

## Validation of Satellite Aerosol Retrievals from AERONET Ground-based Measurements

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Accurate and comprehensive assessment of the parameters that control key atmospheric and biospheric processes including assessment of anthropogenic effects on climate change is a fundamental measurement objective of NASA's EOS program (King and Greenstone, 1999). Satellite assessment programs and associated global climate models require validation and additional parameterization with frequent reliable ground-based observations. A critical and highly uncertain element of the measurement program is characterization of tropospheric aerosols requiring basic observations of aerosols optical and microphysical properties. Unfortunately as yet we do not know the aerosol burden man is contributing to the atmosphere and thus we will have no definitive measure of change for the future. This lack of aerosol assessment is the impetus for some of the EOS measurement activities (Kaufman et al., 1997; King et al., 1999) and the formation of the AERONET program (Holben et al., 1998). The goals of the AERONET program are to develop long term monitoring at globally distributed sites providing critical data for multi-annual trend changes in aerosol loading and optical properties with the specific goal of providing a data base for validation of satellite derived aerosol optical properties.

The AERONET program has evolved into an international federated network of approximately 100 ground-based remote sensing monitoring stations to characterize the optical and microphysical properties of aerosols. The recognized importance of these measurements to the international scientific community has likewise evolved. Initial requirements to provide improved characterization of the atmosphere for atmospheric correction of RS data was later augmented by the need to validate aerosol retrievals from satellites (Holben et al., 1998). Development of cloud cleared and quality assured data sets has anchored that effort (Smirnov et al., 1999). Recent growth and development of the program has further shifted emphasis to a complimentary system with satellite aerosol owing to the improved and new microphysical and optical properties retrieved from the globally distributed network of instruments (Dubovik and King, 2000). AERONET measurements characterize total column aerosol optical and microphysical properties in regions difficult for passive satellite systems, in particular over land where low aerosol loading and high surface reflectance presents only a weak noisy signal for satellite retrievals but is in the normal operating range for sun photometry. Furthermore, the diversity of geographic locations, aerosol types, and water vapor regimes dictates new opportunities for data collection, analysis of results and comparisons to satellite, airborne and in situ observational data sets. Clearly, progress in the earth sciences is driven by more and better measurements integrated with rigorous model development and analysis.

The AERONET program provides an array of aerosol optical and microphysical properties from inversion of direct sun and sky radiance measurements in the UV, visible and near-infrared wavelengths at approximately 100 globally distributed ground-based sites. The resulting temporal data-base of column integrated spectral aerosol optical thickness, spectral single scattering albedo, spectral phase function, particle size distribution among other parameters are quality assured and cloud screened. Accuracy assessments of field instruments have shown typical uncertainties of  $\pm 0.01$ ,  $\pm 0.03$  and  $\pm 0.01$  for AOD, single scattering albedo and effective radius respectively, well within the expected accuracy required for comparisons to and validation

of satellite retrievals. Validation is facilitated by development of a daily updated parameter specific spreadsheet of all AERONET sites thus allowing direct temporal comparisons for all sites as needed for satellite retrievals and statistical assessment.

AERONET sites include most aerosol types such as biomass burning, urban/industrial sulfate, biogenic, marine and desert dust aerosols as well as various combinations of the above. These data have been compared to several satellite aerosol retrieval systems in an effort to provide an assessment of the processing algorithms and ultimately assist in a global aerosol assessment. TOMS, AVHRR, and MODIS represent a wide diversity of satellite system resolutions, spectral sensitivity and methods used to retrieve AEROSOL optical properties that have recently taken advantage of the AERONET data-base. Following is a brief summary of the results and approaches taken to assess satellite retrievals of aerosols.

### TOMS

Total Ozone Mapping Spectrometer (TOMS) developed to assess ozone concentrations in the earth's atmosphere has been processed to detect and characterize global aerosol dynamics (Herman et al., 1997 and Torres et al., 1998). The approach uses space-measured radiances in the 330-380 nm range by the TOMS series of instruments and takes advantage of low and similar reflectances of water and land in the UV allowing characterization of aerosols. Two methods are used to characterize aerosol loading, based on absorbing aerosols (carbonaceous and mineral dust) and scattering aerosols sulfate based aerosols. In the former case, multiple Rayleigh scattering increases the photon path length and the opportunity of absorption by UV absorbing aerosols. Since this technique depends on molecular scattering, in addition to aerosol amount and microphysical properties, the measured radiances at the top of the atmosphere also depend on the height above the ground of the absorbing aerosol layer. The non-absorbing aerosol method depends on added singly scattered radiance to the background scattered radiances, thus is not dependent on the height of the aerosol layer (Torres et al., 1998). The great advantage of the UV-TOMS approaches is aerosol characterization over ice and snow free land and water surfaces, daily global coverage and long-term data archive but the disadvantage is sub pixel cloud contamination of the relatively large 40x40 km pixels. Clearly assessment of the retrieval success is needed.

The following analysis is reported by Torres et al., (2000). Six land-based AERONET sites were chosen for comparison to the EP-TOMS retrievals in the US representing three non-absorbing aerosol sites in the US upper midwest, lower great plains and eastern US; two mineral dust dominated (but some smoke) sites in West Africa and Mongu, Zambia affected by a long biomass burning season. EP-TOMS measurements were averaged over a  $1^\circ \times 1^\circ$  box centered over the AERONET site and compared to quality assured (Smirnov et al., 1999) averaged AERONET observations within 30 minutes of satellite overpass. All AERONET AOT time comparisons clearly show a correspondence however large departures are noted. Analysis of scatter plots of EP-TOMS AOT vs AERONET for the non absorbing sites clearly illustrates that for low optical depths ( $\tau_{380} < 0.2$ ) there is no significant correlation however when all points are considered  $R^2$  of  $\sim 0.5$  is obtained, correlations are improved when high values are included. For sun photometer AOT measurements exceeding 0.2 the level of agreement is within the predicted accuracy ( $\pm 20\%$ ) of correct values (Torres et al., 1998 and Torres et al., 2000). Clearly over estimates by EP-TOMS may be attributed to optically thin clouds increasing the observed radiance with the TOMS FOV.

Comparison to absorbing aerosols shows a similar trend of low correspondence at low AOT however the  $R^2$  is higher due to the larger optical depths observed at these sites driving the correlation. Most points do fall within the limits of uncertainty estimated by Torres et al., (1998)

that may be attributed to aerosol height, cloud contamination and prescribed surface reflectivity. It is postulated that some of the random uncertainty in the comparison is due to the variability in the aerosol distribution across the  $1^\circ \times 1^\circ$  box which is not reflected in the AERONET point observation.

#### **AVHRR**

Zhao et al. (2000) addressed the issue of proper sampling of AERONET and satellite data for comprehensive validation of satellite aerosol retrievals. Their approach is to standardize the validation procedure by identifying through sensitivity studies optimal time/space match-up windows, the ensemble statistical analysis and the best selection of channels of sun-photometer observation and numerical scheme to interpolate/extrapolate sun photometer observations to satellite channels. The validation procedure was developed for and tested with NOAA-4/AVHRR and TRMM/CERES (VIRS) using oceanic AERONET sites with the added complication of extrapolation to  $1.6 \mu\text{m}$  not measured by current AERONET instruments. Three aspects of validation were addressed, the calibration window size (100, 200, 300, 400 and 500 km radius), time from overpass window (1, 2, 3, and 4 hr), interpolation between bands to achieve the best spectral match up, and to determine the best method of selecting points within a time/space window.

A series of linear regressions are computed from aerosol optical depth and Angstrom exponent ( $\tau_{\text{st}}$  vs  $\tau_{\text{sp}}$  and  $\alpha_{\text{st}}$  vs  $\alpha_{\text{sp}}$ ) scattergrams for a variety of daily time and space match-ups. The regression parameters (intercept, slope, standard deviation and  $R^2$ ) may then be analyzed. A non zero intercept suggest the retrieval may be associated with system calibration error or improper assumption of ocean surface reflection. A non-unity slope indicates inconsistency between the aerosol microphysics model used in the retrieval algorithm and the true model. Seven oceanic and coastal sites were used both together and individually in the analysis.

Results from this investigation are absolutely clear. Zhao et al., (2000) report not unexpectedly that 1hr/100km proved to be the optimal time space match up and for AVHRR bands bracketed by the AERONET wavelengths, no significant difference was observed in channel combinations. They also determined that an ensemble of points falling within the 1hr/100km window is superior to specific selection criteria in part for improved statistics with the greater number of ensemble points. With the validation parameters clearly defined, Zhao et al., (2000) addressed questions on the global AVHRR retrieval set relating to retrieval model parameters, aerosol types, and viewing geometry.

#### **MODIS**

The MODERate resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra is the most advanced satellite system to retrieve aerosol optical properties including daily, global aerosol characterization (Tanré et al., 1997; Kaufman et al., 1997). Over cloud-free, glint free ocean scenes, the MODIS aerosol algorithm inverts the measured 500m resolution radiance from six MODIS bands ( $0.55\text{--}2.13 \mu\text{m}$ ) to retrieve the aerosol information on a 10 km grid. Specific retrievals include aerosol optical thickness in seven wavelengths, the effective radius of the aerosol, the fraction of the total optical thickness contributed by the fine mode aerosol and various aerosol-related quantities derived from these primary retrievals (Tanré et al. 1997).

Remer et al., (2000) use a more restrictive time space window (30 min/50 km square) than Zhao to compare to the AERONET observations. Since August, 2000, eleven AERONET 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 central 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). MODIS derives two primary size parameters: the effective radius of the total aerosol size distribution and the fraction of optical thickness contributed by the fine mode aerosol. AERONET employs the Dubovik and King (2000) inversion on the sky radiance data to derive the aerosol size distribution and from the size distribution calculates the effective radius and the aerosol volume in each mode. The Dubovik and King (2000) effective radius is identical to the MODIS effective radius and directly comparable. The MODIS ratio of optical thickness should correlate to the AERONET ratio of volumes, but it is not the same quantity, and the two parameters are not expected to agree quantitatively.

The eleven site ensemble agreement, as represented by the linear fit ( $R^2 = 0.88$  at 660 nm), is exceptionally good and well within the expected uncertainty ( $\Delta\tau = \pm 0.03 \pm 0.05\tau$ ) (Tanré et al., 1997; Tanré et al., 1999; King et al., 1999). The validation of the effective radius and the comparison of the ratio of modes are made for data with  $\tau_{660} > 0.15$ . For most of the range of sizes in this data set, MODIS retrievals fall within  $\pm 0.10 \mu\text{m}$  of the AERONET retrievals. The comparison of modal ratios indicate definite correlation, even though the values of the two parameters differ. This comparison with ground-based data gives us confidence that MODIS can differentiate between large mode and small mode aerosol, and begin to quantify the size of the aerosol particles.

These three examples of satellite aerosol validation represent very recent use of the AERONET data-base. As new AERONET data products are developed and micro and mega validation data-bases improved and made available on the AERONET website (<http://aeronet.gsfc.nasa.gov:8080/>), opportunities for multi satellite, ground-based and model comparisons and validations are expected to arise and improve our understanding of the global aerosol disposition.

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