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Evaluation of satellite remote sensing albedo retrievals over the ablation area of the southwestern Greenland ice sheet

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ABSTRACT

MODerate resolution Imaging Spectroradiometer (MODIS) albedo products have been validated over spatially uniform, snow-covered areas of the Greenland ice sheet (GrIS) using the so-called single 'point-to-pixel' method. This study expands on this methodology by applying a 'multiple-point-to-pixel' method and examination of spatial autocorrelation (here using semivariogram analysis) by using in situ observations, high-resolution WorldView-2 (WV-2) surface reflectances, and MODIS Collection V006 daily blue-sky albedo over a spatially heterogeneous surfaces in the lower ablation zone in southwest Greenland. Our results using 232 ground-based samples within two MODIS pixels, one being more spatial heterogeneous than the other, show little difference in accuracy among narrow and broad band albedos (except for Band 2). Within the more homogenous pixel area, in situ and MODIS albedos were very close (error varied from −4% to +7%) and within the range of ASD standard errors. The semivariogram analysis revealed that the minimum observational footprint needed for a spatially representative sample is 30 m. In contrast, over the more spatially heterogeneous surface pixel, a minimum footprint size was not quantifiable due to spatial autocorrelation, and far exceeds the effective resolution of the MODIS retrievals. Over the high spatial heterogeneity surface pixel, MODIS is lower than ground measurements by 4–7%, partly due to a known in situ undersampling of darker surfaces that often are impassable by foot (e.g., meltwater features and shadowing effects over crevasses). Despite the sampling issue, our analysis errors are very close to the stated general accuracy of the MODIS product of 5%. Thus, our study suggests that the MODIS albedo product performs well in a very heterogeneous, low-albedo, area of the ice sheet ablation zone. Furthermore, we demonstrate that single 'point-to-pixel' methods alone are insufficient in characterizing and validating the variation of surface albedo displayed in the lower ablation area. This is true because the distribution of in situ data deviations from MODIS albedo show a substantial range, with the average values for the 10th and 90th percentiles being −0.30 and 0.43 across all bands. Thus, if only single point is taken for ground validation, and is randomly selected from either distribution tails, the error would appear to be considerable. Given the need for multiple in-situ points, concurrent albedo measurements derived from existing AWSs, (low-flying vehicles (airborne or unmanned) and high-resolution imagery (WV-2)) are needed to resolve high sub-pixel variability in the ablation zone, and thus, further improve our characterization of Greenland's surface albedo.

1. Introduction

The largest body with frozen water in the northern hemisphere, the Greenland Ice Sheet (GrIS), is rapidly losing mass at a rate that has quadrupled between 1992 and 2011 (Shepherd et al., 2012). Increased meltwater production and runoff (e.g., Mernild and Liston, 2012) accounts for half or more of total mass loss (van den Broeke et al., 2009; Enderlin et al., 2014; Khan et al., 2014), which has occurred in concert with increasing near-surface air temperatures (Hall et al., 2013) and

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an observed decline in surface albedo (e.g., Box et al., 2012; Stroeve et al., 2013). Monitoring changes in albedo is crucial given its importance in modulating the surface energy balance, and consequentially, melt and mass balance of the ice sheet.

Surface broadband albedo, hereafter albedo, is defined as the fraction of radiant exitance energy to downwelling solar irradiance integrated across the visible, near-infrared, and shortwave-infrared wavelengths (Schaepman-Strub et al., 2006). Albedo is particularly important for the surface energy balance in ice and snow covered areas of the Arctic, including Greenland (van den Broeke et al., 2011; Vernon et al., 2013). On the GrIS, the high albedo of snow (>0.80) reflects much more solar radiation than darker melting or bare ice surfaces (0.30–0.60; e.g., Moustafa et al., 2015). Over a typical ice sheet melting season, snow melts over vast areas uncovering the ice surface below, effectively reducing albedo. The darker surface leads to increased solar radiation absorption, which further enhances snowmelt. Additionally, ice crystal growth over the melting season reduces albedo. This positive feedback loop is called the ice-albedo feedback and is one of the drivers for the marked GrIS albedo trend for 2000–2011 (-0.056 ± 0.007 June–August; Box et al., 2012).

Greenland albedos have declined the most in the southwestern ice sheet's ablation area (Alexander et al., 2014; Stroeve et al., 2013). This is related to an expansion of bare ice area (Tedesco et al., 2011), high concentration of impurities and melting of outcropped tilted sediment-rich ice layers (Wientjes et al., 2011), and enhanced meltwater production and runoff (Mernild and Liston, 2012). Furthermore, recent studies have identified the considerable influence of seasonal evolution of ice sheet surface types (e.g., snow cover, bare ice, impurity-rich ice) have on the high spatiotemporal variability in ablation area albedos (Alexander et al., 2014; Chandler et al., 2015; Moustafa et al., 2015). As the melt season progresses, the spatial and temporal variability can be very high (Alexander et al., 2014; Moustafa et al., 2015; Tedesco et al. 2016) due to processes discussed below.

GrIS albedo have mainly been characterized with the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High Resolution Radiometer (AVHRR) satellite sensors (e.g., Box et al., 2012; Chandler et al., 2015; Stroeve et al., 2005, 2006, 2013; Wang et al., 2012; Wright et al., 2014). These remotely sensed albedo measurements have been validated with data from up to 17 ground measurements sites (Stroeve et al., 2013) from the dispersed Greenland Climate Network Automatc Weather Stations (GC-Net AWS; Knap and Oerlemans, 1996; Steffen and Box, 2001) using a so-called 'point-to-pixel' method, hereafter, single point-to-pixel method. In this method, the AWS GC-Net time series at individual points are compared to the satellite-derived albedo retrieval from the overlapping pixel. Comparisons reveal that satellite albedo products provide reasonable albedo estimates (Box et al., 2012; Stroeve et al., 2005, 2006, 2013), and compare well with these in situ albedo GC-Net AWS measurements (e.g., root-mean-square-error (RMSE) of 0.067 for the Version 005 MCD43A albedo data product; Stroeve et al., 2013). However, it is recognized that unless the surface is homogeneous or an adequate number of dispersed ground point measurements are collected within a pixel during satellite overpasses, then a 'point-to-pixel' comparison may be insufficient (Liang et al., 2002; Román et al., 2009). These discrepancies are exacerbated by rough surfaces (Lhermitte et al., 2014; Rippin et al., 2015; Ryan et al., 2016), large scan angles (Painter et al., 2009; Campagnolo et al., 2016), and larger (>75°) solar zenith angles (SZAs; Stroeve et al., 2005, 2006; Wang et al., 2012). The ablation area in southwest Greenland is exactly the kind of spatially heterogeneous surface where a sparse network of single point AWS stations may be inadequate for validation of remotely sensed albedo products.

A more suitable validation method for heterogeneous ablation areas could involve data collection at multiple points (hereafter, multiple 'point-to-pixel' method) similar to Wright et al. (2014)'s study where the Version 006 MCD43A albedo data product was re-evaluated against in situ albedo measurements collected at several sites along a transect in the accumulation zone at Summit, Greenland. Whereas Wright et al. (2014) applied their method to a spatially homogenous area, it could easily be adapted for heterogeneous surfaces. Regardless if single or multiple points are used for validation of remotely sensed albedo, these studies point out the fallacy in assuming that point in situ observations are spatially representative of coarser satellite products (i.e., point observations are assumed to be representative at pixel scales; Román et al., 2009), and the need to capture more point observations within a MODIS gridded area (Wright et al., 2014). Therefore, given the varying spatial resolution of in situ and satellite products, scaling errors may occur if albedos differ at different sampling domains, observational locations (Lhermitte et al., 2014), and over rapid changes in surface conditions (e.g., seasonal changes in ablation area ice surface types).

A methodology that quantifies the spatial representativeness of a ground albedometer site for validating the MODIS daily albedo product was developed by Román et al. (2009). In this method, spatial representativeness is referred to as the degree to which in situ albedo measurements are able to resolve the spatial variability of the surrounding ablation area surface extending up to the satellite footprint. This validation technique provides an improved understanding of remotely sensed albedo product uncertainty, and the efficacy of single 'point-to-pixel' comparisons, as well as the satellite and in situ data's capacity to capture spatial and temporal features that characterize the ablation area. Because the in situ retrievals may have shortcomings in representing heterogeneous ground conditions, we argue that it is more appropriate to consider this spatial representative method as a methodology for comparison rather than a validation in its own right. This spatial representative method has been useful for inter-comparisons of surface and satellite albedo in snow-free (e.g., Román et al., 2009, 2010) and seasonally snow-covered tundra (e.g., Wang et al., 2012, 2014) environments, but has not yet been applied to glaciers and ice sheets.

Here we adapt Román et al.'s (2009) and Wang et al.'s (2012, 2014) method to perform a robust spatial inter-comparison of in situ spectral albedo measurements with satellite retrievals of narrow and broad band albedo from the GrIS. In contrast to Román et al. (2009) and Wang et al. (2012, 2014), who used single point in situ observations, our study uses several points along a transect (i.e., a multiple point-to-pixel comparison) similar to Wright et al. (2014). Our transect data was collected with an Analytical Spectral Devices Inc. (ASD) spectroradiometer over southwest Greenland's ablation area, near the town of Kangerlussuaq, during the 2013 melt season, and has undergone a thorough quality assessment (Moustafa et al., 2015) and freely available (Moustafa et al., 2016; https://doi.pangaea.de/10.1594/PANGAEA.867917). The geographical extent of the ground albedo data set allows for careful evaluation of two MODIS pixels, using data from the recently developed MODIS (Version 006) MCD43A daily albedo retrievals. Due to the fixed time period of in situ albedo data collected, temporal variability of albedo is not explicitly assessed in this study. As far as we know, the high density of ground measurements allows for the first-ever spatial characterization of the lower GrIS ablation area's heterogeneous surface as well as an assessment of the utility of each MODIS narrow band. Furthermore, we investigate within-MODIS pixel spatial variability at an intermediate scale between in-situ and MODIS observations by using a high-resolution WorldView-2 (WV-2) image. While MODIS MCD43A albedo is reported at a 500 m gridded resolution, the data product utilizes multiple MODIS surface reflectance values collected at varying view zenith angles. View geometry, variable pixel footprint size, and surface topography have been identified as contributing significant variability to the MODIS snow and albedo data products, but these are not analyzed in this study. Instead, our study only utilizes published MODIS data (assuming fixed pixel sizes at this latitude) that are readily available. A discussion of view zenith angles, adjacency effects, and surface roughness's importance on satellite albedo retrievals is provided in Section 5. Lastly, a comparison between the errors of single and multiple point-to-pixel methods is conducted.