MODIS Albedo and Reflectance Anisotropy Products from Aqua and Terra

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Abstract

MODIS albedo and reflectance anisotropy products of the global land surface have been routinely available since early 2000.   These multi-year satellite-derived measures of surface reflectance anisotropy and albedo are increasingly being utilized by the modeling community to both evaluate and refine a number of climatological and biogeochemical models.   By combining observations from both the Terra and Aqua platforms andeasing both the spatial and temporal resolution in the collection 005 data reprocessing effort, the quality, consistency, and cloud-free coverage of the global land products has increased.

1. Introduction

A primary goal of NASA's Earth observation efforts is the long term monitoring of key biophysical variables and the production of long term and consistent parameters for modeling studies. Global surface albedo, which controls the land surface radiation energy budget, is required by climate models with an absolute accuracy of 0.02-0.05 and at a range of spatial and temporal scales (Dickinson, 1983;1995; Henderson-Sellers and Wilson, 1983; Bonan et al., 2002; Sellers et al., 1996). Therefore, a consistent and accurate global albedo data set is essential to the investigation of the sensitivity of climate to various types of forcing and to the identification of the effects of human activities. Satellite remote sensing represents the only efficient way to compile such consistent global albedo characterizations.

Early global albedo data sets were derived from the Advanced Very High Resolution Radiometer (AVHRR) (Csiszar and Gutman, 1999) and the Earth Radiation Budget Experiment (ERBE) radiometer (Li and Garand, 1994) although these efforts assumed a lambertian surface and did not compensate for surface anisotropy. Now however, routine moderate resolution albedo and reflectance anisotropy products with spatial resolutions of 500m to 20 km and temporal frequencies of daily to monthly are being derived from polar orbiting satellites such as MODIS (Gao et al., 2005; Schaaf et al., 2002; Lucht et al., 2000), MISR (Martonchik et al., 2002; Martonchik et al., 1998a;b), CERES (Clouds and the Earth's Radiant Energy System) (Rutan et al., 2006), and POLDER (Polarization and Directionality of the Earth's Reflectances) currently on board PARASOL (Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL) (Leroy et al., 1997; Hautrecoeur and Leroy, 1998; Bicheron and Leroy, 2000; Maignan et al., 2004; Bacour and Breon, 2005). With an assumption of the reciprocity principle, which is generally acceptable for moderate resolution sensors (Lattanzio et al., 2006; Li et al., 1999), similar products from the geosynchronous satellites, Meteosat (Pinty et al., 2000a;b; Govaerts eta l., 2004; 2006), and MSG (Meteosat Second Generation) (van Leeuwen and Roujean, 2002; Geiger et al., 2005) are

also now available. The retrieval of albedo from these instruments represents a major advance in sensing the spatial and temporal surface heterogeneity, although issues such as atmospheric correction, directional-to-hemispherical conversion, and spectral interpolation can still introduce small and quantifiable uncertainties in to the process. These satellite products rely on sophisticated radiative transfer methods (Vermote et al., 1997; Kotchenova et al., 2006; Berk et al., 1998; Liang et al, 1999; Liang, 2000) and bidirectional anisotropic reflectance modeling (Walthall et al., 1985; Roujean et al., 1992; Rahman et al., 1993; Engelsen et al., 1996; Wanner et al., 1995; Wanner et al., 1997; Martonchik et al., 1998b; Pinty et al., 2000a;b; Bréon et al., 2002; Maignan et al., 2004) to obtain accurate surface quantities. The routine retrieval of high quality and consistent global surface Bidirectional Reflectance Distribution Function (BRDF) estimates from flexible and realistic anisotropic models has therefore become a necessary and inherently useful by-product of the production of accurate surface albedo products.

With more than eight years of MODIS albedo and reflectance anisotropy data now available, the modeling community has been enthusiastically utilizing these global products (Oleson et al., 2003, Zhou et al., 2003, Tian et al., 2004, Roesch et al., 2004, Knorr et al., 2001, Myhre et al., 2005a;b; Lawrence and Chase, 2007). Interannual variations are being explored and limited interannual statistics are being prepared which compensate for transient cloudiness or snow cover (Moody et al., 2005; 2007; Gao et al., 2005; Barlage et al., 2005). In addition to the use of the MODIS products, there is a keen interest in generating analogous surface albedo products from the period prior to the deployment of the MODIS sensors when only operational weather satellites were acquiring relevant data (Saleous et al., 2005) and ultimately to link these historical datasets (despite their limitations in terms of accurate sensor characterization, geolocation, and calibration) with the more modern MODIS albedo and anisotropy products.

2. MODIS Albedo and Reflectance Anisotropy Algorithm

The operational MODIS albedo and reflectance anisotropy algorithm makes use of a kernel-driven, linear model that relies on the weighted sum of an isotropic parameter and two functions (or kernels) of viewing and illumination geometry (Roujean et al., 1992) to estimate the BRDF. One kernel is derived from radiative transfer models (Ross, 1981) and the other is based on surface scattering and geometric shadow-casting theory (Li and Strahler, 1992). The kernel weights selected are those that best fit the cloud-cleared, atmospherically corrected surface reflectances available for each location over a 16 day period (Lucht et al., 2000; Schaaf et al., 2002). This model combination (Ross-Thick/Li-Sparse-Reciprocal or RTLSR) has been shown to be well suited to describing the surface anisotropy of the variety of land covers that are distributed world-wide (Privette et al., 1997; Lucht et al., 2000) and is similar to the kernel-driven schemes used to obtain anisotropy and albedo information by the POLDER (Hautecoeur and Leroy, 1998; Bicheron and Leroy, 2000; Maignan et al., 2004; Bacour and Bréon, 2005) satellite sensor and MSG (van Leeuwen and Roujean, 2002; Geiger et al., 2005). The approach assumes that the geophysical system under investigation does not experience significant changes during the period of data accumulation and the temporal sampling of the radiance field for a given location can be interpreted as instantaneous angular sampling (a

reasonable assumption except in circumstances of abrupt or catastrophic change such as snow, fire, flood, or harvest).

Once an appropriate anisotropy estimate of the BRDF has been retrieved, integration over all view angles results in a Directional Hemispherical Reflectance (DHR) or a black-sky albedo at any desired solar angle and a further integration over all illumination angles results in a bihemispherical reflectance under isotropic illumination (BHR_{iso}) or a white-sky albedo (Schaepman-Strub et al., 2006). These quantities are intrinsic to specific locations and are associated with the structure and optical properties of the land cover. They can be combined with appropriate atmospheric optical depth information to estimate an actual BHR (blue-sky albedo) for a specific time such as would be measured at the surface by field sensors under ambient illumination. The reflectance anisotropy estimates of the BRDF can also be used to determine surface reflectances at view or solar angles other than those typically acquired (such as correcting to a nadir view) with uncertainties that can be quantified by metrics such as the weight of determination. The spectral acquisitions can also be combined via narrow to broadband conversion coefficients (Liang et al., 1999; 2000) to provide broadband anisotropy information and thus broadband albedos similar to those routinely collected in the field with pyranometers and commonly used in large-scale models.

The MODIS instruments on both Aqua and Terra each have a 16-day repeat cycle and provide measurements on a global basis every 1-2 days with multiple overpasses possible at higher latitudes. This 16-day period provides an appropriate tradeoff between the availability of sufficient angular samples and the temporal stability of the surface (Wanner et al., 1997; Gao et al., 2001; Roy et al., 2006). This assumption of stability becomes more tenuous during periods of strong phenological change such as vegetation greenup, senescence, or harvesting. By overlapping processing of the data such that retrievals are attempted every eight days (based on all clear observations over the past 16 days), there are more frequent opportunities to obtain high quality retrievals during periods of intermittent clear sky observations. However, during long periods of clear sky acquisitions, this overlapping technique can result in some autocorrelation between retrievals as some of the observations may end up being used in more than one retrieval period. Additional occurrences of rapid change, such as ephemeral snowfall, also provide challenges in surface albedo retrieval. The MODIS algorithm addresses this by determining whether the majority of the clear observations available over a 16-day period represent snow-covered or snow-free situations and then retrieving the albedo of the majority condition accordingly. The availability of a sufficient number of high quality clear-sky surface observations of either the snow-covered or snow-free situation will not guarantee a high quality retrieval, however, as an adequate sampling of the angular domain is equally important in establishing a model that will accurately estimate the surface reflectance anisotropy (Lucht and Lewis, 2000; Barnsley et al., 1994)).

Whenever the full anisotropic model described above can not be confidently retrieved due to poor sampling or insufficient input observations, a backup algorithm is employed. This method (Strugnell and Lucht, 2001; Strugnell et al., 2001) relies on a global database of archetypal anisotropic models based on a land cover classification and

historical high-quality full-model MODIS retrievals. This *a priori* data base is then used as a first approximation of the underlying reflectance anisotropy and any available observations acquired during the 16-day window are used to constrain the model (Li et al., 2001). Although this magnitude inversion is considered and is flagged as a lower quality result, field validation exercises by Jin et al. (2003a; b) and Salomon et al., (2006) have found that this backup method often performs quite well, routinely falling within 5-10% of field measured albedos.

The MODIS BRDF/Albedo products have now completed their fifth reprocessing. The collection 005 standard operational products (Lucht et al., 2000; Schaaf et al., 2002; Gao et al., 2005) include the best-fit, well-sampled RTLSR model parameters describing the surface anisotropy, both black sky and white sky albedo quantities, the nadir (view-angle-corrected) surface reflectance of each location, and extensive quality information. The best fit RTLSR model parameters are retrieved for the first seven spectral bands of MODIS (centered at 648 nm, 858 nm, 470nm, 555nm, 1240 nm, 1640 nm, and 2130 nm, respectively) and three additional broadbands $(0.3 – 0.7\mu m, 0.7-5\mu m, 0.3-5\mu m)$. These anisotropy models are then integrated to compute white sky albedo and black sky albedo at local solar noon for the same 7 spectral bands and 3 broadbands (Figure 1a). Local solar noon was selected both as a compromise geometry between the Terra and Aqua overpasses and as a value that would ensuremaximum illumination at each location worldwide.

While the precomputed albedo values have enjoyed widespread use, users are increasingly utilizing the BRDF models directly so that they can generate albedos at any desired illumination angle or under realistic atmospheric conditions. Four common shape factors or structural indices are also operationally computed for the modeling community, including an anisotropic factor, a normalized difference anisotropic index (Sandmeier et al., 1998; Sandmeier and Deering, 1999), the structural scattering index (Gao et al., 2003) and the ratio of the white sky albedo to the isotropic model parameter.

As mentioned earlier, users are also interested in using the anisotropy models to directly correct surface reflectances for view angle effects and provide BRFs at a common view angle. The Nadir BRDF-Adjusted Reflectances (NBAR) at local solar noon are operationally computed for the 7 spectral bands (Figure 1b) and are used as the primary input for the MODIS Land Cover and Land Cover Dynamics Products due to their stability and temporal consistency (Friedl et al., 2002; Zhang et al., 2003; 2006).

The collection 005 reprocessing retrieves the surface anisotropy models at a 500m resolution (an improvement over collection 004 and earlier where the finest spatial resolution was 1km). Both the 500m and 1km products are retrieved from those observations that fall in or on each spatial bin and are weighted by their observation coverage. Note however that while most of the directional 500m observations fall fully within a 1km bin, the off-nadir 500m observations are obviously sampling beyond each 500m bin. This means that the 500m BRDFs really represent the anisotropy of an area somewhat larger than $500\text{x}500\text{m}^2$. In addition to the standard 500m and 1-km tiled products provided in a sinusoidal projection, these same science data sets are also

routinely produced at 30 arc-second and 0.05-degree spatial resolutions in global geographic (latitude/longitude) projections specifically for use by global modelers (Gao et al., 2005). In response to user requests, high-quality, snow-free, gap-filled albedo quantities have also been prepared in a collaboration with the MODIS Atmosphere Team (Moody et al., 2005). High quality snow-free retrievals are fit with temporal phenological curves to produce continuous gap-filled annual datasets and multi-year climatologies. More recently equivalent gap-filled BRDF model parameter data sets have also been prepared.

3. Algorithm Quality

In view of the sometimes insufficient angular sampling available from a single polar orbiting sensor, the synergistic use of multi-sensor observations from both Terra and Aqua has offered an opportunity to improve both the coverage and the quality of global MODIS anisotropy and albedo retrievals. Terra has a descending equatorial crossing time of 10:30 a.m., while Aqua flies in an ascending orbit with a 1:30 p.m. equatorial crossing time. By combining MODIS observations from both Terra and Aqua, more high-quality, cloud-free observations (under varying solar zenith angle) are available to generate better-constrained model retrievals (see Figure 2). Since the MODIS-Terra and MODIS-Aqua have similar instrument characterizations and utilize the same atmospheric correction algorithm, the combination of these data is fairly straightforward. However, the calibration and geolocation of both instruments must be continually monitored for compatibility and the quality of the aerosol retrieval from each sensor and its effect on the respective atmospherically-corrected surface reflectances must also be accounted for.

In general, the combined Terra and Aqua MODIS product processing stream begins with a detailed quality check of each atmospherically corrected surface reflectance and then assigns various penalty weights to the individual observations according to the quality flag contained in each surface reflectance product (Schaaf et al., 2002). Thus, the quantified uncertainty of the sensor-specific surface reflectances is directly integrated into the retrieval. Results from the combined Terra-MODIS and Aqua-MODIS algorithm indicate that the increase in the number and angular configuration of observations does result in more higher quality full inversion retrievals (Figure 2) and can decrease the use of the lower quality backup retrievals by as much as 50 percent (Salomon et al., 2006). Use of a 16-day moving window with retrievals attempted every eight days has also served to improve the number of high quality retrievals obtained each month and the ability of the product to capture phenological changes.

Original plans also called for the use of Multiangle Imaging SpectroRadiometer (MISR) in a joint retrieval algorithm (Diner et al., 1990), since the cross track scans of MODIS-Terra and along track multiangular observations of MISR complement each other in the azimuthal dimension. Using surface directional reflectances simulated by a canopy radiative transfer model, Lucht and Lewis (2000) demonstrated that combining MODIS-Terra, MODIS–Aqua, and MISR angular samples could further reduce the uncertainty and random noise amplification of anisotropy retrievals. Jin et al. (2002) developed the methodology to incorporate MISR observations obtained close to the principal plane and

demonstrated that it was possible to further improve the MODIS retrievals on a regional basis.   However, since care must be taken to minimize the effects of any possible observation bias produced by differing spectral band specifications, geometric co-registration, spatial resolution, and atmospheric correction schemes, a global operational implementation has not been undertaken.

The absolute accuracy of the MODIS albedo products has also been established by comparison with field measurements. The products have now been validated to a Stage 1 level, which indicates that product accuracy has been estimated using a small number of independent field measurements obtained from selected locations and time periods (Jin et al., 2003a;b; Salomon et al., 2006). The well-calibrated international Baseline Surface Radiation Network (BSRN) sites, which are represented in the U.S. by the NOAA-operated Surface Radiation (Surfrad) and DOE-sponsored Atmospheric Radiation Measurement Program (ARM) locations, have provided the primary validation field data for broadband albedo. At each site, black-sky albedo quantities are computed for a range of daily solar zenith angles and coupled with white-sky estimates as a function of the atmospheric optical depth of a location. These actual bihemispherical reflectances (BHR) or blue-sky albedos are compared directly with cloud free albedometer measurements at the field tower sites. The accuracy of the high quality MODIS operational albedos at local solar noon has been well within 5% of the measured albedos at the validation sites studied thus far and even those albedo values retrieved with the backup algorithm and thus flagged as low quality measures have been found to be within 10% of field data. It is also anticipated that these low-quality values could be further improved by updating the current *a priori* data base with a pixel-based climatological version that relies on all the years of MODIS reflectance anisotropy model retrievals currently available. In Figure 2, 1 km albedos based on a 16-day retrieval (flagged as v004) are compared with 500m albedos retrieved every 8 days based on the last 16 days (flagged as v005) and daily tower albedometer data at local solar noon from Extended Facility #15 of the ARM Southern Great Plains site. Furthermore, comparison of high quality MODIS retrievals with ARM site #15 tower data collected throughout the day (Figure 3) also demonstrates the ability of the MODIS reflectance anisotropy product to consistently produce cloud-free diurnal albedos at solar zenith angles of less than 70 degrees. Although the anisotropy model of the site was only retrieved every eight days (based on the last 16 days), it could be successfully used on a daily basis with the appropriate solar zenith angles to produce hourly albedos. This attribute (of capturing the solar zenith angle dependence of clear sky albedos) is encouraging meteorological modelers to use these satellite-retrieved models directly in their surface energy budget schemes.

4. Summary

High quality standard land datasets have been operationally produced from MODIS remotely-sensed observations since 2000. The production of accurate MODIS surface albedo data depends on the routine retrieval of high quality and consistent global Bidirectional Reflectance Distribution Function (BRDF) estimates of the surface anisotropy. Refinements, such as the coupled use of both the Terra and Aqua MODIS observations, the implementation of increased spatial and temporal resolutions, and

improvements in cloud-clearing and atmospheric correction, have been implemented in the fifth reprocessing of the data and have resulted in a multi-year, consistent and validated dataset of surface reflectance anisotropy models (and thus surface albedo quantities) for use in a number of modeling and monitoring applications. Although the spectral and spatial resolutions of the MODIS data (not to mention the calibration and geolocation accuracies) are not available from historical satellite observations acquired prior to 2000, attempts are underway to retrieve consistent broadband anisotropy and albedo products from the operational Advanced Very High Resolution Radiometer (AVHRR) weather sensor and thus produce multi-decadal data sets for climate studies (Saleous et al., 2005). In turn, efforts are also focused on continuing these products in the future by using data with similar angular and temporal sampling from the Visible Infrared Imager / Radiometer Suite (VIIRS) on board the next generation of operational weather satellites, the National Polar-orbiting Operational Environmental Satellite System (NPOESS) and its precursor the NPOESS Preparatory Project (NPP), both of which are due to be launched within the next decade.

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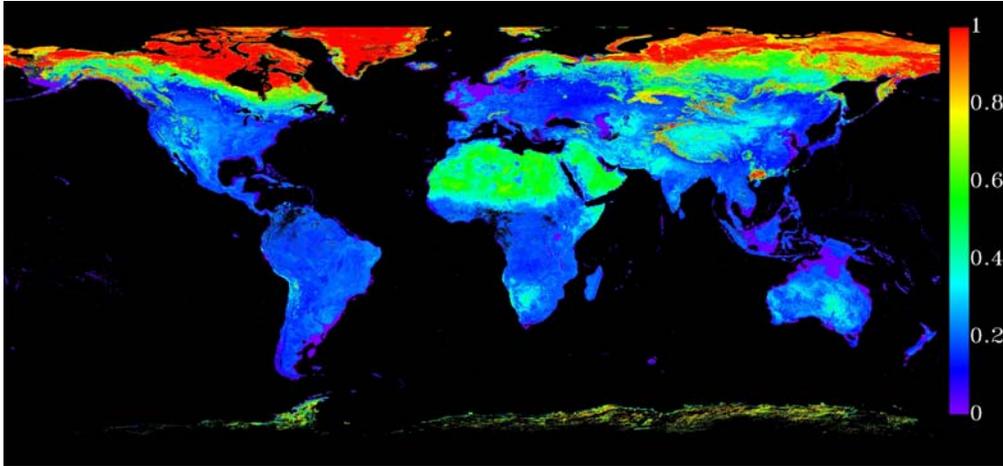
Figure 1a. MODIS global white sky albedo Climate Modeling Grid (CMG) 0.05degree Product (April 2003)
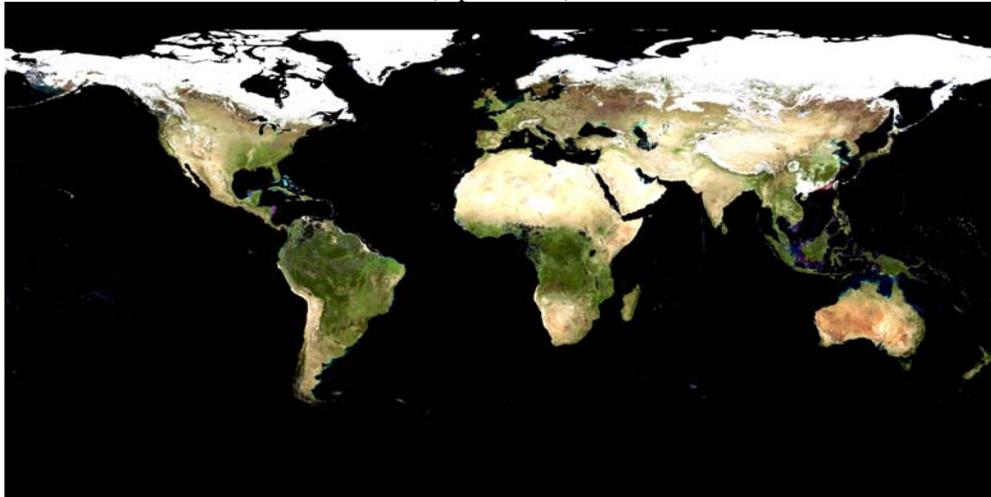

Figure 1b. MODIS Nadir BRDF-adjusted Reflectance (NBAR) Climate Modeling Grid (CMG) 0.05 degree Product (April 2003).
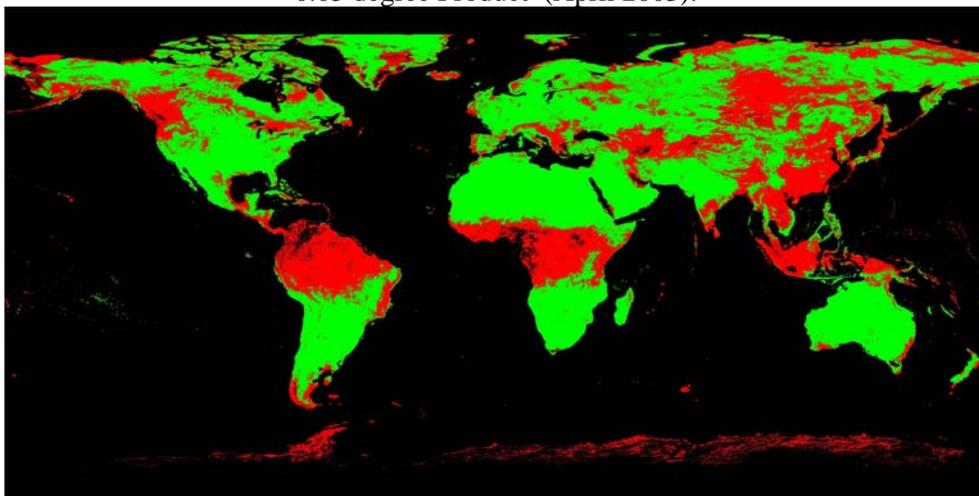

Figure 1c. MODIS Terra and Aqua Aqua Quality Flags(green high quality, red lower quality, black fill values) April 2003.
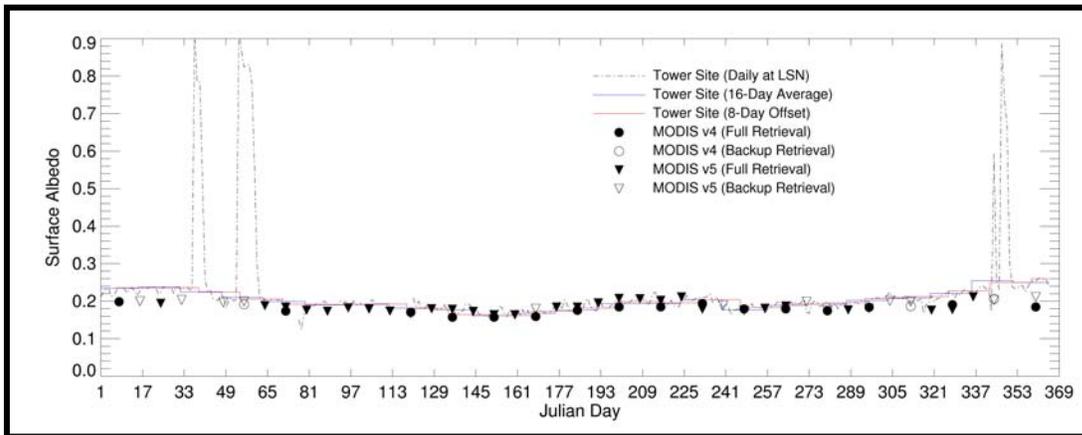
Figure 2. Validation of V005 and V004 MODIS albedo data with daily tower data at local solar noon from the ARM Extended Facility #15 in 2003.
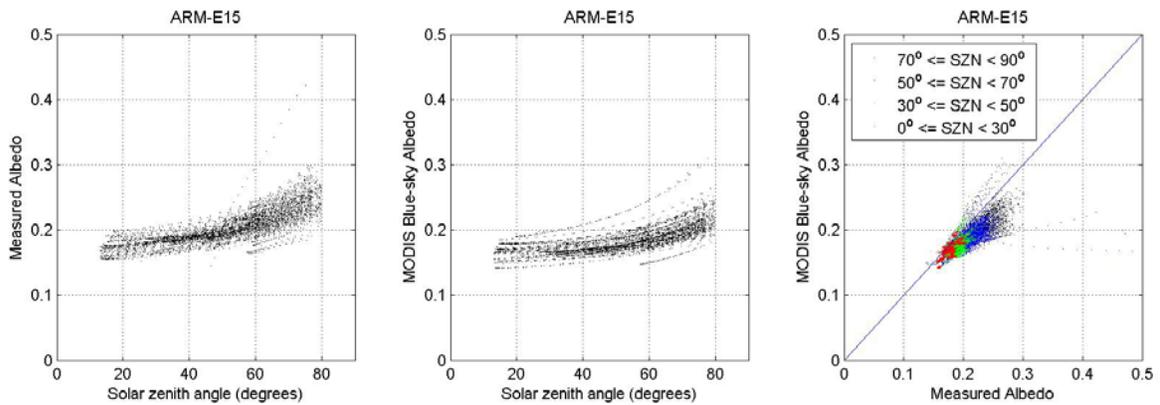

Figure 3 Comparison of MODIS daily albedos for 2003 with tower albedometer data from the ARM Extended Facility #15 (red 0-30ºszn, green 30º-50º, blue 50º-70º, black <70º).