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Quality assessment of BRDF/albedo retrievals in MODIS operational system

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[1] We establish the quality of the MODIS BRDF/albedo retrieval process through the use of the Root Mean Squared Error (RMSE) and Weight of Determination (WoD). These measures are constructed during the inversion process to quantify the retrieval uncertainties. RMSE provides a deviation indicator of the model-fits while WoD evaluates the confidence of the retrieval from given angular samplings. From a statistical analysis of retrievals over a range of surface types, we establish an upper range of thresholds (0.071, 0.097) for high quality RMSE, (1.431, 1.848) for WoD of Nadir Reflectance (assuming a 45° solar zenith angle, (2.122, 2.726) for WoD of White Sky Albedo. An investigation of inversions at typical biomes located at different latitude shows the retrievals are stable with respect to random uncertainty variations in the combined MODIS Terra and Aqua observations under the investigated sun-view geometric angular distribution. The acquired ranges suggest improved thresholds should be implemented for future reprocessing versions of the 500m MODIS operational BRDF/albedo system. **Citation:** Shuai, Y., C. B. Schaaf, A. H. Strahler, J. Liu, and Z. Jiao (2008), Quality assessment of BRDF/albedo retrievals in MODIS operational system, *Geophys. Res. Lett.*, *35*, L05407, doi:10.1029/2007GL032568.

1. Introduction

[2] Land surface albedo, which is defined as the fraction of incident solar radiation reflected by Earth's surface, is a fundamental parameter characterizing the earth's radiative regime [*Strahler et al.*, 1999]. It can be estimated from remotely sensed directional land surface reflectances and models of the Bidirectional Reflectance Distribution Function (BRDF), which describes how the reflectance varies depending on view and illumination geometry [*Nicodemus et al.*, 1977]. The MODIS BRDF/albedo operational system derives BRDF products by inverting observed multiangular surface reflectances [*Lucht et al.*, 2000; *Schaaf et al.*, 2002], which provides a spatial, temporal, spectral, and directional quantification of land surface reflectance for different applications in ecological and climatic modeling.

[3] It is indispensable for the routine MODIS products to be able to assess uncertainty and provide an accuracy evaluation to the user community. The correct interpretation of scientific information from remote sensed data requires the ability to discriminate between product artifacts and changes in the Earth processes being monitored. Product performance information is required by users in order to consider products in the interpretation of their appropriate scientific context, and is also required by the algorithm developers to identify products that are performing poorly so that improvements may be implemented. MODIS Land Science Team adopted a Quality Assessment (QA) approach in the suite of global land surface products made from MODIS instrument data. The formal MODLAND QA contains statements concerning product quality and is stored as metadata and as per-pixel QA information within each product [*Roy et al.*, 2002]. The QA flags provide quality information, such as "passed", "suspect", or "failed" in the metadata [*Justice et al.*, 1998], and also provide incremental quality values associated with the retrieval performance at each pixel. Initial studies on BRDF/albedo retrieval accuracy with respect to particularly angular sampling were done based on *in situ* measurements and numerical MODIS and MISR simulation data [*Hu et al.*, 1997; *Lucht*, 1998]. In this paper, we describe the process of establishing model-fits errors and angular sampling uncertainty for the MODIS BRDF/albedo inversions, analyze their features over different ground biomes, and seek thresholds of quality control variables for future reprocessing collections of the 500m MODIS BRDF/albedo product.

2. Uncertainty in BRDF/Albedo Retrieval

[4] The operational MODIS BRDF/albedo algorithm (MCD43) adopts the 'kernel-driven' linear BRDF model named RossThickLiSparse-Reciprocal (RTLSR, see formula (1)) model, which relies on the weighted sum of an isotropic parameter and two kernels of viewing and illumination geometry [*Roujean et al.*, 1992; *Lucht et al.*, 2000; *Schaaf et al.*, 2002].

$$f_{iso}(\Lambda) + f_{vol}(\Lambda)K_{vol}(\theta_i, \nu_i, \phi_i) + f_{geo}(\Lambda)K_{geo}(\theta_i, \nu_i, \phi_i) = R_i(\theta_i, \nu_i, \phi_i; \Lambda) \qquad (i = 1, \ldots n) \tag{1}$$

where θ, ν and ϕ are the solar zenith, view zenith and relative azimuth angles respectively; $K_{\mathrm{vol}}(\theta_i, \nu_i, \phi_i)$ is the volumetric kernel derived from volume scattering radiative transfer models [*Ross*, 1981], and $K_{\mathrm{geo}}(\theta_i, \nu_i, \phi_i)$ is the geometric kernel computed from surface scattering and geometric shadow casting theory [*Li and Strahler*, 1992] for the *i*th observation respectively. $f_{vol}(\Lambda)$ and $f_{geo}(\Lambda)$ are the spectrally dependent BRDF kernel weights for the volumetric and geometric kernels, and $f_{iso}(\Lambda)$ is a constant corresponding to isotropic reflectance. $R_i(\theta_i, \nu_i, \phi_i, \Lambda)$ is the *i*th inversed reflectance at the given geometry $(\theta_i, \nu_i, \phi_i)$ of waveband Λ.

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Table 1. Available Value Range of RMSE and WoD for Each Tile

Tile Name	H09V05	H11V08	H16V01	H17V01	H17V07	H18V06	H27V05	H28V05
RMSE[a] Red	[0, 0.15]	[0, 0.12]	[0, 0.67]	[0, 0.69]	[0, 0.11]	[0, 0.11]	[0, 0.07]	[0, 0.07]
RMSE[a] NIR	[0, 0.17]	[0, 0.23]	[0, 0.64]	[0, 0.70]	[0, 0.13]	[0, 0.14]	[0, 0.16]	[0, 0.23]
WoD-WDR Red [0, 5],[b] %	99.9	99.9	97.3	97.1	99.9	100	99.9	99.9
WoD-WDR NIR [0, 5],[b] %	99.9	99.8	97.3	97.1	99.9	100	99.9	99.9
WoD-WSA Red [0, 5],[b] %	99.9	98.2	99.8	98.9	99.1	99.9	97.0	98.3
WoD-WSA NIR [0, 5],[b] %	99.9	98.1	99.8	98.8	99.1	99.9	96.6	98.0

[a]Range of test variable for red and near infrared band in one tile.
[b]Percent of the total number of available pixels with a WoD value in [0, 5].

[5] Given observations $\rho(\theta_i, \nu_i, \phi_i; \Lambda)$ (i = 1, ..., n), the minimization e^2 (the square of difference between the inverted reflectance and observed reflectance, see formula (2)) of a Least-Squares Error function (LSE, $\partial e^2/\partial f_k = 0$) establishes the analytical solutions (see formula (3)) for the model parameters $f_k(\Lambda)$ [*Lucht et al.*, 2000].

$$e^2(\Lambda) = \frac{1}{n-3}\sum_{i=1}^{n}\frac{(\rho(\theta_i,\nu_i,\phi_i,\Lambda) - R(\theta_i,\nu_i,\phi_i,\Lambda))^2}{\omega_i(\Lambda)} \quad (2)$$

$$f_k(\Lambda) = \sum_{i=1}^{3}\left\{\sum_{j=1}^{n}\frac{\rho(\theta_j,\nu_j,\phi_j;\Lambda)K_i(\theta_j,\nu_j,\phi_j)}{\omega_j(\Lambda)} \times \left(\sum_{l=1}^{n}\frac{K_i(\theta_l,\nu_l,\phi_l)K_k(\theta_l,\nu_l,\phi_l)}{\omega_l(\Lambda)}\right)^{-1}\right\} \quad (3)$$

where $\omega_j(\Lambda)$ is the weight for the jth observation at waveband Λ.

[6] In the BRDF retrieval, when multiangular observations from different orbits are assembled over a 16-day period to provide a varied angular sampling, a certain amount of noise-like variation caused by slight changes in the surface, residual atmosphere conditions, geolocation, and footprint size from one orbit to the next, may be expected in the MODIS observation. Two kinds of uncertainty are considered in the MODIS BRDF/albedo retrieval. One applies to the BRDF model-fits capability given the available observations. The other investigates the adequacy of the angular sampling under given sun-view geometry. A pre-research [*Lucht and Lewis*, 2000] investigated the noise sensitivity and angular sampling of BRDF/albedo using MODIS and MISR simulation data. This effort uses real satellite data from the Collection V005 reprocessed 500m MODIS BRDF/albedo products.

[7] These RMSE (Root Mean Squared Error, formula (4)) and WoD (Weight of Determination, formula (5)) have been implemented in the operational product to quantify the uncertainty in BRDF retrieval performance [*Lucht and Lewis*, 2000]. RMSE describes the deviation of the RTLSR model-fits from clear observations and is a band dependent function weighted by observation quality. The larger the RMSE is, the higher the uncertainty in the model-fits.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left((\rho(\theta_i,\nu_i,\phi_i,\Lambda) - R(\theta_i,\nu_i,\phi_i,\Lambda))^2 \times w_i\right)}{n-3}} \quad (4)$$

[8] The WoD of term μ (μ is a linear model parameter f_i or a linear combination of model parameters such as a reflectance, white sky albedo, or black sky albedo) describes the behavior of the kernel-driven linear models under the conditions of limited and varying angular sampling.

$$WoD_u = \frac{1}{w_u} = [\mathbf{U}]^T\left[\mathbf{M^{-1}}\right][\mathbf{U}] \quad (5)$$

where $\mathbf{U}$ is a vector composed of the terms μ_i, $\mathbf{M}^{-1}$ is the inverse matrix providing the analytical solution of inversion equations. The WoD depends on the angular sampling, in that $\mathbf{M}^{-1}$ is a function of kernel's variance and covariance. Lower WoD means high confidence on the angular sampling pattern. The directional hemispherical albedo (Black Sky Albedo or BSA) and bihemispherical albedo (White Sky Albedo or WSA) are the integrals of the retrieved BRDF model over the view and solar hemispherical space and different WoDs are associated with these quantities as well as for specific directional reflectances. So, in the operational system, WoD is evaluated for the products NBAR (Nadir BRDF-Adjusted Reflectance) at 45°solar zenith angle and WSA, and named WoD-WDR and WoD-WSA respectively.

3. Features of the RMSE and WoDs

[9] According to the 2003 MOD12C1 IGBP classification scheme, eight tiles of year 2003 (see Table 1) cover typical ground biomes, such as tropical forest, boreal forest, grass, shrub, cropland, desert, snow and ice in the global region. Two sensitive spectral bands (the red and Near InfraRed bands) are explored as a representation of the seven MODIS channels. Table 1 shows that more than 95% of the WoDs of the available retrievals in these tiles fall into the range of values of [0, 5]. Almost all RMSEs are less than 0.3 except for the two high latitude tiles covering Greenland (H16V01 and H17V01). Histograms of the predominant range of [0, 5] for WoD and [0, 0.3] for RMSE, are shown in Figures 1–3.

[10] In general, the trend of histograms of the Red and NIR band are nearly same as Figure 1. RMSE in both bands is quickly convergent to the region (0.05, 0.15) except for the two Greenland tiles. This indicates that good model-fits are routinely performed in all locations except for high latitude snow and ice regions. Most WoD-WDRs (see Figure 2) receive a maximum number within the range of (0.3, 0.7), and rapidly decrease outside of 1.0. The Greenland tiles are exceptional in that more than half of the WoD-

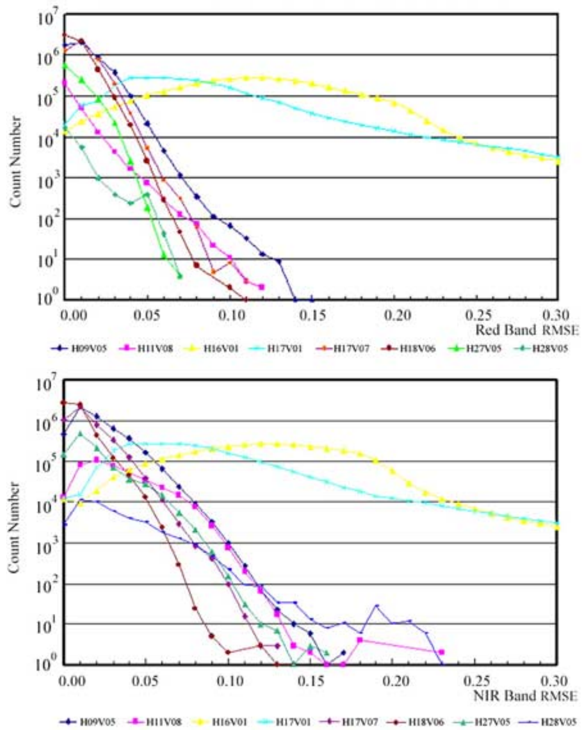

Figure 1. Histograms of RMSE at Red and NIR bands for different tiles.

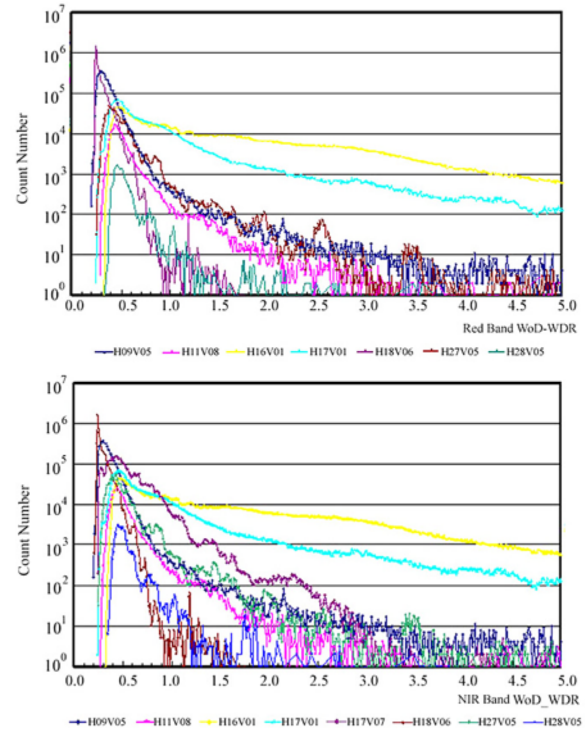

Figure 2. Histograms of WoD-WDR at Red and NIR bands for different tiles.

WDRs retain high values. The WoD-WDR values increase with a change of biomes from barren to forest. However, for WoD-WSA (see Figure 3), the Greenland tiles show trends similar with the other biomes and all of the WoD-WSA peaks fall in the range (0.20, 1.80). Note that tiles at high latitude, such as the two Greenland tiles, do receive more directional observations over a range of illumination conditions during a 16-day period. This may explain why lower WoD-WSA values are more frequently obtained.

[11] The mean (μ) and standard deviation (σ) of RMSE and WoD values are shown in Table 2. Low RMSE values with small standard deviation are acquired in most model-fits except for the enlarged quantities of μ and σ associated with the high latitude Greenland tiles h16v01 and h17v01, which are covered by snow and ice for the whole year. The relatively high mean of these RMSEs indicates the difficulties often experienced by retrievals in the high latitudes. Although more directional measurements can be gained at the high latitudes from a polar orbiting sensor, these observations are not always of the highest cloud-free quality. Furthermore these observations often occupy only a small or extreme part of the viewing and illumination hemisphere, hence causing higher WoD-WDR values (where the WoD is of NBAR at a solar zenith angle of 45°). Since a retrieval must pass all of these three tests before being flagged as high quality, it is understandable why fewer high quality retrievals are routinely seen in the high latitudes. In general the retrieval percent of each tile (percentage of pixels which receive sufficient high-quality, well-sampled observations for inversion) varies from tile to tile, and is affected by cloud contamination, satellite scan geometry, and available land area. About 99.99% of the land pixels in tile H18V06 potentially can be fully inverted, while tile H28V05, which is also located in mid-latitudes, can only achieve an efficient retrieval on 0.55% of the tile due to cloud contamination and land extent. The upper

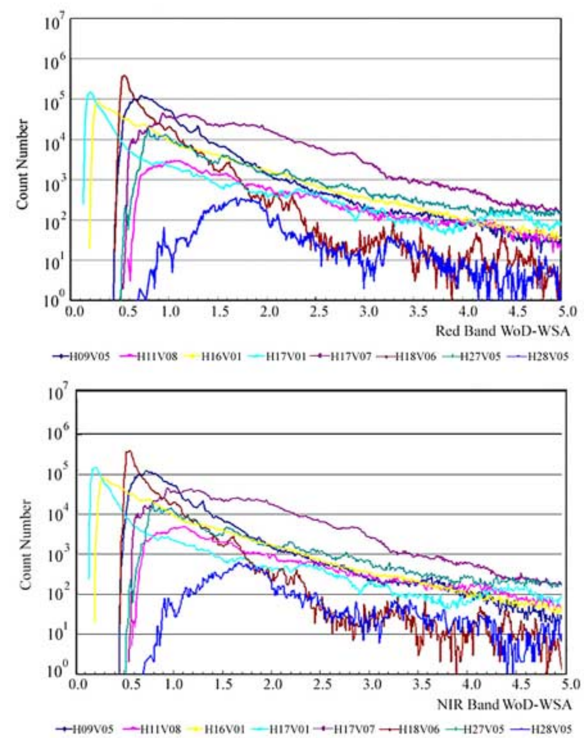

Figure 3. Histograms of WoD-WSA at Red and NIR bands for different tiles.

Table 2. Numeric Features of RMSE and WoD

Tile Name[a]	H18v06	H09V05	H11V08	H16V01	H17V07	H27V05	H28V05	$\mu + 3\sigma$[b]	$\mu + 2\sigma$[b]
				Red Band					
Percent,[c] %	99.99	88.92	4.66	78.57	79.37	16.71	0.55	N/A	N/A
RMSE								0.088	0.071
Mean	0.011	0.016	0.009	0.124	0.015	0.010	0.010		
Std	0.006	0.010	0.008	0.050	0.008	0.008	0.009		
WoD-WDR								1.848	1.449
Mean	0.284	0.356	0.520	1.615	0.527	0.491	0.541		
Std	0.059	0.141	0.202	1.364	0.216	0.208	0.247		
WoD-WSA								2.685	2.122
Mean	0.677	0.914	1.632	0.700	1.609	1.601	2.028		
Std	0.231	0.411	1.065	0.591	0.914	1.407	1.103		
				NIR Band					
Percent,[c] %	99.99	90.28	7.21	55.91	80.08	17.55	0.73	N/A	N/A
RMSE								0.097	0.078
Mean	0.012	0.024	0.035	0.130	0.017	0.021	0.033		
Std	0.007	0.013	0.019	0.049	0.010	0.013	0.023		
WoD-WDR								1.824	1.431
Mean	0.284	0.356	0.507	1.611	0.526	0.489	0.527		
Std	0.059	0.138	0.188	1.365	0.215	0.197	0.171		
WoD-WSA								2.726	2153
Mean	0.677	0.918	1.641	0.698	1.610	1.637	2.056		
Std	0.231	0.422	1.104	0.593	0.912	1.371	1.156		

[a]Tile H17V01 is dropped since its biomes and location is similar with H16V01.
[b]The 3σ and 2σ upper bounds weighted by retrieval percent.
[c]Efficient retrieval percent (%) is a percentage of available land pixels (clear observations > = 7) in each tile.

bounds of RMSE and WoDs for each tile are calculated at the 3σ and 2σ levels. In order to account for the variance from tile to tile and properly evaluate the range of the RMSEs and WoDs, these upper bounds are weighted by the normalized retrieval percents of each tile. The last two columns of Table 2 indicate that the weighted upper bounds from the red and NIR band are similar. The upper bound of RMSE falls in the vicinity of (0.071, 0.097), while an upper bound in the vicinity of (1.431, 1.848) is appropriate for WoD-WDR, and (2.122, 2.726) for WoD-WSA.

4. Summary

[12] We investigate the retrieval quality of the 500m MCD43 BRDF/Albedo using the actual 500m MODIS operational data over a range of biomes. The RMSE has the ability to describe the quality of RTLSR model-fits and good model-fits are routinely performed over for all biomes except for the two high latitude, snow and ice-covered Greenland tiles investigated. The WoDs can quantitatively evaluate the observation angle distribution under given angular sampling scenarios, resulting in low values for retrievals attempted on data with good directional sampling, and high values on those with poor sampling. Realistic ranges of the upper thresholds of the RMSE and WoD are suggested by the statistical features of the operational MODIS data. The upper threshold of RMSE values should therefore fall in the vicinity of (0.071, 0.097), while the threshold for WoD-WDR should fall at (1.431, 1.848), and at (2.122, 2.726) for WoD-WSA. The upper thresholds used in the 1 km MCD43 reprocessed Collection V004 and currently in the 500m reprocessed V005 are 0.10 for RMSE, 1.25 for WoD-WDR, and 2.50 for WoD-WSA. From above discussion, we suggest that slightly tightening the threshold for RMSE, relaxing it for WoD-WDR, and keeping the same value for WoD-WSA might be more appropriate in future reprocessing collections of the MODIS BRDF/Albedo product. This study suggests that upper thresholds of 0.08 for RMSE, 1.65 for WoD-WDR, and 2.5 for WoD-WSA should be considered.

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