Terra Validation Final Report

Study: EOS Validation of Aerosol and Water Vapor Profiles by Raman Lidar
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Summary

There were two main objectives of this study. The first objective was to evaluate the vertical variability of ambient aerosol properties using the aerosol backscattering and extinction profiles measured by the NASA/GSFC Scanning Raman Lidar (SRL), and the Dept. of Energy Atmospheric Radiation Measurement (ARM) SGP (Southern Great Plains) CART (Cloud and Radiation Testbed) Raman Lidars. With support from the EOS Validation and DOE ARM programs, we developed and successfully implemented automated routines to characterize clear sky conditions above DOE ARM SGP site using Raman lidar data. These are used routinely to produce profiles of aerosol extinction, aerosol backscattering, aerosol optical thickness, water vapor mixing ratio, relative humidity, and precipitable water vapor. These measurements were used to:

- identify vertical variations in aerosols associated with elevated layers of smoke produced from Central American fires in May 1998
- characterize the aerosol extinction/backscattering ratio (i.e. "lidar ratio"), which is important for identifying vertical variability of aerosol optical properties as well as for GLAS and CALIPSO aerosol retrieval algorithms
- characterize the seasonal and diurnal variability of aerosols and water vapor over the ARM SGP Site
- characterize the effect of multiple scattering on lidar retrievals of cirrus cloud optical thickness
- identify a potential bias in GOES retrievals of precipitable water vapor caused by undetected thin cirrus

The second objective was to use the ARM SGP measurements to evaluate the aerosol optical thickness (AOT) measured by MODIS and MISR and the precipitable water vapor (PWV) measured by MODIS. The ARM SGP Cimel Sun photometer and Multi Filter Rotating Shadowband Radiometer (MFRSR) measurements of AOT and Microwave Radiometer (MWR) measurements of PWV were used to evaluate the MODIS and MISR measurements. Although the low range of AOT (~0.0-0.3) observed 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=$\pm$0.05$\pm$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 10-20%. MODIS IR PWV were generally higher than the SGP MWR measurements, especially for low water vapor amounts. Initial comparisons have shown that revisions to MODIS IR water vapor retrievals after April 2002 have not produced significantly better agreement with the ARM SGP PWV.

Accomplishments

Data Processing Results

Automated routines were developed to derive water vapor mixing ratio, relative humidity, aerosol extinction and backscatter coefficient, and linear depolarization profiles, as well as total precipitable water vapor and aerosol optical thickness, from the operational Raman lidar at the Atmospheric Radiation Measurement (ARM) program's site in north-central Oklahoma (Turner et al., 2002). These routines were devised to maintain the calibration of these data products, which have proven sensitive to the automatic alignment adjustments that are made periodically by the instrument. These profiles form the basis of a "best-estimate" product designed to characterize the clear-sky state above the ARM SGP site. These profiles are available from the ARM Archive (http://www.archive.arm.gov/) and in a series of daily "quick-look" images (http://playground.arm.gov/~turner/raman_lidar_quicklooks.html).

Science Results

Water Vapor, Temperature, and Aerosol Optical Thickness Evaluations

As part of the routine diagnostics, the CART Raman Lidar (CARL) water vapor mixing ratio profiles were compared with water vapor profiles measured by Vaisala radiosondes launched at the SGP site. Over 500 lidar/radiosonde profile comparisons examined between April 1998 and October 1999 showed that the unscaled radiosondes were about 3-5% drier than the lidar. When the radiosonde water vapor mixing ratio was scaled to match the microwave precipitable water vapor amount, the scaled radiosonde and lidar water vapor profiles agreed generally within 1-2%.

Aerosol optical thicknesses (AOT), which are computed by integrating the Raman lidar aerosol extinction profiles between 0-6 km, have been compared with simultaneous and independent measurements of AOT made by a Cimel sun photometer at the SGP CART site. The lidar and sun photometer AOT values generally agree, with about a 5% bias difference. Of this difference, 3.5% can be explained by the wavelength dependence of aerosol extinction between the two wavelengths (340 nm vs. 355 nm). The CARL AOT also generally show good agreement with the Cimel AOT when compared as a function of season.

Variability of Aerosols and Water Vapor

Average aerosol and water vapor profiles derived from SGP CART Raman lidar measurements over two years (1998 and 1999) show significant differences in the vertical variability of aerosols and water vapor (Turner et al., 2001). The scale height of aerosol extinction varies considerably as both a function of season and aerosol optical thickness, increasing from less than 1 km in the winter to over 2 km during turbid summer days. In contrast, the mean scale height of the water vapor remained very close to 2 km, regardless of season or precipitable water vapor. These results demonstrate the variability of the aerosols as a function of season, AOT and time of day, and suggest that assuming a constant profile and scaling it to agree in AOT can result in large errors between the assumed profile versus a true profile over this mid-latitude continental site.

The lidar profiles were also used to examine the diurnal variability of aerosols and water vapor (Ferrare et al., 2002). Figure 1 shows aerosol extinction, water vapor mixing ratio, and relative humidity profiles averaged over each hour of the day for both the winter (December-February) and summer (June-August) seasons. The average over the summer included CARL measurements from 205 days during these years, and the winter average included CARL measurements over 180 days. Cloudy samples were excluded from these averages. Times of average sunrise and sunset and Terra and Aqua overpassess are also shown. 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. The aerosol extinction profiles show that relatively large (10-25%) changes that occur in the average aerosol extinction profiles have a smaller impact on the AOT. Figure 1 also shows the diurnal variability of both AOT and integrated water vapor for winter and summer. 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.

Profiles of the aerosol extinction/backscatter ratio ("lidar ratio") derived from SGP CART Raman lidar measurements acquired in 1998 and 1999 show that large variations in this ratio occurred 30% of the time (Ferrare et al., 2001). This implies that significant variability in the vertical distribution of the aerosol size distribution, shape, and/or composition often occurs. A subset of these cases showed that these lidar ratios are linearly correlated with the aerosol fine mode effective radius and volume ratio of fine/coarse particles. These ratios were also found to increase slightly with aerosol optical thickness and relative humidity. These measurements are important for remotely characterizing the vertical variability of aerosols over the SGP site as well as for developing parameterizations for space-based lidar retrievals of aerosol extinction and optical thickness.

Evaluation of MODIS and MISR 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 were 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 (340, 380, 440, 500, 670, 870, 1020 nm) and MFRSR (415, 500, 615, 673, 870 nm) AOT data were logarithmically interpolated on wavelength to the MODIS wavelengths. The MODIS and MISR AOT data within a 25 km radius circle around the SGP site were averaged together to give a single value that is compared with the SGP measurements. We required 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 were excluded. MODIS AOT acquired between July 2000 and September 2002 were examined. Comparisons of AOT at 470 nm and 660 nm are shown in Figures 2a and 2b. Linear regression results are shown as well as 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. Figures 2b and 2c show differences between the MODIS and SGP AOT measurements as functions of AOT and time, respectively. Note how MODIS generally overestimates (underestimates) AOT for low (high) values of AOT. Relative errors increase rapidly for AOT below 0.1 and are consequently larger during the winter when AOT is low.

Similar comparisons between SGP and MISR AOT for the period between March and December 2001 are shown in Figure 2e and 2f. 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 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. Initial results from this revised algorithm, which are included in Figures 2c-f, do not as yet show significant improvements over the previous algorithm.

Evaluation of MODIS Precipitable Water Vapor

MODIS near IR and IR PWV were evaluated using PWV measured by the ARM SGP microwave radiometer (MWR), which measures PWV during both daytime and nighttime operations. We examined MODIS near IR PWV between March 2000 and September 2002. As shown in Figure 3a, 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 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. Figures 3c and 3d show that since November 1, 2000, bias and rms differences between the MODIS near IR and SGP MWR PWV measurements are generally less than 10% for PWV below 3 cm and increase to 10-20% for PWV above 3 cm.

We also evaluated MODIS IR (MOD_PR07 algorithm version 3.0) PWV measurements acquired between March 2000 and September 2002. These comparisons, shown in Figure 3b-d, 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%). Several significant updates were applied to the MOD07 total precipitable water vapor algorithm starting in May 2002. These updates, which are summarized at http://modis-atmos.gsfc.nasa.gov/MOD07_L2/history.html, were shown to improve the agreement between the MODIS IR and ARM SGP MWR measurements of PWV for a subset of data acquired during 2001 (Seamann et al., 2002.). Figure 3b shows that these updates did reduce the relative rms error of these measurements, although the actual correlation with the MWR PWV remained essentially unchanged.

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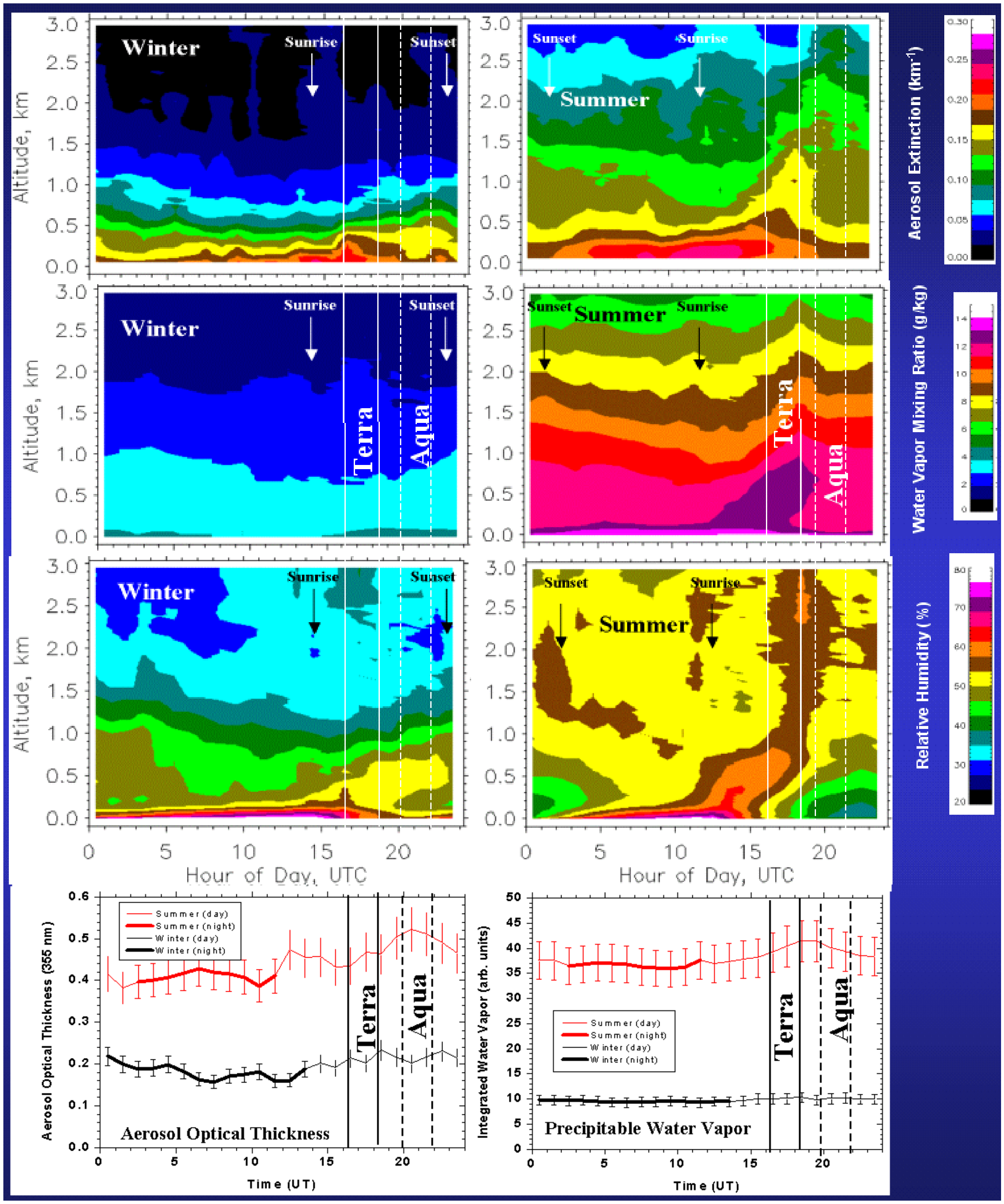

Figure 1. (top) Images showing average diurnal variation of aerosol extinction (top), water vapor mixing ratio (middle), and relative humidity (bottom) profiles measured by CARL for winter (left) and summer (right). (bottom) average AOT (left) and integrated water vapor (right) for summer and winter.

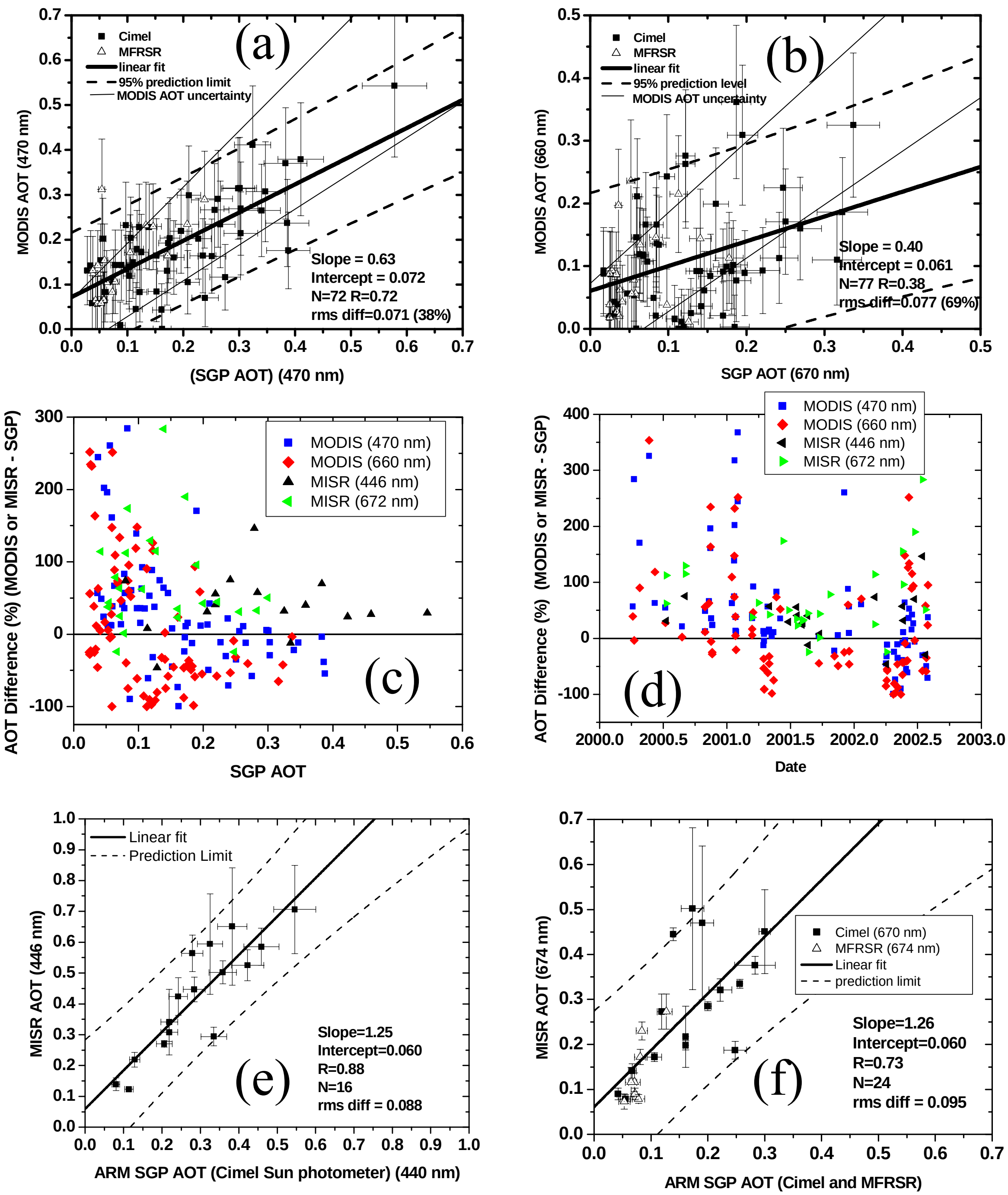

Figure 2. Comparisons of MODIS and ARM SGP AOT at 470 nm (a) and 660 nm (b), differences between MODIS and MISR AOT and ARM SGP AOT versus ARM SGP AOT (c) and date (d), and comparisons of MISR and ARM SGP AOT at 446 nm (e) and 674 nm (f).

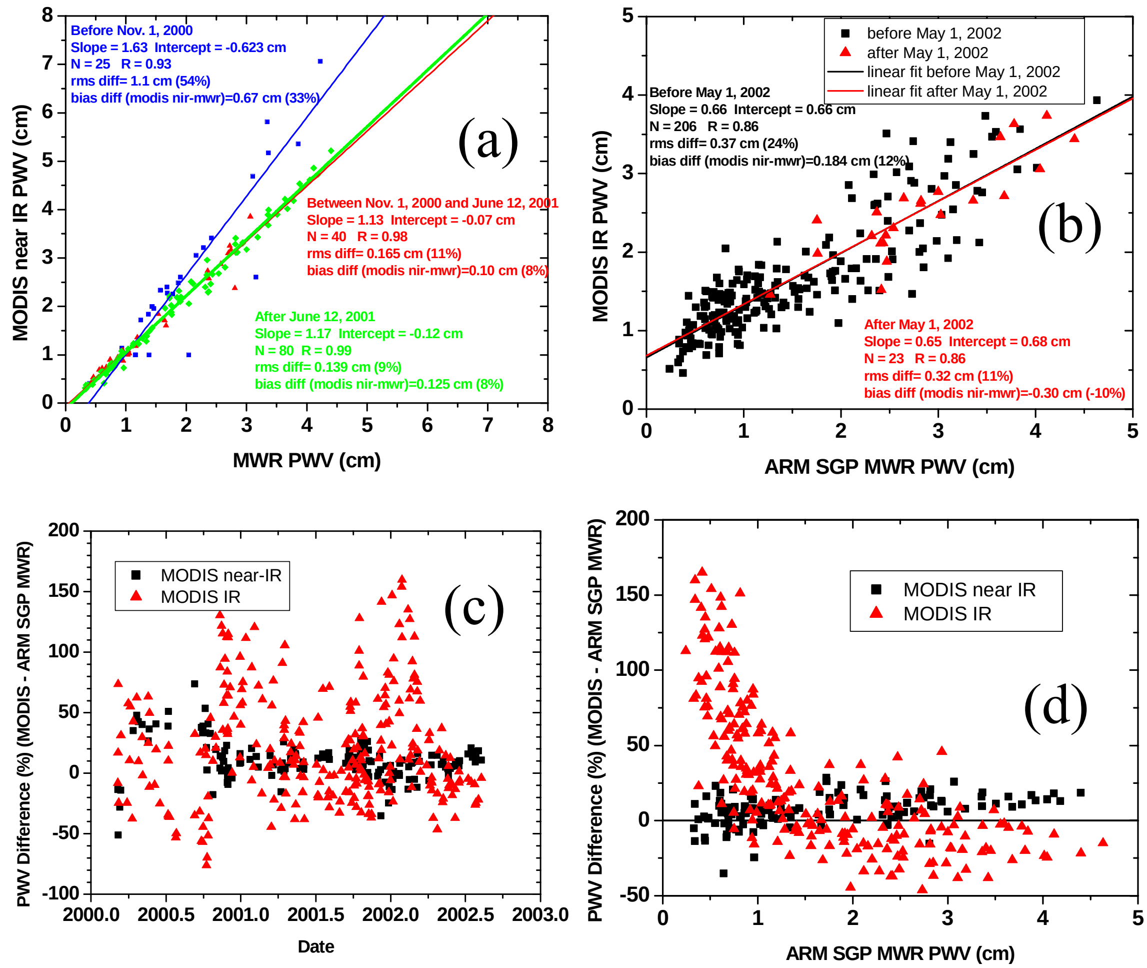

Figure 3. Comparisons of ARM SGP MWR PWV with MODIS near IR PWV (a), and MODIS IR PWV (b), and differences between SGP MWR and MODIS near IR and IR PWV as a function of date (c), and SGP MWR PWV (d).