Greenland, Canadian and Icelandic land-ice albedo grids (2000–2016)

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Albedo, Latin for 'whiteness', is a term used to describe the amount of sunlight reflected by the ground. Fresh snow albedo can exceed 85%, making it among the most reflective natural substances. Warm conditions promote snow crystal metamorphosis that, like the presence of liquid water, bring snow albedo down below 65%. With the darkening, caused by the metamorphosis, absorbed solar energy thus increases by roughly a factor of two. Seasonal snow melts over the lower reaches of a glacier leading to the exposure of bare ice with albedo below 55%. Impurities such as dust, black carbon or microbes can bring glacier-ice albedo below 30%, meaning that snow ablation gives way to impurity-rich, bare glacier ice which increases absorbed sunlight by more than a factor of three.

The thickness of the winter snow layer and the intensity of spring melt are important determinants of the annual glacier-ice melt, as the amount of snow cover governs the timing of darker ice exposure; the earlier the exposure, the more ice can melt. Because snow and ice albedo properties make it an amplifier of climate change, surface albedo has been designated as an Essential Climate Variable and a Target Requirement for climate monitoring (WMO 2011).

Polar orbiting satellites facilitate albedo mapping with Arctic coverage multiple times per day in clear-sky conditions. Satellite-based retrievals of surface albedo depend on accurate compensation of the intervening atmosphere. Thus, without ground truth, the satellite retrievals are uncertain. In Greenland, snow and ice albedo is monitored by automatic weather stations (AWSs) from The Greenland Climate Network (GC-Net; Steffen *et al.* 1996) since 1995 and after 2007 from The Programme for Monitoring of the Greenland Ice Sheet (PROMICE; van As *et al.* 2013). Using the GC-Net data, satellite-derived albedo values are compared with ground data (e.g. Stroeve *et al.* 2013).

Here, we present comparisons of daily GC-Net and PROMICE albedo data to satellite-derived albedo from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) MOD10A1 product (Hall *et al.* 1995). MOD10A1 data have been available since May 2000 and are here de-noised, gap-filled and calibrated into a daily 500 × 500 m grid covering Greenland, Iceland and the Canadian Arctic glaciers (Fig. 1).

Daily albedo from MODIS

The MOD10A1 product contains daily snow extent, snow albedo, fractional snow cover and a data quality assessment at 500 × 500 m resolution (Hall *et al.* 1995). Both NASA Terra and Aqua satellites are equipped with MODIS sensors. Here, Terra data are chosen over Aqua data as they

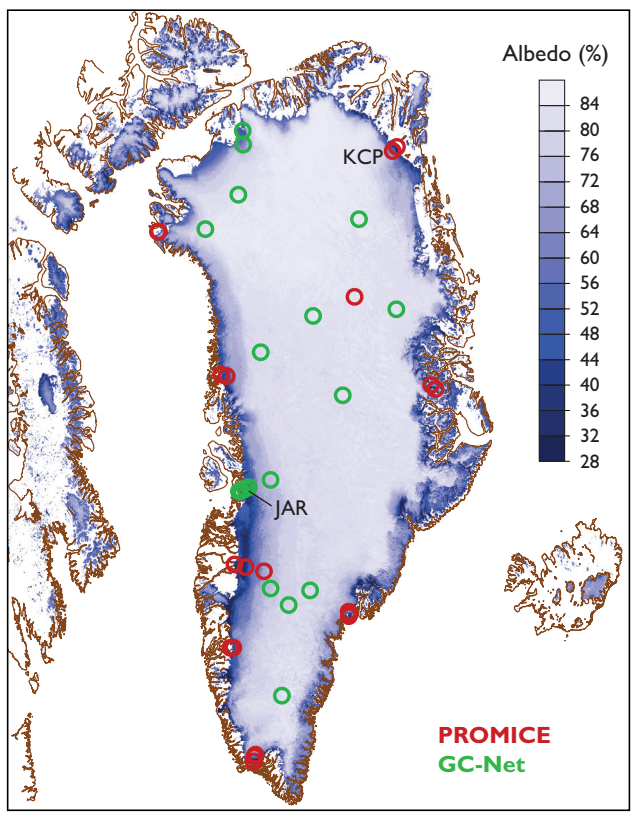

Fig. 1. An example (15 July 2016) of the daily 500 m × 500 m enhanced MOD10A1 Collection 6 albedo product presented here. The circles show positions of ground-truth observations.

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give longer temporal coverage, and Aqua MODIS band 6 detectors (useful in cloud discrimination) have become degraded or non-functional (MODIS Characterization Support Team, NASA, updated February 2017). An alternative MODIS albedo product (MCD43) was not chosen due to its reduced temporal resolution of eight days. The MOD10A1 data used here span the Arctic melt season 15 March (74th day of year) to 26 October (299th day of year) for the 17 year period 2000 to 2016. The two latest MOD10A1 versions are evaluated; Collection 5 (Hall *et al.* 2011) and Collection 6 (Riggs & Hall 2015; Hall & Riggs 2016), hereafter C5 and C6.

MOD10A1 de-noising, smoothing and gap-filling

Inspection of the C5 and C6 albedo imagery reveals that, despite some cases when pixel quality is coded 'best' or 'good', cloud artifacts resembling shadows, aircraft condensation trails, thin clouds, and cloud edges can persist, often over the brightest areas presumably where there is less distinction between clouds and clean snow.

Fortunately, because the artifacts introduce abrupt temporal departures in the albedo (α) time series, it is possible to reject them on a pixel by pixel basis using temporal statistics from multi-day albedo ($\alpha_{N\text{-}days}$) samples. Here, an 11 day $\alpha_{N\text{-}days}$ sample size is selected; five days before and after each day *i*. On a pixel-by-pixel basis, statistics are computed from $\alpha_{N\text{-}days}$. The number of days *N* does not always represent 11 albedo values because some days a pixel may already be dismissed as cloudy, missing or of inadequate quality. Only cases with at least four samples per 11-day window are considered sufficient for an albedo estimate for that day and pixel. The final pixel by pixel daily albedo values are taken as the 11-day average of available values below a fractional noise threshold *(D)* value of 0.4, with *D* computed as:

$$D_i = \left| (\alpha_{N\text{-}days} - median(\alpha_{N\text{-}days})) / median(\alpha_{N\text{-}days}) \right|$$

For low albedo variability areas, for example the dry snow area, when the standard deviation $\alpha_{N\text{-}days}$ is under 0.03, then a more strict *D* threshold of 0.1 is used. The procedure has both a smoothing and a gap filling effect on the albedo time series. The resulting data product can be viewed at *https://tinyurl.com/PROMICE-albedo-Greenland.*

MODIS validation using ground-truth albedo

Daily PROMICE and GC-Net AWS albedo values are compared with the nearest 500 × 500 m resolution MOD10A1 C5 and C6 values for all stations in each of 9 or 16 years that span 2007 to 2016 or 2000 to 2015, respectively. Figure 2 provides an example for C6 data illustrating a typical result of the de-noising procedure, yielding an increased number of MODIS values, increased correlation, reduced root mean squared difference (RMSD) shifting regression slope closer to unity and no real change in bias.

Table 1 lists summary statistics for the multi-year, multi-station comparison with MOD10A1 C5 and C6. The MOD10A1 skill either improves or is stable in the C5 to C6 update. The average bias and root mean squared difference decrease and the correlation and average count of days increase. The number of compared station-years increases. From raw to de-noised, there is also a consistent improvement in agreement between the satellite and ground data (Table 2). In the de-noised product, the RMSDs are 0.08 for PROMICE stations that are concentrated in the ablation

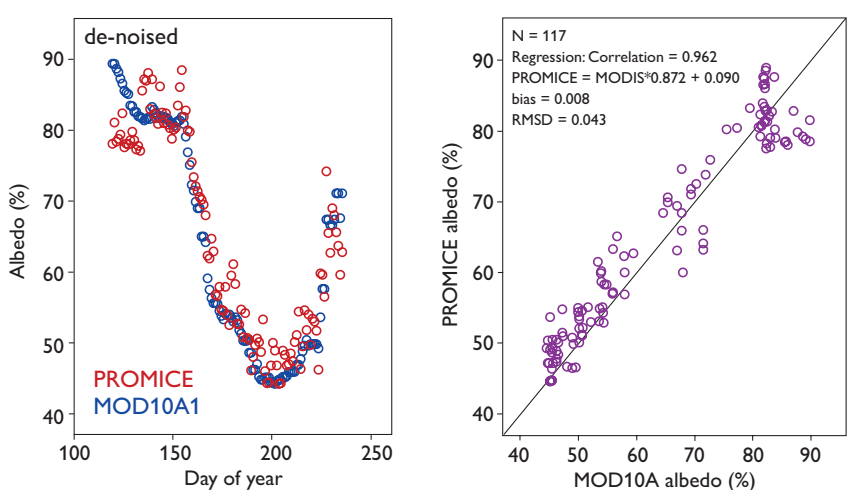

Fig. 2. Year 2013 example comparison of daily de-noised albedo from satellite (NASA MODIS MOD10A1 Collection 6 data) and the ground (PROMICE) for the KPC_L (Fig. 1) station on the north-eastern Greenland ice sheet.

Table 1. Summary statistics for comparison of $\alpha_{MOD10A1}$ Collection 5 and 6 with available $\alpha_{PROMICE}$ and $\alpha_{GC\text{-}Net}$ in the 2000–2016 period (de-noised).

$\alpha_{MOD10A1}$ versus $\alpha_{PROMICE}$	144 station years	Average	St. dev.
Collection 5	Correlation	0.838	0.182
	Bias	–0.024	0.035
	RMSD *	0.086	0.042
	Average count of days	117	37
Collection 6	Correlation	0.832	0.183
	Bias	–0.002	0.034
	RMSD	0.084	0.044
	Average count of days	124	39
$\alpha_{MOD10A1}$ versus $\alpha_{GC\text{-}Net}$	183 station-years	Average	St. dev.
Collection 5	Correlation	0.490	0.225
	Bias	-0.006	0.099
	RMSD	0.104	0.090
	Average count of days	114	33
Collection 6	Correlation	0.581	0.259
	Bias	0.006	0.038
	RMSD	0.050	0.033
	Average count of days	110	32

* Root mean squared difference.

Table 2. Summary statistics for comparison of $\alpha_{MOD10A1}$ Collection 5 and 6 with available $\alpha_{PROMICE}$ and $\alpha_{GC\text{-}Net}$ in the 2000–2016 period (de-noised minus raw).

$\alpha_{MOD10A1}$ versus $\alpha_{PROMICE}$	4 station years	Average	St. dev.
Collection 5	Correlation	0.067	0.003
	Bias	–0.001	0.001
	RMSD *	–0.022	0.003
	Count of days per year	28	13
Collection 6	Correlation	0.070	0.032
	Bias	–0.002	0.001
	RMSD	–0.029	0.003
	Count of days per year	28	13
$\alpha_{MOD10A1}$ versus $\alpha_{GC\text{-}Net}$	19 station-years	Average	St. dev.
Collection 5	Correlation	0.111	–0.048
	Bias	0.002	0.026
	RMSD	0.016	0.031
	Count of days per year	32.000	11.000
Collection 6	correlation	0.170	–0.005
	bias	–0.005	–0.042
	RMSD	–0.030	–0.037
	Count of days per year	29	12

* Root mean squared difference.

area or 0.05 for GC-Net stations that are concentrated in the accumulation area. The lower GC-Net correlation and RMSD values result from the mostly dry snow areas where albedo variability is small. For PROMICE stations which are concentrated in the ablation area (and for the GC-Net Jakobshavn Ablation Region (JAR) stations), the larger MOD10A1 pixel footprint includes a complex contribution from some combination of e.g., crevasses, snow patches and concentrated or distributed snow and ice impurities such as cryoconite. The root mean squared difference is probably more attributable to the ground data because they have a *c.* 5–10 m^2 footprint, four orders of magnitude smaller than the MOD10A1 500 m × 500 m footprint.

MODIS validation using GC-Net albedo

GC-Net albedo data, having a time coverage longer than 10 years, are compared with C5 and C6 to evaluate accuracy in year-to-year albedo changes. MOD10A1 Collection 6 (Hall & Riggs 2016) compensates MODIS sensor degradation found in Collection 5 (Lyapustin *et al.* 2014). C6 is found to compensate the temporal trend bias in dry snow areas (Fig. 3A). The trend bias is usually smaller or non-existent for darker targets such as the ablation area (Fig. 3B). The 0.02 albedo offset at the Summit site is partly attributable to the bias described in the following.

MOD10A1 sun angle bias

Whereas the adjustments to Collection 6 eliminate a spurious darkening trend concentrated over snow and in the northern part of Greenland (Polashenski *et al.* 2015), both Collections 5 and 6 MOD10A1 albedo products have a residual bias based on the angle of the sun above the horizon. The bias is evident over nearly 20° of latitude range of the PROMICE and GC-Net data. In April (days 91–120), there is no bias in southern Greenland but a *c.* 4% bright bias in the northern 2/3 of Greenland (Fig. 4A). By June (days 152–181), the pattern of the bias has shifted to a more uniform dark bias strongest in the south (Fig. 4B). The bias varies over time and latitude (see the animation: *https://tinyurl.com/bias-vs-lat*). We correct the Collection 6 bias according to the daily variation in the regression line (blue dashed line in Fig. 4A, trends in Fig. 4B). The calibration

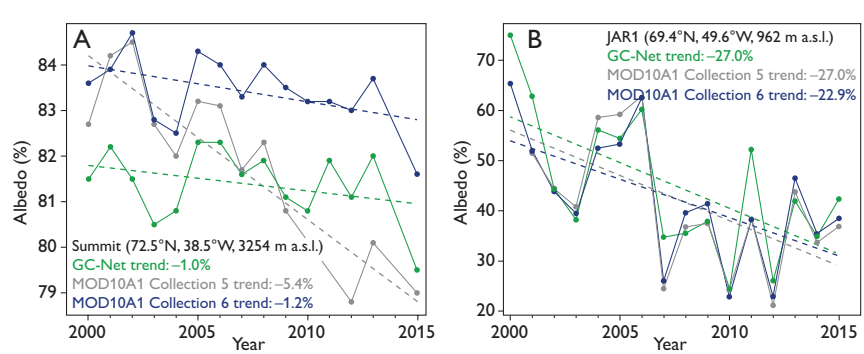

Fig. 3. Examples of July monthly average dry snow area (**A**) and ablation area (**B**) MODIS collection 5 and 6 compared with GC-Net albedo trends spanning 16 summers. **JAR**: Jakobshavn Ablation Region.

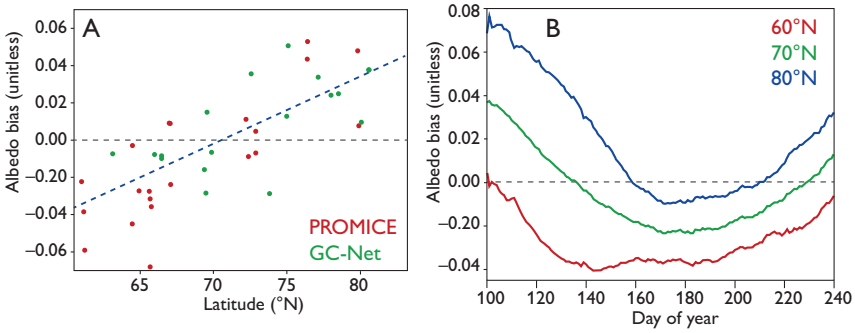

Fig. 4. **A**: Example of NASA MODIS MOD10A1 Collection 6 difference with ground data from automatic weather stations versus latitude, indicating a sun-angle-dependent bias. **B**: Bias for three latitude bands. The station names are abbreviated.

assumes there is no sun-angle-dependent bias in the PROMICE and GC-Net data.

MODIS albedo for Iceland and the Canadian Arctic

The regional product also includes albedo for glaciated areas in Iceland, Jan Mayen and the Canadian Arctic. The occurrence of clouds reduces the coverage of the product, in the case of land ice, especially at the lowest elevations often near oceans. Iceland has data coverage less than half of that of most areas of Greenland. Areas of the Canadian Arctic such as the Devon Ice Cap also have reduced time coverage compared to Greenland, which has a stronger cloud clearing effect from its high pressure areas often centered over the ice sheet.

A new PROMICE data product

The methodology developed here for de-noising, gap filling, and bias correction for the MOD10A1 albedo product yields an enhanced MODIS MOD10A1 Climate Data Record available for download through the PROMICE database via the webpage www.promice.dk

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