/2005JD005760.

Levy, R.C., L.A. Remer, D. Tanré, Y.J. Kaufman, C. Ichoku, B.N. Holben, J.M. Livingston, P.B. Russell and H. Maring, 2003: Evaluation of the MODIS retrievals of dust aerosol over the ocean during PRIDE. *J. Geophys. Res.*, **108** **(**D14), 10.1029/2002JD002460

Levy, R. C., L. A. Remer, J. V. Martins, Y. J. Kaufman, A. Plana-Fattori, J. Redemann, P. B. Russell, and B. Wenny, 2005: Evaluation of the MODIS aerosol retrievals over ocean and land during CLAMS. *J. Atmos. Sci.*, **62**, 974-992.

Levy, R. C., L. A. Remer, and O. Dubovik, 2007a: Global aerosol optical properties and application to MODIS aerosol retrieval over land. *J. Geophys. Res.*, 112, D13210, doi:10.1029/2006JD007815.

Levy, R. C., L. Remer, S. Mattoo, E. Vermote, and Y. J. Kaufman, 2007a: Second-generation algorithm for retrieving aerosol properties over land from MODIS spectral reflectance. *J. Geophys. Res.*, 112, D13211, doi:10.1029/2006JD007811.

Levy, R.C.,. G. G. Leptoukh, R. Kahn, V. Zubko, A. Gopalan and L.A. Remer, 2009b: A critical look at deriving monthly aerosol optical depth from satellite data, *, IEEE Trans. Geosci. Remote Sens.,* in press.

Levy, R.C.., L.A. Remer, D. Tanré, Y.J. Kaufman and S. Mattoo, 2009: Algorithm for Remote Sensing of Tropospheric Aerosol from MODIS: Collection 005 – Revision 2. Algorithm Theoretical Basis Document available at http:// modis-atmos.gsfc.nasa.gov/reference_atbd.php.

Li, R.-R., Y.J. Kaufman, B.-C. Gao and C.O. Davis, 2003: Remote sensing of suspended sediments and shallow coastal waters. *IEEE TGARS*, **41**, 559-566.

Martins, J.V., D. Tanré, L.A. Remer, Y.J. Kaufman, S. Mattoo and R. Levy, 2002: MODIS Cloud screening for remote sensing of aerosol over oceans using spatial variability. *Geophys. Res. Lett.*, **29**, 10.1029/2001GL013252.

Mi, W., Z. Li, X. Xia, B. Holben, R. Levy, F. Zhao, H. Chen, and M. Cribb, 2007: Evaluation of the Moderate Resolution Imaging Spectroradiometer aerosol products at two Aerosol Robotic Network stations in China, *J. Geophys. Res., **112***, D22S08, doi:10.1029/2007JD008474.

O'Neill, N.T., T.F.Eck, , A.Smirnov, B.N.Holben, and S.Thulasiraman, Spectral discrimination of coarse and fine mode optical deph, J. Geophys. Res., 108(D17), 4559, doi:10.1029/2002JD002975, 2003.

Redemann, J., B. Schmid, J. A. Eilers, R. Kahn, R. C. Levy, P. B. Russell, J. M. Livingston, P. V. Hobbs, W. L. Smith, and B. N. Holben, 2005: Suborbital measurements of spectral aerosol optical depth and its variability at subsatellite grid scales in support of CLAMS 2001. *J. Atmos. Sci.*, **62**, No. 4, 993-1007.

Redemann, J., Q. Zhang, J. Livingston, P. Russell, Y. Shinozuka, A. Clarke, R. Johnson, and R. Levy, 2009: Testing aerosol properties in MODIS (MOD35/MYD35) Collection 4 and 5 using airborne sunphotometer observations in INTEX-B/MILAGRO, *Atmos. Chem . Phys.*, in preparation.

Redemann, J., Q. Zhang, B. Schmid, P. B. Russell, J. M. Livingston, H. Jonsson, and L. A. Remer, 2006: Assessment of MODIS-derived visible and near-IR aerosol optical properties and their spatial variability in the presence of mineral dust. *Geophys. Res. Lett.*, **33**, L18814, doi:10.1029/2006GL026626.

Remer, L.A., D. Tanré, Y.J. Kaufman, C. Ichoku, S. Mattoo, R. Levy, D.A. Chu, B.N. Holben, O. Dubovik, A. Smirnov, J.V. Martins, R.-R. Li and Z. Ahmad, 2002: Validation of MODIS aerosol retrieval over ocean. *Geophys. Res. Lett.*, **29**, 10.1029/2001GL013204.

Remer, L. A., Y. J. Kaufman, D. Tanre, S. Mattoo, D. A. Chu, J. V. Martins, R. R. Li, C. Ichoku, R. C. Levy, R. G. Kleidman, T. F. Eck, E. Vermote, and B. N. Holben, 2005: The MODIS aerosol algorithm, products and validation. *J. Atmos. Sci.*, **62**, 947-973.

Remer L. A., et al. 2008: Global aerosol climatology from the MODIS satellite sensors, *J. Geophys. Res.*, **113**, D14S07, doi:10.1029/2007JD009661.

Smirnov A., B.N.Holben, T.F.Eck, O.Dubovik, and I.Slutsker, 2000: Cloud screening and quality control algorithms for the AERONET database, *Rem.Sens.Env.*, **73**, 337-349.

Smirnov, A., B.N.Holben, Y.J.Kaufman, O.Dubovik, T.F.Eck, I.Slutsker, C.Pietras, and R.Halthore, 2002: Optical Properties of Atmospheric Aerosol in Maritime Environments, *J.Atm.Sci.*, **59**, 501-523.

Tanré, D., M. Herman, and Y. Kaufman, 1996: Information on the aerosol size distribution contained in the solar reflected spectral radiances. *J. Geophys. Res.*, **101**, 19043-19060.

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.* (Atmos.), **102**, 16971-16988.

Yu, H., Y. J. Kaufman, M. Chin, G. Feingold, L. Remer, T. Anderson, Y. Balkanski, N. Bellouin, O. Boucher, S. Christopher, P. DeCola, R. Kahn, D. Koch, N. Loeb, M. S. Reddy, M. Schulz, T. Takemura, and M. Zhou, 2006: A review of measurement-based assessments of aerosol direct radiative effect and forcing. *Atmos. Chem . Phys.*, **6**, 613-666.

Xiong, X., J. Sun, W. Barnes, V. Salomonson, J. Esposito, H. Erives, and B. Guenther, 2007: Multiyear On-Orbit Calibration and Performance of Terra MODIS Reflective Solar Bands*, IEEE Trans. Geosci. Remote Sens.,* 45(4), 879-889.

Figures

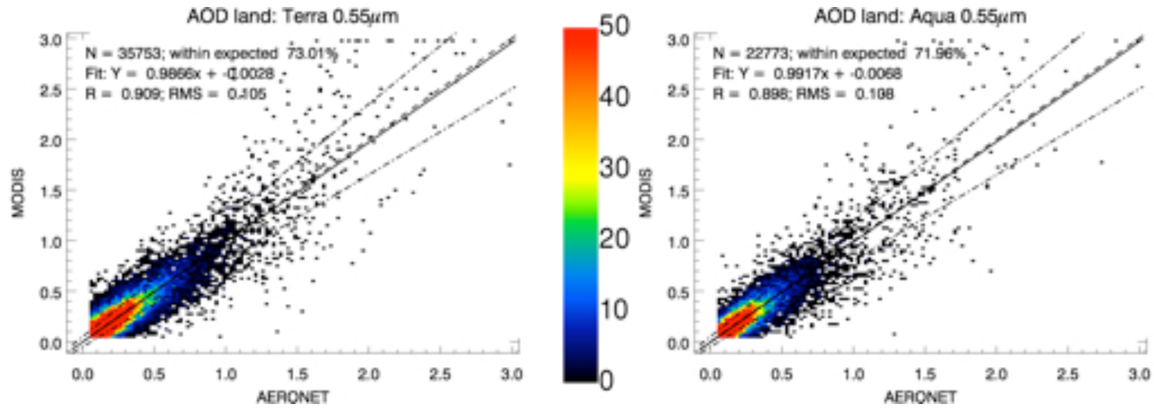

Figure 1: MODIS C005 AOD retrievals over dark land (QC=3) at 550 nm as a function of AERONET observations collocated in space and time, for the entire mission of Terra (left) and Aqua (right). The data were sorted according to ordered pairs (AERONET, MODIS) of AOD in 0.025 intervals, so that color represents the number of cases (colorbar) having that particular ordered pair value. The dashed, dotted and solid lines are the 1-1 line, EU for land AOD (±0.05 ± 0.15τ), and the linear regression of the pre-sorted scatterplot, respectively. At the top of the plot is text that describes: the number of collocations (N), the percent within expected uncertainty, the regression curve, correlation (R), and the RMS error of the fit.

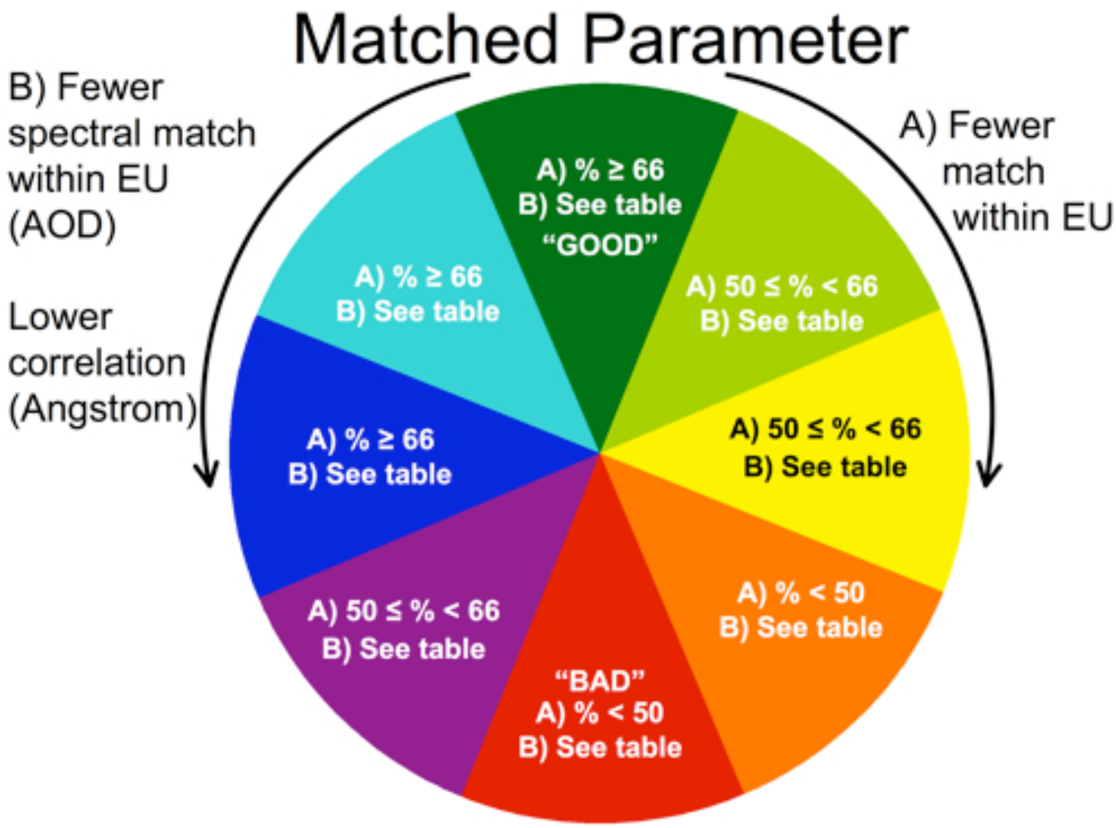

Figure 2: Guide to interpreting seasonal, site-by-site maps of MODIS/AERONET matching quality of certain derived parameters (Figs XXXXX). The color indicates the joint results from of two conditional tests, where each test's result may be described subjectively (e.g., good, marginal, bad). For all parameters, test "A" considers how many of the MODIS/AERONET pairs match within the EU defined for the given parameter, such that the case where >66% match is denoted as "good" and <50% match is "bad." The details of test "B" depend on which parameter is being matched. The green color represents a good overall match, meaning that the result of both tests A and test B is "good". A red color represents the case that the result from both tests is "bad." Circling from green to red counterclockwise (colder colors) represents sites with better results from test A than test B, whereas going clockwise (warmer colors) represents sites with better results from test B than test A. Details of the tests for given parameters is given in Table 2.

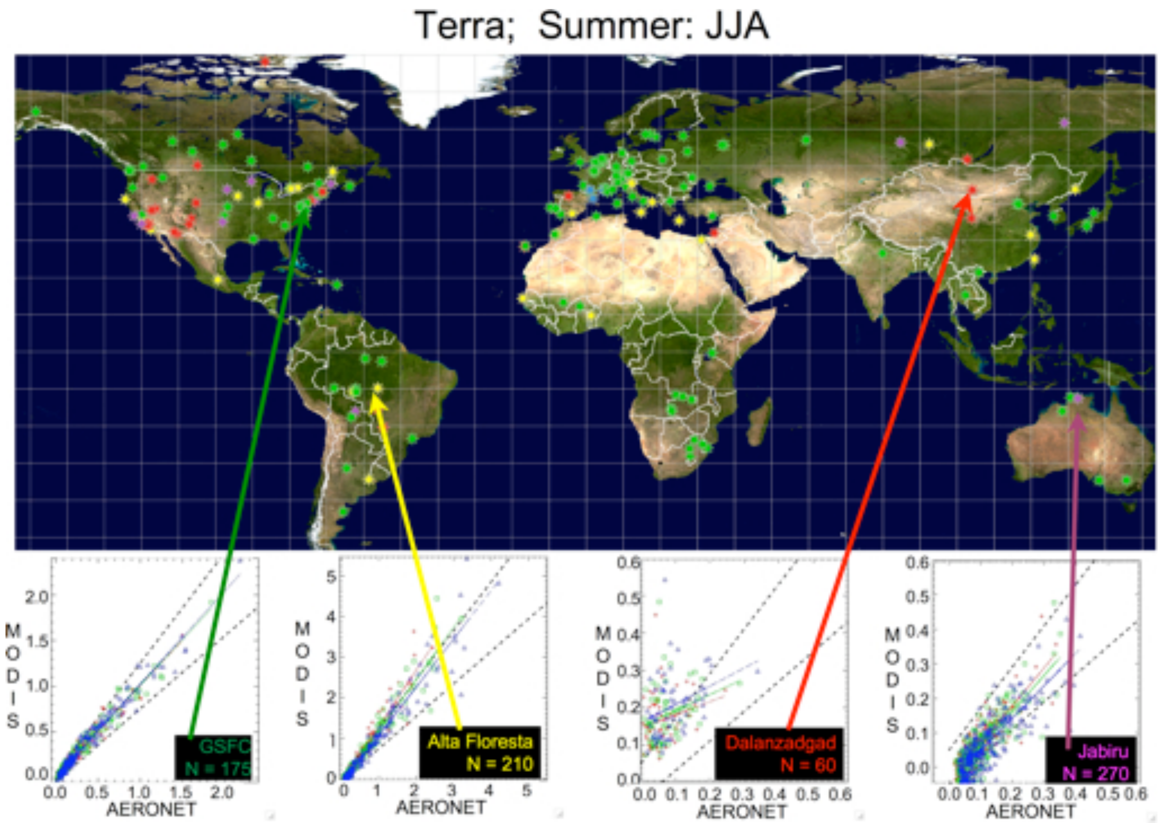

Figure 3: "Quality" of Terra-MODIS/AERONET comparisons of total and spectral AOD over land at each site, from Terra, during the summer. The color at each represents the quality of the comparison (Fig. 2 and Table 2). The comparisons of spectral AOD (different symbols: blue - 0.47 μm, green - 0.55 μm, red - 0.66 μm) at four sites are plotted, including: GSFC (38N, 76W), Alta Floresta (9S, 56W), Dalanzadgad (43N, 104E) and Jabiru (12S, 132E). The dotted lines for each scatterplot are the expected uncertainty (±0.05 ±0.15τ) over land.

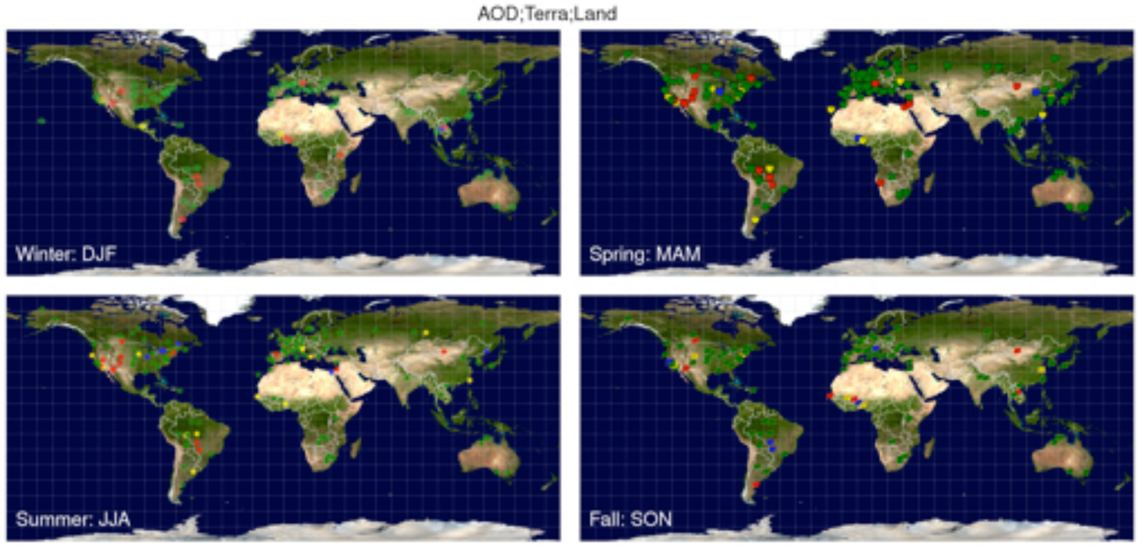

Figure 4: "Quality" of Terra-MODIS/AERONET comparisons of total and spectral AOD over land at each site, separated by season. Icons (Snowflake, Tulip, Sunshine, Leaf) represent each season and colors represent the quality of the comparison (Fig. 2 and Table 2). Note that not all sites have valid collocations for all seasons.

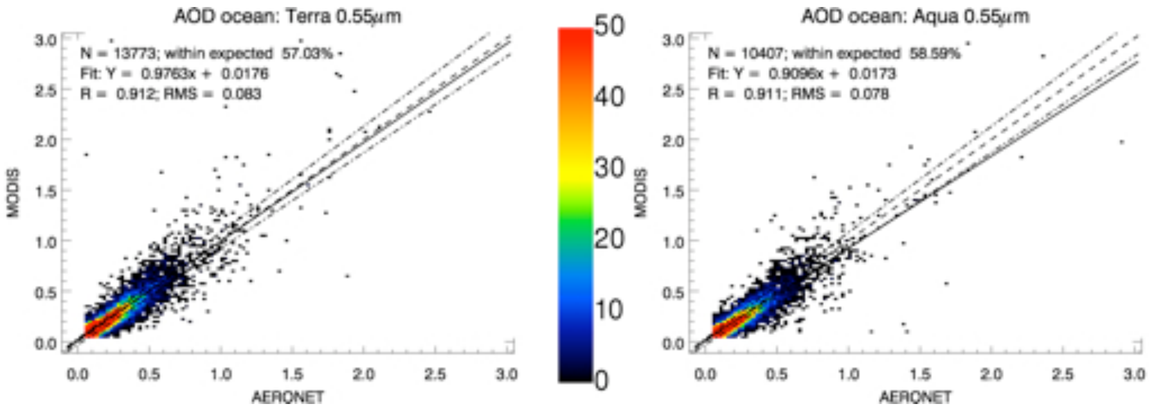

Figure 5: Same as Fig. 1 but for MODIS C005 AOD retrievals over ocean (QC≥1) Here the dotted lines envelope the predefined EU for ocean AOD (±0.03 ± 0.05τ).

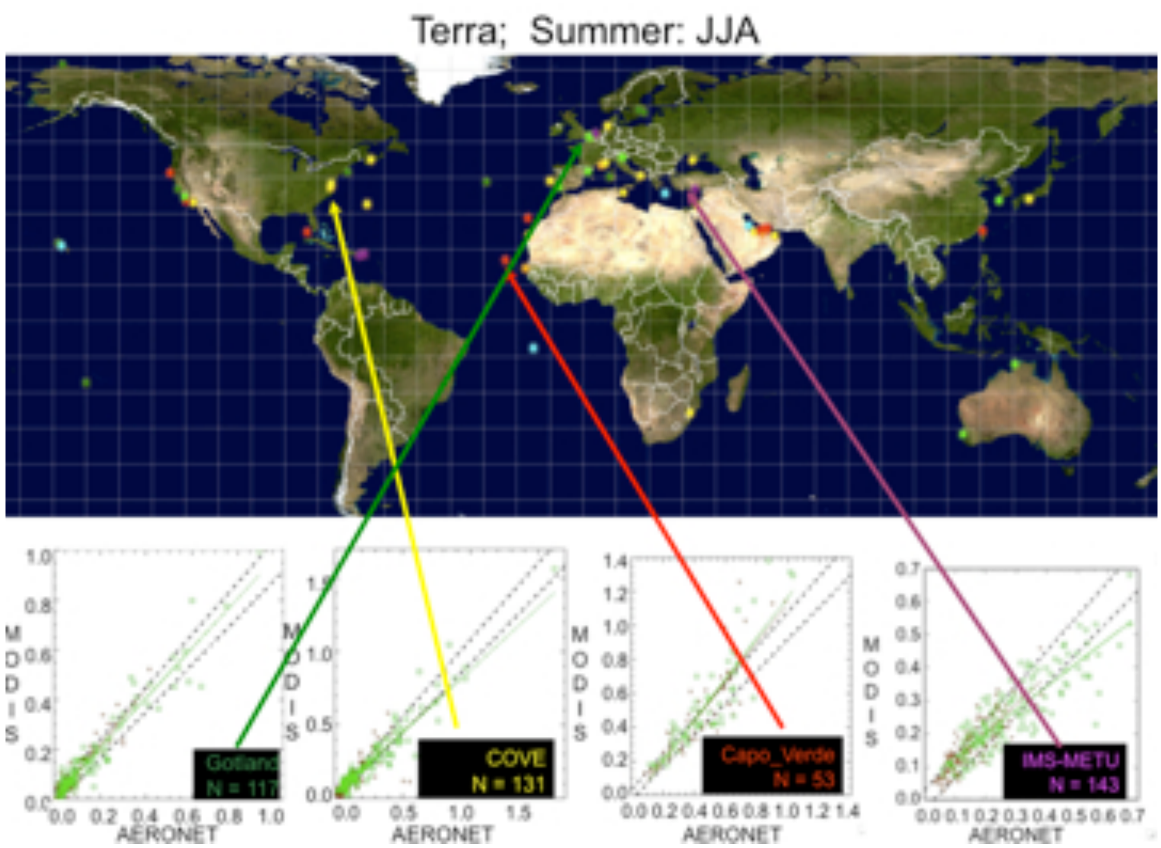

Figure 6: "Quality" of Terra-MODIS/AERONET comparisons of total and spectral AOD over ocean at each site, from Terra, during the summer. The color at each represents the quality of the comparison (Fig. 2 and Table 2). The comparisons of spectral AOD (different symbols: green - 0.55 μm, brown - 0.86 μm) at four sites are plotted, including: Gotland (58N, 19E), COVE (37N, 76W), Capo_Verde (17N, 23W) and IMS-METU (37N, 34E). The dotted lines for each scatterplot are the EU (±(0.04+0.05τ)) for ocean AOD.

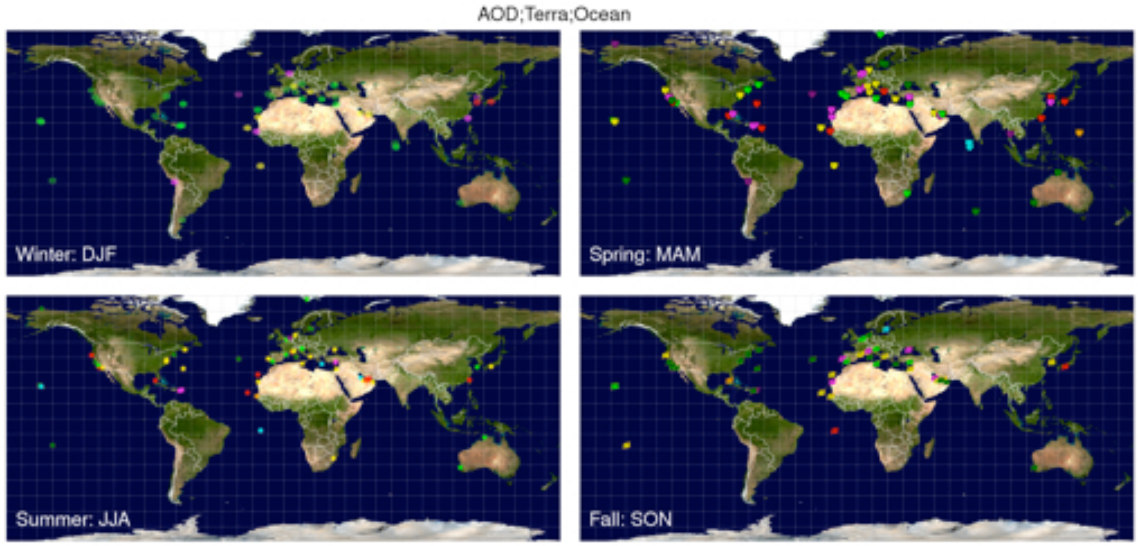

Figure 7: Same as Fig. 4 but for total and spectral AOD over ocean (see Table 2 for details).

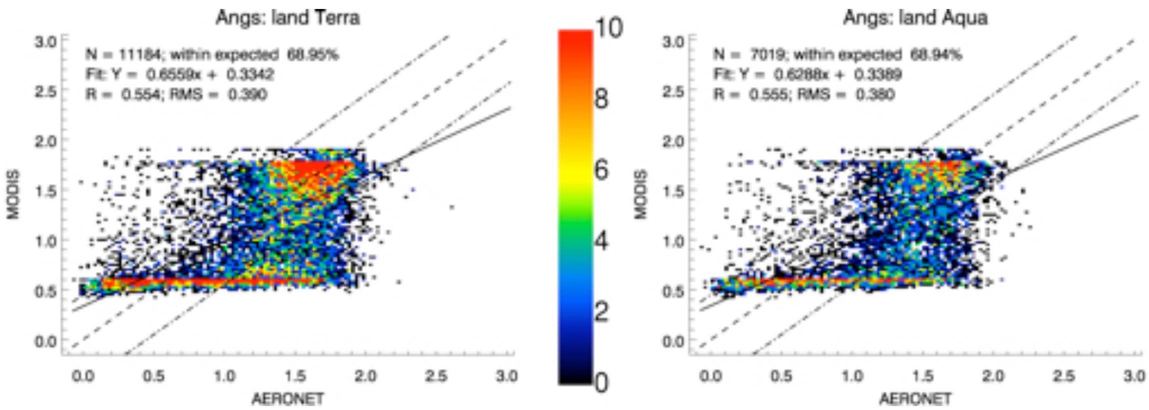

Figure 8: Same as Fig. 1 but for MODIS C005 Ångstrom exponent retrievals (0.47/0.66 μm) over dark land (τ>0.2; QC=3). The dotted lines envelope the EU, (±0.45).

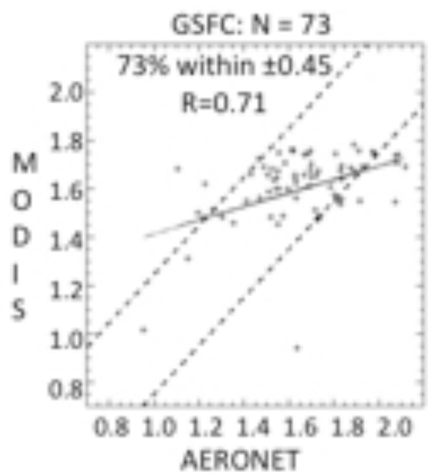

Figure 9: Angstrom exponent over land at GSFC during the summer for Terra compared with AERONET. The dotted lines are the EU (±0.45)

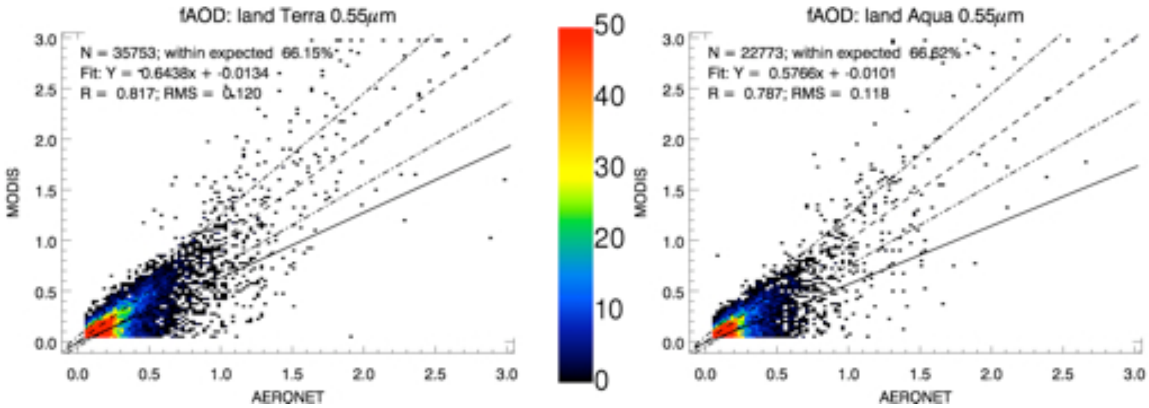

Figure 10: Same as Fig. 1 but for MODIS C005 fAOD retrievals over dark land (QC=3) at 550 nm. The dotted lines envelope the EU, estimated as (±0.05 ± 0.20τ).

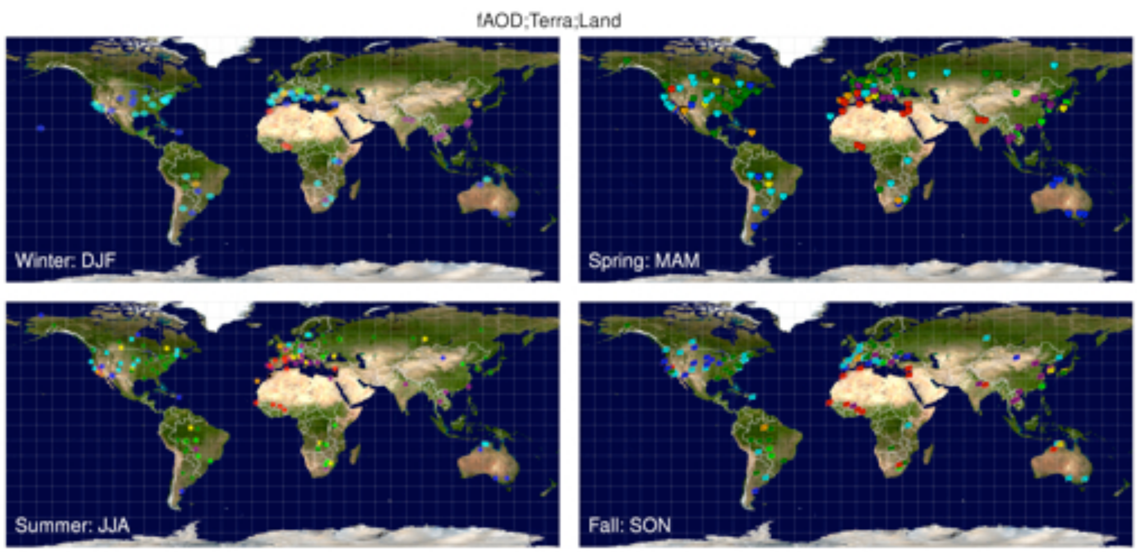

Figure 11: Same as Fig. 4 but for assessing fAOD over land (see Table 2 for details).

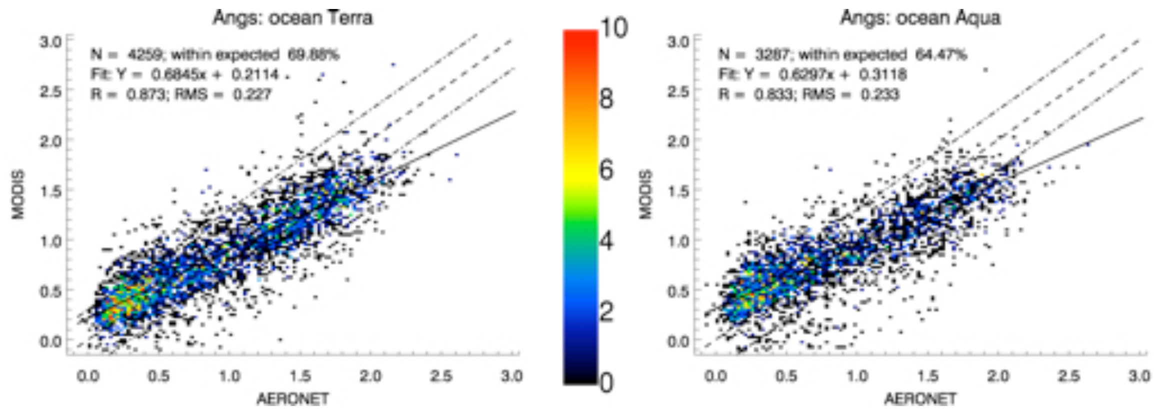

Figure 12: Same as Fig 1, but for MODIS C005 Ångstrom exponent retrievals (0.47/0.87 μm) over water (τ>0.15; QC≥1). The dotted lines represent EU of (±0.3).

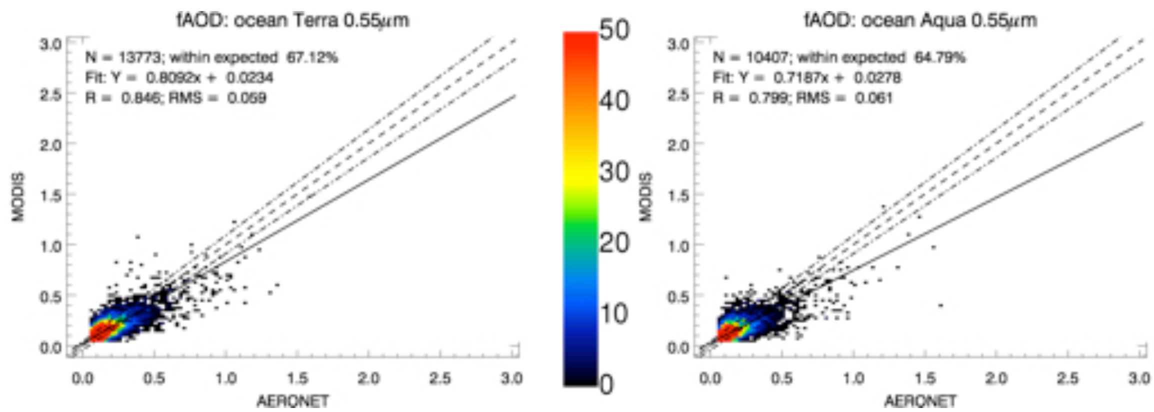

Figure 13: Same as Fig. 1, but for MODIS C005 fAOD retrievals over water (QC≥1) at 550 nm. The dotted lines represent EU of (±0.05 ± 0.05τ).

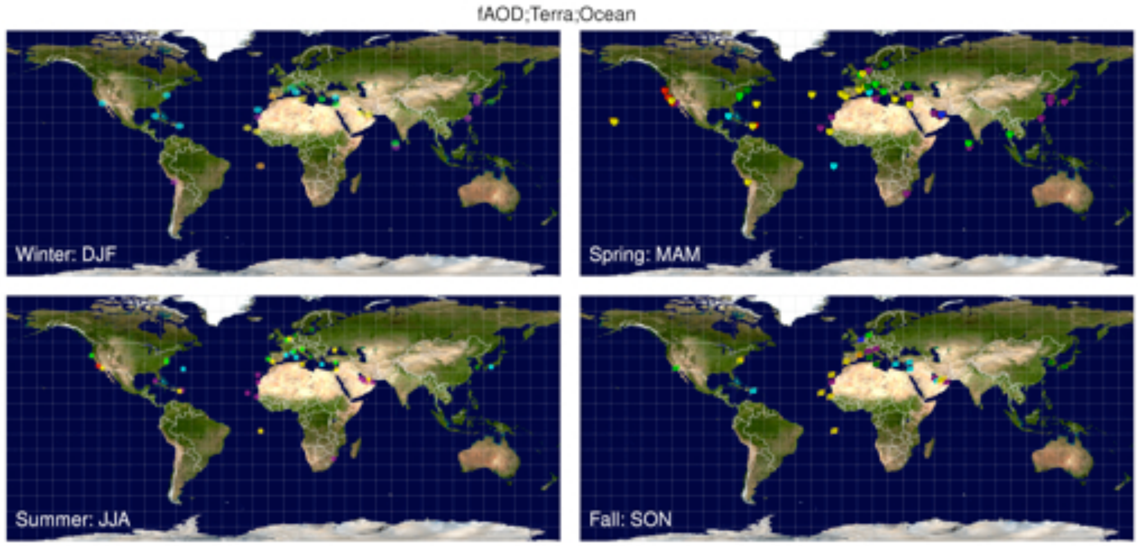

Figure 14: Same as Fig. 4 but for assessing fAOD over ocean (see Table 2 for details).

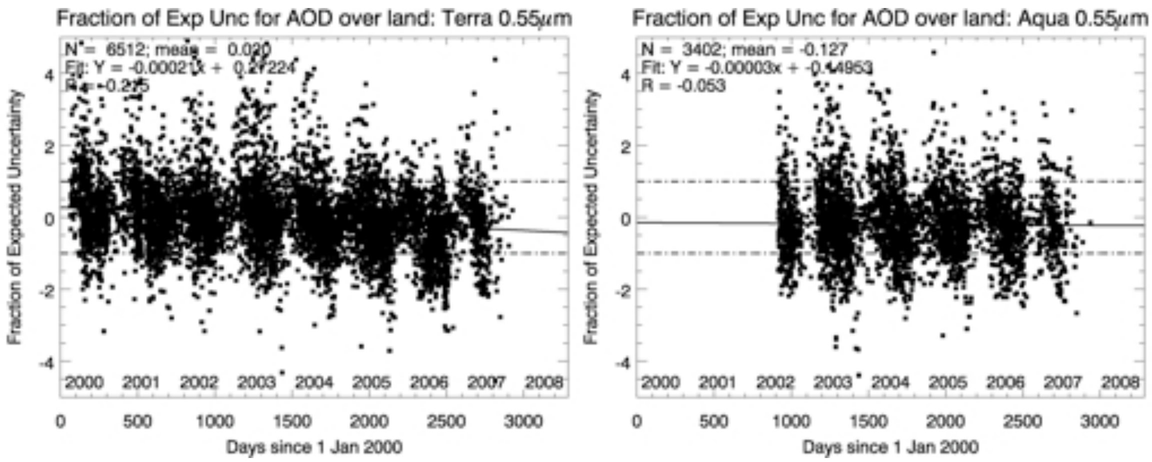

Figure 15: Time series of "fraction of expected uncertainty" (FEU) of MODIS C005 AOD (550 nm) compared to long-term AERONET, over dark land, for Terra (left) and Aqua (right). Points between the dashed lines (±1) are cases where MODIS matches AERONET within EU over land (±0.05 ± 0.15τ). The solid line 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).

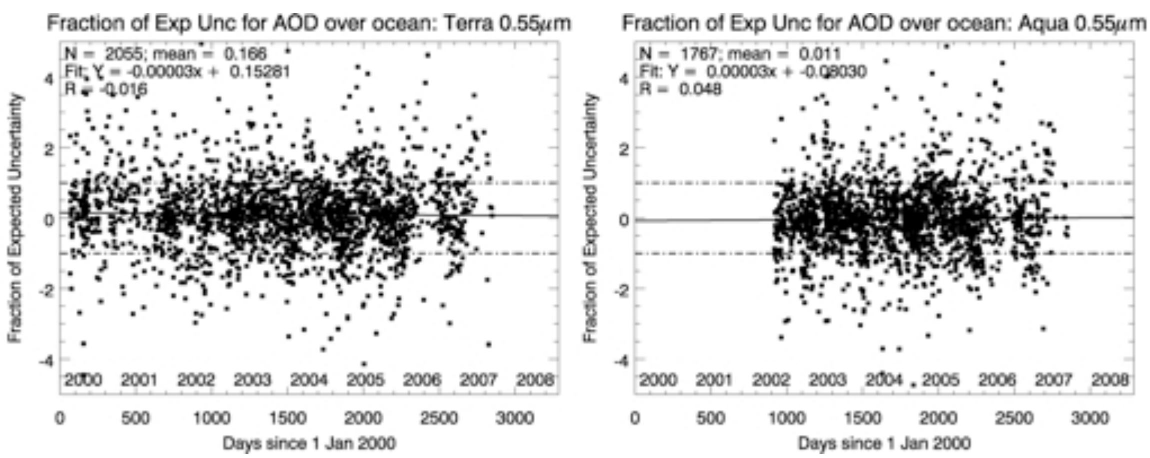

Figure 16: Same as Fig 13, but for MODIS C005 AOD over water. The EU is (±0.04 ± 0.05τ).