Correspondence

Daily temperature variability predetermined by thermal conditions over ice-sheet surfaces

Evolution of continental-scale ice sheets is affected by long-term changes in atmospheric conditions, through shifts of the balance between surface accumulation and melt. Although surface melt primarily follows the annual temperature cycle, it is also significantly affected by occasional excursions of near-surface air temperature above the freezing point caused by daily weather variability (Arnold and MacKay, 1964).

In multimillennial numerical simulations of ice-sheet growth and decay, surface melt is commonly assumed proportional to the number of positive degree-days (PDD; Hock, 2003). Daily variability is then typically included in the models under an assumption of a normal temperature distribution, using a standard deviation parameter, σ, in the PDD computation (Braithwaite, 1984; Reeh, 1991; Calov and Greve, 2005):

$$\mathrm{PDD} = \frac{1}{\sigma\sqrt{2\pi}} \int_{t_1}^{t_2} \mathrm{d}t \int_0^{\infty} \mathrm{d}T\, T \exp\left[-\frac{(T - T_{\mathrm{ac}})^2}{2\sigma^2}\right] \tag{1}$$

$$= \int_{t_1}^{t_2} \mathrm{d}t \left[\frac{\sigma}{\sqrt{2\pi}} \exp\left(-\frac{T_{\mathrm{ac}}^2}{2\sigma^2}\right) + \frac{T_{\mathrm{ac}}}{2} \operatorname{erfc}\left(-\frac{T_{\mathrm{ac}}}{\sqrt{2}\sigma}\right)\right] \tag{2}$$

where t is the time, T is the near-surface daily mean air temperature (°C) and σ is the standard deviation of T (K) from the annual temperature cycle, T_{ac} (°C). According to atmospheric temperature reanalyses, σ is subject to important variations over the globe, which has a significant influence on the response of surface mass balances (Seguinot, 2013).

Over the Greenland ice sheet, an analysis of in situ temperature measurements indicates that the present-day distribution of σ is subject to an annual variability, with lowest values occurring in the melting period and at the ice-sheet margins, and can be linearly related to ice surface elevation (Fausto and others, 2009, 2011). Including seasonally and spatially varied σ in Greenland ice-sheet modelling is crucial to obtaining better agreement with observations of the present-day ice surface response (Rogozhina and Rau, 2014). However, the importance of a PDD approach is its applicability to palaeoglaciological studies, requiring realistic σ values under climate conditions different from today. Here we present evidence from an atmospheric reanalysis, that the σ distribution over the Greenland ice sheet is largely related to variations in near-surface air temperature, which provides the basis for a parameterization of daily variability over ice-sheet surfaces.

Using the 2 m air temperature field from the European Centre for Medium-Range Weather Forecasts' ERA-40 re-analysis (Uppala and others, 2005) over a 44 year period, 1958–2001, we compute the spatial distribution of long-term monthly mean temperature, T_{m}, and long-term monthly standard deviation of daily mean temperature, σ. The daily mean temperature, T, is computed as an average of the four daily analysis time-steps (00:00, 06:00, 12:00, 18:00). In order to remove variability associated with the annual cycle, monthly standard deviation σ is calculated over the entire time period, after subtraction of the long-term daily mean component. This approach is an improvement over our previous methods (Seguinot, 2013; Rogozhina and Rau, 2014), which included seasonal variability in the standard-deviation calculation, and therefore tended to overestimate σ values during spring and autumn, when the seasonal trend over a given month may be significant. Because we focus on temperature variability over ice-sheet surfaces, ice-free gridcells are excluded from our analysis using the ERA-40 vegetation types and land/sea masks.

Over the Greenland ice sheet, there exists an anti-correlation between long-term monthly temperature means, T_{m}, and long-term monthly standard deviations, σ (Fig. 1). Although a significant spread exists around winter temperatures (Fig. 1, blue), this spread becomes much more restricted when approaching conditions of intensive surface melting during summer (Fig. 1, red), when the standard-deviation parameter exerts strongest influence on modelled melt rates. Using a $1/\sigma$-weighted least-square regression, we derive a linear relationship between σ and T_{m} over the Greenland ice sheet,

$$\sigma = -0.15 \cdot T_{\mathrm{m}} + 1.66 \tag{3}$$

To emphasize conditions in which daily variability has strongest influence on modelled melt rates, we define the effective temperature for melt as

$$T_{\mathrm{eff}} = \frac{\mathrm{d(PPD)}}{\mathrm{d}t} = \frac{\sigma}{\sqrt{2\pi}} \exp\left(-\frac{T_{\mathrm{m}}^2}{2\sigma^2}\right) + \frac{T_{\mathrm{m}}}{2} \operatorname{erfc}\left(-\frac{T_{\mathrm{m}}}{\sqrt{2}\sigma}\right) \tag{4}$$

The net effect of daily variability, σ, on melt can then be expressed as a shift in effective temperature (Fig. 1, dashed lines),

$$\Delta T_{\mathrm{eff}} = T_{\mathrm{eff}} - \max(T_{\mathrm{m}}, 0) \tag{5}$$

Note that ΔT_{eff} is always positive (Fig. 1, three-dimensional inset), hence the use of higher σ values systematically results in increased modelled surface melt. The decrease of σ in response to increasing temperature, most probably modulated by endothermic phase changes around the freezing point, tends to restrict ice surface melt, thereby indicating a natural mechanism for self-inhibition of ice loss from the ice sheet (Fig. 1).

The strong dependence of σ on near-surface air temperature shown by the reanalysis points out that previously discussed relationships between standard deviation and ice surface elevation (Fausto and others, 2009, 2011) originate from lapse-rate effects on temperature and are only valid under present-day climatic conditions. However, a nearly linear dependence of σ on temperature provides a simple proxy for a dynamic adjustment of the standard deviation parameter to evolving climate forcing. Although the inferred relationship (Eqn (3)) needs to be validated against observations, the observational record over the Greenland ice sheet is currently both too spatially scarce and too short to allow for the present analysis (Rogozhina and Rau, 2014). It should also be noted that this relationship does not generally hold true over ice-free territories, where more complex connections should be expected (Seguinot, 2013). However, our analysis reveals that similar connections between daily variability and summer temperature exist over parts of Antarctica (Fig. 2). This indicates a potential for parameterization of daily temperature variability over glacierized regions with essentially different geographic and climatic settings than that of the Greenland ice sheet.

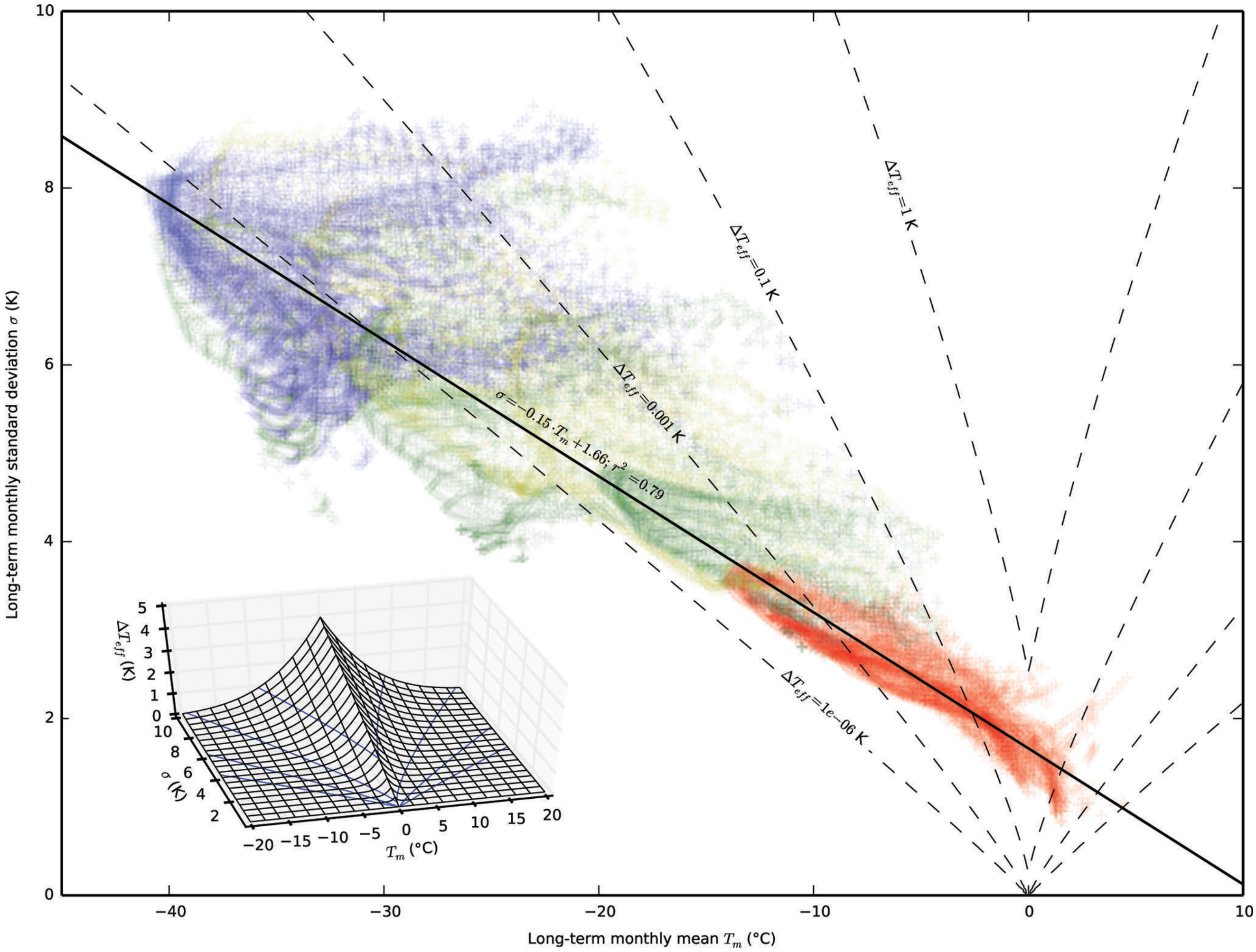

Fig. 1. Long-term monthly standard deviation σ versus long-term monthly mean near-surface air temperature, T_m, over the Greenland ice sheet, according to the ERA-40 reanalysis (Uppala and others, 2005) over a 44 year period, 1958–2001. Seasons are coloured in red (JJA), yellow (SON), blue (DJF) and green (MAM). The solid line corresponds to a $1/\sigma$-weighted least-square regression over all data points (Eqn (3)). Dashed lines represent the effect of daily variability on effective temperature for melt, ΔT_{eff} (Eqn (4)). As shown by the three-dimensional wireframe inset, ΔT_{eff} is always positive, and increases when T_m approaches the melting point (Eqn (5)).

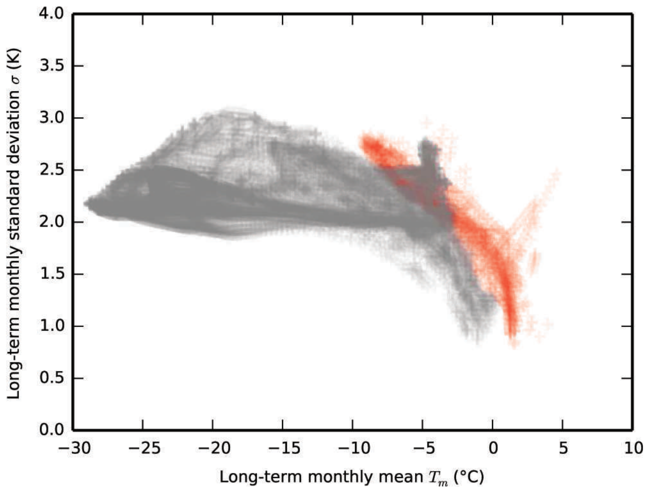

Fig. 2. July Greenland (red) and January Antarctic (grey) long-term monthly standard deviation, σ, versus long-term monthly mean near-surface air temperature, T_m, over the ice sheets, according to ERA-40 reanalysis (Uppala and others, 2005) over a 44 year period, 1958–2001.

ACKNOWLEDGEMENTS

We thank Arjen P. Stroeven, Qiong Zhang and Johan Kleman for detailed suggestions on how to improve the manuscript, and two anonymous reviewers for supporting publication and spotting a deadly misprint. Funding was provided by the German Academic Exchange Service (DAAD) grant No. 50015537, the Knut and Alice Wallenberg Foundation and the Lillemor and Hans W:son Ahlmanns fund for geographic research to J. Seguinot, and by the Swedish Research Council (VR) grant No. 2008-3449 to A.P. Stroeven. This study is part of the multinational research initiative IceGeoHeat.

Helmholtz Centre Potsdam
GFZ German Research Centre
for Geosciences
Potsdam, Germany

Julien SEGUINOT
Irina ROGOZHINA

Department of Physical Geography
and Quaternary Geology and
Bolin Centre for Climate Research
Stockholm University, Stockholm, Sweden

E-mail: julien.seguinot@natgeo.su.se

12 May 2014

https://doi.org/10.3189/2014JoG14J036 Published online by Cambridge University Press

REFERENCES

Arnold KC and MacKay DK (1964) Different methods of calculating mean daily temperatures, their effects on degree-day totals in the High Arctic and their significance to glaciology. *Geogr. Bull.*, **21**, 123–129.

Braithwaite RJ (1984) Calculation of degree-days for glacier–climate research. *Z. Gletscherkd. Glazialgeol.*, **20**, 1–20.

Calov R and Greve R (2005) Correspondence. A semi-analytical solution for the positive degree-day model with stochastic temperature variations. *J. Glaciol.*, **51**(172), 173–175 (doi: 10.3189/172756505781829601)

Fausto RS, Ahlstrøm AP, Van As D, Bøggild CE and Johnsen SJ (2009) A new present-day temperature parameterization for Greenland. *J. Glaciol.*, **55**(189), 95–105 (doi: 10.3189/002214309788608985)

Fausto RS, Ahlstrøm A, Van As D and Steffen K (2011) Correspondence. Present-day temperature standard deviation parameterization for Greenland. *J. Glaciol.*, **57**(206), 1181–1183 (doi: 10.3189/002214311798843377)

Hock R (2003) Temperature index melt modelling in mountain areas. *J. Hydrol.*, **282**(1–4), 104–115 (doi: 10.1016/S0022-1694(03)00257-9)

Reeh N (1991) Parameterization of melt rate and surface temperature on the Greenland ice sheet. *Polarforschung*, **59**(3), 113–128

Rogozhina I and Rau D (2014) Vital role of daily temperature variability in surface mass balance parameterizations of the Greenland Ice Sheet. *Cryosphere*, **8**(2), 575–585 (doi: 10.5194/tc-8-575-2014)

Seguinot J (2013) Correspondence. Spatial and seasonal effects of temperature variability in a positive degree-day glacier surface mass-balance model. *J. Glaciol.*, **59**(218), 1202–1204 (doi: 10.3189/2013JoG13J081)

Uppala SM and 45 others (2005) The ERA-40 re-analysis. *Q. J. R. Meteorol. Soc.*, **131**(612), 2961–3212 (doi: 10.1256/qj.04.176)