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EVALUATION OF TERRA AEROSOL AND WATER VAPOR MEASUREMENTS USING ARM SGP DATA

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1. INTRODUCTION

NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging Spectroradiometer (MISR) sensors, which are on board the Earth Observing System (EOS) Terra satellite platform launched in December 1999, have provided new data sets to monitor the Earth's atmospheric properties. As part of the EOS Validation Program, we have evaluated aerosol optical thickness (AOT) and precipitable water vapor (PWV) from the Level-2 MODIS Atmosphere Product and AOT from MISR using measurements from ground based sensors at the Department of Energy's Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site in northern Oklahoma (36.605 N, 97.489 W).

2. TERRA MODIS AND MISR MEASUREMENTS

The MODIS Aerosol Product (MOD04_L2) monitors aerosol type, aerosol optical thickness, particle size distribution, aerosol mass concentration, optical properties, and radiative forcing. The MODIS aerosol retrieval algorithm operates by comparing radiances measured at several visible and infrared wavelengths with tabulated radiances that have been computed for specific aerosol models. Over land, the algorithm retrieves aerosol optical thickness (AOT) at three visible wavelengths, 470 nm, 550 nm, and 660 nm, with a spatial resolution of 10x10 km.

The MODIS Water Vapor Product (MOD05) monitors total column atmospheric water vapor, which is also referred to as precipitable water vapor (PWV). Near-IR bands and the traditional IR bands are used for water vapor retrievals. MODIS has several channels located within and around the 940 nm water vapor absorption region for retrieving PWV during the daytime. These near-IR PWV amounts are derived from the transmittances based on theoretical radiative-transfer calculations and using look-up-table procedures. For the IR algorithm, PWV is also derived by integration of the MODIS water vapor profile retrieved from the thermal infrared sounding data. This IR PWV is derived for both daytime and nighttime measurements.

The Multi-angle Imaging Spectroradiometer (MISR) images the surface at nine view angles up to 70.5 degrees fore and aft of vertical at four wavelengths (446, 558, 672 and 866 nm). MISR radiances are measured at 1.1 km resolution. The MISR AOT algorithm uses spatial contrasts in the scene with candidate aerosol models, along with modeled atmospheric path radiances to compute AOT. Measurements of AOT are averaged within 17.6x17.6 km^2 over all the successful candidate aerosol models to compute the regional mean optical thickness (Diner et al., 2001).

3. AEROSOL OPTICAL THICKNESS

ARM SGP Cimel Sun photometer (Cimel) and Multi Filter Rotating Shadowband Radiometer (MFRSR) measurements of AOT acquired within +/-45 minutes of the Terra overpass are used to evaluate the MODIS and MISR AOT retrievals. For daytime measurements over the SGP site, these overpasses occur between 16:00-19:00 UT (10:00-13:00 CST). The Cimel is part of the operational Aerosol Robotic Network (AERONET) of Sun photometers (Holben et al., 1998). Calibration errors for the MFRSR and Cimel instruments are expected to be less than 1.0% (Michalsky et al; 2001). Intercomparisons have shown AOT differences of less than 0.02 (Schmid et al., 1999). The Cimel (340, 380, 440, 500, 670, 870, 1020 nm) and MFRSR (415, 500, 615, 673, 870 nm) AOT data are logarithmically interpolated on wavelength to the MODIS wavelengths. The MODIS and MISR AOT data within a 25 km radius circle around the SGP site are averaged together to give a single value that is compared with the SGP measurements. We require at least two of the SGP AOT measurements be within +/- 45 minutes of Terra overpass, and at least 3 successful MODIS retrievals out of a possible 25 for the evaluations that follow. Retrievals in regions classified as either cloudy or probably cloudy by the MODIS (MOD35) cloud mask are excluded.

We examined MODIS AOT between July 2000 and December 2001. Comparisons of AOT at 470 nm and 660 nm are shown in Figure 1. Linear regression results are shown for 470 nm but not at 660 nm where the linear correlation coefficient was less than 0.3. Also shown are the retrieval errors of $\Delta AOT=\pm 0.05 \pm 0.2*AOT$ expected for retrievals over land (Kaufman et al., 1997). The error bars on the MODIS retrievals represent these error estimates; the error bars on the SGP AOT values are the maximum of 10% of the AOT or 0.01. Although the low range of AOT over the SGP site generally results in a large scatter of the MODIS retrieval values, most of the MODIS AOT retrievals fall within the expected retrieval errors. Other comparisons of MODIS AOT over land, which have examined data covering a larger range of AOT, have found generally better agreement between surface and MODIS AOT

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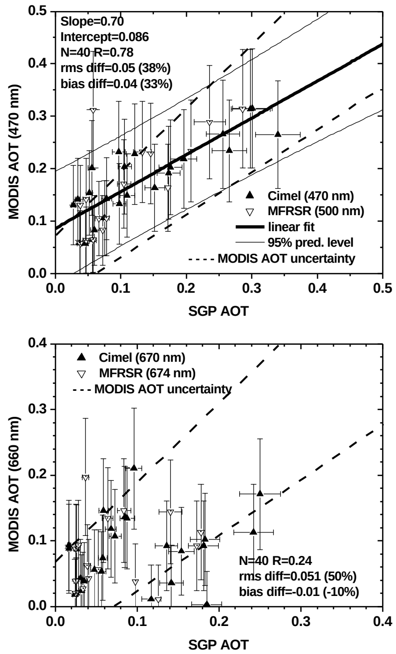


Figure 1. Comparison of AOT derived from MODIS measurements at 470 nm (top) and 660 (nm) bottom with corresponding ARM SGP AOT.

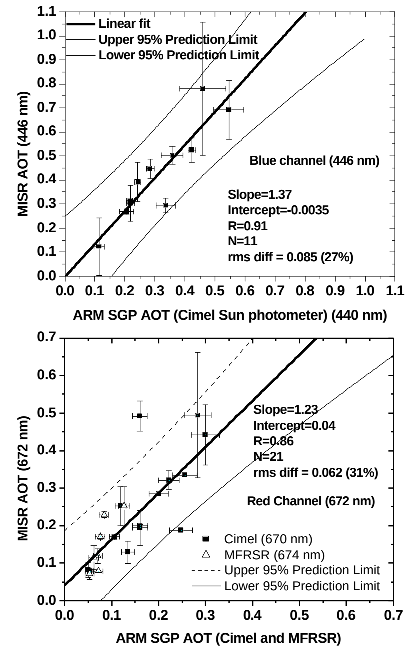


Figure 2. Comparison of AOT derived from MISR measurements at 446 nm (top) and 672 (nm) bottom with corresponding ARM SGP AOT.

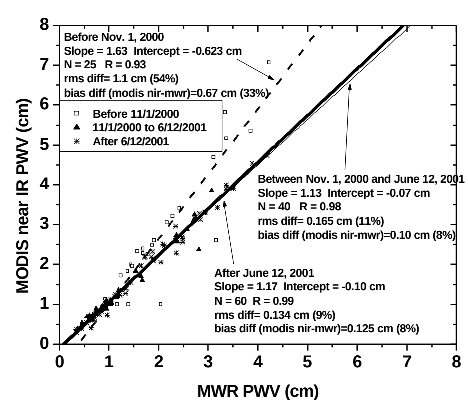
measurements, where the differences between the MODIS and AERONET AOT values are within the expected retrieval errors (Chu et al., 2001).

Similar comparisons between SGP and MISR AOT (version F02_0006) for the period between March and December 2001 are shown in Figure 2. Fewer points are available than the MODIS comparisons because of the shorter period and the smaller scan width of MISR (~400 km) as compared to MODIS (~2300 km). The MISR AOT values are well correlated to the SGP AOT with linear correlation coefficients of 0.91 (446 nm) and 0.85 (672 nm), but are systematically higher than the SGP values by about 20-30%. Previous comparisons of MISR and AERONET AOT found a small (~10%) high bias of MISR AOT retrievals that was reduced when potential thin cirrus contamination of the AERONET retrievals was removed (Diner et al., 2001). MISR algorithms were revised in April 2002; we have not yet examined the results of this revision.

4. PRECIPITABLE WATER VAPOR (PWV)

MODIS near IR and IR PWV are evaluated using PWV measured by the SGP microwave radiometer (MWR), Raman lidar, and Cimel. The Raman lidar PWV measurements used here are from only nighttime operations, the Cimel PWV measurements are from only daytime measurements, and the MWR PWV measurements are from both daytime and nighttime operations. The Raman lidar as been calibrated such that the lidar PWV matches the MWR PWV.

We examined MODIS near IR PWV between March 2000 and March 2002. As shown in Figure 3, the MWR and MODIS near IR measurements acquired after November 1, 2000 show much better agreement than similar comparisons for data acquired before this date. Around November 1, 2000, the water vapor transmittance lookup table was changed. At the same time, MODIS was switched to the side-b electronics, which resulted in improved radiometric calibrations, particularly for the 1.24 μm MODIS channel. For MODIS data acquired before November 1, 2000, the 1.24 μm apparent reflectances were consistently higher than expected. Consequently, when the 0.865 μm channel and 1.24 μm channels were used to estimate the 0.94 μm spectral background level, the estimated background levels were erroneously high, which resulted in an overestimate of water vapor absorption



Fgure 3. Comparison of PWV derived from MODIS near IR measurements with SGP MWR PWV.

for the 0.94 µm channel. Therefore, PWV values were much greater than the PWV measured by the SGP MWR. Subsequently, HITRAN2000 and a line-by-line code were used to regenerate lookup tables for the MODIS near IR water vapor algorithm. These line-by-line based lookup tables are now used in the operational algorithm since about June, 2001. Figure 3 shows that since November 1, 2000 bias and rms differences between the MODIS near IR and SGP MWR PWV measurements are generally less than 10%.

We also evaluated MODIS IR (MOD_PR07 algorithm version 3.0) PWV measurements acquired between March 2000 and March 2002. These comparisons, shown in Figure 4, show relatively large relative errors at low PWV due to an apparent MODIS IR PWV offset (i.e. floor around 5-7 mm). Mean differences are around 2 mm (~25%) with MODIS IR PWV greater than SGP MWR PWV and rms differences around 6 mm (~50%). MODIS IR PWV appears to have better agreement with SGP PWV for daytime measurements as shown by the smaller offset, increase in slope closer to unity, and higher linear correlation coefficient. Several significant updates were applied to the MOD07 total precipitable water vapor algorithm starting in Mayl 2002. These updates, which are summarized at http://modis-atmos.gsfc.nasa.gov/MOD07_L2/history.html, should improve the agreement between the MODIS IR and ARM SGP measurements of PWV.

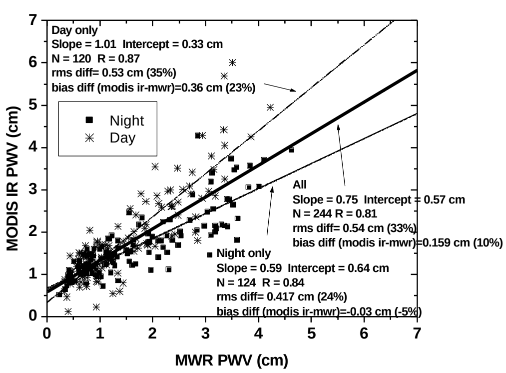


Figure 4. Comparison of PWV derived from MODIS IR measurements with SGP MWR PWV.

5. AVERAGE PROFILES

Average aerosol and water vapor profiles for the time of the Terra overpass (16:00-19:00 UT) were derived from SGP CART Raman lidar measurements acquired over 946 days between March 1, 1998 and December 31, 2001. During this period, CARL operated an average of about 55% of the time. These profiles, which are shown in Figure 5, indicate that the average water vapor mixing ratio and aerosol extinction profiles vary differently with season. This is consistent with earlier results that showed that while the scale height of aerosol extinction varies considerably as both a function of season and aerosol optical thickness, the mean scale height of the water vapor remained very close to 2 km, regardless of season or precipitable water vapor (Turner et al., 2001).

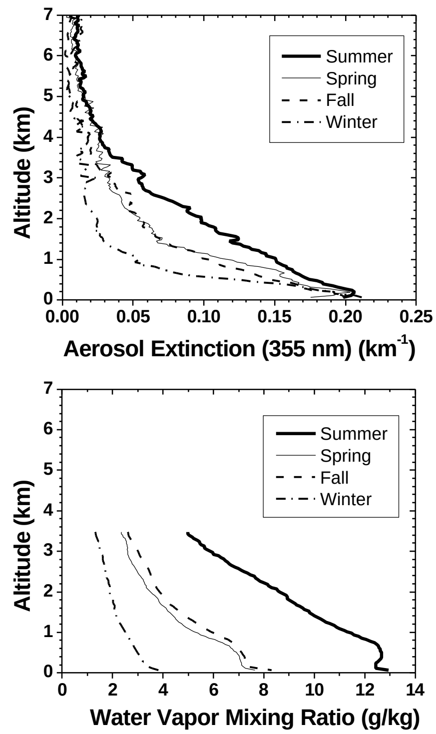


Figure 5. Average aerosol extinction (top) and water vapor mixing ratio (bottom) profiles derived from ARM SGP Raman lidar measurements between 16:00-19:00 UT.

6. DIURNAL VARIABILITY

Raman lidar profiles were also used to characterize the diurnal variability of aerosols and water vapor. Aerosol extinction, water vapor mixing ratio, and relative humidity profiles were averaged over each hour of the day for all seasons. The highest aerosol extinction was generally observed close to the surface during the nighttime just prior to sunrise. The high values of aerosol extinction are most likely associated with increased scattering by hygroscopic aerosols, since the corresponding average relative humidity values were above 70%. After sunrise, relative humidity and aerosol extinction below 500 m decreased with the growth in the daytime convective boundary layer. The largest aerosol extinction for altitudes above 1 km occurred during the early afternoon most likely as a result of the increase in relative humidity. The water vapor mixing ratio profiles generally showed smaller variations with altitude between day and night. Figure 6 shows the diurnal variability of both AOT and integrated water vapor for winter and summer. These results show that the relatively large (10-25%) changes that occur in the average aerosol extinction profiles have a smaller impact on the AOT. The standard deviation of the AOT was about 10% of the daily average AOT during both summer and winter. In contrast, the water vapor profiles showed about half this variability for both the summer and winter cases.

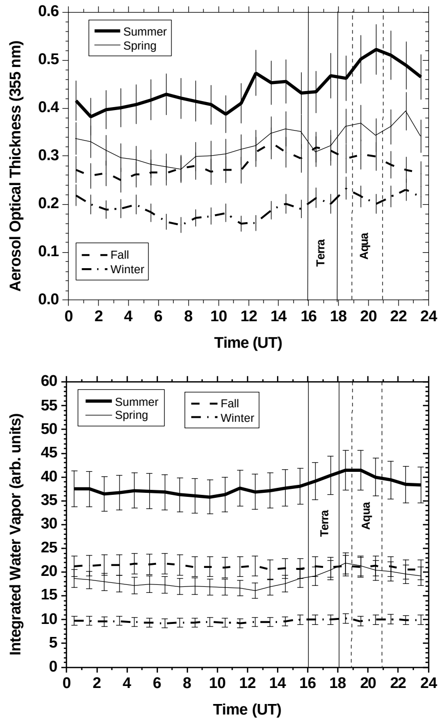


Figure 6. Diurnal variation of AOT (top) and integrated water vapor (bottom) derived from ARM SGP Raman lidar measurements.

7. SUMMARY

Terra MODIS and MISR measurements of AOT and MODIS measurements of PWV are evaluated using measurements from ground based sensors at the DOE ARM SGP site. Although the low range of AOT observed (~0.0-0.3) over this site hampered full evaluation of the MODIS AOT and produced relatively large rms differences (33-50%), the MODIS AOT agreed with the SGP AOT measurements within the expected uncertainties (ΔAOT=±0.05 ±0.2*AOT) of MODIS AOT retrievals. The MISR AOT values were well correlated with the ARM SGP AOT measurements but were systematically 20-30% higher than the SGP values. MODIS near IR PWV agreed well with the ARM SGP MWR PWV measurements with bias and rms differences generally less than 10%. MODIS IR PWV were generally higher than the SGP MWR measurements, especially for low water vapor amounts. Revisions to MODIS IR water vapor retrievals after April 2002 should produce better agreement with the ARM SGP PWV. *These evaluations of MODIS and MISR measurements are for the ARM SGP site only, and do not necessarily reflect performance at other locations.*

Average aerosol extinction and water vapor profiles at the time of Terra overpass were derived from Raman lidar measurements. The seasonal variability of the average aerosol extinction profiles are different from the seasonal variabilty of the water vapor profiles. Although the diurnal variability of AOT and PWV is generally less than 10%, relatively large (10-25%) diurnal changes occur in average aerosol extinction profiles.

8. ACKNOWLEDGEMENTS

SGP CART Raman lidar and Cimel Sun photometer data were obtained from the Atmospheric Radiation Measurement (ARM) Program sponsored by the U.S. Department of Energy, Office of Energy Research, Office of Health and Environmental Research, Environmental Sciences Division. The Cimel Sun photometer is also part of AERONET, a network of Sun photometers managed by B. N. Holben, NASA/GSFC. Funding for this work was provided by the NASA EOS Validation and DOE ARM Programs. We thank Suzanne Wetzel Seemann (Univ. of Wisconsin-Madison) for updates regarding the MODIS IR PWV retrievals, and Dave Diner (JPL) for updates regarding the MISR AOT retrievals.

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