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Evaluation of Moderate-resolution Imaging Spectroradiometer (MODIS) snow albedo product (MCD43A) over tundra

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A B S T R A C T

This study assesses the MODIS standard Bidirectional Reflectance Distribution Function (BRDF)/Albedo product, and the daily Direct Broadcast BRDF/Albedo algorithm at tundra locations under large solar zenith angles and high anisotropic diffuse illumination and multiple scattering conditions. These products generally agree with ground-based albedo measurements during the snow cover period when the Solar Zenith Angle (SZA) is less than 70°. An integrated validation strategy, including analysis of the representativeness of the surface heterogeneity, is performed to decide whether direct comparisons between field measurements and 500-m satellite products were appropriate or if the scaling of finer spatial resolution airborne or spaceborne data was necessary. Results indicate that the Root Mean Square Errors (RMSEs) are less than 0.047 during the snow covered periods for all MCD43 albedo products at several Alaskan tundra areas. The MCD43 1-day daily albedo product is particularly well suited to capture the rapidly changing surface conditions during the spring snow melt. Results also show that a full expression of the blue sky albedo is necessary at these large SZA snow covered areas because of the effects of anisotropic diffuse illumination and multiple scattering. In tundra locations with dark residue as a result of fire, the MODIS albedo values are lower than those at the unburned site from the start of snowmelt.

1. Introduction

Surface albedo describes the amount of solar energy not absorbed by the Earth system and defines the lower boundary for atmospheric radiative transfer (Hu et al., 1999; Vermote, et al., 1997). Surface albedo is an essential climate variable (Schaaf et al., 2008) and the accurate global estimations of terrestrial albedo for all surface types during all seasons are required for climate and biogeochemical modeling efforts (Dickinson, 1995; Lofgren, 1995; Oleson, et al., 2003; Ollinger et al., 2008; Roesch et al., 2004; Tian et al., 2004).

Snow albedo has a strong positive feedback in the surface–atmosphere system (Betts & Ball, 1997; Bonan et al., 1995; Viterbo & Betts, 1999). The surface-temperature response in the Arctic area is amplified about 33% by surface albedo feedback (Graversen & Wang, 2009). Fletcher et al. (2009) found that up to 25–30% of the intermodal spread in projections of the circulation response to climate change is linearly related to the surface snow albedo feedback strength. The North American surface climate anomalies related to ENSO (El Nino–Southern Oscillation) have also been found to be greatly enhanced by local snow-albedo feedback (Yang, et al., 2001). The terrestrial changes in summer albedo contribute substantially to recent high latitude warming trends (Chapin et al., 2005) and the increased poleward retreat of the spring continental snow cover over northern latitudes is consistent with an enhanced snow-albedo feedback (Déry & Brown, 2007). Snow albedo has also been linked to variations in the Asian summer monsoon rainfall (Souma & Wang, 2010). Therefore, high quality global surface albedo is needed to further explore snow-albedo feedback impacts (Qu & Hall, 2007).

General Circulation Models (GCMs) currently estimate snow albedo based on snow surface temperature, snow age, grain size, and solar illumination angle (Koltzow, 2007; Molders et al., 2008). But the values of modeled albedo vary more than the observed albedo and

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often underestimate or overestimate albedo (Molotch & Bales, 2006; Pedersen & Winther, 2005; Wang & Zeng, 2010). For several of the models, the estimated snow albedo decreases faster or by a greater magnitude than observed albedo during winter snow transitions (Pedersen & Winther, 2005), and the models do not outperform simulations using airborne data (Molotch & Bales, 2006). The model ECHAM4 GCM underestimated the albedo by up to 0.2 during snow cover periods at stations which experience severe winters in Russia, Scandinavia, and Canada (Roesch et al., 1999) necessitating new formulations (Dutra et al., 2010). The Community Land Model (CLM2) overestimated snow albedo by about 20% compared with MODIS data (Oleson, et al., 2003), which emphasizes the need for more accurate snow albedo characterizations that improve model estimates of climate sensitivity (Gardner & Sharp, 2010; Lawrence & Chase, 2007; Levis et al., 2007; Wang & Zeng, 2010).

The albedo is obtained via estimates of BRDF that must be obtained using multiple looks provided at a variety of sun-surface-satellite directions. Early global albedo datasets were produced from the Earth Radiation Budget Experiment (ERBE) radiometer (Li & Garand, 1994) and the Advanced Very High Resolution Radiometer (AVHRR) (Csiszar & Gutman, 1999) while current albedo products are available from a number of satellite systems. Albedo values are derived from Multi-angle Imaging SpectroRadiometer (MISR) with the Rahman-Pinty-Verstraete (RPV) model (Martonchik et al.,1998a,b, 2002; Rahman et al., 1993) while the Roujean BRDF model (Roujean et al., 1992) is used to generate albedo from the Polarization and Directionality of the Earth's Reflectances (POLDER) and Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) products (Carrer et al., 2010; Geiger et al., 2008; Maignan et al., 2004; Samain et al., 2006; van Leeuwen & Roujean, 2002). The model combination RossThick-LiSparse Reciprocal (RTLSR) has been identified as the semi-empirical linear model best suited for the operational MODIS BRDF/Albedo algorithm (Gao et al., 2005; Lucht et al., 2000; Privette et al., 1997; Schaaf et al., 2002, 2011a; Wanner et al., 1995, 1997) as it is able to describe the reflectance anisotropy of a large variety of global land covers.

This study focuses on the ability of the MODIS algorithm to capture the conditions of large SZA and high anisotropic diffuse illumination and multiple scattering experienced by high latitude tundra. The vegetation in tundra areas is mainly composed of dwarf shrubs, sedges and grasses, mosses, and lichens and permafrost, with tall alder, willow, and birch shrubs in some locations. The region is entirely snow covered for many months of the year, only reverting to active vegetation with numerous ponds and bogs during the short growing season. Snow albedo values thus decrease as the melt season progresses. The decreases can be very rapid across tundra, which can drop from 0.80 to 0.15 in only 2 weeks (Grenfell & Perovich, 2004). Therefore snowmelt, which is dependent on the net balance of the surface radiative and turbulent fluxes, is a crucial variable in determining the timing of the spring transition (Lynch et al., 1998).

Recent validation studies have indicated that the MODIS standard product (MCD43) works well over completely snow-covered sites in Greenland (Liang et al., 2005; Stroeve et al., 2005), with more difficulties encountered at extremely large SZAs (>65°) and during times of spring snow melt (noting that these coincide). Stroeve et al. (2005) found a 0.05 low bias for albedo values exceeding 0.7. The difficulties during these shoulder months are partly caused by atmospheric correction and cloud detection limitations; and validation is made difficult by the rapid changes in the surface spatial heterogeneity in these regions during sporadic snow fall and snow melt. Furthermore there are substantial snow grain size and water content changes being experienced by the snowpack. Nevertheless, the MCD43 standard albedo product retrieves high quality snow albedo with an average RMSE of 0.04 which compares well with the in situ tower measurements of the Greenland Climate Network (GC-Net), which exhibit a RMSE = 0.035 uncertainty (Schaaf et al., 2011b; Stroeve et al., 2005). Chen et al. (2008) showed that there are relatively large differences between field measured albedo and MISR albedo products during the snow/ice-covered period on Greenland. It must be noted that the GC-Net instruments only sense across a broad spectral range (0.4–1.1 μm), so the narrowband MISR channels were converted to 0.4–1.1 μm broadband values and were then compared with ground data. The MISR shortwave albedo values tended to overestimate the ground albedo values, while this study also showed that the MODIS albedo values were generally lower than the MISR albedo values during periods of snow/ice cover. However, it is important to acknowledge that sparse angular sampling primarily due to cloud cover always makes retrievals difficult in these extreme geometric conditions.

It must also be acknowledged that the tower heights at GC-Net sites are less than 4 m, resulting in footprints of less than 60 m diameter, which is much less than that of the 500 m gridded MODIS products. While it is reasonable to compare the two kinds of data (i.e., via point-to-pixel comparisons) if the surface is homogenous, such comparisons will lead to large discrepancies if the surface is heterogenous. Furthermore these discrepancies will increase for undulating surfaces and areas where shadowing due to larger SZA is important. Unfortunately, the tundra surfaces that are quite uniform while snow covered are often considerably more heterogeneous during partly snow covered periods.

This study aims to evaluate the accuracy of MODIS albedo products over high latitude tundra areas during the snow-covered and snow melt situations. Section 2 introduces the field measurements and the MODIS albedo products used. Section 3 describes the evaluation strategy. Section 4 shows the accuracy of MODIS albedo products and Section 5 discusses the effects of retrieval quantity (i.e., the number of clear-sky observations) and quality, as well as the influence of high anisotropic diffuse illumination, multiple scattering, and large SZA conditions on the accuracy of the MODIS BRDF/Albedo product.

2. Datasets

2.1. Ground data

The Atmospheric Radiation Measurement Program (ARM) (Ackerman & Stokes, 2003) initiated an extensive field program to obtain necessary climate quality measurements in the North Slope of Alaska (NSA). One of the sites is the NSA-Barrow facility, also part of Baseline Surface Radidation Network (BSRN) (McArthur, 2005). The Barrow site, located on the most northern point of the United States, provides the highest quality tower measurements available of a tundra location (Fig. 1). Data are collected from a 4 m instrument height. The tundra vegetation at the Barrow site is unmanaged and undisturbed with the dominant species being *Carex aquatilis*, *Dupontia fisheri* and *Arctophila fulva*. Although the measurements at the Barrow site are made over open tundra, there are large lagoons and a number of lakes in the vicinity.

The upwelling and downwelling radiation flux at Barrow are measured by shortwave Kipp and Zonen pyranometers (0.3–2.8 μm). Normal incidence pyranometers and shaded pyranometers are used to measure the direct normal and diffuse shortwave fluxes. Ground albedo is calculated by the ratio of upwelling radiation and downwelling radiation during the local mid-day time. The footprint of the 4 m instrument height is about 50.5 m in diameter (FOV = 81°).

$$f2H\tan(FOV^{o}) \quad (1)$$

Where f is the circular footprint of ground tower measurements, H [m] is the instrument height, and FOV [degrees] is its field of view.

The Anaktuvuk River fire in Alaska burned about 1000 km^2 of tundra from July to October 2007. The Arctic Long Term Ecological Research (ARC-LTER) program installed three tower sites across a burn severity gradient (i.e. severely-, moderately- and un-burned tundra)