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Assessment of biases in MODIS surface reflectance due to Lambertian approximation

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ABSTRACT

Using MODIS data and the AERONET-based Surface Reflectance Validation Network (ASRVN), this work studies errors of MODIS atmospheric correction caused by the Lambertian approximation. On one hand, this approximation greatly simplifies the radiative transfer model, reduces the size of the look-up tables, and makes operational algorithm faster. On the other hand, uncompensated atmospheric scattering caused by Lambertian model systematically biases the results. For example, for a typical bowl-shaped bidirectional reflectance distribution function (BRDF), the derived reflectance is underestimated at high solar or view zenith angles, where BRDF is high, and is overestimated at low zenith angles where BRDF is low. The magnitude of biases grows with the amount of scattering in the atmosphere, i.e., at shorter wavelengths and at higher aerosol concentration. The slope of regression of Lambertian surface reflectance vs. ASRVN bidirectional reflectance factor (BRF) is about 0.85 in the red and 0.6 in the green bands. This error propagates into the MODIS BRDF/albedo algorithm, slightly reducing the magnitude of overall reflectance and anisotropy of BRDF. This results in a small negative bias of spectral surface albedo. An assessment for the GSFC (Greenbelt, USA) validation site shows the albedo reduction by 0.004 in the near infrared, 0.005 in the red, and 0.008 in the green MODIS bands.

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1. Introduction

Land applications of the optical remote sensing data require conversion of the top of atmosphere (TOA) signal into surface reflectance. The conversion procedure is called atmospheric correction (AC). The TOA signal is formed through complex processes of scattering and absorption of sunlight in the atmosphere and reflection from non-homogeneous anisotropic surface. The anisotropic surface reflectance is characterized by the bidirectional reflectance factor (BRF) which gives the reflection coefficient for a given angle of incidence from a collimated source and a given view angle in the absence of atmosphere (see Martonchik et al., 2000; Nicodemus et al., 1977; Schaepman-Strub et al., 2006. The anisotropy of land surface reflectance has been extensively studied in the past three decades from the ground, aircraft and spaceborne measurements (e.g., Bicheron, & Leroy 2000; Deering, & Leone 1986; Gatebe et al. 2003; Kimes 1983; Sandmeier, & Itten 1999) as well as through model development (e.g., Li, & Strahler 1992; Rahman et al., 1993; Roujean et al., 1992). Theoretical analysis done in the past showed that surface anisotropic reflectance should be taken into account in the atmospheric correction procedure (Lee, & Kaufman 1986; Lyapustin 1999; Vermote, & Vermeulen 1999). Presently, anisotropic surface model is implemented in the MISR land algorithm (Martonchik et al. 1998) and in METEOSAT land processing (Pinty et al., 2000). However, standard approach in the atmospheric correction, including operational MODIS AC algorithm, has traditionally been using Lambertian surface assumption (Vermote, & Kotchenova 2008).

The Lambertian assumption largely simplifies the radiative transfer model, reduces the size of the look-up tables, and creates faster algorithm which is important in the operational processing. At the same time, it creates systematic angle-dependent biases in derived surface reflectance reducing anisotropy of reflectance. The Lambertian assumption re-distributes reflected energy between all directions, reducing reflectance where BRF is high and enhancing it where BRF is low (e.g., Lyapustin 1999; Vermote, & Vermeulen 1999). For a typical bowl-shaped bidirectional reflectance distribution function (BRDF), this assumption will produce higher reflectance for near-nadir view, and lower reflectance for high view/solar zenith

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angle. The error increases with the amount of total scattering in the atmosphere, in other words at shorter wavelengths and at higher aerosol optical thickness. The bias can be very large in the angle regions of high anisotropy of BRDF, for example in the broad glint region and in the backscattering region over snow-covered surfaces (Lyapustin et al. 2009).

In the MODIS land processing, the derived surface reflectance is assimilated by the BRDF/albedo algorithm (Schaaf et al. 2002), which uses 16 days of data to retrieve parameters of the Ross-Thick Li-Sparse (RTLS, Lucht, Schaaf, & Strahler 2000) model and produce surface albedo. Inherently, the surface reflectance biases are translated into reduced anisotropy of the RTLS model, which may also affect albedo.

At least several large-scale investigations of MODIS surface reflectance have found underestimation of MODIS surface reflectance in the visible bands, especially at large view angles (Pinty et al. 2008; Pinty et al. 2009; Roesc et al., 2004; Yi et al., 2008). The Lambertian assumption certainly plays a role in this bias, though the magnitude of the effect is yet to be studied from the experimental data.

Recently, we developed an AERONET-based Surface Reflectance Validation Network (ASRVN), which is an appropriate tool for this analysis. ASRVN is an automated data collection and processing system (Lyapustin et al. 2006; Wang et al., 2009) which receives 50×50 km^2 subsets of MODIS L1B data from MODIS adaptive processing system (MODAPS) and Aerosol Robotic Network (AERONET, Holben et al. 1998) aerosol and water vapor information and performs atmospheric correction for about 100 AERONET sites based on accurate radiative transfer theory with complex quality control of the input data. The ASRVN algorithm uses a high accuracy semi-analytical Green's function solution (Lyapustin, & Knyazikhin 2001), which does not rely on Lambertian approximation. In combination with the RTLS BRDF model, this solution provides an explicit parameterization of TOA reflectance in terms of three BRDF model parameters. The ASRVN algorithm derives RTLS coefficients directly by fitting the radiative transfer solution to the measured TOA reflectance accumulated over a 4- to 16-day period.

In this paper, a multi-year ASRVN data record is used to assess biases in the MODIS surface reflectance due to Lambertian approximation. The study is performed over the vegetated areas, where MODIS aerosol retrievals are known to have a good accuracy (Levy et al., 2007). This limits the unknown impact of errors from aerosol retrievals on our analysis. The selected sites include the Earth Observing System (EOS) land validation sites such as Bondville, Konza EDC, Walker Branch, Mongu, and others (Morisette et al., 2002). Section 2 of this paper provides an experimental evidence of the Lambertian bias, which is solely based on the ASRVN result. In this case, we are comparing ASRVN retrievals made with the full algorithm and with the reduced algorithm based on Lambertian assumption. Following this demonstration, we study the errors of MODIS surface reflectance comparing it with ASRVN BRF/albedo data in Section 3. Finally, Section 4 provides conclusions from this analysis.

2. Demonstrating Lambertian bias with ASRVN

The ASRVN algorithm retrieves three parameters of RTLS BRDF model by fitting the radiative transfer solution to the TOA reflectances accumulated for the period of 4–16 days. MODIS data are first gridded to 1-km resolution. For each day, the aerosol parameters and atmospheric column water vapor are known from the AERONET data. Following retrievals of RTLS parameters for each 1 km grid cell, the ASRVN also derives several other products including surface albedo and a bidirectional reflectance factor (ASRVN BRF) from a given MODIS observation. In the original paper describing ASRVN (Wang et al. 2009), the ASRVN BRF product was called an instantaneous BRF or IBRF. This terminology is clearly redundant (see Martonchik et al. 2000; Schaepman-Strub et al. 2006) and will not be used further on. The ASRVN BRF is a reflectance value for specific viewing geometry of the latest MODIS observation in the absence of atmosphere. It is computed from the directly transmitted surface-reflected signal while the diffuse component of the signal is computed using found RTLS model parameters (for detail, see Wang et al. 2009). Based on this definition, ASRVN BRF is a direct analogue to MODIS surface reflectance. The ASRVN albedo is defined as a ratio of surface-reflected to incident radiative fluxes. Thus, it represents surface albedo at a given solar zenith angle in ambient atmospheric conditions, the value which can be directly compared to the ground-based albedometer measurements.

Prior to analysis of MODIS operational data, it is worthwhile to demonstrate the impact of Lambertian assumption by simulating it using the ASRVN framework and real MODIS measurements. To this end, a Lambertian reflectance (ρ_{Lamb}) from a given MODIS observation was computed for every grid cell in addition to the standard ASRVN products. Because the TOA MODIS measurement and atmospheric parameters, used to generate Lambertian reflectance and ASRVN BRF, are the same, comparing these values will allow us to make a direct assessment of biases due to Lambertian assumption.

As we mentioned above, errors of Lambertian approximation result from incomplete removal of atmospheric scattering effects which depend on the view geometry (mainly solar and view zenith angles), atmospheric opacity and wavelength. To separate these effects in observation data, we stratified the input (MODIS measurements) into four categories resulting from low ($<45°$) and high ($\geq45°$) sun/view zenith angles and low and high values of aerosol optical thickness (AOT<0.3 or AOT≥0.3). Here, AOT pertains to the measured AERONET value at wavelength 0.44 μm.

Fig. 1 shows the pixel-by-pixel comparison results for the Goddard Space Flight Center (GSFC, 38.9925°N, 76.84°W) generated using all cloud-free ASRVN retrievals of high quality according to ASRVN quality assurance (QA) flag. This site is a mixture of vegetation and urban residential areas. The data include all 1-km grid cells in 50×50 km^2 subset area centered at GSFC and 9 years of MODIS TERRA data (2000–2008). Panels on the left and right show results for the MODIS red and green bands, respectively. One can see that the slope of regression ρ_{Lamb} vs. BRF is the highest and close to 1 when both zenith angles and AOT are low. This case corresponds to least amount of atmospheric scattering and maximal direct transmittance. The slope progressively decreases when optical path through the atmosphere increases at higher solar/view zenith angles, higher AOT, and shorter wavelength. For example, the slope decreases from 0.94 (ZA$<45°$, AOT<0.3) to 0.83 (ZA$\geq45°$, AOT≥0.3) in the red band and from 0.85 to 0.64 in the green band. This example clearly demonstrates reduction of surface reflectance anisotropy by the Lambertian assumption. It also shows residual atmospheric distortions in the surface retrievals, which are positive when BRF is low and negative when it is high. On average, the bias is negative for about 70% of retrievals and positive for the rest 30% for the data shown in Fig. 1. Considering all view geometries, the negative bias representing higher (off-nadir) view zenith angles is observed in 2/3–3/4 of all cases. In absolute magnitude, the negative bias of Lambert reflectance can be as high as ~15% in the red band and ~40% in the green band.

3. Comparing MODIS surface reflectance products with ASRVN data

In this section, we compare the ASRVN surface retrievals with MODIS surface reflectance (MOD09), and with surface BRDF/albedo (MCD43) products, which are derived from the MODIS surface reflectance. MODIS atmospheric correction algorithm has an internal aerosol retrieval algorithm, which is similar to MODIS operational aerosol algorithm (MOD04) and has a good accuracy over dark vegetated surfaces (Levy et al. 2007). Therefore, in order to minimize the impact of unknown aerosol-related errors, we limit our analysis to vegetated surfaces where MOD09 is expected to be accurate.

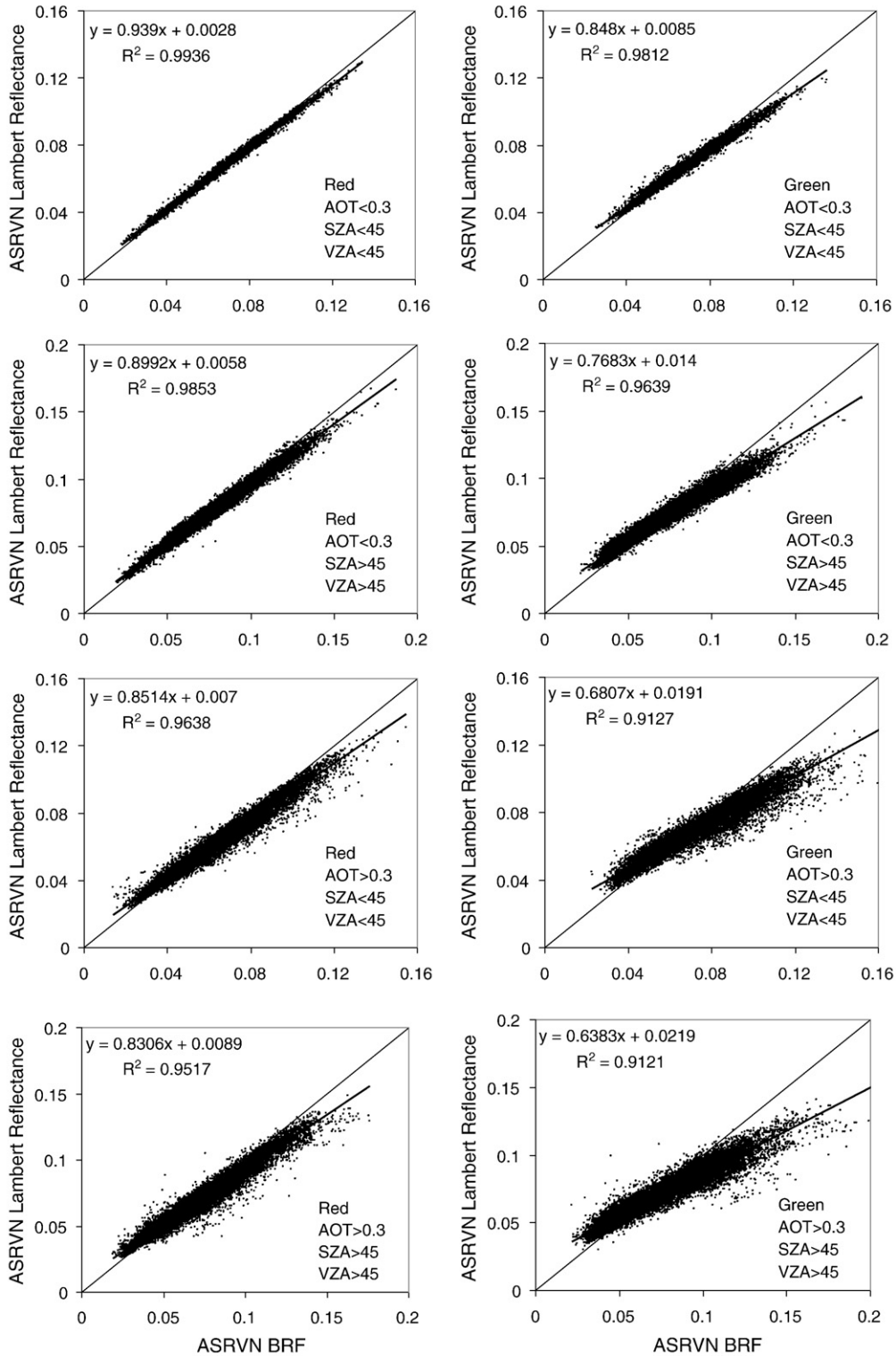

Fig. 1. Pixel-by-pixel comparison (for 2000–2008) of ASRVN BRF and ASRVN Lambertian reflectance for GSFC site in red (on the left) and green (on the right) bands. The results are stratified into 4 categories according to AOT and solar/view zenith angle.

3.1. Analysis method

We downloaded 50×50 km^2 subsets of MODIS 8-day composite surface reflectance (MOD09A1) and 16-day BRDF-Albedo (MCD43A1) products, and subsets of 25×25 km^2 MODIS daily surface reflectance data (MOD09GA) for selected AERONET stations, for year 2000–2008. The data were obtained from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC). To minimize the gridding difference between MODIS products and ASRVN, data were averaged over a 10×10-km^2 area with center at AERONET locations. The resulting MOD09 surface reflectance and BRDF/Albedo are compared with similarly averaged ASRVN products.

To make comparison with MODIS 8-day surface reflectance product, one needs to identify a specific day which was used to

generate MOD09A1. The ASRVN BRF granule was selected for comparison based on the Day of Year and Sun-View geometry layers in the MOD09A1 subsets. Cloudy pixels, water pixels, and pixels with unmatched sun-view geometry were filtered. Only the highest quality MOD09A1 and MOD09GA data (with band quality bit 0000) were used. Finally, for all data sets, only days with more than 80% of good quality pixels in the 10×10-km^2 area were retained for analysis.

3.2. Comparison of ASRVN and MOD09

Figs. 2 and 3 compare MODIS surface reflectance and ASRVN BRF for Konza EDC (39.102328°N, 96.6096°W) and Walker Branch (35.958333°N, 84.2875°W) sites. The land cover type of these sites is grass land for Konza EDC and broadleaf forest for Walker Branch. The left and right panels show scatterplots for MODIS 8-day

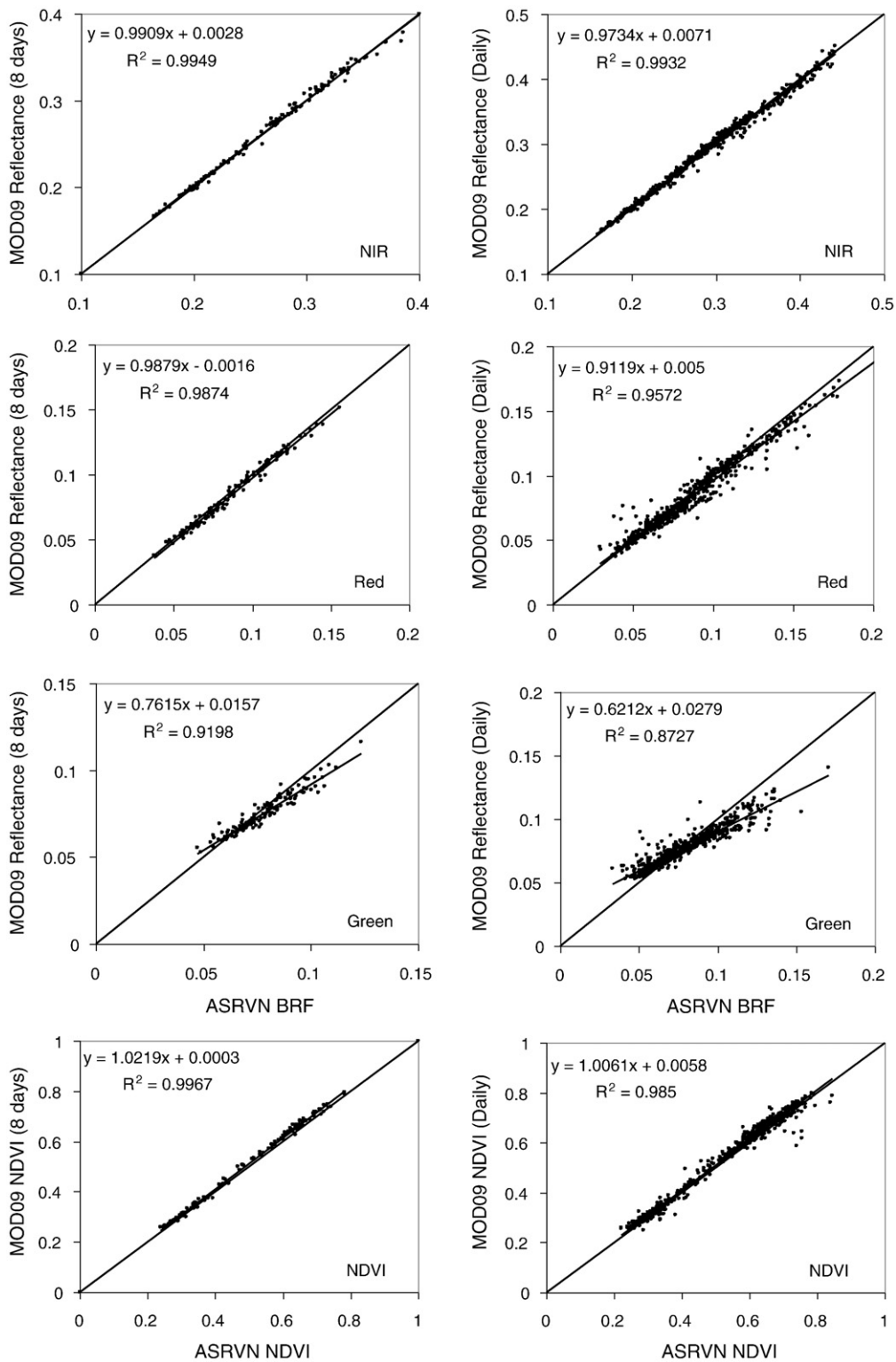

Fig. 2. Comparison of MODIS 8-day composite (left) and of daily surface reflectance (right) with ASRVN BRF for Konza EDC site, for 2000–2008. The bottom row shows scatter plots for NDVI.

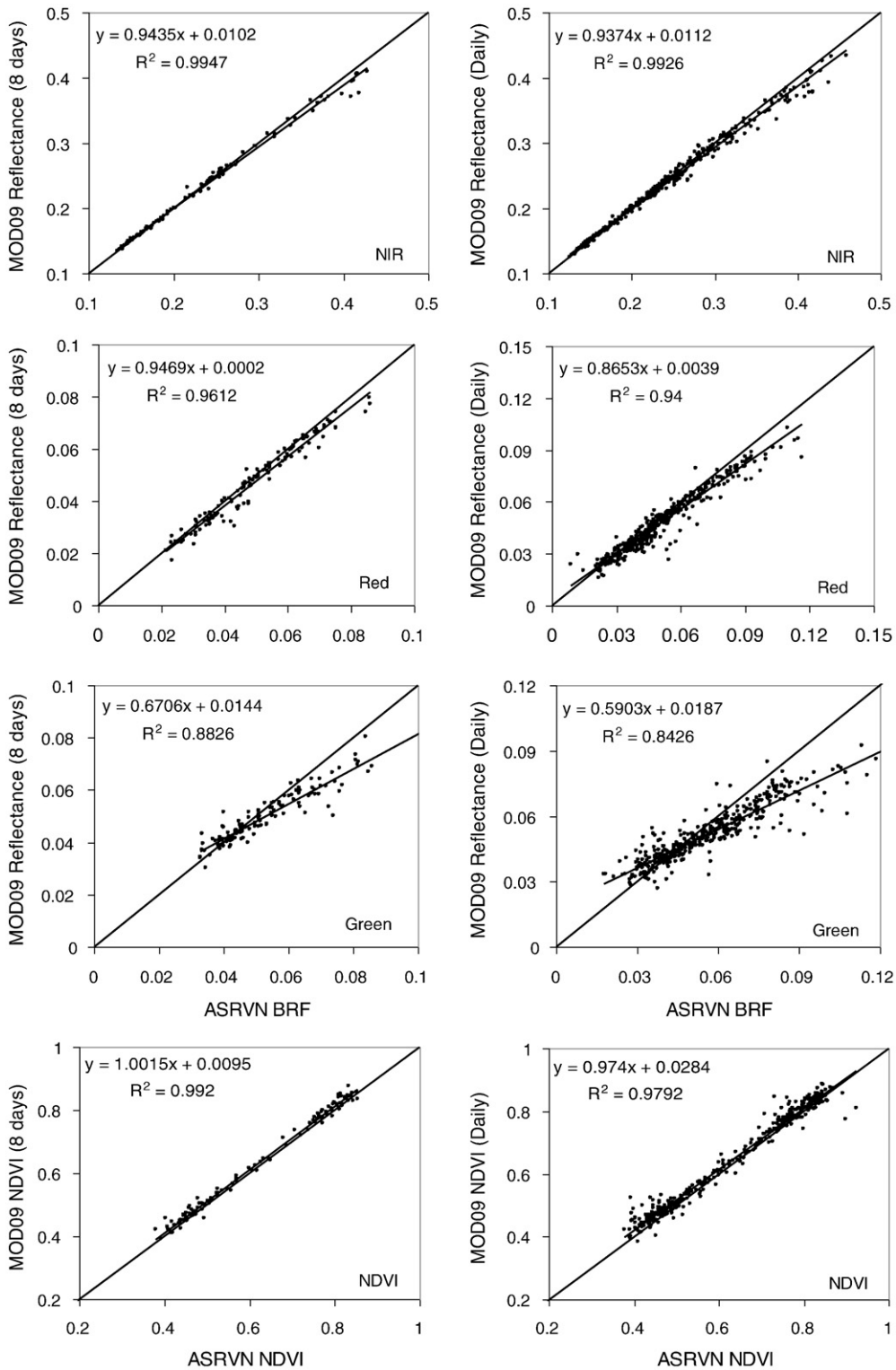

Fig. 3. The same as Fig. 2, only for Walker Branch site.

composite (MOD09A1) and for MODIS daily (MOD09GA) surface reflectance, respectively. The results are shown for the near infrared (NIR), red and green bands, as well as for the Normalized Difference Vegetation Index (NDVI). The slope of regression is close to one in the near infrared, and it decreases at shorter wavelengths in agreement with analysis given in Section 2. The slope is close to 0.6 in the green band and further decreases in the MODIS blue channel. We are not discussing the blue band results in this work following recommendation of Vermote, and Kotchenova (2008) who cautioned against using the blue band in the land applications since it is used primarily for the aerosol retrievals.

Figs. 2 and 3 show that MODIS surface reflectance is slightly lower than the ASRVN counterpart over both sites. The negative error increases at shorter wavelengths, along with increase of atmospheric scattering. Although the effect is rather low in the red and NIR, it leads to overestimation of NDVI by ~0.001–0.03 for Konza EDC and Walker Branch sites. A comparison statistics over several other EOS core land validation sites with AERONET stations is summarized in Table 1.

Table 1
Regression coefficients of ASRVN BRF and MODIS surface reflectance over selected AERONET sites.

Site	NIR			Red			Green		
	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept
GSFC	0.995	0.957	0.008	0.947	0.922	0.001	0.817	0.614	0.02
Mongu	0.945	0.919	0.018	0.928	0.943	0.002	0.667	0.602	0.033
Skukuza	0.989	0.941	0.01	0.96	0.871	0.007	0.847	0.595	0.025
Ispra	0.984	0.897	0	0.835	0.737	0.006	0.584	0.419	0.022
Howland	0.997	0.938	0.01	0.921	0.96	0.001	0.913	0.786	0.008
Cuiaba-Miranda	0.988	0.883	0.027	0.962	0.859	0.01	0.824	0.62	0.027
Alta-Floresta	0.966	0.897	0.027	0.977	0.887	0.005	0.882	0.731	0.016
Konza EDC	0.995	0.991	0.003	0.987	0.988	0.002	0.92	0.762	0.016
Walker Branch	0.995	0.944	0.01	0.961	0.947	0.0002	0.883	0.671	0.014

These results show that the described effect is generic, and at least part of it is due to the Lambertian approximation used in the MODIS atmospheric correction algorithm. The magnitude of biases may vary with locations according to the surface brightness, which would affects aerosol retrievals, and with the overall aerosol loading. For example, the average bias is higher in the world regions of biomass burning with higher mean AOT.

To further demonstrate the impact of Lambertian approximation, we conducted analysis stratified by the solar/view zenith angles and AOT for MODIS daily surface reflectance (MOD09GA), similarly to our analysis of Section 2. The results for Konza EDC and Walker Branch sites are shown in Figs. 4 and 5, respectively. One can see that these results are very similar in pattern and in magnitude to the data shown in Fig. 1. The slope of regression decreases (bias grows) for higher zenith angles and AOT. Compared to ASRVN BRF, the negative bias of MODIS surface reflectance is larger at higher zenith angles, which indicates "flattening" of BRF shape. This effect is more prominent in the green band compared to the red band, and at higher AOT when there is more atmospheric scattering.

The uncompensated atmospheric effects from Lambertian approximation can also explain the slight difference in the regression slope between the 8-day composite and daily data in Figs. 2 and 3. The slope of the MODIS composite reflectance is always slightly higher than that of the daily reflectance, since the compositing process tends to select pixels with smaller AOT and zenith angles (Vermote, & Kotchenova 2008), which have a smaller bias when compared to the ASRVN BRF.

3.3. Comparison of ASRVN with MCD43

In the MODIS land processing, the derived surface reflectance is used in the MODIS BRDF/albedo algorithm MCD43 (Schaaf et al. 2002). The Lambertian "flattening" effect on BRDF can be demonstrated by comparing the ASRVN BRF with its counterpart from the MODIS BRDF product (MCD43A1). Fig. 6 shows the principle plane BRF (SZA = 45°) in the NIR, red and green bands computed using RTLS parameters from ASRVN and from MCD43A1. The results are shown for the vegetated pixel of GSFC site for day 209, 2008. In this particular example, the reduction of anisotropy is most obvious in the NIR and green bands. Please note that this study is limited to vegetated surfaces, which typically have a bowl-shaped BRF. The last image of Fig. 6 shows simulated principal plane NDVI. The error is positive mainly due to underestimation of the red band reflectance. In the given example, the error changes little with the view angle, although in other cases we found that it may grow with the view angle, especially in the forward scattering directions. This result is consistent with validation data from other groups. For example, Yi et al. (2008) found that the leaf area index (LAI) derived from MODIS surface reflectance tends to be overestimated at high view zenith angles, which generally implies overestimation of NDVI at these angles. Hilker et al. (2009) showed that correlation of photochemical reflectance index (PRI—an NDVI-like index computed from MODIS bands 11 (531 nm) and 12 (551 nm)) with ground measured PRI significantly improved when only the backscattering angles were used. This confirms that the atmospherically corrected surface reflectance may add noise at the forward scattering angles which deteriorates performance of the PRI index.

The surface albedo is an integrated function of BRDF. In ideal conditions, albedo should not depend on the Lambertian errors because BRDF underestimation at high view angles will be compensated by its overestimation at near-nadir observations. In reality, however, MODIS angular sampling during 16-day interval is biased towards higher view angles. Because RTLS coefficients are derived with the least squares algorithm, the simple fact of a larger number of MODIS measurements at high view zenith angles (where reflectance has a negative error) in the inversion procedure will skew the result towards lower BRDF on the whole, and lower albedo as a result. We tested this conclusion with the ASRVN processing system where we replicated the MODIS (MOD09-MCD43) land processing scheme. Specifically, we used the ASRVN Lambertian reflectance ρ_{Lamb} (see Section 2) to derive $RTLS_{Lamb}$ model parameters and used those to compute surface albedo in ambient atmospheric conditions. Fig. 7 compares thus derived "Lambertian" albedo with the standard ASRVN albedo product for the GSFC site using 9 years of MODIS TERRA measurements. The data are shown for the red and green bands and are split into cases of low (<45°) and high (≥45°) solar zenith angles. One can see that indeed the "Lambertian" albedo is slightly lower. As with the surface reflectance, the difference increases at higher solar zenith angles and at shorter wavelengths. Overall, this exercise confirms the reduction of albedo by the Lambertian assumption but shows that the overall effect is relatively low and much smaller than the effect on surface reflectance.

In Fig. 7, we simulated the net effect of Lambertian model on MODIS land processing barring all other errors, for example from aerosol retrievals. The next Fig. 8 compares MODIS surface albedo with ASRVN albedo for 9 years of MODIS TERRA and AQUA data for GSFC site. Because MCD43 algorithm uses MODIS TERRA and AQUA data jointly to increase temporal resolution, we modified the ASRVN algorithm accordingly to be consistent with MDC43 product. The MODIS albedo was computed for the ambient conditions using MCD43 RTLS parameters and AERONET aerosol data. In this analysis, we used both the high quality values of MCD43 albedo data set, according to the quality assurance flag (QA), and all reported values representing all conditions. We found that with our screening procedure and over vegetated sites the result is almost identical between the high quality and all MCD43 data. Fig. 8 shows comparison with the high quality data.

On average, MCD43 albedo is lower than the ASRVN albedo. The average difference is about 0.008 in the green, 0.005 in the red, and 0.004 in the NIR bands. These numbers are slightly larger but very close to the

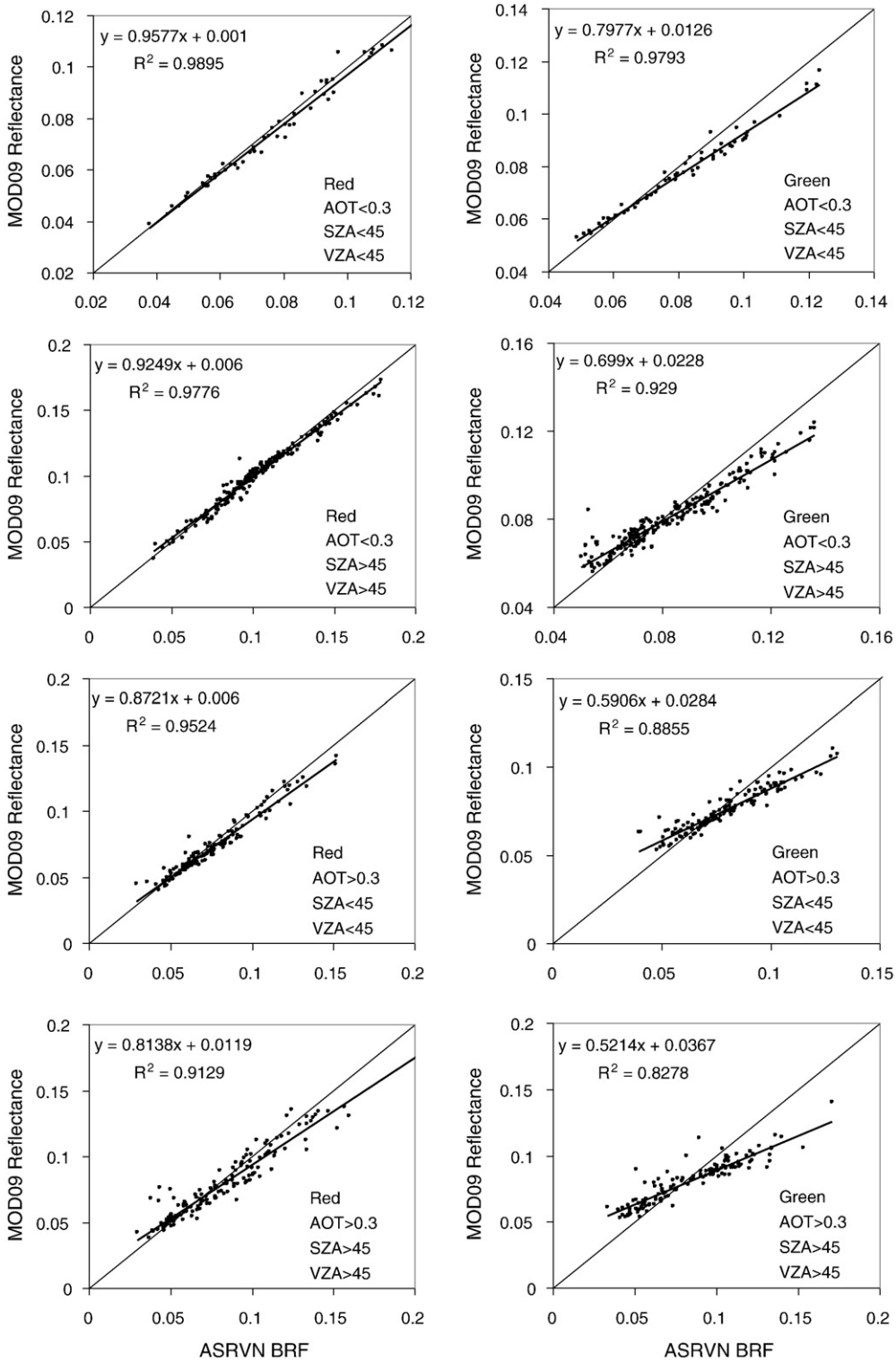

Fig. 4. Comparison of MOD09 daily reflectance with ASRVN BRF in red (left) and green (right) bands for Konza EDC site for 2000–2008. To avoid geolocation differences, the data were averaged over 10×10 km^2. Data are stratified into four categories according to AOT and solar/view zenith angles.

expected albedo reduction from the Lambertian assumption. Several different studies (Lyapustin et al. 2006; Pinty et al. 2009; Roesc et al., 2004) comparing MODIS and MISR surface albedo found that MODIS albedo is generally lower. The current analysis shows that MODIS albedo has a low but systematic negative bias due to Lambertian assumption, removal of which would narrow the gap between the two global data sets.

4. Conclusions

The original design of the MODIS atmospheric correction algorithm included provision for an iterative compensation of the BRDF effects based on the input from the MODIS BRDF/albedo algorithm. This paper investigated errors in the surface reflectance retrievals caused by the Lambertian approximation which is used in the current

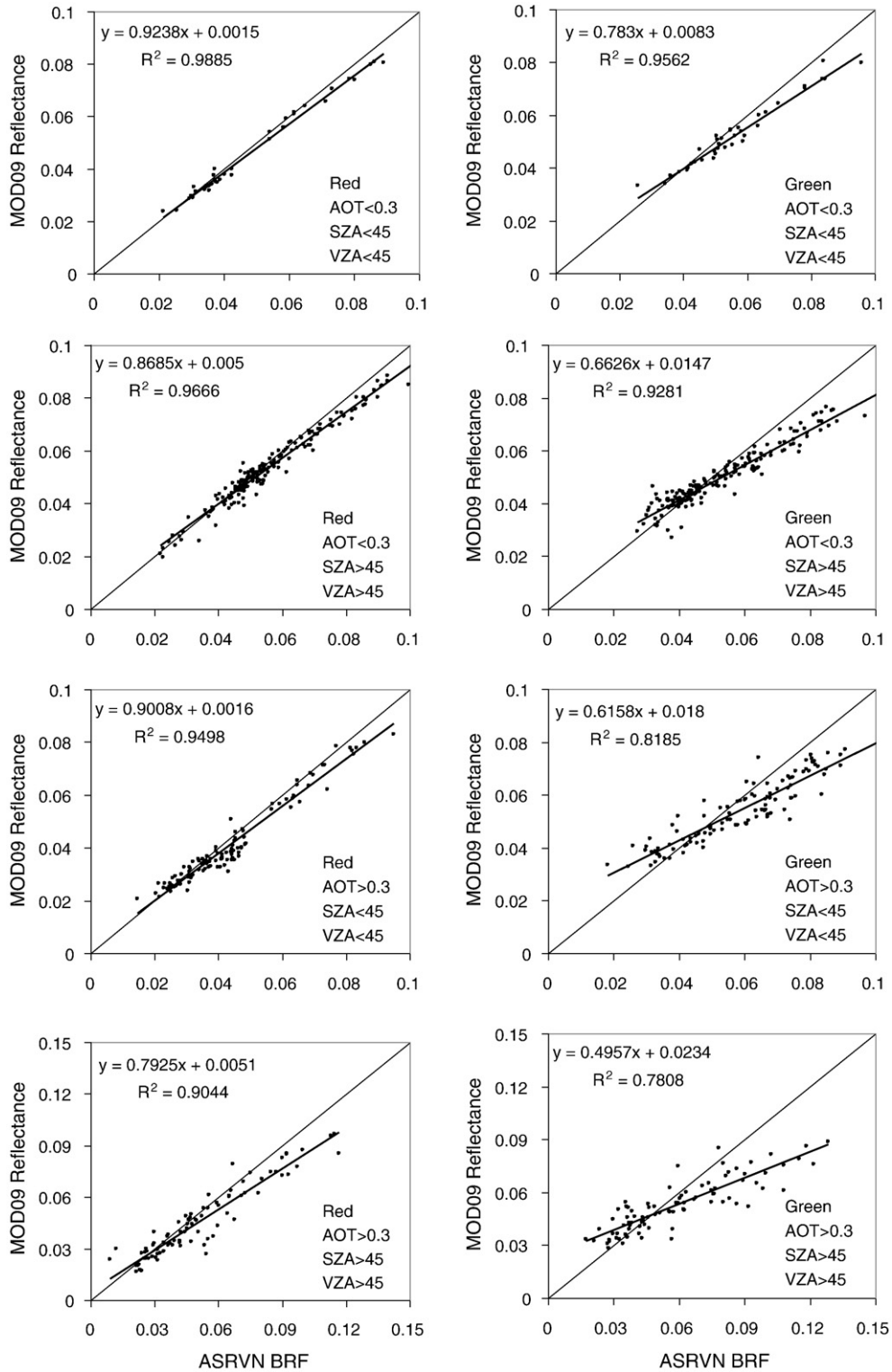

Fig. 5. The same as Fig. 4, only for Walker Branch site.

MODIS atmospheric correction algorithm. On one hand, this approximation greatly simplifies the radiative transfer model, reduces the size of the look-up tables, and makes operational algorithm faster. On the other hand, uncompensated atmospheric scattering caused by this approximation systematically biases the results. For example, for a typical bowl-shaped BRF, the derived reflectance is underestimated where BRF is high, i.e., at high solar or view zenith angles, and is overestimated where BRF is low, i.e., at low zenith angles. The magnitude of biases grows with the amount of scattering in the atmosphere, i.e., at shorter wavelengths and at higher aerosol concentrations. The error propagates into the MODIS BRDF/albedo algorithm: the retrieved BRDF becomes lower than the true BRDF and less anisotropic. This results in a small negative bias of spectral surface albedo.

We have demonstrated these errors using the ASRVN framework and the comparison of MODIS surface reflectance products (MOD09 and MCD43) with ASRVN retrievals. To decouple the influence of aerosol retrievals in the MODIS atmospheric correction algorithm, the

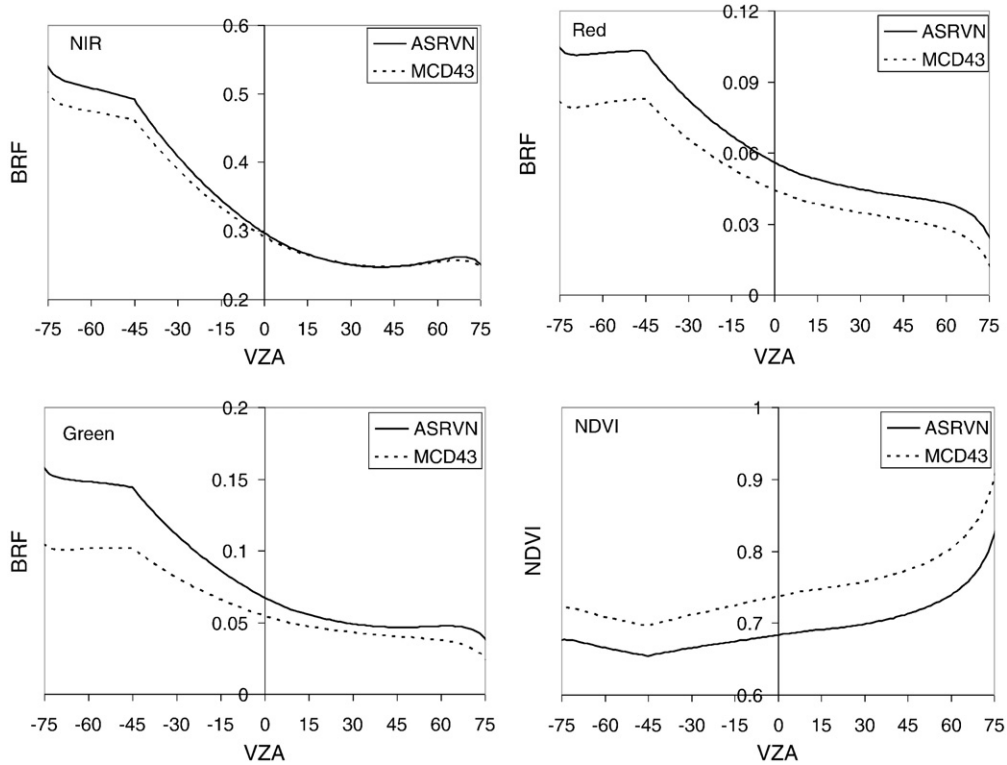

Fig. 6. Simulated principal plane BRF using RTLS parameters of ASRVN and of MCD43 for GSFC site, day 209 of 2008. The last plot shows simulated principal plane NDVI.

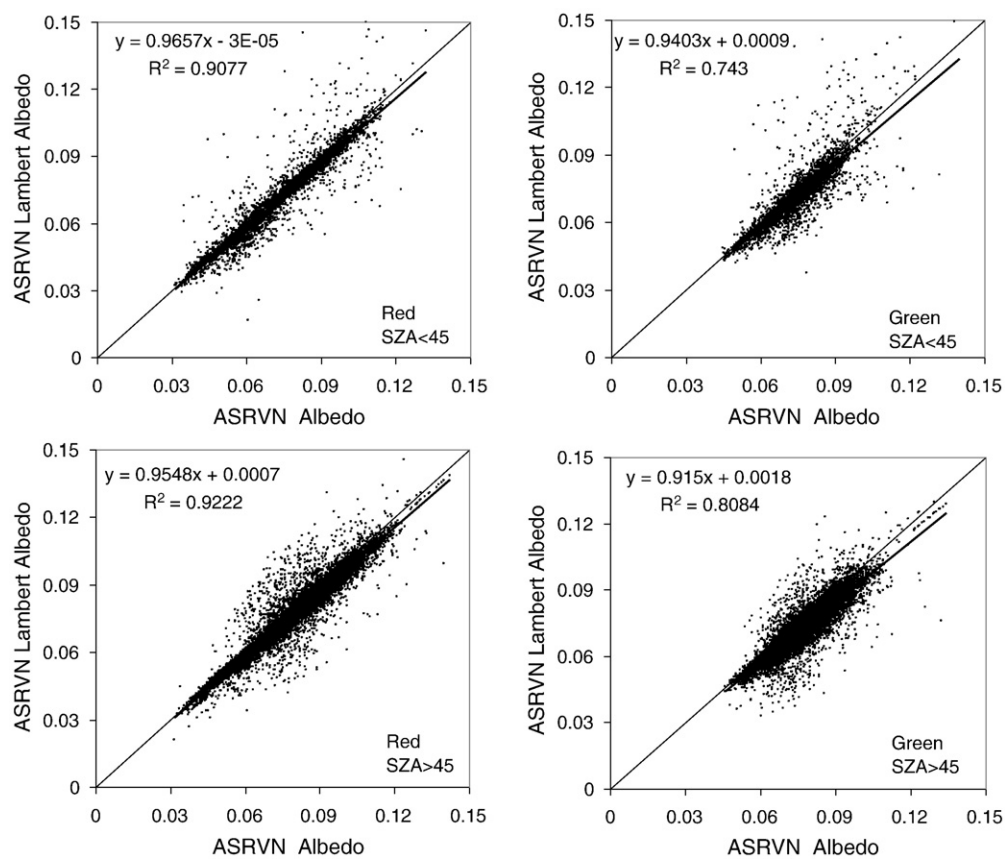

Fig. 7. Comparison of ASRVN surface albedo derived from MODIS data using Lambertian approximation and using the full algorithm. The data, representing 9 years (2000–2008) of MODIS TERRA measurements over GSFC site, are shown for the red and green bands, and for high and low solar zenith angles separated at 45°.

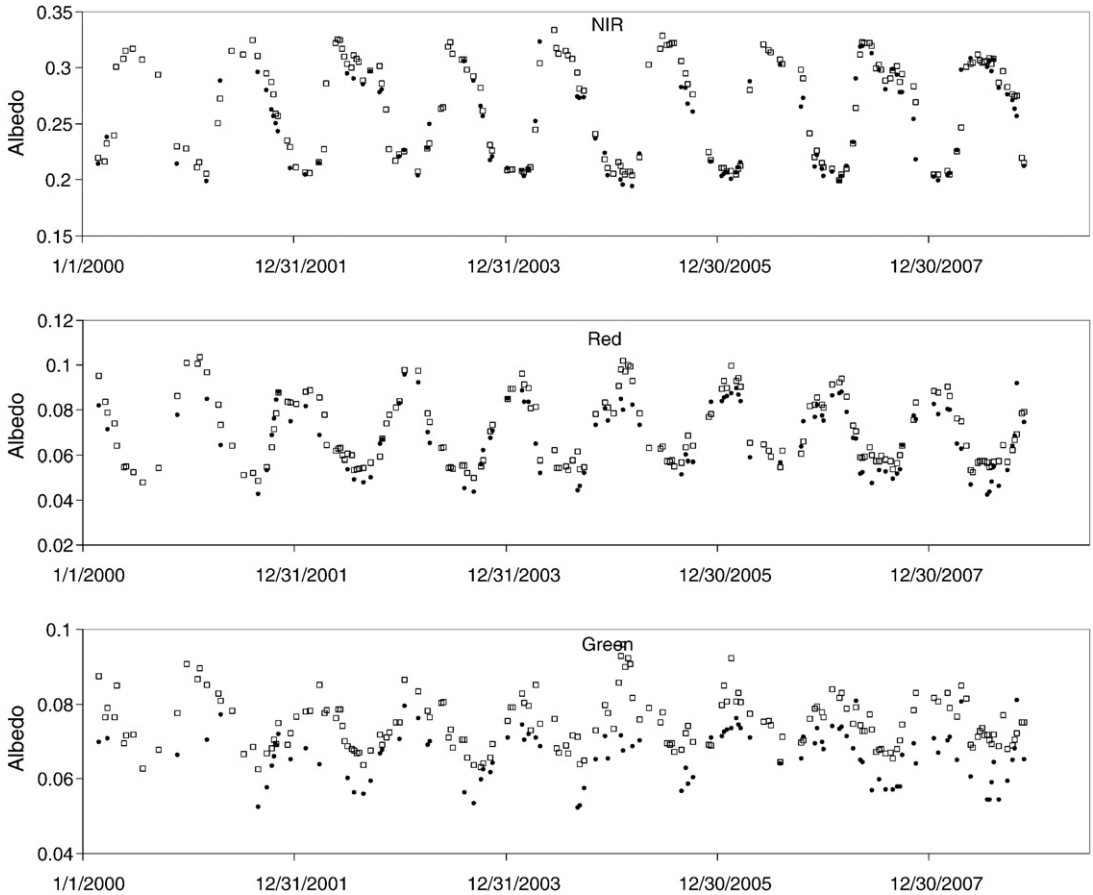

Fig. 8. Nine-year time series (2000–2008) of surface albedo over GSFC site. The empty squares are ASRVN albedo and solid circles represent MCD43 albedo, respectively. The MCD43 albedo for ambient conditions is computed using MCD43 RTLS parameters and AERONET aerosol data.

study was performed over vegetated sites where MODIS aerosol algorithm is known to have a high accuracy. Both the internal ASRVN analysis with and without Lambertian assumption, and comparison between ASRVN and MOD09/MCD43 products showed similar results, as summarized below:

- The slope of regression of Lambertian surface reflectance vs. ASRVN BRF is about 0.85 in the red and 0.6 in the green bands. Stratified analysis clearly shows an uncompensated effect of atmospheric scattering which increases at shorter wavelengths, higher AOT and higher zenith angles.
- The Lambertian approximation "flattens" BRDF shape and slightly reduces spectral surface albedo. Analysis for GSFC site shows the albedo reduction by about 0.004 in the NIR, 0.005 in the red, and 0.008 in the green MODIS bands.

Results of this analysis were reported on the Vegetation Workshop (Missoula, Montana, USA, June15–19, 2009).

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