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Validation of MODIS aerosol retrieval over ocean

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[1] The MODerate resolution Imaging Spectroradiometer (MODIS) algorithm for determining aerosol characteristics over ocean is performing within expected accuracy. A two-month data set of MODIS retrievals co-located with observations from the AErosol RObotic NETwork (AERONET) ground-based sunphotometer network provides the necessary validation. Spectral radiation measured by MODIS (in the range 550–2100 nm) is used to retrieve the aerosol optical thickness, effective particle radius and ratio between the submicron and micron size particles. MODIS-retrieved aerosol optical thickness at 660 nm and 870 nm fall within the expected uncertainty, with the ensemble average at 660 nm differing by only 2% from the AERONET observations and having virtually no offset. Roughly seventy percent of MODIS retrievals of aerosol effective radius for optical thickness greater than 0.15 agree with AERONET retrievals to within ±0.10 μm. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1640 Global Change: Remote sensing; 3360 Meteorology and Atmospheric Dynamics: Remote sensing

1. Introduction

[2] The MODerate resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra spacecraft began collecting data in February 2000. One of the important products delivered by MODIS is the Level 2 daily, global aerosol characterization parameters [*Tanré et al.*, 1997; *Kaufman et al.*, 1997]. The aerosol characteristics are derived over the land and oceans separately, using independent algorithms. This paper describes a preliminary validation of the algorithm used for aerosol retrievals over oceans. A companion paper [*Chu et al.*, this issue] addresses the retrievals over land. A comprehensive validation encompassing a more global data set and an annual cycle is planned for the future.

[3] Over oceans, the MODIS aerosol algorithm inverts the measured 500m resolution radiance from six MODIS bands (550–2100 nm) to retrieve the aerosol information. Specifically, in cloud-free, glint-free ocean scenes [*Martins et al.*, this issue], MODIS retrieves aerosol properties at a 10 km resolution. Primary products include: spectral aerosol optical thickness, the effective radius of the aerosol, and the fraction of the total optical thickness contributed by the fine (sub-micron size) mode aerosol [*Tanré et al.*, 1997]. Plate 1 shows the global distribution of the monthly mean primary products for September 2000. The optical thickness confirms previously reported global distributions [*Husar et al.*, 1997] with large values near Africa due to dust and biomass burning activities north and south of the equator, respectively. Previous determinations of global aerosol optical thickness from other satellites, such as AVHRR, have been extensively validated with the standard error estimated to be 0.04 [*Stowe et al.*, 1997].

[4] MODIS' major innovation is the additional information about particle size. MODIS can derive two pieces of information about particle size, for example, the size of the dominant mode and the ratio between modes [*Tanré et al.*, 1997]. The total aerosol effective radius shown in the middle panel of Plate 1 is a combination of these two pieces of information and is neither totally independent nor totally redundant of the small mode fraction seen in the bottom panel. We will concentrate our quantitative validation of size parameters on the total particle effective radius. This focus should not detract from the importance of the small mode fraction that even qualitatively can help to distinguish between man-made aerosol (primarily small mode) and natural aerosol (dominated by coarse mode aerosol such as mineral dust and sea salt).

2. Validation Strategy

[5] Roughly six months after MODIS began collecting radiance data the sensor's calibration had stabilized to the point where accurate validation of the aerosol products could begin. Our primary validation strategy is to co-locate MODIS retrievals with automatic Sun/sky radiometers of the AErosol RObotic NETwork (AERONET) [*Holben et al.*, 1998] coastal and island stations (http://aeronet.gsfc.nasa.gov). We calculate the statistics of the aerosol products in a spatial subset consisting of an array of 5 by 5 aerosol "pixels", centered on the AERONET location [*Ichoku et al.*, this issue]. Since the aerosol "pixel" size is 10 km, the subsetted area is approximately 50 km square. The selection and spatial subsetting of the MODIS product is objective and automatic [*Ichoku et al.*, this issue]. Not all of the 25 aerosol pixels contain ocean aerosol retrievals at every co-located overpass. Some pixels are over land, and some contain clouds or are otherwise rejected by the MODIS algorithm during processing. We require at least 5 of the 25 aerosol pixels to contain ocean aerosol retrievals before including in the validation data set.

[6] The AERONET data provide the ground truth for the MODIS validation. The globally distributed ground-based AERONET radiometers measure aerosol optical thickness in seven channels (340 to 1020 nm) although certain stations record only a subset of these channels [*Holben et al.*, 1998]. The instruments make measurements every 15 minutes. We calculate statistics from the observations taken within ±30 minutes of the MODIS overpass time [*Ichoku et al.*, this issue]. Therefore the maximum number of AERONET observations in the hour surrounding overpass is 5. Fewer observations in the hour indicate data has been removed by the AERONET Run-Time Cloud Checking procedure. We require that there be at least 2 of the 5 observa-

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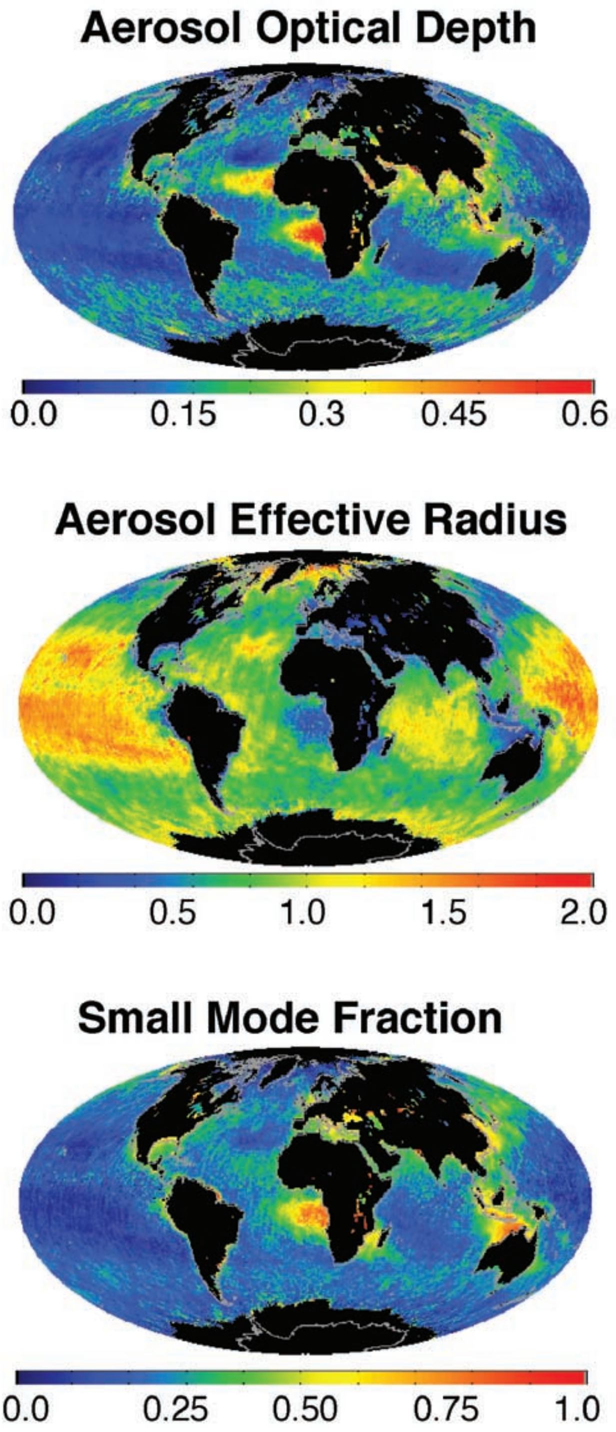

Plate 1. September 2000 monthly mean distribution of aerosol optical thickness at 550 nm (top), effective radius in μm (middle) and aerosol fine mode contribution to optical thickness at 550 nm (bottom).

tions in order for the AERONET data to be included in the validation data set. We also use the size parameter quantities derived from the AERONET sky retrievals based on the Dubovik inversion scheme [*Dubovik and King*, 2000; *Dubovik et al.*, 2000]. The sky retrievals occur less frequently than the optical thickness measurements. We require the size parameters to have been retrieved ±2 hours of MODIS overpass.

[7] Data used in this study were collected globally for 2 months starting August 21, 2000. Eleven stations were included in the validation data set. These represent the Mediterranean (4 stations), the coastal western North Atlantic (2 stations), the Caribbean (2 stations) and a few island sites in the North and South Atlantic (2 stations) and Indian oceans (1 station). The Pacific is not represented. All MODIS data used in this study are derived with Version 2.6.1 of the algorithm (http://modis-atmos.gsfc.nasa.gov). All AERONET data is Level 1.5, which indicates preliminary cloud clearing, but no final calibration or Quality Assurance [*Smirnov et al.*, 2000].

3. Aerosol Optical Thickness Validation

[8] Plate 2 shows the scatter plots of co-located MODIS and AERONET aerosol optical thickness (τ). Although MODIS and AERONET both report aerosol optical thickness for seven wave-

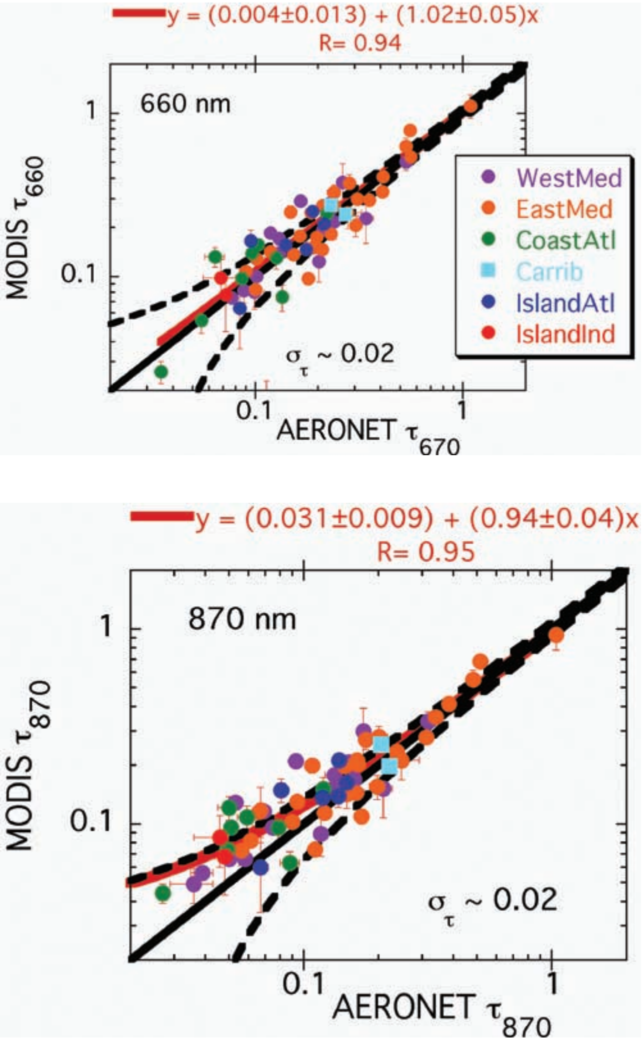

Plate 2. MODIS retrieved aerosol optical thickness (τ) at wavelengths 660 and 870 nm plotted as function of identical AERONET derived quantities. The linear regression coefficients with associated uncertainty, the correlation coefficients and standard error are shown. The dashed lines denote the expected uncertainty in the retrieval [*Tanré et al.*, 1997; *Tanré et al.*, 1999; *King et al.*, 1999]. The different colors represent the different geographical locations: western Mediterranean (purple), eastern Mediterranean (orange), coastal Atlantic (green), Caribbean (light blue), Atlantic islands (dark blue) and the Indian Ocean island (red). Altogether there are 64 co-located measurements that span 2 months and represent 11 stations.

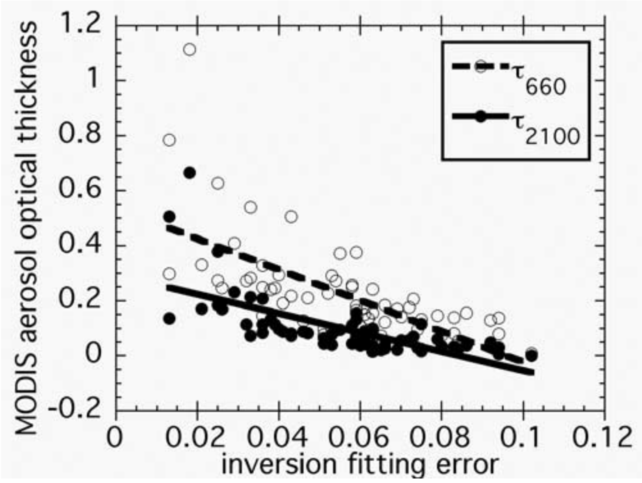

Figure 1. MODIS retrieved aerosol optical thickness in two wavelengths (660 nm—open circles and 2100 nm—solid circles as function of residual error from fitting the observed MODIS radiances using the calculated look-up table. The dashed line (660 nm) and solid line (2100 nm) represent the linear regression through the points.

lengths, only the 660nm (670 nm for AERONET) and 870 nm channels are sufficiently similar for direct comparison. Plotted are the mean values of the 5 × 5 MODIS subset and the ±30 minute temporal average of the AERONET time series. Log-log plots are used simply for visualization purposes, with the statistics calculated for linear space. The ensemble agreement, as represented by the linear fit (R = 0.94 at 660 nm), is well within the expected uncertainty ($\Delta\tau = \pm 0.03 \pm 0.05\tau$) as denoted by the dashed lines in the figure [*Tanré et al.*, 1997; *King et al.*, 1999]. Even by removing the one very high optical thickness point the correlation remains high (R = 0.90) and the linear regression changes only slightly to $\tau_{\mathrm{MOD}} = 0.005 + 1.01\ \tau_{\mathrm{AER}}$. The 870 nm validation shows MODIS to be slightly offset from AERONET, but still within the expected uncertainty. The standard error calculated for both wavelengths is ~0.02, half the error reported by AVHRR validation [*Stowe et al.*, 1997].

[9] Figure 1 demonstrates the primary source of the algorithm error. The residual fitting error tells us how well the calculated top of atmosphere radiances from the look-up table match the radiances measured by MODIS. It is defined as

$$\varepsilon = \sqrt{\frac{1}{n_k}\sum_{k=1}^{n}\left(\frac{L_k^m - L_k^c}{L_k^m + 0.01}\right)^2} \qquad (1)$$

where L_k^m and L_k^c are the measured and computed radiances in channel k, respectively. *Tanré et al.* [1997] explain the constant "0.01" in the denominator and the angular dependence of the radiances. The largest residuals occur at small optical thickness where a variety of additive errors dominate. These include surface contributions such as foam and ocean color, radiance offsets, Rayleigh optical thickness errors and instrument signal-to-noise issues. At higher optical thickness, the aerosol signal dominates and residual fitting error is attributed to errors in the aerosol models of our look-up table. Figure 1 shows that residuals decrease for the higher optical thicknesses, and this increases our confidence in our aerosol models and the inherent inversion method.

4. Size Parameter Validation

[10] We focus the size parameter validation on comparisons between MODIS-derived and AERONET-derived values of the aerosol effective radius. AERONET employs the *Dubovik and King* [2000] inversion scheme on the sky radiance data to derive the aerosol size distribution and from the size distribution calculates the effective radius. The *Dubovik and King* [2000] effective radius is identical to the MODIS effective radius and directly comparable.

[11] Figure 2 shows the validation of the effective radius. Only data with $\tau_{660} > 0.15$ are plotted. At low optical thickness, as seen in Figure 1, there is greater susceptibility to all algorithmic and sensor uncertainties including small calibration and retrieval errors for both instruments [*Ignatov et al.*, 1998]. These errors make little difference in optical thickness retrieval but create large errors when size parameters are calculated. Figure 2 shows 72% of the MODIS retrievals in this data set fall within ±0.10 μm of the AERONET retrievals, as indicated by the dashed lines. Over most of the world's oceans optical thickness falls below the 0.15 threshold and larger errors can be expected.

[12] *Tanré et al.* [1997] estimate the expected uncertainty of the retrieved dominant mode modal radius to be ±30% and the ratio between modes to be ±25%. The effective radius is a combination of these two parameters and its uncertainty was never specifically addressed. The thin solid lines of Figure 2 show the ±25% uncertainty expected of the mode ratio. All but five points fall within this uncertainty.

5. Discussion and Conclusions

[13] We have shown that the MODIS aerosol algorithms are performing within expectations for this validation data set yet, caution needs to be taken. The data set spans a mere two months. It is skewed towards coastal sites, and has a heavy emphasis on the Mediterranean. We will expect more cloud contamination than is apparent in the scatter plots when the MODIS retrievals are not selected to correspond to cloud-screened AERONET data. Fur-

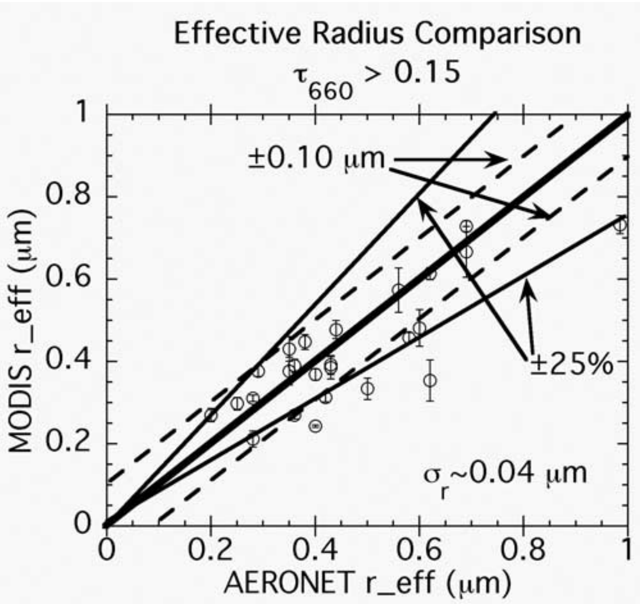

Figure 2. MODIS retrieved aerosol particle effective radius plotted against AERONET-derived effective radius. Only points with AERONET $\tau_{660} > 0.15$ are plotted. The standard error (σ_r) is roughly 0.04 μm. The pre-launch expected uncertainty for effective radius is unknown. The dashed lines denote ±0.10 μm, which encompasses 72% of the points. The thin lines denote an uncertainty of ±25%, which is the expected uncertainty of the ratio between modes, one of the components of effective radius. There are 25 co-located measurements.

thermore, there are indications that nonsphericity may affect some retrieved products and needs to be further examined. Still, this first validation exercise suggests that the operational MODIS algorithm can characterize ocean aerosol optical thickness with an unprecedented accuracy and determine aerosol size for moderate or larger aerosol loadings.

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References

Chu, D. A., Y. J. Kaufman, C. Ichoku, L. A. Remer, D. Tanré, and B. N. Holben, Validation of MODIS aerosol optical depth retrieval over land, *Geophys. Res. Lett.*, this issue.

Dubovik, O., and M. D. King, A flexible inversion algorithm for retrieval of aerosol optical properties from Sun and sky radiance measurements, *J. Geophys. Res.*, *105*, 20,673–20,696, 2000.

Dubovik, O., A. Smirnov, B. N. Holben, M. D. King, Y. J. Kaufman, T. F. Eck, and I. Slutsker, Accuracy assessments of aerosol optical properties retrieved from Aerosol Robotic Network (AERONET) Sun and sky radiance measurements, *J. Geophys. Res.*, *105*, 9791–9806, 2000.

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, AERONET—A federated instrument network and data archive for aerosol characterization, *Rem. Sens. Environ.*, *66*, 1–16, 1998.

Husar, R. B., L. L. Stowe, and J. M. Prospero, Characterization of tropospheric aerosols over the oceans with the NOAA advanced very high resolution radiometer optical thickness operational product, *J. Geophys. Res.*, *102*, 16,889–16,910, 1997.

Ichoku, C., D. A. Chu, S. Mattoo, L. A. Remer, Y. J. Kaufman, D. Tanré, and B. Holben, A spatio-temporal approach for the validation of MODIS aerosol and water vapor products, *Geophys. Res. Lett.*, this issue.

Ignatov, A., L. Stowe, and R. Singh, Sensitivity study of the Angstrom exponent derived from AVHRR over oceans, *Adv. Space Res.*, *21*, 439–442, 1998.

Kaufman, Y. J., D. Tanré, L. A. Remer, E. Vermote, A. Chu, and B. N. Holben, Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectroradiometer, *J. Geophys. Res.*, *102*, 17,051–17,067, 1997.

King, M. D., Y. J. Kaufman, D. Tanré, and T. Nakajima, Remote sensing of tropospheric aerosols from space: Past, present, and future, *B. Am. Meteor. Soc.*, *80*, 2229–2259, 1999.

Martins, J. V., D. Tanré, L. Remer, Y. Kaufman, S. Mattoo, and R. Levy, MODIS cloud screening for remote sensing of aerosol over ocean using spatial variability, *Geophys. Res. Lett.*, this issue.

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

Stowe, L., A. Ignatov, and R. Singh, Development, validation, and potential enhancements to the second-generation operational aerosol product at the National Environmental Satellite, Data and Information Service of the National Oceanic and Atmospheric Administration, *J. Geophys. Res.*, *102*, 16,923–16,934, 1997.

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

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