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Darkening of the Greenland ice sheet due to the melt-albedo feedback observed at PROMICE weather stations

Dirk van As, Robert S. Fausto, William T. Colgan, Jason E. Box and the PROMICE project team*

The Greenland ice sheet is losing mass (Barletta *et al.* 2012) and at least half of this loss is caused by an increase in surface melt (e.g. Tedesco *et al.* 2013). The other part is caused by increased dynamic mass loss, as marine-terminating glaciers lose resistive stresses (Nick *et al.* 2009) due to both retreat and meltwater lubrication at the bed (Sasgen *et al.* 2012).

In 2007, the Programme for Monitoring of the Greenland Ice Sheet (PROMICE) was initiated with the aim of gaining an insight into the causes of the ice-mass budget changes based on quantitative observations. This is primarily done by assessing how much mass is gained as snow accumulation on the surface versus how much is lost by calving and surface ablation (Ahlstrøm *et al.* 2008). PROMICE monitors the surface mass balance by means of automatic weather stations (AWSs) designed to quantify accumulation and ablation, as well as the specific energy sources contributing to ablation. These observations are vital to interpreting the physical mechanisms for ice-sheet response to climate change and for the calibration and validation of both satellite observations and climate models.

In the wake of several record-breaking warm summers – increasing surface melt rate and extent (Nghiem *et al.* 2012) – interest in Greenland’s surface mass balance has increased (Tedesco *et al.* 2013). Observations of net ablation at PROMICE stations provided *in situ* confirmation of extreme mass-loss events in 2010 (Fausto *et al.* 2012) and 2012, primarily documented by other workers through satellite data. In this paper, we present atmospheric temperatures and surface solar reflectivity (known as albedo) of the Greenland ice sheet in the PROMICE period. Albedo modulates the absorption of solar radiation, which is the primary source of melt energy. It is reported to be decreasing in Greenland in recent years (Box *et al.* 2012), causing the monitoring of albedo variability to be increasingly important. Air temperatures, besides being strongly correlated to surface melt rates, affect surface albedo by controlling the rate of snow-grain metamorphism and the fraction of summer precipitation falling as rain versus snow. To elucidate the so-called melt-albedo feedback, whereby increased melt darkens the ice sheet and further enhances

melt, the relationship between albedo and air temperature, observed at PROMICE stations, is examined in this study.

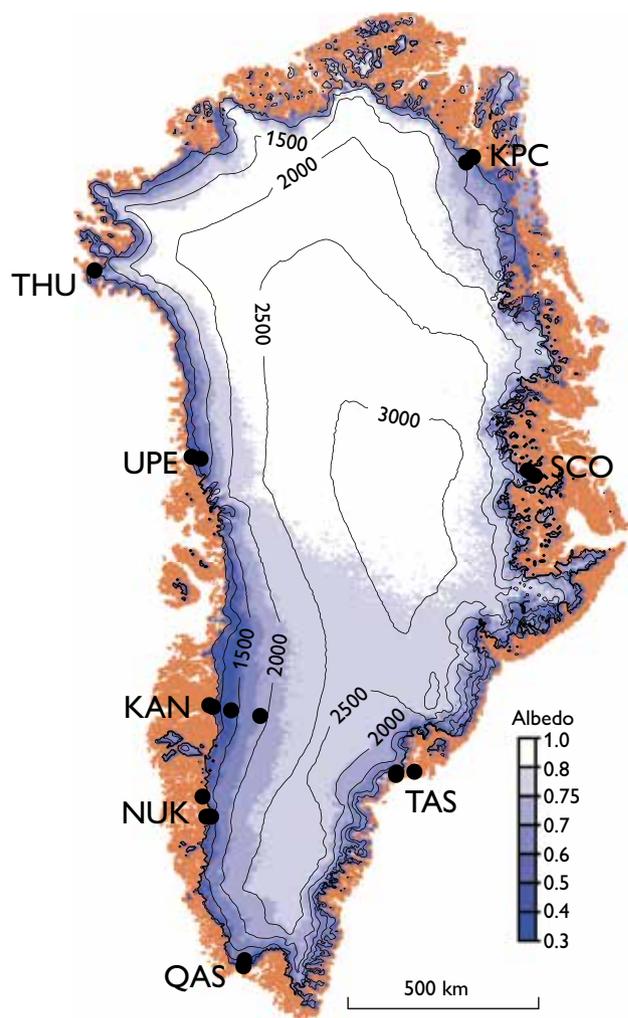


Fig. 1. Map of Greenland showing the locations of the 21 PROMICE weather stations in eight regions. The blue colours show mean satellite (MODIS) derived albedo for the months of June, July and August for 2008–2012. The contour lines show elevations (m) of the ice-sheet surface.

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PROMICE measurements

The original PROMICE network consisted of 14 AWSs in the regions Kronprins Christian Land (KPC), Scoresbysund (SCO), Tasiilaq (TAS), Qassimiut (QAS), Nuuk (NUK), Upernavik (UPE) and Thule (THU), each region monitored with a lower (L) and an upper (U) station in the ablation area (Fig. 1). PROMICE has both contributed to and received contributions from other projects in the Kangerlussuaq, Nuuk and Tasiilaq regions, leading to the installation of seven additional stations. The PROMICE study regions were selected to best complement the spatial distribution of existing ice-sheet weather stations, such as in the Greenland Climate Network (Steffen *et al.* 1996), by providing data from the under-represented ablation area (Ahlström *et al.* 2008).

The PROMICE AWSs measure meteorological variables including air temperature (at *c.* 2.7 m above the surface), pressure and humidity, wind speed, downward and upward solar (shortwave) and terrestrial (longwave) radiation. The AWSs also record temperature profiles in the upper 10 m of the ice, GPS-derived location and diagnostic parameters such as station tilt angles. A pressure transducer and two sonic rangers measure snow and surface-height change associated with ablation and accumulation (Fausto *et al.* 2012). Most variables are measured every ten minutes, with the data stored locally awaiting collection during maintenance visits. Hourly averages of the most transient variables are transmitted via satellite between days 100 and 300 of each year, while the remaining variables are transmitted at six-hour intervals. Transmissions have a daily frequency in the remaining (winter) period. All data and metadata including sensor specifications are archived in the PROMICE database and made freely available for display and download at www.promice.dk.

In this study, we present monthly mean measurements of air temperature and surface albedo. To obtain the temperature averages, we first calculate daily mean air temperatures for all days in which data coverage of hourly mean values exceeds 80%. Subsequently, we calculate monthly mean air temperature for all months in which data coverage of daily mean values exceeds 24 days. To calculate surface albedo, we divide instantaneous values of upward shortwave radiation by the downward component before averaging. However, instrument tilt induces significant errors in the measurement of shortwave radiation (van den Broeke *et al.* 2004), which is a common problem in the ice-sheet ablation area due to irregular melting of the ice surface on which the AWS stands. Therefore we employ the tilt correction method as described by van As (2011) that uses the measured AWS tilt to correct downward shortwave radiation. In contrast to the temperature averaging, a minimum of one successful hourly mean albedo is sufficient to produce a daily mean, provided that the direct solar radiation (which oc-

curs when skies are not overcast) hits the upper dome of the radiometer at angles exceeding 30°, where measurements are more precise. The low sun angle in winter prevents calculation of albedo values.

Atmospheric temperature

All PROMICE sites record a distinct annual cycle in air temperature (Fig. 2A). As is common for Arctic climates, temporal variability is largest in winter due to a more vigorous atmospheric circulation. The amplitude in the annual air temperature cycle is largest for stations at high latitudes or high elevations since above-freezing temperatures and thus a melting ice surface capable of local thermo-regulation, are least common at these stations. The more northerly stations also show a larger annual temperature cycle due to the increasing contrast in the lengths of polar day and night with increas-

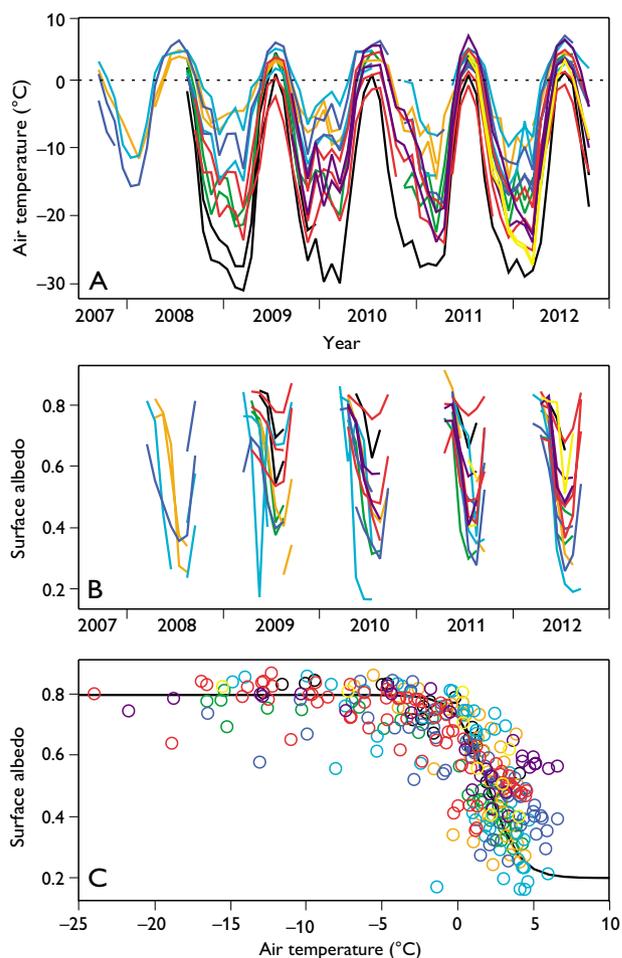


Fig. 2. **A:** Monthly mean air temperatures at the 18 PROMICE sites installed on the ice sheet and before 2012. **B:** Same but for albedo. **C:** Albedo versus temperature. Black lines: KPC stations, green: SCO, orange: TAS, light blue: QAS, dark blue: NUK, red: KAN, purple: UPE, yellow: THU.

ing latitude. The smallest amplitude in the annual temperature cycle is seen at QAS_L, the most southerly PROMICE site. Here, free-atmospheric temperatures can exceed 20°C, leading to strong melt. In 2010, the large heat content of the atmosphere, low summer albedo and anomalously low winter accumulation combined to yield a long net-ablation season and the largest ever recorded ablation in Greenland in a single melt season (9 m of ice; Fausto *et al.* 2012).

As the greater part of mass loss by melt takes place during the summer, we calculated the four- or five-year trends in combined mean air temperature for the months of June, July and August, for eight stations with a sufficiently long coverage. Given the relatively short PROMICE record length, these trends are not free from the influence of inter-annual, natural climatic variability and thus not climatological trends. The data show that at all except two sites the summers have become warmer over the PROMICE period. Most noteworthy is that the warming is most pronounced (*c.* 0.6°C/year) at the high latitude/elevation sites, where the influence of a melting ice surface is spatially and temporally limited. At the sites that experience the highest temperatures and strongest melt, inter-annual variability of free-atmospheric temperatures has had limited effect on air temperatures over the nearly permanently melting ice-sheet surface in summer.

The inter-annual temperature variability is shown in an anomaly plot (Fig. 3A). It is seen that 2010 was a warm year, especially in West Greenland, and mostly early and late in the year, with anomalies exceeding 5°C. The widespread and large melt in 2012 (Nghiem *et al.* 2012) was the result of high temperatures in July, as seen from positive air temperature anomalies at all PROMICE sites.

The record-warm years/summers of 2010 and 2012 (e.g. Tedesco *et al.* 2013), following the warmest decade in Greenland's instrumental temperature record, are consistent with persistent warming observed globally, but are suggested to be a consequence of North Atlantic Oscillation variability affecting atmospheric heat transport (Fettweis *et al.* 2013). Atmospheric warming has been reported to be highest in South and West Greenland. This is confirmed by the PROMICE observations in West Greenland, but observations at KPC_U in north-eastern Greenland show a similar rate of short-term warming. These observations provide *in situ* indications that the atmospheric warming may be spatially pervasive.

Darkening ice-sheet surface

The surface albedo is generally high in the cold, snow-covered interior of the ice sheet (>0.75), and lower along the ice-sheet margin where melting occurs in summer (Fig. 1). In winter, the ice sheet is fully snow covered except where wind erosion

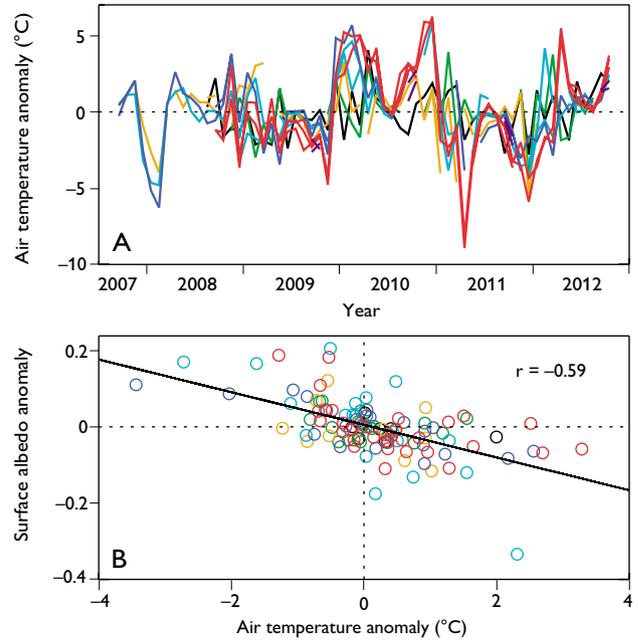


Fig. 3. A: Monthly mean air temperature anomalies, i.e. after subtracting the mean annual cycle for stations with data series spanning a minimum of three years. B: Albedo versus temperature anomalies plotted for months with mean temperatures exceeding -2°C in order to extract melt-season values only.

dominates. Depending on the location of each AWS in the ablation area, snow melt starts in April or May as seen from air temperatures and decreasing albedo (Fig. 2B). Thereafter, albedo drops throughout the melt season until snowfall occurs in autumn, yielding a distinct annual cycle which is largest at the high-melt sites. Surface melt causes this annual darkening of the ice-sheet surface as snow undergoes heat-driven metamorphosis, or completely melts to expose darker bare ice. The ice-sheet surface may also darken as impurities collect on the ice surface or supraglacial meltwater-filled features become more abundant. We find that on average surface albedo drops below fresh snow values as monthly mean temperatures exceed *c.* -2°C (Fig. 2C). The hyperbolic shape of the scatter plot is primarily a consequence of the annual cycle in albedo (α) and can be approximated by

$$\alpha = \frac{\alpha_{max} + \alpha_{min}}{2} - \frac{\alpha_{max} - \alpha_{min}}{2} \left(\frac{1 - e^{-\frac{T - T_0}{C}}}{1 + e^{-\frac{T - T_0}{C}}} \right)$$

where T is near-surface air temperature and maximum (α_{max}) and minimum albedo (α_{min}) are prescribed as 0.8 and 0.2, respectively. T_0 and C , taken as 2 and 1°C respectively, are empirical constants characterising a melting point offset and the exponential scaling length of $\alpha(T)$.

Though there are exceptions, taken as a whole the PROMICE data indicate that albedo has decreased over the past five years while temperature has increased. This is most notable at the higher-elevation sites; the lower sites are completely snow-free in every summer and thus exhibit little change. By calculating the temporal correlations between temperature and albedo for all individual stations for the months of June, July and August separately (minimum four-year time series), we isolate the inter-annual variability by eliminating the annual cycle. We observe 36 out of 39 correlation coefficients to be negative, implying a widespread association of temperature-induced melt with surface albedo on the ice sheet. Mean correlation is strongest in June (-0.76 ± 0.28), followed by August (-0.54 ± 0.39) and July (-0.43 ± 0.45).

The surface albedo at most AWSs was relatively low in 2010 and 2012, coincident with the warm summers of the past years. In order to assess the impact of atmospheric warming on ice-sheet darkening at any given site on the Greenland ice sheet, we plot the albedo anomalies versus the temperature anomalies in Fig. 3B for monthly temperatures exceeding -2°C , hereby isolating the melt season. The correlation of -0.59 between the plotted variables is statistically significant. A linear fit yields that one degree of warming in the near-surface air temperature will lead to an average albedo reduction of 0.043. This value is sensitive to the temperature cut-off value (here taken at -2°C) and will become more accurate with longer AWS time series. Since the PROMICE stations measure close to the ice surface where temperature variability is dampened over a melting surface, a stronger correlation could be expected between albedo and local free-atmospheric temperatures, although the regions with low temperature variability are also associated with low albedo variability (Fig. 3B).

As mentioned, this darkening is likely due to an increase in surface melt, which cannot be linked to changes in solar radiation in recent years and thus may very well be directly and indirectly caused by changes in air temperature. Although absorbed solar radiation is the primary source of melt energy, the melt-albedo feedback is initiated by the energy fluxes that respond to changes in temperature, such as downward longwave radiation and the turbulent heat fluxes. Since both atmospheric warming and ice-sheet darkening increase surface melt intensity and melt area, the anticipated future warming will result in a self-reinforcing ice sheet mass-loss contribution from the melt-albedo feedback. While increased surface melt is a primary mechanism for ice loss in Greenland, an increase in meltwater may also enhance mass

loss due to ice dynamics, through processes such as basal lubrication and warming of the ice matrix.

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