Evaluation and Windspeed Dependence of MOD Aerosol Retrievals Over Open Ocean

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***Abstract*--The Maritime Aerosol Network (MAN) data set provides high quality ground-truth to validate the MODIS aerosol product over open ocean. Prior validation of the ocean aerosol product has been limited to coastal and island sites. Comparing MODIS Collection 5 ocean aerosol retrieval products with collocated MAN measurements from ships shows that MODIS is meeting the pre-launch uncertainty estimates for aerosol optical depth (AOD) with 64% and 67% of retrievals at 550 nm, and 74% and 78% of retrievals at 870 nm, falling within expected uncertainty for Terra and Aqua, respectively. Angstrom Exponent comparisons show a high correlation between MODIS retrievals and shipboard measurements (R= 0.85 Terra, 0.83 Aqua), although the MODIS aerosol algorithm tends to underestimate particle size for large particles and overestimate size for small particles, as seen in earlier Collections. Prior analysis noted an offset between Terra and Aqua ocean AOD, without concluding which sensor was more accurate. The simple linear regression reported here, is consistent with other anecdotal evidence that Aqua agreement with AERONET is marginally better. However we cannot claim based on the current study that the better Aqua comparison is statistically significant. Systematic increase of error as a function of wind speed is noted in both Terra and Aqua retrievals. This wind speed dependency enters the retrieval when winds deviate from the 6 m/s value assumed in the rough ocean surface and white cap parameterizations. Wind speed dependency in the results can be mitigated by using auxiliary NCEP wind speed information in the retrieval process.**

Index Terms—Aerosols, Remote sensing.

I. Introduction

One of the largest unknowns in estimating climate forcing is the characterization of atmospheric aerosols and these particles' effects on clouds. [1] Because approximately two-thirds of the Earth's surface is covered by ocean, to understand global climate and be able to accurately predict potential climate change, characterizing aerosol forcing and aerosol effects on clouds above the world's oceans is imperative. However, measurements are sparse over the ocean, and not until satellites began providing quantitative aerosol products [2]-[5] models making climate predictions were largely unconstrained. Now an improved arsenal of aerosol-quantifying satellite sensors provide the observations to constrain models [6]-[10]. As a consequence climate-predicting models tend to converge in their representations of total aerosol optical depth (AOD) [11]. Still these "observations" from satellite sensors are retrievals, based on assumptions and simplifications, and require evaluation against a more accurate ground truth.

Over land, ground truth has been provided for aerosol-observing satellites by the Aerosol Robotic NETwork (AERONET) [12]. For aerosol retrievals over ocean, AERONET has also been the validation tool of choice, confining comparisons to a relatively few number of island and coastal sites and the relatively shallower waters near these sites [6], [13], [14]. There have been several efforts to compare satellite aerosol retrievals from over ocean with shipboard sun photometer measurements [15]-[18]. However, shipboard measurements suffer from a variety of problems including inexperienced operators, differing protocols from cruise to cruise, irregular and insufficient attention to calibration, and sparseness of data in any single cruise archive. (See summary in Smirnov *et al.* 2002) [19].

The recent establishment of the Maritime Aerosol Network (MAN) under the umbrella of the AERONET program has overcome most of these difficulties in using shipboard sun photometer measurements for satellite-derived aerosol validation [20]. The handheld instruments are all calibrated at the same facility before and after each cruise so that calibration drift can be monitored. The MAN data protocol is standardized, data quality is checked and the data is processed, stored and archived following the AERONET model. The result is a high quality database of oceanic spectral AOD observations all archived in the same format, in the same location, which makes the data base easy to acquire and use.

Here we use the MAN data as a basis to evaluate the MODerate resolution Imaging Spectroradiometer (MODIS) over-ocean aerosol products of spectral AOD and Angstrom Exponent. This is the first comprehensive evaluation of the MODIS aerosol product over the open ocean, and allows for the quantification of retrieval biases with wind speed.

II. MODIS Aerosol Retrievals Over Ocean

The MODIS algorithm for deriving spectral aerosol optical depth and various particle size parameters over ocean has been thoroughly described in the literature [14], [21], [22]. The algorithm uses six MODIS channels (550, 660, 870, 1200,

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1600 and 2100 nm) and a Look Up Table (LUT) spanning four fine mode models and five coarse mode models over a range of AOD and geometries. The algorithm considers the 20 different pairs of one fine mode and one coarse mode to match LUT spectral radiances at top-of-atmosphere with the measured MODIS values. Inherent in the LUT are assumptions about the ocean surface. The current algorithm is unchanged in its assumptions of ocean surface properties since inception of operational production of Terra-MODIS data in 2000.

The ocean surface is affected in three ways: water-leaving radiance, rough ocean surface producing sun glint patterns and white caps (ocean foam). Suspended material in the ocean surface layer such as phytoplankton and Suspended Dissolved Organic Material (SDOM) determine the magnitude and spectral signature of water-leaving radiance [23], [24]. These values vary, especially in coastal regions, but the MODIS aerosol algorithm assumes a single value of 0.005 reflectance in the 550 nm channel and 0.0 reflectance at all longer wavelengths for all retrievals at any time. The 550 nm channel is the shortest wavelength used by the algorithm, successfully avoiding a higher degree of variability in water-leaving radiance at the short end of the wavelength spectrum [21]. The algorithm uses a Cox and Munk [25] rough ocean surface model to provide the glint pattern, and although the algorithm masks all geometry within 40^{o} of specular reflection, there remains sufficient reflectance to affect a retrieval outside of this mask. Glint patterns are determined by wind speed. The MODIS aerosol algorithm assumes a single value of 6 m/s for all retrievals at any time. The third parameter affecting ocean surface properties is ocean foam, also determined by wind speed. The algorithm uses a Koepke *et al.* [26] model to account for the reflectance contribution of ocean foam. Again, the algorithm assumes a wind speed of 6 m/s in the ocean foam model for all retrievals at any time.

Assumptions about surface wind speed are built into the operational LUT for MODIS aerosol retrievals. The value of 6 m/s was chosen to represent mean conditions over the global oceans. This single value has enabled over ocean MODIS aerosol retrievals to fall within expected error bounds of $\pm0.03\pm0.05AOD$ roughly 2/3 of the time on a global basis when compared with land-based AERONET or aircraft observations [6], [13], [14], [27]-[30]. This error envelope corresponds to the 1σ error bounds. Using a constant wind speed opens the possibility for systematic retrieval biases when the actual wind speeds do not match our assumption [8], [31]. Such biases above and below the average will not be apparent in the global analysis because of compensating errors. Here we have a validation data set over open ocean which allows us to explore these possible biases and correct for them. Varying the wind speed by calculating alternative LUTs and evaluating the results from the MODIS retrieval has not been previously explored in a publication until now.

III. Data and Collocations

The Maritime Aerosol Network (MAN) component of AERONET provides ship-borne aerosol optical depth measurements from Microtops II sun photometers [20]. Microtops are hand held instruments, which are used to manually take direct measurement of solar radiance in 5 wavelengths and automatically convert these values to AOD [32], [33]. These instruments have been deployed since 2006 on ships of opportunity and research vessels to monitor aerosol properties over the World Oceans. In this study we use MAN data from cruises to evaluate the performance of the MODIS collection 5 AOD and Angstrom Exponent products over open ocean.

Microtops II instruments currently in the MAN network have five spectral channels and can have several possible filter configurations within the spectral range 340-1020 nm. In addition, the instrument has built-in temperature and pressure sensors as well as the ability to log accurate time and geographical position using a GPS. The Microtops instruments are calibrated at the NASA Goddard Space Flight Center (GSFC) calibration facility via a transfer calibration procedure between the Microtops and the master Cimel sun photometer at GSFC. The master instrument traces its calibration to a Langley plot calibration at Mauna Loa, Hawaii. In general, the estimated uncertainty of the aerosol optical depth in each channel does not exceed plus or minus 0.02 [34], which is twice the uncertainty of AERONET field (not master) instruments [35] . In this study all microtops were equipped with 500, 675, and 870 nm channels. All microtops except those deployed on the Flip (2008), Marion Dufresne (2009), and Polarstern (April – May 2007) were equipped with the 440 nm channel.

The Version 2 AERONET direct sun algorithm is employed to compute AOD from the MAN observations. (See details in Smirnov et al. 2004 and at http://aeronet.gsfc.nasa.gov/new_web/Documents/version2_table.pdf). Similar to the procedure for standard AERONET observations, MAN AOD data is classified as level 2 if it has had both pre- and post-deployment calibrations applied to the observations as well as screening for clouds and pointing errors, and manually inspected. Data is classified as level 1.5 if it has not had post-deployment calibration.

MAN data used in this study consists of level 2 data collected between October 2004 (two pilot projects were conducted in 2004 [36] and 2005) and November 2009. Each MAN data point is typically a set of measurements that is grouped into a "series". Series are any set of measurements where there is less than 2 minutes between any two consecutive measurements. Series typically contain 5 or more measurements. Values in a series are averaged to give a single point value. The term "MAN data point" in this paper will refer to a series average.

For this study some modifications were made to the original Ichoku *et al.* [37] spatio-temporal collocation procedure. All MAN data points within +/- 30 minutes of a MODIS overpass are identified as a possible co-location for that overpass. In cases where there is more than one potential MAN co-location and the variation between points is less than 0.02 AOD the series closest to the overpass time is selected as the MAN data point for the study. In cases where the variability between points is greater than 0.02, values were averaged. There were a few cases with variability in the hour window, more than two series in that hour and one of the points with an AOD significantly different than the other series. If upon further inspection of the outlying point the shape of the spectral response of the MAN data was significantly different from the other series this point was judged to be an outlier and eliminated. The collocated MODIS data undergo a spatial averaging of all retrievals in a 5x5 box (50 km) around the location of the ship at overpass. Note that the ship is moving during this hour so that there will be slight differences in the MODIS data corresponding to each potential MAN co-location. In a few cases there are significant differences in the number of MODIS pixels associated with the various potential co-locations but almost no difference in the MAN AOD. In these cases the paired co-location with the greater number of MODIS pixels is selected.

There are a total of 284 co-located data points for MODIS-Aqua and 278 co-located points for MODIS-Terra. Over 90% of the MAN data points used in this study are the closest temporal match to the MODIS overpass time. There are very few co-locations in the open waters of the Central Pacific Ocean.

Wind speeds for the co-located points are taken from the National Centers for Environmental Protection (NCEP) / National Center for Atmospheric Research (NCAR) Reanalysis data set [38]. We used the NCEP 6 hourly surface winds gridded into 1 x 1 degree boxes to evaluate the effect of winds on the MODIS AOD retrieval. There were a small number of points where there is no wind data available and these are not included in the wind speed analysis.

IV. Validation of MODIS Aerosol Parameters Over Open Ocean

Fig. 1 is the scatter plot of co-located MODIS and MAN points for both Aqua and Terra at 550 and 870 nm. MAN values at 500 nm have been interpolated to 550 nm using a log-linear interpolation between 440 and 675 nm or 500 and 675 nm [39] . The solid lines in the graph show the expected error boundaries, which reflect the prelaunch expected uncertainty ($\Delta\tau = \pm 0.03 \pm 0.05\tau$) [40], [41]. The percentage of points within the expected uncertainty at 550 nm (64% Terra, 67% Aqua) is slightly higher than reported by Remer *et al.* [14] (62% Terra), although the offsets are also slightly higher. In the 870 nm channel the slopes, correlations and number of points within the expected uncertainty (74% Terra, 78% Aqua) are all a slight improvement over Remer *et al.* [14] results (70% Terra). The apparent improved performance at 870 nm can be attributed to the relatively larger window as a percent. It is important to note that Remer et. al. were comparing MODIS collection 3 and 4 data with stationary Cimel sun photometers from island and near-ocean sites and were working with a data set almost ten times as large as that reported in the current study. Nevertheless results from this study reinforce the validation findings discussed in Remer *et al.* [13] and provide confirmation that their findings are valid over areas of open ocean.

We also investigated the how well the MODIS collection 5 product retrieves particle size information by comparing spectral dependence using a two channel Angstrom exponent. Fig. 2 shows the Angstrom exponent (550/870 nm) for both Terra and Aqua plotted against the MAN Angstrom exponent (550/870 nm) for MAN AOD values of 0.2 and above. We use the MAN 550 nm values interpolated from 500 nm as explained above. Lowering the AOD threshold to below 0.20 degrades the correlation and slope of the relationship significantly. This is because at low AOD values the relative errors of each wavelength used in the Angstrom exponent calculation are higher and can have a greater effect on the spectral slope than at higher AODs. Both MODIS instruments show very similar results in that they overestimate the Angstrom exponent at low values and underestimate at high values. This response is very similar to what was reported in Kleidman *et al.* [42] where they compared MODIS collection 4 fine fraction aerosol with results obtained by stationary AERONET sun photometers using the O'Neill spectral deconvolution algorithm [43], [44]. In response to the findings of Kleidman *et al.* [42] the refractive index of the coarse aerosol models used by the MODIS algorithm was adjusted for collection 5.

V. MODIS Aerosol Retrieval Wind Speed Dependence

Fig. 3 shows the difference between MODIS and MAN AOD at 550 nm as a function of NCEP wind speed. As wind speed increases beyond the assumed value of 6 m/s, retrieval error increases as a clear positive bias. The positive bias indicates that MODIS AOD is systematically too high, as compared with MAN. As wind speed increases, glint reflection spreads beyond the 40° mask and the sea forms more white caps. Both the increased glint reflectance and the increased foam act to brighten the actual surface in the scene. However, the MODIS algorithm assumes a darker surface and interprets the extra reflectance seen at top-of-the-atmosphere as extra AOD.

Using the same radiative transfer code used to build the operational MODIS over ocean algorithm's LUTs [45], we recalculate the tables for a wind speed of 10 m/s. Inherent in this new table are brighter ocean surface reflectances from broader glint effects and more white caps. We then simply direct the retrieval algorithm to use the 6 m/s LUT for when the collocated NCEP surface wind speed is less than 8 m/s, and to use the 10 m/s LUT when wind speeds exceed 8 m/s. The results of this reprocessing are shown by the red and reddish symbols in Fig. 3, with the large red filled circles representing averages for different wind speed bins. The wind speed dependency is essentially gone and the bias reduced to AOD = 0.005 or less. The two wind speed method also results in an increase in the percentage of points within expected error at AOD 550 from 64% to 67% for Terra and from 67% to 74% for Aqua.

VI. Geographic Analysis of Algorithm Performance

Fig. 4 shows the global performance of MODIS collection 5 vs MAN AOD. "A" symbols refer to Aqua and "T"s to Terra. Green symbols show MODIS values within prelaunch expected error bounds, Red symbols show where MODIS values are higher than MAN and beyond the pre-launch expected error limits, and Blue where MODIS lower than MAN and is below the prelaunch expected error limits.

One area where MODIS tends to be high is along the Atlantic coast of Africa, especially Northern Africa in the vicinity of the Saharan Desert. This may be due to the MODIS algorithm's generally poor performance in measuring non-spherical dust particles [22]. Another area where MODIS overestimates AOD is in the Southern Ocean. Zhang *et al.* [46] and Zhang and Reid [31] have noted that this is an area where the MODIS product is subject to cloud contamination and effects of high wind speeds. The two wind speed algorithm significantly improved performance in both of these locations especially for Aqua in the waters of the Atlantic Ocean near the Saharan Desert. The map inset of South America shows the results of the comparison using the two wind speed retrieval algorithm. This area also shows significant improvement.

The only area where MODIS (Terra) collection 5 consistently underestimated the AOD at 550 nm was in the Bay of Bengal. This underestimation was not seen in the 870 nm channel. This is consistent with a fine mode dominated aerosol that is too absorbing to be represented by any of the fine models in the LUT. Here the absorbing aerosol prevents light from being reflected back to space, and the MODIS retrieval interprets this darker target scene as containing less aerosol.

VII. Conclusion

The MAN data set provides unprecedented high quality ground-truth to validate the MODIS aerosol product over open ocean for the first time. While limited to specific cruises, the data set provides a new perspective and broader sample of oceanic aerosol and environmental conditions than any previous validation data set, including the AERONET coastal and island sets. Using this data we show that the Collection 5 over ocean aerosol retrieval is meeting the uncertainty estimates for AOD set before launch and confirmed in the Collection 4 validation exercises published previously. We note that Collection 5 Terra has a positive offset from Aqua, of the same magnitude noted in Remer *et al.* [6]. At the time of that publication it was not known which instrument produced the more accurate mean AOD. Here we show that Aqua's offset from the ground-truth is less than Terra's. This leads us to believe that Aqua's over open ocean values of AOD are more accurate than Terra's. In a concurrent study using the traditional AERONET coastal and island stations, the better accuracy of Aqua is not apparent [47].

The data set also allowed us to characterize and correct for a wind speed dependence of the AOD. A new multi-wind speed LUT will be implemented into the Collection 6 operational algorithm that will begin producing products in 2011. Rather than a step function application of a multi-wind speed LUT used in this paper for illustration, the Collection 6 algorithm will interpolate between wind speed nodes to avoid unphysical discontinuities.

MODIS over ocean retrievals produce a quantitatively useful measure of aerosol particle size that correlates with ground-truth. Even so, there is an under prediction of particle size for large particles and an over prediction for small particles. This systematic issue surfaces in any representation of particle size including fine mode fraction, effective radius or the spectral dependence of AOD (Angstrom exponent) shown here.

The final remaining issue with the MODIS retrieval shown here is the systematic low bias in retrievals of AOD when either small absorbing or large dust particles are present with moderate to heavy loading.

The Maritime Aerosol Network provides a validation opportunity never before available for satellite retrievals of aerosol over ocean. Comparing over open ocean is different than comparing at coastal and ocean sites. Only with the MAN analysis could we draw firm conclusions concerning the offset between Terra and Aqua, and to move Collection 6 forward in terms of reducing wind speed dependence in the product.

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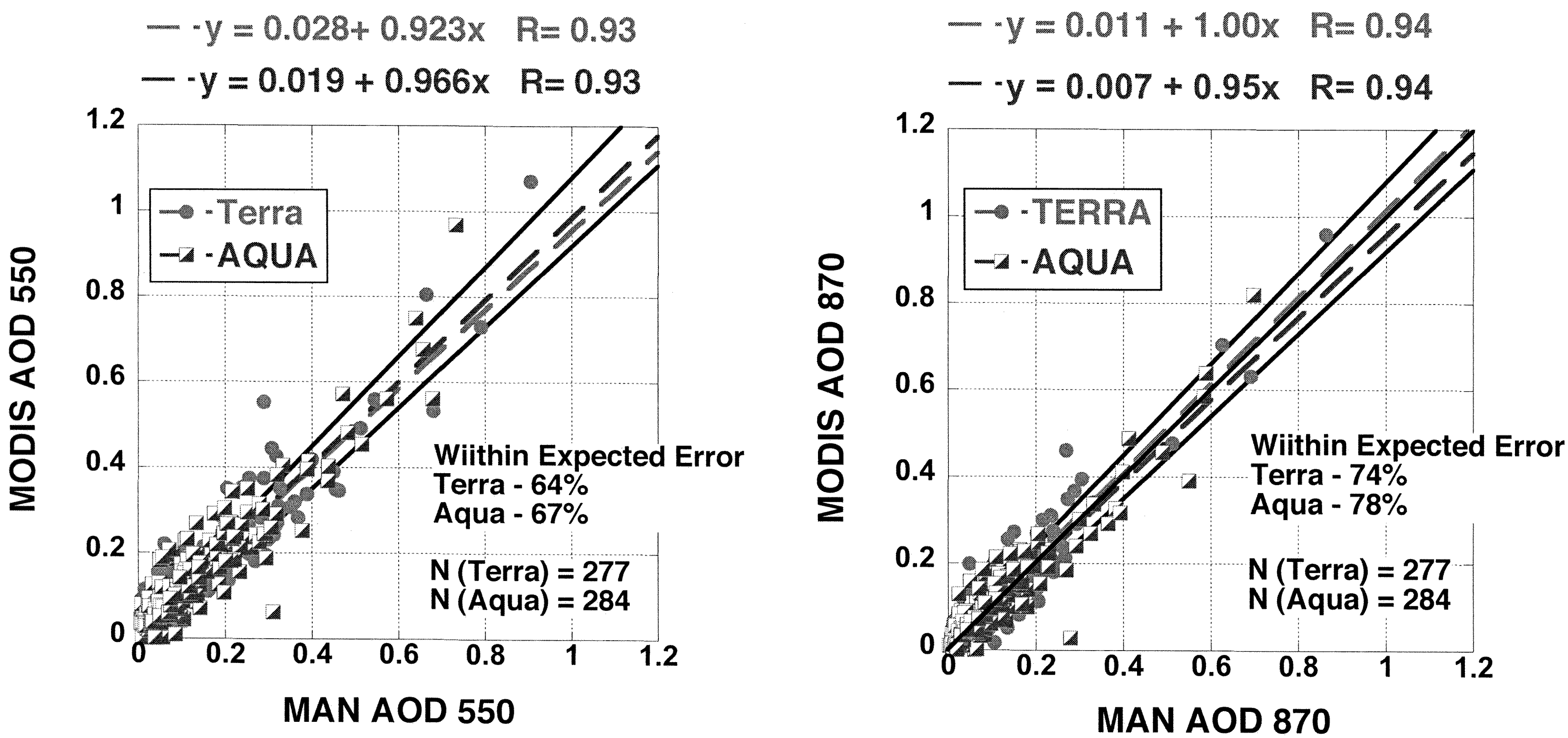
Fig. 1. Scatter plots of co-located MODIS (Moderate Resolution Spectroradiometer) Collection 5 ocean algorithm aerosol optical depths (AOD) and MAN (Maritime Aerosol Network) AOD. Left panel is for 550 nm where MAN data has been interpolated from its 500 nm channel. Right panel is for 870 nm. Results show that the performance of the ocean algorithm over open ocean meets or exceeds results of prior validation conducted by Remer *et al.* [14] which compared MODIS collection 4 AOD with stationary island and coastal AERONET sun photometers.

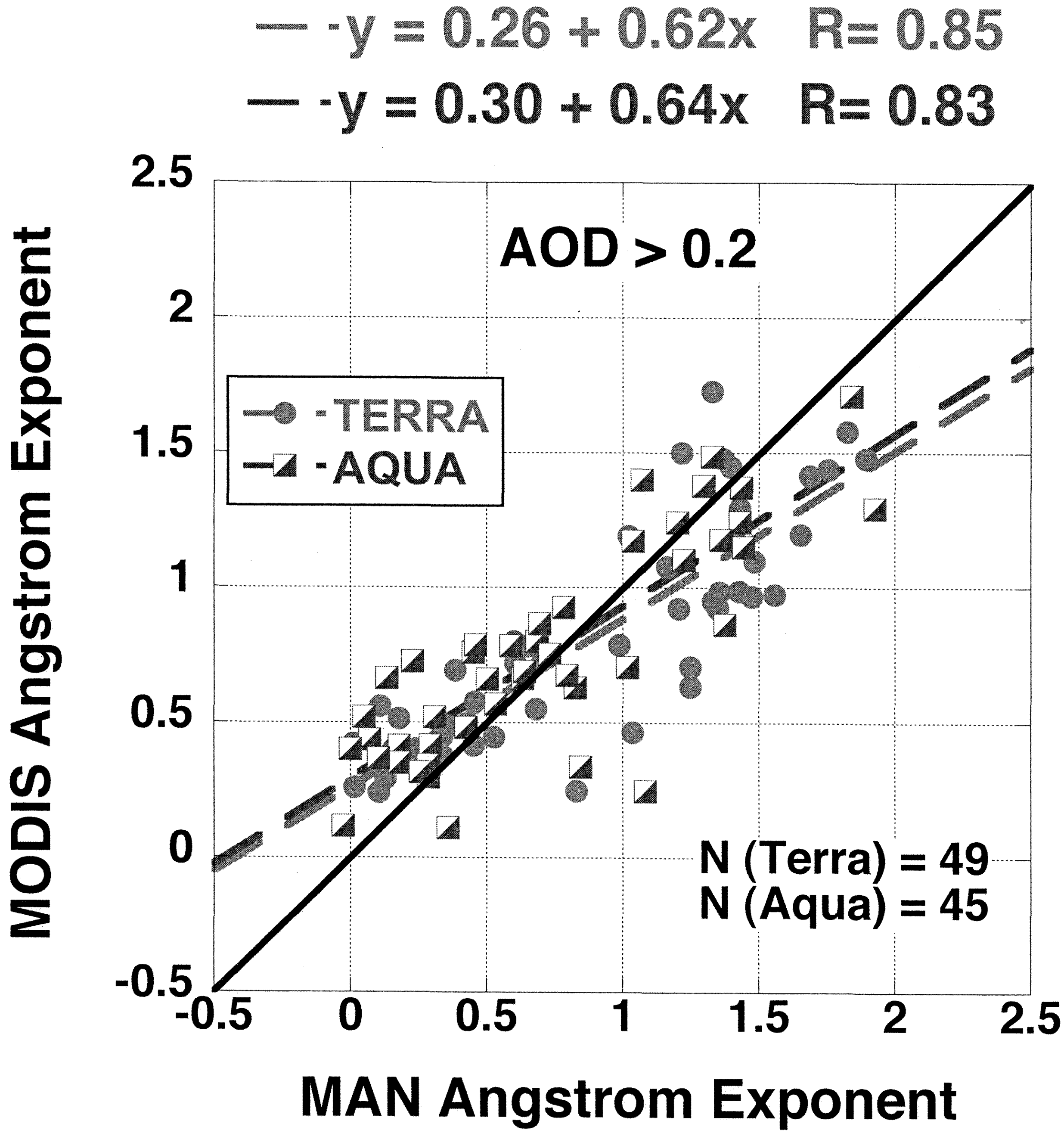
Fig. 2. Scatter plot of co-located MODIS and MAN Angstrom exponents (550nm/870nm) for both Terra and Aqua for AOD ≥ 0.2 The MODIS collection 5 algorithm is sensitive to the particle size but will underestimate the size of very large particles and overestimate the size of very small particles. The sensitivity to very large particles has improved since collection 4 owing to an adjustment in the refractive indices used in the algorithm's models for coarse particles.

Fig. 3. Differences in AOD (MODIS – MAN) for Aqua (top panel) and Terra (bottom panel) as a function of NCEP wind speed. The collection 5 algorithm assumes a wind speed of 6 m/s to calculate surface reflectance for all points. The bias in the AOD product (blue half squares) apparent at higher wind speeds is removed by using a two wind speed method (brown half squares) to calculate surface reflectance for all points with a wind speed greater than 8 m/s. The large black half squares (6 m/s) and red circles (2 wind speeds) show average AOD differences for bins of 2 m/s wind speeds. The correlations shown are calculated for the individual points.

Fig. 4. Global map of MODIS collection 5 AOD 550 nm results when compared with MAN AOD. "A" – Aqua, "T" – Terra. GREEN symbols - MODIS results are within prelaunch error expectations, RED symbols – MODIS is higher than MAN and above prelaunch error expectations. BLUE symbols – MODIS is lower than MAN and below prelaunch error expectations. Insert of South America at left shows the same comparison using the two wind speed retrieval algorithm. The two wind speed method also resulted in improved performance in the Southern Oceans and the Atlantic coast of Africa.



-y = 0.028+ 0.923x R= 0.93
-y = 0.019 + 0.966x R= 0.93
-Terra
-AQUA
Wiithin Expected Error
Terra - 64%
Aqua - 67%
N (Terra) = 277
N (Aqua) = 284
MODIS AOD 550
MAN AOD 550
-y = 0.011 + 1.00x R= 0.94
-y = 0.007 + 0.95x R= 0.94
-TERRA
-AQUA
Wiithin Expected Error
Terra - 74%
Aqua - 78%
N (Terra) = 277
N (Aqua) = 284
MODIS AOD 870
MAN AOD 870



y = 0.26 + 0.62x R= 0.85
y = 0.30 + 0.64x R= 0.83
AOD > 0.2
TERRA
AQUA
N (Terra) = 49
N (Aqua) = 45
MODIS Angstrom Exponent
MAN Angstrom Exponent
-0.5
0
0.5
1
1.5
2
2.5