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The accuracy of satellite-derived albedo for northern alpine and glaciated land covers

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ABSTRACT

Alpine and Arctic land cover can present a challenge for the validation of satellite-derived albedo measurements due, in part, to the complex terrain and logistical difficulty of accessing these regions. We compared measurements of albedo on transects from northern mountain land covers (snowfield, glacier ice, tundra, saline silt river delta) and over a large elevation range to the coincident 8-day MODIS (MCD43) albedo product. We also compared field measurements at snow covered sites to the coincident daily MODIS (MOD10A1) snow albedo product. For each transect, we measured a range of albedo values, with the least variability on the silt river delta (range = 0.084) and the largest over mid-elevation glacier ice (range = 0.307). The highest elevation snowfield (0.170) had nearly the same range of albedo values as tundra (0.164). The MODIS shortwave White Sky Albedo product (MCD43A3) was highly correlated with the field transect albedo ($R^2 = 0.96$), with a Root Mean Square Error (RMSE) of 0.061. The MODIS shortwave Black Sky Albedo product was similarly correlated with field transects ($R^2 = 0.96$; RMSE = 0.063). These results indicate that remote observation of albedo over snow covered and alpine terrain is well constrained and consistent with other studies. Albedo varied by ~15% both spatially and temporally for the high elevation snowfields at the point in the season where albedo variation should be at its minimum. There were several instances where MCD43A3 albedo was not produced over snow and was instead classified as cloud covered, despite field observations of cloud free skies. There were also several instances where daily MOD10A1 albedo was produced during the coincident 8-day period at these locations. This suggests that the cloud mask in the MCD43 product is overly conservative over snow. Spatial variation in albedo within the MODIS grid cell (500 m), especially for snow and glacier ice, combined with the uncertainty associated with positional accuracy of MODIS, indicates that the accuracy of MODIS albedo will be dependent on both land cover type and the period of observation.
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1. Introduction

Determining the Earth's albedo is most efficiently undertaken by satellite remote sensing, but assessing the accuracy of such measurements is challenging, particularly in complex terrain. Climate modeling relies on the accurate determination of albedo. The values typically used for characterizing the accuracy of land surface albedo in general circulation models are in the range of ±0.05 (Henderson-Sellers and Wilson, 1983) to ±0.02 (Sellers, 1993). Barry (1985) recommends an albedo accuracy of 0.02 for snow cover modeling. Constraining the accuracy of albedo measurements is therefore important, and there are several methods for validating coarse spatial resolution satellite albedo products. Satellite data can be compared to field measurements of albedo, or compared to finer spatial resolution albedo which is often collected at a more coarse temporal resolution from satellite or aircraft.

Field measurements of albedo are commonly calculated from upward and downward facing broadband pyranometers sensitive to the visible and near-infrared portion of the electromagnetic spectrum. The advantage of this technique is that conditions influencing surface albedo (e.g., solar zenith angle, surface properties and atmospheric conditions) can be identified and constrained. These field measurements are typically made at either a stationary meteorological station or with a mobile sampling apparatus. One of the few examples of spatial and temporal

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sampling of albedo variability across the accumulation and ablation zones of a glacier is from Haut Glacier d'Arolla, Switzerland, where Brock et al. (2000) reported that albedo can vary by as much as 20–30% across a 500 m transect for some sections of the glacier at particular times of year. Spatial sampling of albedo across snow covered Alaskan tundra (Sturm et al., 2005) using pyranometers suspended on 50 m cable transects indicated variability in albedo of nearly 90% across tundra with residual spring snow patches.

Several studies have compared spatial albedo ground sampling to satellite derived albedo. For example, Lucht et al. (2000) sampled grasslands and shrublands with various degrees of visible soil and compared the results to AVHRR derived albedo. They found that the field albedo data varied by up to 0.08 and that the field measurements agreed with AVHRR values within ±0.05. Liang et al. (2002) compared field measurements of albedo and LandSat ETM + albedo to validate MODIS albedo measurements for the USDA Agricultural Research Centre in Beltsville, MD, USA, with the land cover types including soils, crops, natural vegetation and urban. They reported an accuracy between MODIS albedo and the validation measurements of <0.05, in most instances.

Validation of MODIS-derived snow and ice albedo values on the Greenland Ice Sheet using pyranometer-derived albedo from stationary meteorological stations (Stroeve et al., 2005, 2006, 2013) have been conducted assuming that the albedo of high elevation ice sheets is more homogeneous than other land cover types. The pyranometer used in these studies was the LI-COR 200SZ which has a spectral range of 0.4–1.1 μm, and which requires a correction to convert to the full short wave spectrum. Although the corrections are well understood and likely introduce little error, the field measurements do not share the same spectral range as MODIS total short wave albedo, which is 0.3–5.0 μm spread across 7 spectral bands. Stroeve et al. (2013) report an RMSE of 0.067 for high quality MCD43 data (combined MODIS Terra and Aqua at 500 m resolution) in comparison with *in situ* albedo data. Stroeve et al. (2005) reported a RMSE of 0.04 for *in situ* data versus MODIS Terra (MOD43) generated data. Post-processing of MODIS geolocation in conjunction with ground control points produces a positional error of approximately 50 m (1σ) at nadir for Terra and approximately 65 m for Aqua (Wolfe et al., 2002), although the positional error of low-resolution albedo products is likely not larger than 125 m (Stroeve et al., 2006).

High latitude alpine areas are typically difficult to access and are poorly covered by meteorological monitoring stations, which make continuous measurements of albedo rare. Furthermore, issues related to spatial scale are difficult to assess because it is logistically challenging to access these remote areas to conduct albedo sampling. Here we report on albedo measurements made in transects over a range of alpine and glaciated terrain in the southwest Yukon, Canada. These observations are compared with concomitant MODIS albedo values. Our primary objective was to determine the spatial variability in albedo within a MODIS grid cell of different alpine land covers. Our secondary objective was to compare and validate MODIS derived albedo values over a wide range of elevations and alpine land covers.

2. Methods

2.1. Field measurements and study area

Albedo was measured along transects at six locations in alpine and glaciated terrain in the southwest Yukon in summer 2013 and 2015 under a variety of cloud cover conditions (Table 1; Fig. 1; Fig. 2). The measurement locations were purposely chosen in regions that had low slopes (<5°), consistent aspects and were >1 km from large changes in elevation or land cover. These locations are therefore considered to be representative of the surface type being measured and were far enough away from other land surfaces to avoid contamination from adjacent land cover types within 500 × 500 m MODIS grid cells. The transects consisted of parallel or perpendicular lines, with albedo measurements made approximately every 30–50 m. The transects ranged between 200 m and 1000 m in length, and each location had at least one transect that was 500 m in length. The sampling regime could not be precisely replicated at each sample location due to hazards from features such as meltwater channels and crevasses.

Albedo measurements were made with a CMA11 instrument (Kipp & Zonen, Delft, The Netherlands) mounted on a portable tripod, with the differential voltage output connected to a CR10X data logger (Campbell Scientific, Logan, Utah). The albedo measurement apparatus is shown in the foreground in Fig. 2 (panels C & E). The CMA11 consists of an upward and a downward facing secondary class pyranometer that is sensitive to wavelengths in the 0.300–2.400 μm range of solar radiation. This pyranometer is the highest precision class solar radiation measurement instrument manufactured by Kipp & Zonen. The logger was programmed to record incoming and reflected solar radiation every minute, as the average of five second samples. The logger clock was synchronized with a wrist watch, and moved at approximately 10 min intervals along each sampling transect. The location of each site was recorded with a handheld GPS.

To determine representative minimum surface albedo values, measurements should ideally be taken under direct sunlight and cloud free conditions, and close to diurnal minimum zenith angle. The land covers in this study fall into two broad types: snow and ice, and partially vegetated barren ground. Increasing the solar zenith angle acts to increase albedo on these land cover types (e.g., Ohmura, 1981; Dozier, 1989; Carroll and Fitch, 1981). Consequently, albedo measurements were made within ~3 h of local solar noon to minimize sun illumination effects caused by comparing measurements made at variable zenith angles, or from zenith angles greater than ~50° (Brock et al., 2000). Solar zenith angles greater than 70° have been shown to cause degradation in the quality of MODIS albedo (Stroeve et al., 2005, 2006). Similarly, Wang and Zender (2010) suggest that while the spatiotemporal patterns of MODIS albedo may be correct for large solar zenith angles, the accuracy may deteriorate for angles > 55° and may become physically unrealistic for angles > 65°. In our study, the values for solar zenith angle are almost entirely <55° (Table 1), likely mitigating much of this uncertainty. However, we are aware that the relationship between solar zenith angle and surface albedo observations is complex (e.g., Cronin, 2014).

Changing atmospheric and surface conditions also influence albedo. Cloud cover affects snow and dry tundra vegetation albedo differently. For an increase in solar elevation angle at small angles (from 10° to 40°) under complete cloud cover, snow albedo increases by up to ~2% (Choudhury and Chang, 1981); in general snow albedo for cloudy skies is a few percent higher than those from under clear skies. Under diffuse solar radiation caused by cloud cover vegetation albedo can be decreased by up to ~2% (Eugster et al., 2000). The albedo of bare soil increases as it dries, a phenomenon which is observed both diurnally and seasonally (Eugster et al., 2000). The albedo of snow is primarily determined by grain size, where weathering of fresh snow increases grain size and decreases albedo (e.g., Dozier, 1989).

Details of the sample locations are listed in Table 1 and shown in Fig. 2. The high elevation snowfield location A (accumulation zone of the Kaskawulsh Glacier) was measured on August 8, 2015. This site consisted of flat, wet, partially weathered snow. The ablation region of the Kaskawulsh Glacier was measured at an elevation of 1370 m on August 9, 2015 (Site E). This site comprised glacier ice

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