Remote Sensing of Environment 140 (2014) 60–77

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Evaluation of MODIS albedo product (MCD43A) over grassland, agriculture and forest surface types during dormant and snow-covered periods

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ARTICLE INFO

Article history:
Received 25 October 2012
Received in revised form 14 August 2013
Accepted 17 August 2013
Available online 19 September 2013

Keywords:
MODIS standard and daily albedo product
Snow albedo
Forest
Grassland
Spatial representativeness

ABSTRACT

This study assesses the Moderate-resolution Imaging Spectroradiometer (MODIS) BRDF/albedo 8 day standard product and products from the daily Direct Broadcast BRDF/albedo algorithm, and shows that these products agree well with ground-based albedo measurements during the more difficult periods of vegetation dormancy and snow cover. Cropland, grassland, deciduous and coniferous forests are considered. Using an integrated validation strategy, analyses of the representativeness of the surface heterogeneity under both dormant and snow-covered situations are performed to decide whether direct comparisons between ground measurements and 500-m satellite observations can be made or whether finer spatial resolution airborne or spaceborne data are required to scale the results at each location. Landsat Enhanced Thematic Mapper Plus (ETM+) data are used to generate finer scale representations of albedo at each location to fully link ground data with satellite data. In general, results indicate the root mean square errors (RMSEs) are less than 0.030 over spatially representative sites of agriculture/grassland during the dormant periods and less than 0.050 during the snow-covered periods for MCD43A albedo products. For forest, the RMSEs are less than 0.020 during the dormant period and 0.025 during the snow-covered periods. However, a daily retrieval strategy is necessary to capture ephemeral snow events or rapidly changing situations such as the spring snow melt.

1. Introduction

Surface albedo, defined as the ratio of the total (hemispheric) reflected solar radiation flux to the incident flux upon the surface, quantifies the radiation interaction between the atmosphere and the land surface. It plays a crucial role in land surface climate and biosphere models (Dickinson & Hanson, 1984; Dirmeyer & Shukla, 1994; Lofgren, 1995). Carbon-only accounting approaches which ignore the albedo impacts of forests can significantly overestimate the climatic benefit of offsets (Thompson, Adams, & Johnson, 2009). As a key land physical parameter controlling the surface radiation energy budget, an absolute accuracy of 0.02–0.05 is required by climate models for global surface albedo (Dickinson, 1983, 1995; Dickinson et al., 2008; Henderson-Sellers & Wilson, 1983).

The surface reflectivity changes significantly with the appearance of snow. Snow also alters the exchange of moisture between the surface and the atmosphere especially during the snowmelt period (Marshall, Roads, & Glatzmaier, 1994). The snow albedo contributes a strong positive feedback in surface modeling studies (Betts & Ball, 1997; Bonan, Chapin, & Thompson, 1995; Gardner & Sharp, 2010; Koltzow, 2007; Li, Sun, Wang, & Liu, 2009; Molders, Luijting, & Sassen, 2008; Pedersen, Godtliebsen, & Roesch, 2008; Pedersen, Roeckner, Luthje, & Winther, 2009, Qu & Hall, 2006; Rutter et al., 2009; Thomas & Rowntree, 1992; Viterbo & Betts, 1999; Wyser et al., 2007). The albedo at local solar noon for snow-covered forests is usually less than 0.3 in the shortwave, but it can reach 0.57 or higher for snow-covered grassland and barren locations (Jin et al., 2002).

The Moderate-resolution Imaging Spectroradiometer (MODIS) BRDF/albedo products (Schaaf, Wang, & Strahler, 2011a, Schaaf et al., 2002, 2008) have been available since 2000 and provide high quality surface reflectance anisotropy retrievals over a variety of land surface

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http://dx.doi.org/10.1016/j.rse.2013.08.025

types (Jin et al., 2003b; Liang et al., 2002; Liu et al., 2009; Román et al., 2009, 2010). The Bidirectional Reflectance Distribution Function (BRDF) models and shapes (Gao, Schaaf, Strahler, Jin, & Li, 2003; Hill, Averill, Jiao, Schaaf, & Armston, 2008) are also increasingly being used to provide information about the surface vegetation structure and the albedo quantities have been embraced by the global climate modeling and numerical assimilation communities (Dickinson et al., 2008; Fang et al., 2007; Lawrence & Chase, 2007; Morcrette, Barker, Cole, Iacono, & Pincus, 2008; Myhre, Kvalevag, & Schaaf, 2005, Oleson et al., 2003; Roesch, Schaaf, & Gao, 2004; Tian et al., 2004; Wei et al., 2001; Zhou et al., 2003).

Although reported on a 500 m grid, the MODIS BRDF/albedo products are usually retrieved utilizing observations from a larger area depending on the view angles. The footprint of observations increases with the increase in the scanning angle (Tan et al., 2006; Wolfe, Roy, & Vermote, 1998). Observations are weighted by angular coverage before the retrieval but it must still be acknowledged that the 500 m gridded product actually represents information from a larger area.

A number of studies have validated the MODIS albedo product by a direct "point-to-pixel" comparison (Chen, Liang, Wang, Kim, & Martonchik, 2008; Liu et al., 2009; Salomon, Schaaf, Strahler, Gao, & Jin, 2006; Wang et al., 2004) with the assumption that both the tower and satellite albedo roughly sample the same spatial domain. However, ground measurements from tower usually only cover a limited area, which is much smaller than the MODIS spatial resolution. An important difficulty encountered whenever attempts are made to compare satellite-retrieved albedo values to tower-measured albedo data is that the footprint of the ground measurement is not always representative of the greater satellite footprint. This is particularly true of rapidly changing surface conditions during senescence, green-up, and varying periods of snow cover. Assessments of spatial representativeness using Landsat data can provide an estimate of the general ability of the satellite retrievals to capture the tower measurements (Román et al., 2009, 2010). However, conditions can change so rapidly during dormancy and ephemeral snow events that such assessments must be reconsidered frequently for each situation.

Initial investigations with "point-to-pixel" comparisons at the AmeriFlux Canadian University of California-Irvine (UCI) burn forest sites in Canada suggest that the MODIS winter values were usually lower than the tower values (Román et al., 2009). However these locations represent field sites with high spatial heterogeneity during winter periods. To consider the spatial scaling effect, finer spatial resolution Landsat Enhanced Thematic Mapper Plus (ETM+) data have been usually used to validate MODIS BRDF/albedo products (Fang, Liang, Chen, Walthall, & Daughtry, 2004; Jin et al., 2003b; Liang et al., 2002; Susaki, Yasuoka, Kajiwara, Honda, & Hara, 2007). Barnsley et al. (2000) and Lucht, Hyman, et al. (2000) used Landsat data to analyze the spatial scaling effect on the albedo of a semi-desert environment prior to the launch of MODIS. It must be noted however that most of these studies have assumed a Lambertian surface to estimate Landsat albedo although Jin et al. (2003b) calculated a Landsat albedo by applying the ratio of the MODIS hemispherical albedo at local solar noon to the directional surface reflectance at the Landsat observing geometry.

While the MODIS BRDF/albedo products have been evaluated during the growing season for a number of vegetated land covers with high accuracy (Disney, Lewis, Thackrah, Quaife, & Barnsley, 2004; Jin et al., 2003a, 2003b; Knobelspiesse, Cairns, Schmid, Román, & Schaaf, 2008; Liang et al., 2002; Liu et al., 2009; Lyons, Jin, & Randerson, 2008; Roesch et al., 2004; Román et al., 2009, 2010; Salomon et al., 2006; Samain et al., 2008; Shuai, Schaaf, Strahler, Liu, & Jiao, 2008; Stone, Anderson, Shettle, Andrews, & Loukachine, 2008; Susaki et al., 2007; Wang, Barlage, Zeng, Dickinson, & Schaaf, 2005; Wang et al., 2004), the assessment of the results during dormant and snow-covered seasons (Román et al., 2009, 2010; Schaaf, Liu, Gao, & Strahler, 2011b; Wang et al., 2012) has only just begun.

The spatial patterns of albedo will change seasonally if the surface is comprised of different land types. This is especially true during dormant periods (when vegetation is not photosynthetically active and leaves are either brown and/or very few). Jin et al. (2002) analyzed the effect of snow over different land covers and showed that snow caused high heterogeneity in the surface albedo making validation more difficult. Therefore, differences between the tower measurements and MODIS albedo should be expected and any evaluation of the MODIS BRDF/albedo products over dormant seasons, both snow-covered and snow-free, needs to pay particular attention to spatial scaling effects.

For agricultural and temperate grassland areas, the ground is often covered by dense uniform vegetation during the growing season. Thus, the surface is relative homogenous and ground measurements match well with MODIS products (Chen et al., 2008; Jin et al., 2003b; Liang et al., 2002; Liu et al., 2009; Román et al., 2009, 2010; Susaki et al., 2007). However, these surfaces are often considerably more heterogeneous during dormant or partly snow-covered periods. Jin et al. (2003b) and Chen et al. (2008) showed that there are relatively large differences between ground albedos and MODIS albedo products during these seasons.

Modeling and monitoring the albedo of forests during the snow-covered periods can be difficult. A snow-covered forest in winter is made up an upper layer of dark leaves and branches and a lower layer of bright snow on the forest floor. Because of the upper foliage in dense evergreen forests, the reflected photons from the snow surface have difficulties escaping the forest canopy especially under high zenith viewing angles; moreover, a large fraction of the understory may be shaded in winter scenes, owing to the higher solar zenith angles. However, the reflectance from deciduous forests, where snow information is more visible through a canopy of bare branches, is relatively high. The density of the canopy can also affect whether a pixel is designated as snow-covered or snow-free.

This study aims to assess the accuracy of MODIS albedo products by comparison with ground measurements after establishing the spatial representativeness of vegetated surfaces during dormant and snow-covered situations. Section 2 describes both the ground measurements and MODIS albedo products and Section 3 outlines the assessment strategy. In Section 4, we compare the ground measurements to MODIS albedos and Landsat albedos where appropriate and discuss the overall accuracy of MODIS products during the dormant and snow-covered seasons.

2. Datasets

2.1. Ground measurements

The primary validation sites used for the MODIS Albedo product have historically been the Surface Radiation Budget Network (SURFRAD) sites (Augustine, DeLuisi, & Long, 2000) which are maintained in the United States by NOAA as part of the Baseline Surface Radiation Network (BSRN) (Ohmura et al., 1998). The World Climate Research Programme (WCRP) Radiative Fluxes Working Group initiated the BSRN to support the research projects of the WCRP and other scientific programs. These seven SURFRAD sites (Fort Peck, MT, Sioux Falls, SD, Penn State, PA, Bondville, IL, Table Mountain, CO, Goodwin Creek, MS and Desert Rock, NV) (Table 1) are used again in this study. In addition to the seven SURFRAD sites, the Boulder, CO site is also another BSRN site close to the Table Mountain site that utilizes pyranometers mounted on a 300 m tower. These eight sites provide the highest quality intercalibrated albedo measurements.

Three additional sites of New England forests from the AmeriFlux network are also used in this study. AmeriFlux was established by the Department of Energy (DOE) in 1996 to provide continuous observations of ecosystem level exchanges of CO_2, water, and energy, including surface albedo (Law et al., 2002; Running et al., 1999).

Table 1
SURFRAD, BSRN, and AmeriFlux ground sites.

Station name	Latitude/longitude	Tower height/footprint (m)	State	Land cover	MODIS tile	Network
Boulder	40.05/ 105.01	300/3788.25	Colorado	Grassland	H09V04	BSRN
Fort Peck	48.31/ 105.10	10/126.28	Montana	Grassland	H11V04	SURFRAD
Goodwin Creek	34.25/ 89.87	10/126.28	Mississippi	Grassland	H10V05	SURFRAD
Sioux Falls	43.73/ 96.62	10/126.28	South Dakota	Grassland	H11V04	SURFRAD
Table Mountain	10/126.28	Colorado	Grassland	H09V04	SURFRAD	
40.13/ 105.24						
Desert Rock	36.62/ 116.02	10/126.28	Nevada	Desert, sparse grass	H08V05	SURFRAD
Bondville	40.05/ 88.37	10/126.28	Illinois	Agriculture	H11V04	SURFRAD
Penn State	40.72/ 77.93	10/126.28	Pennsylvania	Agriculture	H12V04	SURFRAD
Harvard EMS	42.538/ 72.172	30/366	Massachusetts	Mixed forest	H12V04	AmeriFlux
Howland Larch	45.216/ 68.709	30/366	Maine	Deciduous needleleaf forest	H13V04	AmeriFlux
Howland West	45.209/ 68.747	30/366	Maine	Evergreen needleleaf forest	H13V04	AmeriFlux

Total downward and upward radiation (0.28–3.0 μm) is measured by Eppley pyranometers mounted on the 10 m towers at the SURFRAD sites while the Boulder site utilizes a 300 m tower. Normal Incidence Pyranometers and shaded pyranometers are used to measure the direct normal and diffuse shortwave fluxes (Augustine et al., 2000). The instruments are ventilated and heated during the winter so that there is a great deal of confidence in the winter measurements as well as the growing season ones. Kipp and Zonen albedometers in the shortwave (0.3–2.8 μm) are used to measure albedo at AmeriFlux sites. These albedometers are mounted on 30 m towers and not routinely heated and ventilated, therefore the data are not considered as reliable during snow precipitation periods. Ground albedo is calculated by the ratio of upwelling radiation and downwelling radiation during the local mid-day time. The footprints of 10 m, 30 m, and 300 m towers are estimated to be about 126 m, 366 m and 3788 m in diameter respectively.

$$f = 2H \tan \mathrm{HFOV} \tag{1}$$

where f is the circular footprint of ground tower measurements, H [m] is the tower height, and HFOV [degrees] is its half of field of view. HFOV is 81° (Michalsky, Harrison, & Berkheiser, 1995).

The Bondville SURFRAD site is located southwest of Champaign, Illinois, in an agricultural region (Fig. 1). This site represents a mixture of crops and drainage ditches which are maintained with a variety of harvesting and fallowing practices. It is quite heterogeneous at the MODIS scale (Liu et al., 2009; Salomon et al., 2006). The Sioux Falls SURFRAD site is located on the grounds of the Earth Resources Observation and Science (EROS) Data Center, South Dakota, and is covered by grass. The Goodwin Creek site, west of Oxford, Mississippi, is located on rural pasture land surrounded by deciduous trees. The Penn State University (PSU) SURFRAD site is located on the grounds of PSU's agricultural research farm about 6 miles southwest of State College, Pennsylvania and is in a broad Appalachian valley between the Tussey and Bald Eagle Ridges. The Fort Peck SURFRAD station is located on the Fort Peck Tribes Reservation in Montana. This site is dominated by native grasses. The Table Mountain SURFRAD station is located in Colorado and is a mix of exposed rocks, sparse grasses, desert shrubs and small cactus. The Boulder BSRN station, also in Colorado, is very close to the Table Mountain station and is covered by grass. The Desert Rock SURFRAD station is covered with very sparse vegetation and lies to the northwest of Las Vegas, Nevada. The AmeriFlux site at Howland Forest is located in central Maine, U.S.A., about 35 miles north of Bangor. The natural stands in this boreal–northern hardwood transitional forest consist of hemlock–spruce–fir, and hemlock–hardwood mixtures. The evergreen needle-leaf canopy height at Howland West Tower is about 20 m. The albedo data used here are from 2007 to 2009, and the albedometer was heated during the winter of 2009. The Howland Larch Tower is surrounded by deciduous needle-leaf trees (larch, *Larix laricina*) (Hollinger, Ollinger, Richardson, Meyers, & Dail, 2010). The albedo data were collected in 2008 for the Larch Tower. The AmeriFlux Harvard Environmental Measurement Station (EMS) tower at Harvard Forest lies in the central Massachusetts town of Petersham. The dominant species include red oak, red maple, black birch, white pine, and hemlock.

2.2. Satellite albedo

2.2.1. MCD43A standard BRDF/albedo product

The standard MODIS BRDF/albedo product (MCD43A) (Lucht, Schaaf, & Strahler, 2000; Schaaf et al., 2002) provides the weighting parameters associated with the RossThick-LiSparse Reciprocal (RTLSR) BRDF model that describes the reflectance anisotropy of each pixel at a 500-m gridded resolution. Both a sufficient number of observations and good angular sampling are needed to achieve a full inversion retrieval and estimate a high quality BRDF. Acknowledged as a tradeoff between the temporal stability of the surface reflectance and the availability of sufficient angular samples, a 16-day period of cloud-free, atmospherically-corrected surface reflectances from both Terra (MOD) and Aqua (MYD) is used to derive MCD43A BRDF/albedo (Gao, Schaaf, Strahler, & Lucht, 2001; Roy, Lewis, Schaaf, Devadiga, & Boschetti, 2006; Wanner et al., 1997). With an 8 day system of overlapping processing, more phenological variability can be accurately characterized. A backup algorithm (also called a magnitude inversion) is employed if a high quality full inversion retrieval cannot be accomplished due to poor angular sampling or insufficient input observations (Schaaf et al., 2002). This a priori knowledge method often performs quite well under normal situations (Jin et al., 2003a, 2003b; Liu et al., 2009; Salomon et al., 2006) but should be considered a poor quality result and is assigned a poor quality flag. The MCD43A BRDF/albedo standard product only retrieves a snow albedo quantity when the majority of observations during a 16 day period are snow-covered. Snow-covered and non-snow observations are currently always processed separately.

The intrinsic black-sky albedo (BSA) at local solar noon and the white-sky albedo (WSA) is generated by integrating the BRDF calculated from the three retrieved parameters (f_{iso}, f_{geo} and f_{vol}). Blue sky albedo, which considers both the diffuse and direct incident radiation for a specific time and atmospheric state, can be calculated as follows (Lewis & Barnsley, 1994):

$$\alpha_{\text{blue-sky}}(\theta_i) = \mathrm{SKYL}(\theta_i)\,\alpha_{\text{white-sky}} + (1 - \mathrm{SKYL}(\theta_i))\,\alpha_{\text{black-sky}}(\theta_i) \tag{2}$$

where SKYL(θ_i) is the proportion of diffuse irradiation at a certain solar zenith angle θ_i. The SKYL is measured by the shaded pyranometer at the SURFRAD and Howland Forest (West and Larch) sites. Harvard EMS Forest does not have ground SKYL data and the MODIS aerosol product (MOD08) is used to calculate the proportion of diffuse irradiation.

Fig. 1. The locations of the eleven SUFRAD, BSRN and AmeriFlux sites — Boulder, Goodwin Creek, Fort Peck, Sioux Falls, Table Mountain, Desert Rock, Bondville, Penn State, Harvard EMS, Howland West and Howland Larch sites from Google map.

In addition to the spectral quantities, three broadband albedos of VIS (0.3–0.7 μm), NIR (0.7–5.0 μm) and shortwave (0.3–5.0 μm) are calculated from the 7 spectral bands via narrow to broadband conversion coefficients (Liang, Strahler, & Walthall, 1999; Stroeve et al., 2005).

$$\alpha_{shortwave,snowfree} = 0.3973\alpha_1 + 0.2382\alpha_2 + 0.3489\alpha_3 + 0.2655\alpha_4 + 0.1604\alpha_5 + 0.0138\alpha_6 + 0.0682\alpha_7 + 0.0036 \quad (3)$$

$$\alpha_{shortwave,snow} = 0.1574\alpha_1 + 0.2789\alpha_2 + 0.3829\alpha_3 + 0.1131\alpha_5 + 0.0694\alpha_7 + 0.0093. \quad (4)$$

2.2.2. MCD43A direct broadcast (DB) albedo data

The MODIS DB BRDF/albedo product (Shuai, 2010) which is utilized for regional applications (e.g., forest, agriculture and disturbance monitoring) is operated in a daily rolling mode to provide more frequent surface Nadir BRDF-Adjusted Reflectances (NBAR) and albedos than the current standard product. Two versions of the DB mode are utilized in this study. First, the 16-day daily mode uses 16 days worth of reflectances as input but weights the more recent clear observations (with the highest observation coverage) more heavily. A retrieval is attempted each day based on the proceeding 16 days' worth of data. Full inversions are performed if there are sufficient high quality and well sampled angular observations, where the quality of the angular sampling is determined by reference to the Weights of Determination (Lucht & Lewis, 2000). Otherwise a magnitude inversion will be processed with the a priori backup database being updated with the most recent full inversion results. Second, the 1-day daily mode, a magnitude inversion is performed each day using the full inversions from the 16-day daily mode as the a priori information for each succeeding day. While this mode emphasizes the single day observation the most heavily, it is also more sensitive to any cloud contamination or residual aerosols affecting that single look.