

The Greenland ice sheet – snowline elevations at the end of the melt seasons from 2000 to 2017

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The Arctic region is warming more rapidly than the global average (AMAP 2017) and it is well established that this warming is at least partially responsible for the Greenland ice sheet losing mass at an accelerating rate, raising concern worldwide (e.g. Kahn *et al.* 2015; Rahmstorf *et al.* 2015). It is essential to monitor the changes of the Greenland ice sheet to be able to assess the potential environmental, social and economic implications around the globe, and to provide decision-makers with reliable data. The annual mass-budget deficit of the Greenland ice sheet has grown over the past two decades due to increases in surface melting (Van den Broeke *et al.* 2017) and ice-flow acceleration (Kahn *et al.* 2015). Currently, and for the last two decades, the Greenland ice sheet is the single largest Arctic cryospheric contributor to global sea-level rise and the Greenland ice-surface melt rates are projected to increase as the Arctic continues to warm (AMAP 2017).

The snowline is here defined as the maximum elevation during the melt season at which snow remains from the previous accumulation season (Cogley *et al.* 2011). The snowline is a valuable climate indicator as its position integrates the competing effects of melt (increasing snowline elevation) and snow accumulation (decreasing snowline elevation). Thus the snowline provides a key holistic variable indicating climate change.

We have developed a methodology that determines snowline elevation utilising the moderate resolution imaging spectroradiometer (MODIS) sensor on the Terra satellite. The MODIS sensor produces a global dataset on a daily basis, with a resolution varying between 250 m and 1 km, in 36 bands covering the visible to thermal wavelengths. Using MODIS, we derived the maximum snowline altitude for the Greenland ice sheet for the years 2000–2017. We are producing a freely available, consistent dataset that provides an important tool for the monitoring of the long-term impact of climate change on the Greenland ice sheet. Direct comparison with field observations from automatic weather stations (AWSs) from the Programme for Monitoring of the Green-

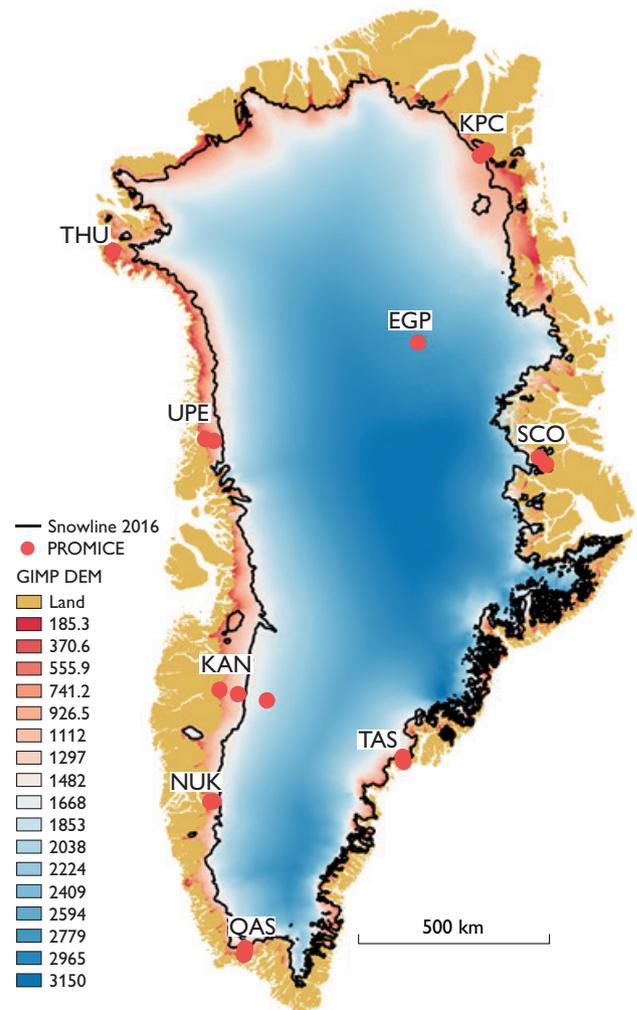


Fig. 1. Greenland map showing the location of PROMICE automatic weather stations and the 2016 snowline as derived from Terra satellite data using the moderate resolution imaging spectro-radiometer (MODIS) sensor. The locations of the ground-control automatic weather stations (PROMICE) are indicated. EGP: East GRIP. KAN: Kangerlussuaq. KPC: Kronprins Christian Land. NUK: Nuuk. QAS: Qassimiut. SCO: Scoresby Sund. TAS: Tasiilaq. THU: Thule. UPE: Upernavik. DEM: Digital elevation model. GIMP: Greenland ice mapping project.

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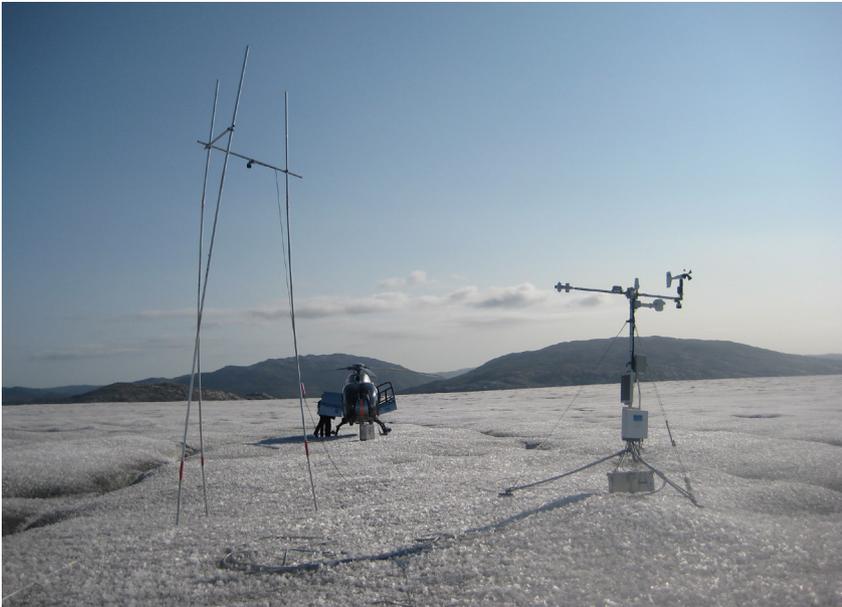


Fig. 2. South Greenland PROMICE automatic weather station at the end of the 2013 melt season. From the stakes to the left of the weather station, the amount of melt (*c.* 4 m) is directly visible. The melt is also measured with a pressure transducer system drilled into the ice.

land Ice Sheet (PROMICE) network validates the snowline dataset derived from MODIS. We use the services of the CryoClim internet portal, providing an operational and permanent service for long-term systematic climate monitoring of the cryosphere, to distribute our snowline product. More specifically, end-of-melt season, 1 km² resolution raster grids illustrating snow and bare-ice surfaces, and snowline shape files can be downloaded via CryoClim. Here, we describe the snowline classification algorithm, its validation and its inter-annual variations for 18 years spanning 2000–2017.

Snowline classification algorithm

We processed all MODIS MOD12KM and MOD03 scenes covering Greenland from late July to the beginning of September 2000–2017. We used the surface-type detection algorithm of Fausto *et al.* (2015) that distinguishes between bare-ice and snow surfaces. Fausto *et al.* (2015) uses normalized thresholds (Th) from calibrated radiances (MOD021KM) between the near-infrared band 5 (1230–1250 nm) and the visible band 10 (483–493 nm) with surface-type thresholds $Th_{dry\ snow} \leq 0.86$, $0.86 < Th_{melting\ snow} < 0.94$ and $Th_{glacier\ ice} \geq 0.94$. The classification algorithm is updated by implementing a new surface-type threshold to address a ‘noisy’ snow classification over the northern part of the ice sheet identified by Fausto *et al.* (2015). The algorithm is thus supplemented by $Th_{bare\ ice} > 265 - 2.1 \times LAT$, where LAT is latitude. $Th_{bare\ ice}$ is defined as:

$Th_{bare\ ice} = c_0 + c_1 \times b_1 + c_2 \times b_2 + c_3 \times b_3 + c_5 \times b_5 + c_7 \times b_7$ where $c_0 = -0.0015$, $c_1 = 0.160$, $c_2 = 0.291$, $c_3 = 0.243$, $c_5 = 0.112$, $c_7 = 0.081$ and b_1 to b_7 designate band 1 to band 7.

Cloud-covered regions are removed using the MOD35_L2 dataset. Subsequently pixels are classified for every MODIS scene as either snow or bare ice for the whole Greenland ice sheet.

Daily classification scenes are aggregated to yield a maximum extent of bare ice to define an end-of-melt-season snowline. Snowlines from peripheral glaciers are generally excluded, and the snowline products are based on an algorithm success rate of over 95% classified pixels.

Validation

To help validate the MODIS data we make use of the PROMICE automatic weather station network that currently consists of two or three stations primarily in the ablation area in eight ice sheet regions. Each automatic weather station records a suite of meteorological and glaciological measurements, supplemented by e.g. surface-height changes due to accumulation or ablation (Fig. 1; Van As *et al.* 2016).

To validate the classified snowline elevation at the end of the melt season, we use the mass-budget values from the PROMICE weather stations (Fig. 2; e.g. Fausto *et al.* 2012) at different elevations to calculate the vertical surface mass-balance gradient for all eight PROMICE transects to determine the equilibrium line altitude (ELA, zero mass budget), for direct comparison with MODIS estimated snowline elevation (Fig. 1). AWS balance profiles from the Upernavik region, and those indicating an ELA above 2000 m are excluded as we find them unrealistic. The location of the upper AWS should be close to the actual ELA to get the best balance profiles. In total, we exclude 25% or 17 out of 67 balance profiles.

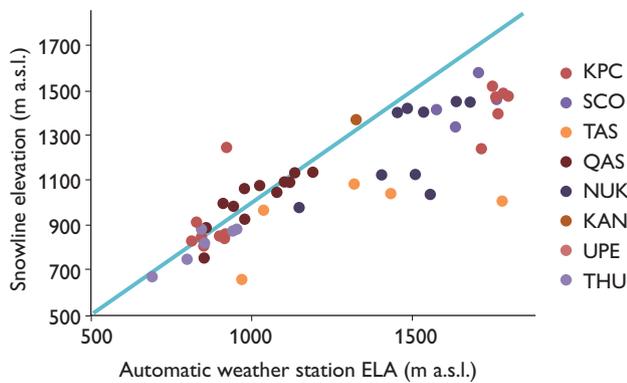


Fig. 3. The end-of-melt-season snowline elevation for 2000 to 2017 from MODIS vs. the PROMICE AWS-derived equilibrium line altitude (ELA). The blue line gives the 1:1 relation. The locations of the PROMICE automatic weather stations are shown in Fig. 1.

Figure 3 illustrates the performance of the MODIS end-of-melt-season snowline algorithm for all PROMICE regions in Greenland. The correlation ($r=90\%$, $p=0.0001$, $n=50$) and the root-mean-square error ($RMSE=200$ m) are reasonable as the ELA and snowline elevation can be different due to superimposed ice formation (Cogley 2011). The mean difference between snowline altitude and ELA is -104 m.

Results and discussion

Figure 1 illustrates the location of remotely sensed snowline plotted on top of the digital elevation model (DEM) from the Greenland Ice Mapping Project (GIMP, Howat *et al.* 2014). The snowline is easily visible in the southern, western, and northern parts of Greenland due to the relatively even terrain, while the snowline shows a more complicated pattern in the mountainous terrain in East Greenland (Fig. 1).

The snowline separates bare ice from snow areas and can therefore be used to document the change in bare-ice areas. We find the extent of bare-ice exposure to be increasing in the period 2000–2017 at an average rate of *c.* 500 km² per year (Fig. 4), which roughly corresponds to the size of the Danish island of Bornholm. This increase in the bare-ice area is insignificant, but it demonstrates a small average gain of melt over accumulation since 2000. The increasing trend in the bare-ice area is consistent with increasing Greenland mass loss due to surface processes (Van den Broeke *et al.* 2017). Both independent, *in situ* observations (Machguth *et al.* 2016) and remotely sensed observations (Hall *et al.* 2012; Tedesco *et al.* 2017) show that the Greenland melt area is expanding to higher elevations. Further, the increase in bare ice enhances the positive feedback mechanism of a darkening ice

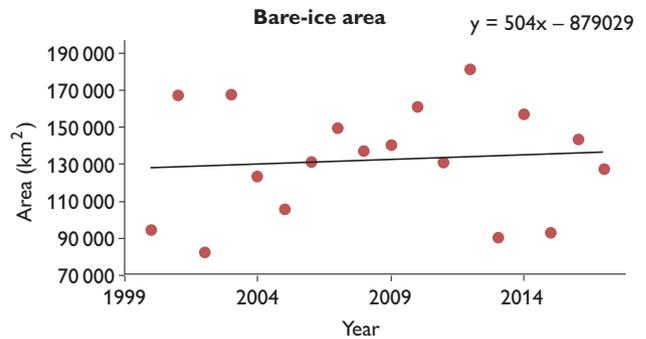


Fig. 4. End-of-melt-season bare-ice area for the Greenland ice sheet for the years 2000–2017.

sheet surface (ice is darker than snow), which affects the surface mass and energy balance of the Greenland ice sheet (Box *et al.* 2012). Figure 4 also illustrates the inter-annual variability of the 2000–2017 snowlines, which is highly dependent on the complicated seasonal weather systems around Greenland. For instance, the below average snowline of the snowy year of 2016/2017 is consistent with positive albedo anomalies that reduced melting in 2017 (Tedesco *et al.* 2017).

Uncertainties associated with the different surface-type detection are assessed with the ELAs derived from the AWS surface mass-budget observations. Figure 3 shows a significant correlation between the MODIS snowline and ELAs derived independently from PROMICE AWSs. A reason for the difference between the two can be that the MODIS data have a spatial resolution of 1 km², pan-ice sheet coverage and quasi-daily temporal coverage, while the footprints of the *in situ* measurements are small (5 – 50 m²), and surface patchiness is clear in aerial photography (Stroeve *et al.* 2006).

Fausto *et al.* (2015) discuss an August anomaly in their monthly surface-type data set during the 2010–2014 period, illustrated by a noisy melting-snow classification in the northern ice sheet, which was most likely due to false classification. However, with the updated bare-ice threshold, we improve the detection of snow and ice surfaces (Fig. 1), visualised by a less noisy snow classification of snow in the northern part of the ice sheet, resulting in a more reliable climate indicator for Greenland.

Conclusions

Remotely sensed MODIS data can yield daily, automated classification of the Greenland ice sheet surface type (snow and ice). Validation indicates a high correlation (0.9) between MODIS-derived snowline altitudes and ELAs estimated from *in situ* measurements. The end-of-melt-season

snowline is useful as an ice-sheet climate indicator for the competing processes of surface accumulation and ablation, quantified by an average annual increase of *c.* 500 km² of the bare-ice area for the 2000–2017 period.

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