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Comparison of Moderate Resolution Imaging Spectroradiometer (MODIS) and Aerosol Robotic Network (AERONET) remote-sensing retrievals of aerosol fine mode fraction over ocean

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[1] Aerosol particle size is one of the fundamental quantities needed to determine the role of aerosols in forcing climate, modifying the hydrological cycle, and affecting human health and to separate natural from man-made aerosol components. Aerosol size information can be retrieved from remote-sensing instruments including satellite sensors such as Moderate Resolution Imaging Spectroradiometer (MODIS) and ground-based radiometers such as Aerosol Robotic Network (AERONET). Both satellite and ground-based instruments measure the total column ambient aerosol characteristics. Aerosol size can be characterized by a variety of parameters. Here we compare remote-sensing retrievals of aerosol fine mode fraction over ocean. AERONET retrieves fine mode fraction using two methods: the Dubovik inversion of sky radiances and the O'Neill inversion of spectral Sun measurements. Relative to the Dubovik inversion of AERONET sky measurements, MODIS slightly overestimates fine fraction for dust-dominated aerosols and underestimates in smoke- and pollution-dominated aerosol conditions. Both MODIS and the Dubovik inversion overestimate fine fraction for dust aerosols by 0.1–0.2 relative to the O'Neill method of inverting AERONET aerosol optical depth spectra. Differences between the two AERONET methods are principally the result of the different definitions of fine and coarse mode employed in their computational methodologies. These two methods should come into better agreement as a dynamic radius cutoff for fine and coarse mode is implemented for the Dubovik inversion. MODIS overestimation in dust-dominated aerosol conditions should decrease significantly with the inclusion of a nonspherical model.

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1. Introduction

[2] Aerosols play an important role in determining the Earth's radiation budget and in modifying clouds and precipitation [*Kaufman et al.*, 2002; *Rosenfeld and Lensky*, 1998]. Aerosols also adversely affect human health [*Samet et al.*, 2000]. Understanding the aerosols' physical and optical characteristics as well as their distribution patterns is necessary in order to forecast air quality and make estimates of potential climate change [*Chu et al.*, 2003; *Kaufman et al.*, 2002].

[3] One of the important physical characteristics of aerosols is their size. Knowing particle size distribution is critical to estimating the role of aerosols in Earth's energy balance, in determining the effect the particles will have on cloud development and on human health. In addition, aerosol size is the key to using satellite remote sensing to separate natural from man-made aerosols. Anthropogenic aerosol optical thickness is dominated by fine (mode) aerosol (effective radius between 0.1 and 0.25 μm), while natural aerosols contain a substantial component of coarse (mode) aerosol (effective radius between 1 and 2.5 μm) [*Kaufman et al.*, 2001; *Tanré et al.*, 2001]. Therefore measurement of the fine aerosol fraction or the ratio of fine to coarse mode can be used to identify and quantify the extent and role in climate of anthropogenic aerosol [*Kaufman et al.*, 2002].

[4] Aerosol particle size parameters such as fraction of the fine mode or the ratio of fine to coarse mode can be measured by in situ volumetric and optical sampling mea-

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surements [*Anderson et al.*, 2003]. However, using remote sensing, either from the ground or space provides the size characteristics of the total column ambient particles that determine aerosol radiative forcing. Also, remote sensing provides frequent global coverage that is impossible from in situ samplers.

[5] The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard both NASA's Terra and Aqua spacecraft produces a number of global aerosol products on a daily basis [*Tanré et al.*, 1997; *Kaufman et al.*, 1997; *Remer et al.*, 2005]. The two main products are the aerosol optical thickness (AOT), a measure of the aerosol column concentration, and the fraction of the optical thickness contributed by the fine (submicron) aerosols. MODIS has separate algorithms for retrieving its products over land and ocean. In this paper we are only interested in the parameters produced over ocean.

[6] The Aerosol Robotic Network (AERONET) network of Sun/sky radiometers [*Holben et al.*, 1998] derives the total column aerosol characteristics from ground-based measurements of solar radiance. These instruments make two separate types of observations: Sun measurements and sky measurements. The Sun measurements are direct observations of the Sun intensity in 4 to 7 wavelengths using a 1-degree field of view. These measurements are used to derive the aerosol optical thickness. The sky measurements scan the sky, away from the Sun, and measure the radiation scattered down to the radiometer in 4 wavelengths and over a wide range of scattering angles. Each of these types of measurements can be inverted to derive aerosol size parameters including the fraction of fine mode aerosol. The combined sky and optical depth spectra observations are inverted using a method developed by *Dubovik and King* [2000] that makes use of the spectral and angular information. These inversions have been thoroughly tested and are included in the standard AERONET data [*Dubovik et al.*, 2000].

[7] *O'Neill et al.* [2001, 2003] recently proposed a spectral deconvolution method for using AERONET solar extinction data to optically derive the fine to coarse mode optical depth ratio. It differs from the Dubovik and MODIS inversions in that fine mode/coarse mode discrimination is referenced to the spectral behavior of fine and coarse mode particles rather than to the microphysical space of the particle size distribution. The assumptions of the O'Neill method are that the spectral derivatives of the coarse mode are small and known and that the derivative of the fine mode Angstrom exponent is an approximate function of the fine mode Angstrom exponent. These assumptions were verified analytically in terms of Mie computations for a large variety of refractive indices and fine and coarse mode lognormal distributions as well as empirically for fine and coarse mode optical depth statistics (retrieved using the Dubovik inversion). The ensemble of refractive indices and particle size distributions employed in the fine and coarse mode simulations included climatological and empirical estimates for urban and rural aerosols, fresh and aged smoke, fog, fresh and aged dust, soil particles, marine particles and thin cloud. The uncertainty in the fine and coarse mode derivatives and the attendant uncertainties in the retrieval of parameters such as the fine mode fraction are incorporated in a stochastic error model [*O'Neill et al.*, 2001]. The technique is not yet included in the standard AERONET database.

[8] These three independent techniques for deriving aerosol size parameters have been intercompared previously, but only in limited data sets. *Remer et al.* [2002, 2005] used AERONET Dubovik inversion data to perform a preliminary validation of the effective radius size parameter over ocean but were limited by a small data set. *O'Neill et al.* [2003] compared the two types of AERONET retrievals of fine mode optical depth at just three stations. To date, there has been no in-depth evaluation of the MODIS fine mode fraction product against either AERONET retrieval. In this study we make a three way comparison of aerosol fine mode fraction derived from MODIS over ocean, the AERONET Dubovik sky inversions and the AERONET O'Neill inversions, keeping in mind the strengths and weaknesses of each technique.

2. Comparison Data Set

[9] We first acquired a colocated data set for comparison of MODIS retrievals with AERONET Sun measurements. Colocated data are defined according to the method of *Ichoku et al.* [2002]. AERONET data collections within a 1-hour window (±30 min) around the MODIS overpass are averaged and compared with the mean of the MODIS data collected in a 50 km per side box (2500 km^2 composed of 5×5 10-km^2 mean values) centered around the AERONET site. This 50 km box most closely matches the air mass that the AERONET instrument will see within the 1-hour period for typical mean transport wind speeds [*Ichoku et al.*, 2002]. Only coastal and island sites were used in this study. The current MODIS land algorithm produces a fine mode fraction that is at best a qualitative estimate. There is not enough information to separate atmospheric from land surface radiance and accurately derive fine mode fraction.

[10] In order for a data point to be included in our analysis we require a minimum of two AERONET retrievals within the hour and 5 out of 25 MODIS ocean retrievals within the box. The MODIS Aerosol and Associated Parameters Spatio-temporal Statistics (MAPSS) database [*Ichoku et al.*, 2002] was used to generate the data set. The data we employed from MAPSS span the time period from February 2000 to December 2003 and include data from 30 sites.

[11] AERONET data were restricted to the level 2 product, which is both cloud screened and quality assured [*Smirnov et al.*, 2000] and also includes both a predeployment and postdeployment calibration. In order to apply the O'Neill method we were further limited to AERONET instruments taking simultaneous direct Sun AOT measurements in at least four of the 0.38, 0.44, 0.50, 0.67 and 0.87 μm wavelengths. Uncertainty of the AERONET level 2 AOT is 0.02 at 380 nm, and ~0.01 for the other four wavelengths [*Eck et al.*, 1999].

[12] MODIS is less sensitive to aerosol characteristics at low AOT values, e.g., <0.1, because of the effects of errors in MODIS calibration and assumptions concerning surface reflectance. Ground-based methods that are wholly or partially dependent on interband spectrometry are also prone to larger errors at low AOT values because the spectral information is progressively more contaminated

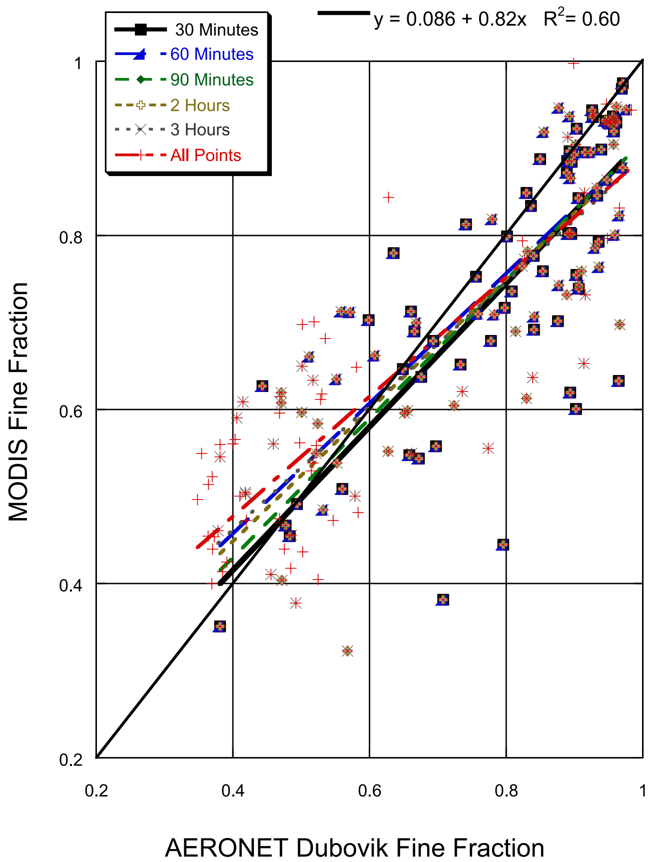

Figure 1. MODIS fine fraction aerosol versus AERONET sky data fine fraction (Dubovik inversion) for individual colocated observations. Results are shown as a function of the time difference between the MODIS and AERONET observations. Each increasing time interval includes all of the points from the preceding time interval. The fit is shown for the shortest time interval (±30 min) that corresponds to the best spatiotemporal match of the data [*Ichoku et al.*, 2002].

by spectral calibration errors. For these reasons we only compare results for AOT values greater than or equal to 0.1 at 0.55 μm. Limiting the values to AOT > 0.1 eliminates results from marine-dominated aerosol conditions that occur at very low fine mode values. Few coincident samples from smoke-dominated aerosols exist in this data set; however, there is no reason to believe that smoke aerosols will behave in a substantially different fashion from pollution-dominated aerosols, since both have similar fine mode particles size with effective radius ~0.20 ± 0.05 μm.

[13] Once this initial data set was compiled, we used the AERONET web site (aeronet.gsfc.nasa.gov) to collect a matching set of AERONET sky (alumucantar) data to which the Dubovik inversion was applied. We started with any available alumucantar retrieval that matched the site and date of a MODIS–AERONET Sun colocation. Error and solar zenith angle restrictions were applied to the Dubovik inversion according to the type of aerosol model, either spherical or spheroid, used to invert the data. A spheroid model [*Dubovik et al.*, 2002] was used for sites that usually produce dust aerosols. Obtaining the data sets in this order was the most efficient way to ensure we could compare MODIS to both AERONET methods as well as intercompare the AERONET methods to each other.

[14] In summary, we have a data set of 600 colocated MODIS Terra ocean and AERONET Sun measurement points from 30 sites meeting the minimum AOT, temporal and spatial constraints used for MODIS-O'Neill individual retrieval comparisons. Monthly mean comparisons are derived from this set of 600 points. There are 175 AERONET Sun/sky retrievals that are coincident (same day and site) with the 600 colocated points. These Sun/sky retrievals are used for both MODIS-Dubovik comparisons and for Dubovik-O'Neill comparisons. When used for Dubovik-O'Neill comparisons the two methods are making use of the same AOT data to derive fine fraction.

3. Results

[15] We first compared MODIS and AERONET Dubovik inversion fine fraction retrievals since both methods have been in operational use for several years. For the Dubovik inversion the optical extinction ratios of fine to total aerosol are calculated at 0.44 μm and 0.67 μm and interpolated to the MODIS reference wavelength at 0.55 μm. We use a ±30 min time interval similar to the matchups between MODIS and the AERONET Sun measurements, described above. Relative to the results of the Dubovik inversion, MODIS tends to slightly underpredict fine fraction for high values (anthropogenic-dominated aerosols) (Figure 1). As we relax the time interval used to determine a colocation between MODIS and a Dubovik inversion more points become available from the low-fine-fraction (dust-dominated) sites. It is difficult to obtain sky radiance inversions in dust-dominated regimes because of the prevalence of inhomogeneous sky conditions. Relaxing the time constraint shows that MODIS tends to slightly overestimate fine fraction for low values (dust-dominated aerosols), with respect to the Dubovik inversion. Note that the regression lines calculated from intervals of 30 min to 3 hours are statistically the same.

[16] We next compare MODIS with AERONET O'Neill fine fraction retrievals for individual points (Figure 2). MODIS underestimation at high values and overestimation at low values is apparent and much stronger than when compared against the Dubovik inversion. MODIS typically returns values in the range of 0.1–0.2 higher than O'Neill for dust and salt aerosol regimes. It is noted that the stochastic error model of the O'Neill method [*O'Neill et al.*, 2003] yielded an ensemble of estimated fine mode fraction errors with a mean and standard deviation 0.16 ± 0.07 for values of AOT(0.55 μm) > 0.1.

[17] Figure 3 shows the results of a comparison of individual AERONET retrievals of the Dubovik inversion and O'Neill method. The inversions are made from the same set of observations for all points with a minimum AOT of 0.1 at 0.55 μm. The results are highly correlated and exhibit a relationship very similar to that of the MODIS and O'Neill results shown in Figure 2.

[18] Comparing colocated simultaneous observations as we have done in Figures 1–3 answers questions about the basic retrievals, but does not necessarily give us information about the product's use in long-term climate studies. These

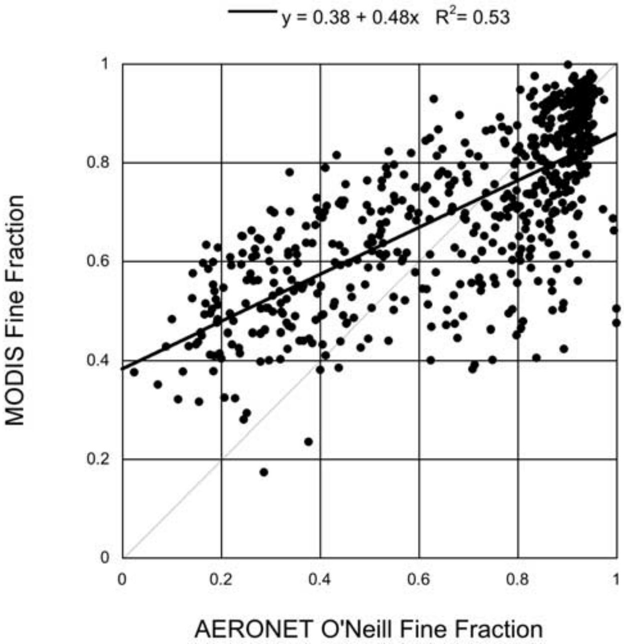

Figure 2. MODIS fine fraction aerosol versus AERONET Sun (O'Neill method) fine fraction aerosol. Results are from individual colocated observations with a minimum AOT of 0.1 at 0.55 μm. MODIS overestimates low values of fine fraction and underestimates high values of fine fraction to a greater extent than when compared with sky observations shown in Figure 1.

plots represent the colocated points only for the points when both the MODIS and the AERONET cloud masking algorithms indicated that no clouds were present, and only for the time of day of satellite overpass. It is also interesting to compare longer-term statistics such as monthly means calculated independently in each data set, with no regard for simultaneity. We employ a data set of direct Sun measurements inverted by the O'Neill method to compare monthly means of MODIS and AERONET fine mode fraction (Figure 4). A monthly mean point requires at least five individual retrievals within the month, from any year of the data set, for both MODIS and AERONET. We are interested in the monthly mean fine fraction of the dominant aerosol events and therefore weight the fine fractions of all of the points within the month by AOT at 0.55 μm before averaging. The relationship of monthly means is almost identical to that of the individual points from Figure 2. Thus MODIS climatology of fine mode fraction should not expect biases due to improper cloud clearing or diurnal sampling. Because of the scarcity of AERONET sky retrievals it is almost impossible to make a similar comparison of MODIS and the Dubovik inversion over a large geographical range.

[19] The results of the three methods are plotted together against a two-wavelength Angstrom exponent (alpha) defined from the 0.44 μm and 0.87 μm wavelengths of AERONET data (Figure 5). This plot demonstrates that all three methods are nonlinearly related to Angstrom exponent but can be approximated as linear over a shorter range of Angstrom exponent values (from about 0.40 to values greater than 1.6). The sensitivity of Angstrom exponent to determine fine mode fraction decreases as the fine mode becomes dominant. Caution should be exercised in those situations when using Angstrom exponent as the primary aerosol size parameter. The size of the fine mode particles themselves also contributes to a significant variation of the Angstrom exponent, which is evident at larger values of alpha [*Eck et al.*, 2005]. The fact that the fine mode fraction is at least linear with Angstrom exponent over much of its range is expected from equation (1a) of *O'Neill et al.* [2003] (in the presence of roughly constant fine and coarse mode component optics). It can also be demonstrated that the nonlinearity is due to the employment of finite differences in the calculation of multiband Angstrom exponents (as opposed to the pure spectral derivatives used by *O'Neill et al.* [2003]).

4. Discussion

[20] The three methods compared in this study have different definitions of aerosol fine mode fraction, and individual strengths and weaknesses. These differences contribute to the results seen in section 3.

[21] Some of the difference between the results of the three retrieval methods is due to the different ways in which they define fine and coarse modes. The Dubovik inversion uses a cutoff of 0.6 micron particle radius to make this distinction, while the MODIS algorithm defines coarse and fine modes by separating the component (whole-mode) log normal distributions of the total aerosol retrieval. The O'Neill method separates the two components in a spectral fashion; this approach effectively amounts to a type of

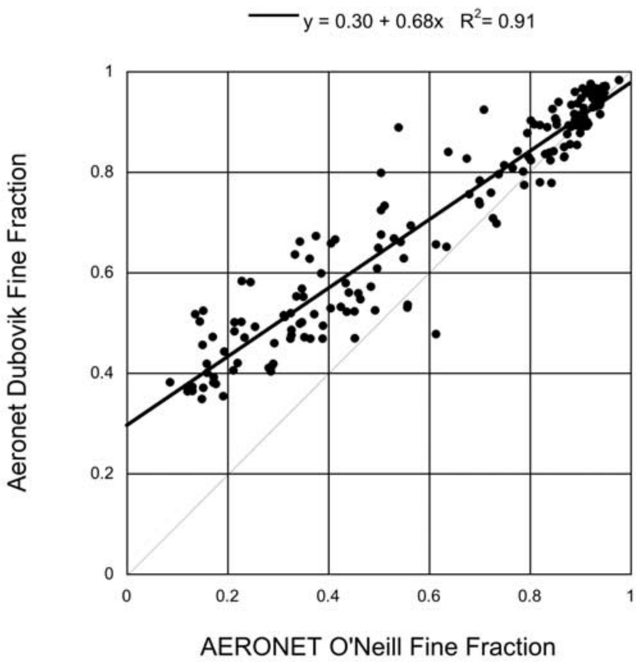

Figure 3. AERONET sky (Dubovik inversion) fine fraction versus AERONET Sun (O'Neill method) fine fraction for individual points with minimum AOT of 0.1 at 0.55 μm. The Dubovik inversion overestimates at low values similar to the MODIS relationship with O'Neill results shown in Figure 2.

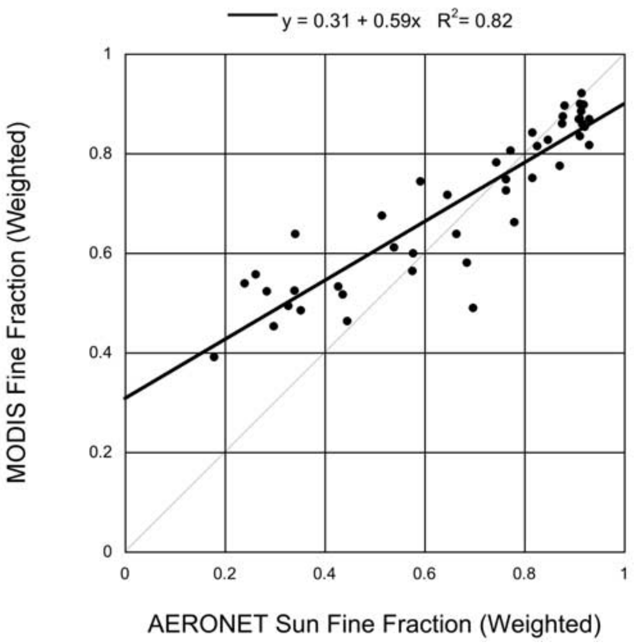

Figure 4. Monthly means of MODIS fine fraction aerosol versus AERONET O'Neill fine fraction. Fine fractions are weighted by AOT before combining results into monthly means. Each point represents at least 5 days from an individual month at a single AERONET site. Days may be from the same month but different years. The trend of MODIS overestimation at low fine fractions and underestimation at high fine fractions is repeated here.

whole-mode discrimination, which more closely resembles the MODIS approach. The differences between the approaches of radius cutoff and whole-mode discrimination is a function of the volume of particles in the overlapping tails of the component distributions and the location of this overlap relative to the 0.6 micron cutoff used by Dubovik [*O'Neill et al.*, 2003]. (It should be noted that a future version of the Dubovik retrieval code is soon to be released that will incorporate a dynamic radius threshold for fine-coarse mode based on the individual size distribution retrieval itself.)

[22] The Dubovik inversion sorts fine and coarse mode aerosols in a manner that mimics the discrimination effected by microphysical sampling devices (i.e., in terms of a mechanical radius cutoff). However, separating the particles into their component whole-mode distributions can give information about the aerosols parent material and chemistry. This would possibly make the MODIS and O'Neill methods (or even a modified Dubovik result that relies on two component fits to the general inverted particle size distribution) more appropriate for investigating anthropogenic versus naturally occurring aerosols.

[23] Each definition of fine and coarse mode emphasizes a slightly different information content of the aerosol retrieval. The Dubovik inversion, which incorporates the most input information, provides the most detailed information of the observed aerosol including complete particle size distributions. The O'Neill method, which uses much less input data than the Dubovik method, simply provides the fine mode fraction using spectral AOT information. Because MODIS uses longer wavelengths than the O'Neill method, it should, in addition to providing an estimate of fine mode fraction, be more sensitive to the size of the coarse mode and thus permit some discrimination of coarse mode particle size [*Tanré et al.*, 1996]. However, unlike the two AERONET methods, MODIS is limited to a small library of possible aerosol models and must choose between the modes available.

5. Conclusions

[24] The MODIS ocean algorithm underestimates the fine mode fraction by up to ~0.10 with respect to both the Dubovik inversion and O'Neill method for high fine fraction values (0.6–1.0). This range of values corresponds to predominantly smoke and pollution aerosol regimes. For values below this range that correspond to dust- and salt-dominated aerosols, MODIS and the Dubovik inversion are similar to each other and return values typically 0.1–0.2 higher than the O'Neill method. The MODIS results, although a closer match to the Dubovik inversion than the O'Neill method, still overestimate fine mode fraction for dust-dominated aerosol conditions. This error is consistent with the lack of a nonspherical aerosol model in the MODIS algorithm. The MODIS ocean algorithm chooses from one of four fine mode models and five coarse mode models, each of which has a fixed mean effective radius value [*Tanré et al.*, 1997; *Remer et al.*, 2005]. All possible

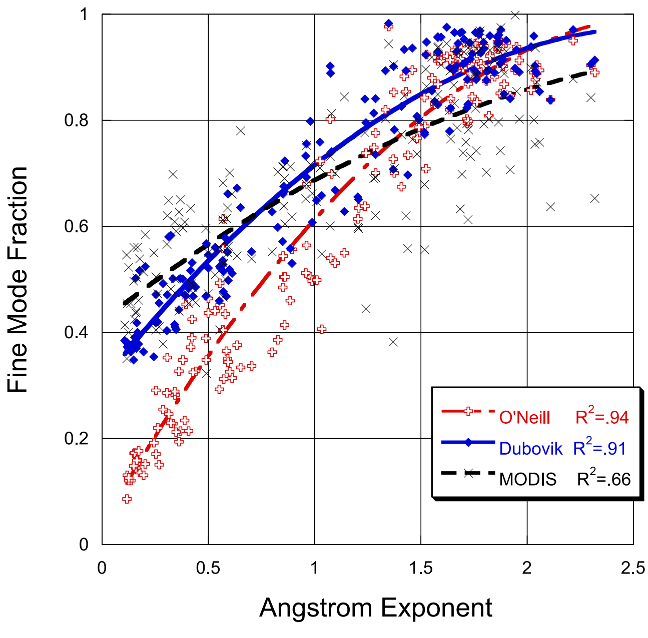

Figure 5. Fine mode fraction for MODIS and both AERONET methods as a function of a two- wavelength Angstrom exponent (440/870 AERONET). Each of the methods shows a linear relationship over the range of values from 0.4 to 1.6. The sensitivity of Angstrom exponent to determine fine mode fraction decreases as the fine mode becomes dominant. The size of the fine mode particles themselves also contributes to a significant variation of the Angstrom exponent (alpha), which is evident at larger values of alpha [*Eck et al.*, 2005].

combinations of the models are evaluated and the relative amounts of coarse and fine mode aerosols adjusted until a solution is found that minimizes the error of measured radiances over the six wavelengths used by the ocean algorithm. When confronted with nonspherical phase functions the algorithm still interprets them as spherical and compensates for changes in the measured radiances by increasing the relative amount of fine mode aerosol to minimize the error [*Levy et al.*, 2003]. When the Dubovik inversion uses a spherical model to retrieve nonspherical particles [*Dubovik et al.*, 2002] a similar false peak of fine mode is produced. MODIS results should improve significantly with the inclusion of a nonspherical model.

[25] The major advantage of the O'Neill method is that it requires only direct Sun measurements, which are collected every 15 min to obtain the solar extinction data. The Dubovik inversion requires sky radiance data, which are collected every hour. Sky radiance measurements require relatively homogenous sky conditions with little or no cloud cover and a high solar zenith angle whereas direct Sun measurements require only a clear field of view around the Sun. The result is that the O'Neill method affords a much larger data pool than the Dubovik inversion. For example, when we required there to be at least 5 Dubovik retrievals at a particular site in a given month in order to calculate a monthly mean value for that site, then only 4 of the 30 stations used in this study met that minimum requirement. In contrast, there were sufficient O'Neill retrievals for all 30 of those stations to contribute a monthly mean value. On the other hand, the Dubovik inversion has the advantages of providing a higher degree of information content than the O'Neill method and can provide full particle size distributions if these were required. Monthly mean values of fine mode fraction produced by the MODIS algorithm and compared to independently calculated monthly mean O'Neill method results show that MODIS climatology of fine mode fraction should not be biased because of cloud contamination or diurnal sampling.

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