The Cryosphere, 8, 575–585, 2014
www.the-cryosphere.net/8/575/2014/
doi:10.5194/tc-8-575-2014

The Cryosphere
Open Access

Vital role of daily temperature variability in surface mass balance parameterizations of the Greenland Ice Sheet

I. Rogozhina and D. Rau

Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Section 1.3: Earth System Modelling, Telegrafenberg A20, 14473 Potsdam, Germany

Correspondence to: I. Rogozhina (valmont@gfz-potsdam.de) and D. Rau (dorager@googlemail.de)

Received: 31 May 2013 – Published in The Cryosphere Discuss.: 14 June 2013
Revised: 17 February 2014 – Accepted: 18 February 2014 – Published: 7 April 2014

Abstract. This study aims to demonstrate that the spatial and seasonal effects of daily temperature variability in positive degree-day (PDD) models play a decisive role in shaping the modeled surface mass balance (SMB) of continental-scale ice masses. Here we derive monthly fields of daily temperature standard deviation (SD) across Greenland from the ERA-40 (European Centre for Medium-Range Weather Forecasts 40 yr Reanalysis) reanalysis spanning from 1958 to 2001 and apply these fields to model recent surface responses of the Greenland Ice Sheet (GIS). Neither the climate data set analyzed nor in situ measurements taken in Greenland support the range of commonly used spatially and temporally uniform SD values ($\sim 5\,^{\circ}$C). In this region, the SD distribution is highly inhomogeneous and characterized by low values during summer months (~ 1 to $2.5\,^{\circ}$C) in areas where most surface melting occurs. As a result, existing SMB parameterizations using uniform, high SD values fail to capture both the spatial pattern and amplitude of the observed surface responses of the GIS. Using realistic SD values enables significant improvements in the modeled regional and total SMB with respect to existing estimates from recent satellite observations and the results of a high-resolution regional model. In addition, this resolves large uncertainties associated with other major parameters of a PDD model, namely degree-day factors. The model appears to be nearly insensitive to the choice of degree-day factors after adopting the realistic SD distribution.

1 Introduction

Over the past several decades, observing climate and evolution of the cryosphere has received increasing attention from the scientific community and has become more precise than ever (Rahmstorf et al., 2007). Nevertheless, complex physical processes within large-scale ice masses cannot be understood from observation alone. Since the late 1970s numerical modeling has therefore become established as an important technique for understanding the dynamic behavior and internal structure of ice sheets and glaciers (Budd and Jenssen, 1975; Ritz et al., 1997; Oerlemans et al., 1998; Calov et al., 2005; Larour et al., 2012; Rogozhina et al., 2012), deriving the past climate variability (Lhomme et al., 2005; Huybrechts et al., 2007), and predicting responses of ice sheets to global climate changes (Huybrechts and De Wolde, 1999; Greve, 2000; Ridley et al., 2005). Although numerical simulations can potentially provide answers to major questions within the context of past and future climate changes and their impacts on global sea level and ice cover extents, these remain poorly constrained and are subject to multiple simplifying assumptions within the models used.

Recent observations have shown that the GIS (Greenland Ice Sheet) is losing its mass at an increasing speed (Joughin et al., 2010; Sasgen et al., 2012) and has experienced record high ice surface melt (Fettweis et al., 2011; Tedesco et al., 2013) due to unprecedented air temperatures over the summer months (Mote, 2007). As the second largest ice sheet on Earth, the GIS may have major impacts on the global ecosystem if its degradation is to continue at the observed rate. The evolution of ice sheets is mainly controlled by snow accumulation and ice loss through surface melting and calving into the ocean driven by the contemporaneous climate conditions. At present the two major sources of ice loss are contributing to ice mass changes in Greenland in nearly equal shares (van den Broeke et al., 2009); surface melt is, however, increasing faster than ice discharge (Sasgen et al., 2012) and is implicated in potentially larger impacts on the GIS stability in the future as the ice sheet continues to retreat from the coasts (Goelzer et al., 2013).

Two approaches are widely used for modeling ice loss through surface runoff, namely surface energy balance (SEB) and PDD (positive degree-day) models. Each of the two approaches has its area of applicability and its limitations. SEB models are generally more physical than PDD models, since the former take into account a wide range of factors such as cloudiness, ice albedo and solar energy that exert influence on ice surface responses (Bougamont et al., 2005). However, these components of climate forcing are difficult to obtain outside the observational period. In contrast, PDD models use precipitation rates and air temperatures that can be extrapolated into the past using local climate reconstructions (e.g., Petrunin et al., 2013).

In this study, we evaluate existing parameterizations of ice surface melting and refreezing processes utilized by continental-scale ice-sheet models and emphasize the role of SD (daily temperature standard deviation) in numerical simulations of ice surface evolution using a PDD approach. Strong spatial variability of this major parameter was first discussed by Fausto et al. (2009a), who performed their analysis of daily temperature variability using measurements from 27 automated weather stations (Fausto et al., 2009b) and developed a parameterization of spatially variable summer SD for Greenland. The SMB (surface mass balance) parameterization of Fausto et al. (2009a) was later substituted by an updated version of Fausto et al. (2011), who discovered a significant annual variability in the SD parameter and included seasonal effects in their initial SMB parameterization. Recently Charbit et al. (2013) adopted the parameterization of Fausto et al. (2009a) for modeling former glaciations in the Northern Hemisphere and confirmed their conclusions about the importance of spatial variability and elevation dependence of the SD parameter for modeling paleo-ice sheets. Independently, Rau (2012) and Seguinot (2013) analyzed spatial variability of SD in Greenland and worldwide using the ERA-40 (European Centre for Medium-Range Weather Forecasts 40 yr Reanalysis) and ERA-Interim temperature time series and demonstrated a more complex nature of SD than had been assumed in previous studies. Here we validate this new approach and previously used SMB parameterizations on a regional scale by comparing modeled SMB of the GIS with the results of a high-resolution SEB model and observations over the instrumental record.

2 Method

In this study, surface ice melting is specified with a PDD method (Braithwaite, 1984) implemented as part of the large-scale ice sheet model SICOPOLIS (SImulation COde for POLythermal Ice Sheets; Greve, 1997). A PDD approach parameterizes annual surface-melt rates of snow and ice based on the assumption of their proportionality to the number of PDDs, which is given by an integral of surface-air temperature excess above 0 °C in 1 yr (Braithwaite, 1995). Braithwaite (1984) suggested calculating the number of PDDs using normal probability distributions around long-term monthly mean temperatures. Here we apply the formulation of a PDD method modified by Reeh (1991) that computes the PDD sum from the annual temperature cycle T_{acc} and the known standard deviation of daily surface temperature from the annual cycle T_{acc}, $\sigma\,(=\mathrm{SD})$:

$$\mathrm{PDD} = \frac{1}{\sigma\sqrt{2\pi}} \int_0^A \mathrm{d}t \int_0^\infty \mathrm{dT}T \exp\left(-\frac{(T - T_{\mathrm{acc}}(t))^2}{2\sigma^2}\right), \tag{1}$$

where t is the time and T is the air temperature. Following the common approach, SICOPOLIS computes the number of PDDs (Eq. 1) using the semi-analytical solution of Calov and Greve (2005) to enable fast computations. The value of SD, σ, plays an important role by indicating whether daily surface temperature may have risen above the melting point (0 °C) over the months characterized by negative mean temperatures.

Observations in Greenland (Braithwaite and Olesen, 1989) have shown that melting rates of snow and ice can be linearly related to the number of PDDs using degree-day factors for snow (β_{snow}) and ice (β_{ice}), which are other major parameters controlling the output of PDD models.

Conversion from mean monthly precipitation data to monthly snowfall and rainfall rates is done using a simple empirical relation of Marsiat (1994):

$$S_{\mathrm{mm}}(x,y) = P_{\mathrm{mm}}(x,y) \times \tag{2}$$
$$\begin{cases} 0, & T_{\mathrm{mm}} > +7\,^\circ\mathrm{C} \\ (7\,^\circ\mathrm{C} - T_{\mathrm{mm}}(x,y))/17\,^\circ\mathrm{C}, & T_{\mathrm{mm}} \in [-10\,^\circ\mathrm{C}, +7\,^\circ\mathrm{C}]\,, \\ 1, & T_{\mathrm{mm}} < -10\,^\circ\mathrm{C} \end{cases}$$

$$R_{\mathrm{mm}}(x,y) = P_{\mathrm{mm}}(x,y) - S_{\mathrm{mm}}(x,y), \tag{3}$$

where $S_{\mathrm{mm}}(x,y)$, $R_{\mathrm{mm}}(x,y)$ and $P_{\mathrm{mm}}(x,y)$ are the monthly snowfall, rainfall and precipitation fields, and $T_{\mathrm{mm}}(x,y)$ is the monthly mean temperature given in each grid point (x,y). In the following sections, all fields are implicitly given in the same grid points.

2.1 Simulation setup

For the period from 1958 to 2010, our simulations are run with the ice sheet surface fixed at its observed elevation

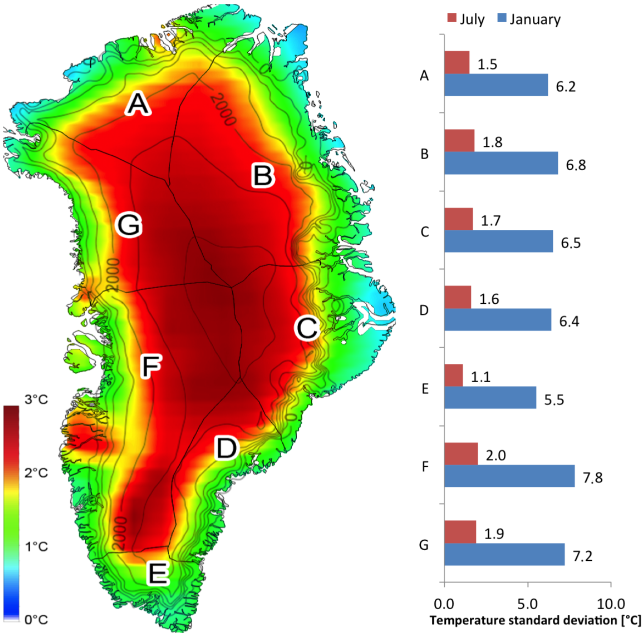

Fig. 1. Map of daily temperature standard deviation (SD), σ (see Eq. 1), derived for the July month using ERA-40 temperature fields across Greenland (1958–2001). The bars on the right show July and January SD values averaged over major drainage basins A–G.

(Bamber et al., 2001). They are informed by the monthly temperature, precipitation and evaporation gridded reanalysis products from the ERA-40 (1958–1988) and ERA-Interim (1989–2010) archives (Betts et al., 2009; Dee et al., 2011) given on a $0.5° \times 0.5°$ grid. From the monthly precipitation (P) and evaporation (E) data, time series of P–E have been calculated. Temperature (T) and P–E fields have been transformed from the original spherical grid to Cartesian coordinates in a stereographic plane. T fields have been corrected for the difference between ice elevations corresponding to Cartesian and spherical grid cells using monthly temperature lapse rates (Fausto et al., 2009b). The new monthly T and P–E fields have been derived on a $10\,\mathrm{km} \times 10\,\mathrm{km}$ grid, the resolution adopted for all simulations. Note that this resolution is comparable with the horizontal resolution of $11\,\mathrm{km} \times 11\,\mathrm{km}$ utilized by the RACMO2/GR model (Regional Atmospheric Climate Model; Ettema et al., 2009), which is used along with observational data to validate our simulations on a regional scale (see Sect. 3.2).

Although the above transformations from spherical to Cartesian grids and lapse-rate corrections to the original temperature fields may distort, to some extent, the climate data set used, these are needed to ensure a uniform resolution of the climate forcing across Greenland. Indeed, using the ERA-40 and ERA-Interim fields on their original spherical grids would have coarsened the resolution of our SMB estimates towards the southern limit of Greenland, thus complicating the regional comparison of our simulations with the results of the RACMO2/GR model (see Sect. 3.2).

In this study we analyze three existing SMB parameterizations of Greve (2005), Huybrechts (2002) and Tarasov and Peltier (2002) with uniform SD values ranging between 4.5 and 5.2 °C (see Sect. 2.2). In addition, we consider the parameterization of Fausto et al. (2009a) with spatially variable distribution of summer SD parameterized using in situ temperature measurements (Fig. 3, see Sect. 2.3), and develop our own parameterization with spatially and seasonally variable SD derived from the ERA-40 reanalysis spanning from 1958 to 2001 (Figs. 1–3, see Sect. 2.4).

2.2 Parameterizations with spatially and temporally uniform SD

Here we provide the description of model parameters in their originally published units and the conversion factors where these are needed (i.e. ice equivalent; w.e. water equivalent).

The SMB parameterization of Huybrechts (2000) makes use of the uniform SD value of 5 °C and degree-day factors $\beta_{\mathrm{ice}} = 8$ (mm w.e./(° C d)) and $\beta_{\mathrm{snow}} = 3$ (mm w.e./(° C d)). In combination with these parameters, we adopt a physically based refreezing parameterization (retention model) suggested by Pfeffer et al. (1991) and Janssens and Huybrechts (2000) and adopted in the mathematical formulation of Tarasov and Peltier (2002) with the active thermodynamic layer of $d = 2$ m:

$$F_{\mathrm{w}} = \quad (4)$$
$$\begin{cases} \min\left(R_{\mathrm{ma}} + M_{\mathrm{ma}}; 2.2 \cdot (S_{\mathrm{ma}} - M_{\mathrm{ma}}) \right. & M_{\mathrm{ma}} \le S_{\mathrm{ma}} \\ \left. -d \cdot \frac{c}{L} \min(T_{\mathrm{ma}}, 0\,°\mathrm{C})\right), & \\ \min\left(R_{\mathrm{ma}} + M_{\mathrm{ma}}; -d \cdot \frac{c}{L} \min(T_{\mathrm{ma}}, 0\,°\mathrm{C})\right), & M_{\mathrm{ma}} > S_{\mathrm{ma}}, \end{cases}$$

where F_{w}, R_{ma}, M_{ma} and S_{ma} are the annual refreezing, rainfall, melt and snowfall rates, T_{ma} is the mean annual surface temperature, $c\,(T) = 2115.3 + 7.79T$ (J (kg K)$^{-1}$) is the ice specific heat capacity in the formulation of Huybrechts (2002) and $L = 3.35 \times 10^5$ (J kg^{-1}) is the latent heat of fusion.

The parameterization of Tarasov and Peltier (2002) uses the uniform SD value of 5.2 °C and different degree-day factors for ice melt and snowmelt under cold and warm climate conditions:

$$\beta_{\mathrm{ice/snow}} = \quad (5)$$
$$\begin{cases} \beta^{\mathrm{cold}}, & T_{\mathrm{jja}} \le -1\,°\mathrm{C} \\ (\beta^{\mathrm{cold}} - \beta^{\mathrm{warm}}) & T_{\mathrm{jja}} \in [-1\,°\mathrm{C}, +10\,°\mathrm{C}] \\ \cdot \left(\frac{10\,°\mathrm{C} - T_{\mathrm{jja}}}{11\,°\mathrm{C}}\right)^n + \beta^{\mathrm{warm}}, & \\ \beta^{\mathrm{warm}}, & T_{\mathrm{jja}} \ge +10\,°\mathrm{C} \end{cases}$$

where $\beta^{\mathrm{cold}}_{\mathrm{ice}} = 17.22$ (mm i.e./(°C d)), $\beta^{\mathrm{warm}}_{\mathrm{ice}} = 8.3$ (mm i.e./(°C d)), $\beta^{\mathrm{cold}}_{\mathrm{snow}} = 2.65$ (mm i.e./(°C d)), $\beta^{\mathrm{warm}}_{\mathrm{snow}} = 4.3$ (mm i.e./(°C d)), $n = 3$ ($n = 1$) for ice (snow), and T_{jja} is the mean summer temperature. Please, note that a scaling factor of 0.91 should be applied for conversion from i.e. to w.e.

Here we adopt the same retention model as for the parameterization of Huybrechts (2002) but with the active thermodynamic layer of $d = 1$ m as suggested by Tarasov and Peltier (2002) and the temperature-dependent ice specific heat capacity of Tarasov and Peltier (2002): $c(T) = 152.5 + 7.122T$ (J (°C kg)$^{-1}$).

Finally, the parameterization of Greve (2005) uses the spatially uniform SD of 4.5 °C and the values of degree-day factors dependent on mean July temperature (versus mean summer temperature used by Tarasov and Peltier, 2002), $\beta_{\mathrm{ice}}^{\mathrm{cold}} = 15$ (mm w.e./(°C d)), $\beta_{\mathrm{ice}}^{\mathrm{warm}} = 7$ (mm w.e./(°C d)), $\beta_{\mathrm{snow}}^{\mathrm{cold}} = \beta_{\mathrm{snow}}^{\mathrm{warm}} = 3$ (mm w.e./(°C d)). South of 72° N (including areas D and E and large parts of areas C and F in Fig. 1), degree-day factors for warm conditions are applied. Following Greve (2005), we employ a simple retention model of Reeh (1991) with a constant and uniform saturation factor, $P_{\mathrm{max}} = 0.6$, for the formation of superimposed ice.

2.3 Parameterization with spatially variable summer SD from in situ measurements

The parameterization of Fausto et al. (2009a) uses an elevation-dependent mean summer SD (Fig. 3):

$$\sigma = 1.574 + 1.2224 \cdot z_{\mathrm{s}}, \quad (6)$$

where z_{s} is the elevation above sea level in kilometers. The above relation between the surface elevation and SD has been derived by obtaining a least-mean square fit to the values inferred from temperature measurements at the locations of 27 automatic weather stations with the lengths of observation periods ranging from 2 months to 10 yr (Fausto et al., 2009b). The original parameterization of Fausto et al. (2009a) has been validated at the locations of automatic weather stations by approximately fitting the observed SMB over the observational period using the degree-day factors and the ice specific heat capacity formulation of Greve (2005), namely, $c(T) = 146.3 + 7.253T$ (J (°C kg)$^{-1}$), the parameters we employ in the present study (see Sect. 2.2). In addition, we use the retention model of Tarasov and Peltier (2002) with the active thermodynamic layer of $d = 2$ m (see Sect. 2.2), which is similar to but not exactly the same as that suggested by Fausto et al. (2009a). This is done to enable a one-to-one comparison with the results of simulations using the parameterizations of Huybrechts (2002), Tarasov and Peltier (2002) (see Sect. 2.2) and our new parameterization of SD (see Sect. 2.4).

2.4 New parameterization with spatially and seasonally variable SD from reanalysis data

Our parameterization with spatially and seasonally variable SD uses the same degree-day factors, retention model and ice specific heat capacity as the parameterization of Fausto et al. (2009a) (see Sect. 2.3). Twelve monthly fields of SD are derived from the complete temperature time series of the ERA-40 reanalysis (Uppala et al., 2005) as standard deviations of daily temperature from the long-term monthly temperature means. In short, we first compute mean monthly fields of near-surface temperature on a spherical grid using daily temperature means over the period of 1958–2001. Then we calculate the standard deviation of daily temperature from these mean monthly temperature fields using the entire temperature time series (similar to Seguinot, 2013). The SD fields are then transformed from the original spherical grid to a Cartesian grid in a stereographic plane (Fig. 1) following the same procedure as described in Sect. 2.1.

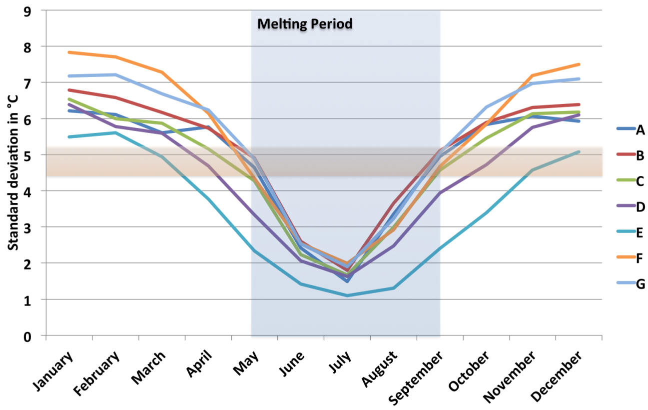

Fig. 2. Monthly SD values derived from ERA-40 temperature time series (1958–2001) and averaged over major drainage basins A to G (see Fig. 1 for area locations). The horizontal shaded area outlines the range of commonly used uniform SD values. The vertical shaded area shows a typical period of ice/snow surface melt in Greenland (Rennermalm et al., 2009).

3 Results and discussion

3.1 Spatial and seasonal variation in daily temperature standard deviation

We derive twelve monthly SD fields across Greenland (Fig. 1) from the ERA-40 temperature time series from 1958 to 2001 (see Sect. 2.4 for detail). In agreement with the findings of Fausto et al. (2009a, 2011), our analysis reveals a distinct annual cycle (Fig. 2) and strong lateral gradients (Fig. 1) in the SD distribution, with the lowest SD occurring over the melting period and its value decreasing dramatically towards the coasts. For the warmest summer month (July), SD values in the areas characterized by the highest surface melting rates vary between 0.6 and 1.8 °C, while occasionally reaching values as high as 2.5 °C in some coastal areas (Fig. 1, western coast). In general, July SD values do not exceed 3 °C, even at high elevations. If averaged over the major drainage basins A–G (Figs. 1, 2), low values of July SD, 1.1–2 °C,

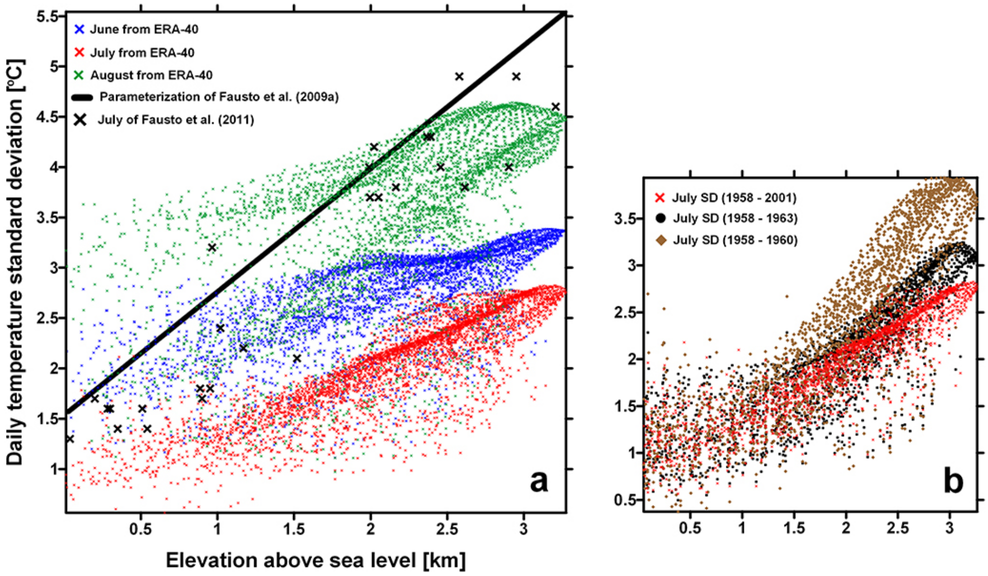

Fig. 3. SD values versus surface elevation above sea level. **(a)** Scatter plots of June (blue), July (red) and August (green) SD values derived from ERA-40 temperature time series across Greenland. Thick black line depicts the relation between mean summer SD values and surface elevation suggested by Fausto et al. (2009a). Black crosses depict the July SD values interred from temperature measurements from 27 weather stations in Greenland (Fausto et al., 2011). **(b)** Sensitivity of SD values to the length of a temperature time series used: 44 yr (red), 6 yr (black), and 3 yr (brown).

are in contrast to significantly higher values of 5.5–7.8 °C in winter (January). Depending on the particular area, our estimated mean annual SD values are ∼ 3.3–4.9 °C, close to the range of traditional uniform SD values (Fig. 2). It is however obvious that these mean annual values are not suitable for modeling surface responses of the GIS over the summer period (Fig. 2), whereas surface melting rates in Greenland are negligibly low over the rest of the year (Rennermalm et al., 2009). Generally, the use of such high SD values should result in a largely exaggerated surface melt, even though surface runoff rates within different drainage basins may show different degrees of sensitivity to the use of regional SD values.

The annual variability visible in our regional SD values (Fig. 2) is qualitatively similar to that identified by Fausto et al. (2011) at several locations of automatic weather stations. Nevertheless, the quantitative agreement between Fausto et al. (2009a, 2011)'s values and those inferred from the ERA-40 analysis lags behind. For example, our July SD is generally up to two times as low as the summer SD values of Fausto et al. (2009a), and the August SD significantly exceeds the June and July values (Figs. 2, 3), as opposed to the observation of Fausto et al. (2011). Fausto et al. (2009a) parameterize SD values using summer (June, July and August) temperatures gathered from in situ measurements. These are a priori higher than the corresponding July SD values due to seasonal effects (see Fig. 2). However, the July SD values derived by Fausto et al. (2011) from the same measurements are still higher than the corresponding values we obtain from the ERA-40 time series and are closer to the spread of values we estimate for June and August rather than for July (Fig. 3a). These comparatively higher SD estimates from in situ measurements are challenged by the independent global analysis of the 34 yr long ERA-Interim reanalysis (Seguinot, 2013). As opposed to the estimates of Fausto et al. (2011), the ERA-Interim reanalysis does not display July SD values higher than 3 °C across Greenland. This inconsistency raises questions about the causes underlying significant discrepancies between measurements and the SD values derived from ERA climate data sets. Some of the discrepancies may originate from the following factors: (i) the distinctly different spatial and temporal resolution of the data used, (ii) simplifying assumptions within the ERA data sets, (iii) periods of observation limited to a maximum of 3 yr at low elevations and a maximum of 10 yr at higher elevations (Fausto et al., 2009b), (iv) a measurement period coinciding with the rapid changes in regional air temperature and precipitation patterns (Sasgen et al., 2012), and (v) finally, an inhomogeneous distribution of stations across Greenland. In general, estimated SD values show high sensitivity to the length of a temperature time series used (Fig. 3b) and potentially to a particular choice of the period over which they are calculated. In the following we refrain, however, from the quantitative comparison of our SD values with the few measurements taken in Greenland and focus rather on assessing the effects of these differences on the modeled SMB of the GIS.

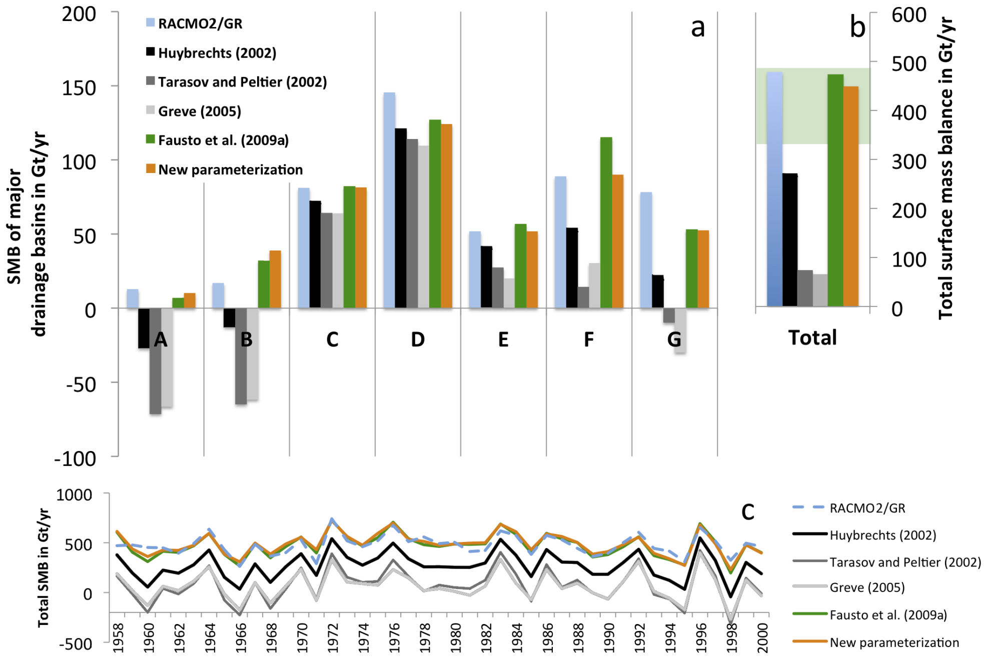

Fig. 4. Comparison of modeled values of regional and total SMB obtained from RACMO2/GR (adopted from Ettema et al., 2009; blue), SMB parameterizations of Huybrechts (2002), Tarasov and Peltier (2002), Greve (2005) (black, dark grey and light grey, respectively) and Fausto et al. (2009a) (green), and the new SMB parameterization with spatially and seasonally variable SD (orange). Fig. 1a and b depict the SMB values averaged over the reference period 1958–2001. Areas A–G are given in Fig. 1. Light green shading in **(b)** shows the range of independent estimates of total SMB from Vernon et al. (2013) averaged over the period from 1960 to 1990.

3.2 Evaluation of existing surface mass balance parameterizations on a regional scale

To assess the performance of existing SMB parameterizations with uniform and spatially variable SDs of Huybrechts (2002), Tarasov and Peltier (2002), Greve (2005) and Fausto et al. (2009a) versus our new approach, we designed an ensemble of transient simulations of the GIS surface responses over the period from 1958 to 2010 (see Sect. 2.1) and compared the outputs with the regional estimates from the high-resolution model RACMO2/GR (Ettema et al., 2009), and the mass changes from satellite observations (Sasgen et al., 2012).

3.2.1 Comparison with the regional estimates from the RACMO2/GR model

The first-order effects of the SD parameter on the modeled SMB time series can be estimated by comparing regional averages of modeled SMB values over the reference period, 1958–2001. According to independent estimates (Vernon et al., 2013), this period had a relatively stable SMB of the GIS (see also Fig. 4c), making it a good choice for averaging.

As compared to the results of RACMO2/GR and a range of other independent SMB estimates (Vernon et al., 2013), total SMB values taken during the reference period are largely underestimated when calculated using existing SMB parameterizations with uniform SD values (Fig. 4b). Among the three parameterizations in question, the parameterization of Huybrechts (2002) matches closest with all independent estimates. The average value of total SMB resulting from this simulation is only 50 Gt yr^{-1} apart from the lower range of anticipated SMB values as opposed to significantly larger deviations of nearly 300 Gt yr^{-1} shown by the parameterizations of Greve (2005) and Tarasov and Peltier (2002). We conclude that all three simulations with uniform SD values result in overestimated runoff rates. In contrast, the simulations driven by the new parameterization and that of Fausto et al. (2009a) arrive at nearly perfect agreement with the results of RACMO2/GR and fall within the range of other independent estimates close to the upper bound of the estimated range. Both SMB parameterizations demonstrate an excellent ability to reproduce the evolution of the total SMB suggested by RACMO2/GR (Fig. 4c) by capturing the interannual variability in the SMB relatively well throughout the reference period. In contrast, the parameterizations of Greve (2005) and Tarasov and Peltier (2002) produce up to 500 Gt yr^{-1} lower SMB and higher amplitudes in its variation.

On a regional scale, modeled SMB values resulting from three parameterizations with uniform SD values are only relatively close to the results of RACMO2/GR within the eastern and southern major drainage basins (areas C–E). All three parameterizations fail to reproduce the positive SMB values suggested by RACMO2/GR in northern Greenland (areas A and B), thus underestimating regional SMB by 40–80 Gt yr^{-1} in each of the two areas. The parameterizations of Greve (2005) and Tarasov and Peltier (2002) have a general tendency to produce too-high runoff rates and thus too-low SMB in all drainage basins considered. This is also true for the parameterization of Huybrechts (2002) but the latter results in a considerably better fit with the regional SMB values estimated from RACMO2/GR as compared to the other two parameterizations.

The use of spatially (and seasonally) variable SD derived from the ERA-40 reanalysis and the parameterization of Fausto et al. (2009a) enables a high degree of agreement with the regional SMB values from RACMO2/GR, showing relatively insignificant differences between the results of our simulations. The simulation driven by the parameterization of Fausto et al. (2009a) produces a slightly better agreement within areas B and D and a slightly worse fit within areas A and E, while strongly overestimating the SMB in area F. Although fitting the SMB value within area F is especially important, since surface runoff from this area accounts for around 40 % of the total runoff in Greenland (Ettema et al., 2009), one must acknowledge that the estimates from RACMO2/GR are the result of a modeling exercise and may be irrelevant to the actual state of affairs (Sasgen et al., 2012; see Sect. 3.2.2).

Vernon et al. (2013) compare four reconstructions of regional and total SMB of the GIS over the period of 1960–2008 from independent modeling studies, including the study of Ettema et al. (2009) with the application of RACMO2/GR. In this comparison, they show that large uncertainties exist in the modeled total SMB (340–470 Gt yr^{-1}; Fig. 4b, green shading) over the period of 1960–1990 (included in our reference period). Regionally, this results, for example, in an SMB of 44–80 Gt yr^{-1} too high in area D + E from RACMO2/GR relative to the estimates from the other three models. Our simulations with spatially variable SD consistently arrive at an SMB about 20 Gt yr^{-1} lower in area D, with the value in the combined area $\mathrm{D} + \mathrm{E}$ falling within the range of independent estimates. In area B, where both simulations with spatially variable SD seem to produce exorbitant regional SMB values, RACMO2/GR shows a regional SMB that is 4–24 Gt yr^{-1} too low when compared to the other three models considered by Vernon et al. (2013). Thus, this allows for a certain trade-off between our outputs and those from RACMO2/GR. In contrast, all four models utilized by Vernon et al. (2013) produce fairly consistent SMB values in area F, with the anticipated error of ± 5 Gt yr^{-1}, and thus engenders confidence in the regional SMB estimated by RACMO2/GR in this area. The robustness of existing SMB estimates in area F validates our new parameterization that fits precisely with the regional SMB value from RACMO2/GR, whereas the parameterization of Fausto et al. (2009a) overestimates at ~ 30 Gt yr^{-1}. Apart from this difference, large deviations of Fausto et al. (2009a)'s parameterization from the SD values inferred from the ERA-40 data set (Fig. 3) have surprisingly little effect on the modeled regional and total values of SMB.

3.2.2 Validation versus satellite observations

Finally we validate our modeling results by comparing them with the ice mass trends estimated in Greenland from recent satellite observations (Sasgen et al., 2012). To enable such comparison, one must separate changes in ice mass induced by increased/decreased surface runoff from those due to acceleration/deceleration of ice discharge into the ocean. Here we assume that trends in the observed ice mass change induced by ice discharge are relatively well captured by regional estimates from the InSAR (Interferometric Synthetic Aperture Radar) satellite observations (Rignot and Kanagaratnam, 2006; Rignot et al., 2011). We therefore calculate "observed" SMB trends (the instrumental record from 2003 to 2010 relative to the reference period adopted by Sasgen et al., 2012) by subtracting this estimated contribution of ice discharge (Sasgen et al., 2012) from the regionally observed mass trends (Fig. 5). We then compare these with the corresponding trends in the modeled SMB from RACMO2/GR and simulations informed by the parameterizations of Tarasov and Peltier (2002), Fausto et al. (2009a), and our new parameterization.

The comparison of SMB trends reveals that the use of spatially and seasonally variable SD from the ERA-40 time series follows the trends estimated across Greenland relatively well (falling within the range of estimated errors, Sasgen et al., 2012), except in area F where the modeled SMB trend is largely exaggerated. However, this failure is characteristic of the results from RACMO2/GR and can be explained by either poor skill of both models in reproducing the observed trend or erroneous estimates of the ongoing ice discharge/ice mass change rates. Using the parameterization of Fausto et al. (2009a) leads to insignificant deviations from the results of the new parameterization within areas C–E and produces a trend within area A that is too high and falls out of the estimated range. In contrast, it enables improvement with respect to the trend estimated in area F. Overall, both parameterizations with spatially variable SD produce meaningful results for both regional and total SMB trends, as opposed to the parameterization of Tarasov and Peltier (2002) that strongly inflates regional trends in the north and west of Greenland, consequently overestimating the total SMB trend by 60–130 Gt yr^{-1}.

3.3 The effects of uncertainties in degree-day factors on the modeled surface mass balance

One may question the choice of other preferred parameters of a PDD model in the above comparison. Indeed, the uncertainties in degree-day factors are large and the good fit

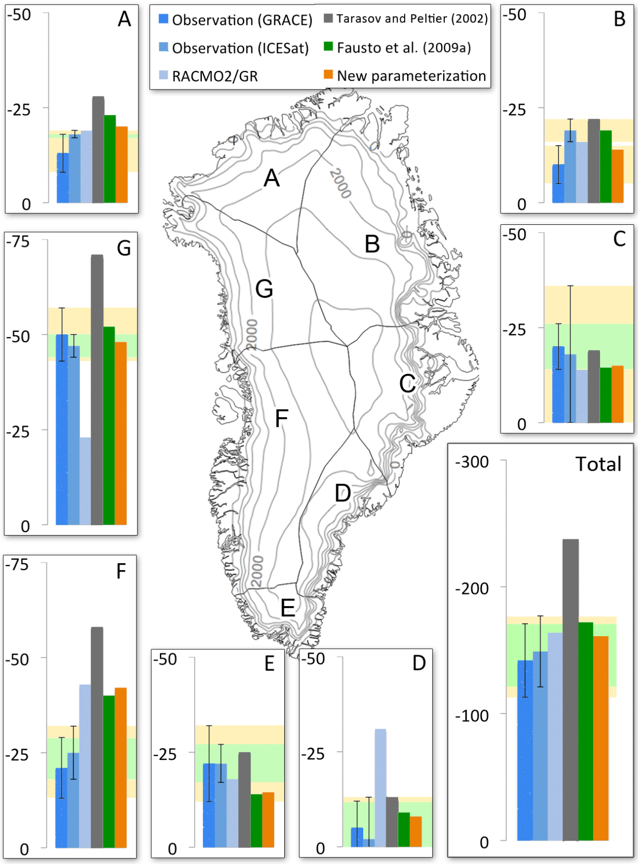

Fig. 5. Modeled versus "observed" SMB trends of the GIS ($\mathrm{Gt\,yr^{-1}}$) (2003–2009 relative to the reference period). The "observed" trends (dark blue) are estimated using the satellite-derived ice mass trends (Sasgen et al., 2012) corrected for the satellite-derived ice discharge contribution (Rignot and Kanagaratnam, 2006; Rignot et al., 2011; see Sect. 3.2.2 for detail). Error bars for the GRACE and ICESat satellite-derived estimates are adopted from Sasgen et al. (2012) and depicted by a light yellow shading, with the overlapping interval marked by a light green shading. Modeled SMB trends are from RACMO2/GR (Ettema et al., 2009; light blue) and SICOPOLIS simulations using the parameterizations of Tarasov and Peltier (2002) (dark grey), Fausto et al. (2009a) (green) and our new parameterization with spatially and seasonally variable SD (orange).

obtained from simulations with spatially and seasonally variable SD may be coincidental, partly determined by the choice of degree-day factors. Comparison of our simulations using the parameterizations of Huybrechts (2002) and Tarasov and Peltier (2002) demonstrates high sensitivity of the modeled SMB to the choice of these parameters. Apart from different degree-day factors and slightly different SD values, both parameterizations use similar parameters, which are shown to produce negligibly small effects on the modeled SMB (Charbit et al., 2013). Previous work has suggested that degree-day factors may be used to tune the modeled SMB to fit the observed configuration of the GIS (e.g., Greve et al., 2011).

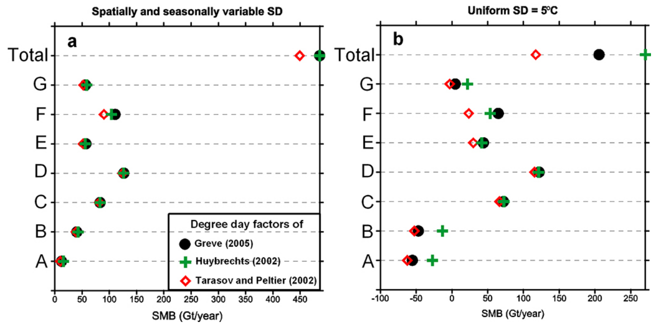

Fig. 6. Sensitivity of the modeled regional and total SMB to a selection of degree-day factors. Modeled SMB values are averaged over the reference period from 1958 to 2001 and over major drainage basins shown in Fig. 1. **(a)** shows the results of simulations with spatially and seasonally variable SD and degree-day factors of Greve (2005), Huybrechts (2002) and Tarasov and Peltier (2002) in contrast to the results of analogous simulations with the uniform SD value of 5 °C shown in **(b)**.

Observing factors is challenging, whereas lack of observation creates a certain degree of freedom to choose the values that produce the best fit.

Here we perform a sensitivity analysis of our modeled regional and total SMB to a selection of degree-day factors from a wide range of commonly used values (Fig. 6). Of the two simulation series, one adopts the commonly used SD value of 5 °C, whereas the other makes use of the spatially and seasonally variable SD discussed in previous sections. We find that the previously discussed sensitivity of the modeled SMB to degree-day factors is largely biased by implementing unrealistically high SD values. In contrast, modeled SMB remains largely insensitive to variations in degree-day factors if realistic SD values are adopted, thereby obviating the necessity to manipulate degree-day factors when modeling the evolution of continental-scale ice sheets.

4 Summary and conclusions

In this case study of the Greenland Ice Sheet (GIS), we show that the use of a positive degree-day approach for modeling the surface evolution of large-scale glaciations requires realistic values of daily temperature standard deviation (SD): these are decisive to the success of modeling experiments. We suggest a method for deriving the spatial and seasonal variability of this major model parameter from existing climate reanalyses and compare the resulting SD fields with estimates from in situ measurements taken in Greenland (Fausto et al., 2009b). This reveals significant discrepancies between the values suggested by the two independent data sets but with surprisingly minor influence on the modeled regional SMB of the GIS over the period from 1958 to 2010. We evaluate the performance of our new approach versus other existing SMB parameterizations according to the extent of their agreement with the results of the regional model RACMO2/GR and recent satellite observations. We conclude that the modeled SMB of the GIS is largely determined by the low summer SD values identified by in situ measurements and ERA-40 time series during the melting period in Greenland, with uncertainties in degree-day factors playing an insignificant role. The high sensitivity of modeled SMB to the choice of degree-day factors is strongly caused by using the traditional, high SD values, which contradict both observational and reanalysis data sets. The traditional approach suggests using a uniform SD up to six times higher relative to our estimated values over the melting period. This consequently results in enormous underestimation of SMB of the GIS, regardless of ongoing improvements in meltwater retention models and twists in degree-day factors. Our conclusions suggest that the traditional approach to long- and short-term modeling of ice surface evolution using PDD models should be reconsidered. Although the applicability of the SD distribution derived from the present-day climate data is likely to be limited to the most recent history of the GIS when its geometry did not strongly deviate from the present-day configuration, our method opens up opportunities to study the range of factors inducing spatial and seasonal variation in SD over the globe and thus to design realistic approximations of SD distribution in presently and formerly glaciated areas.

Acknowledgements. This study is party based on the bachelor study of Dominik Rau and is part of the multinational research initiative IceGeoHeat (www.facebook.com/IceGeoHeat). We thank Sylvie Charbit, Nicole Schlegel, Fuyuki Saito and the anonymous reviewer for their thoughtful reviews and interesting suggestions that helped us to polish our results and conclusions. We express our sincere gratitude to the editor, Eric Larour, for his continuous support throughout the peer-review process. We are grateful to Ingo Sasgen for sharing the materials of his study (Sasgen et al., 2012). Special thanks to Robert Dill for providing the ERA-40 and ERA-Interim climate data sets and Gwendolyn Reid-Kuhlmann for editing the text.

The service charges for this open access publication have been covered by a Research Centre of the Helmholtz Association.

Edited by: E. Larour

References

Bamber, J. L., Layberry, R. L., and Gogineni, S. P.: A new ice thickness and bed data set for the Greenland ice sheet: 1. Measurement, data reduction, and errors, J. Geophys. Res., 106, 773–33, 2001.

Betts, A. K., Köhler, M., and Zhang, Y.: Comparison of river basin hydrometeorology in ERA-Interim and ERA-40 reanalyses with observations, J. Geophys. Res., 114, 1–12, 2009.

Bougamont, M., Bamber, J. L., and Greuell, W.: A surface mass balance model for the Greenland Ice Sheet, J. Geophys. Res., 110, F04018, doi:10.1029/2005JF000348, 2005.

Braithwaite, R. J.: Calculation of degree-days for glacier-climate research, Z. Gletscherkd. Glazialgeol., 20, 1–20, 1984.

Braithwaite, R. J.: Positive degree-day factors for ablation on the Greenland ice sheet studied by energy-balance modelling, J. Glaciol., 41, 153–160, 1995.

Braithwaite, R. J. and Olesen, O. B.: Calculation of glacier ablation from air temperature, West Greenland, Glacier fluctuations and climatic change, Kluwer Academic Publisher, Dordrecht, 1989.

Budd, W. F. and Jenssen, D. Numerical modelling of glacier systems, Snow and Ice Symposium, 104, 257–291, 1975.

Calov, R. and Greve, R.: Correspondence, J. Glaciol., 51, 173–188, 2005.

Calov, R., Ganopolski, A., Petoukhov, V., Claussen, M., Brovkin, V., and Kubatzki, C.: Transient simulation of the last glacial inception. Part II: sensitivity and feedback analysis, Clim. Dynam., 24, 563–576, 2005.

Charbit, S., Dumas, C., Kageyama, M., Roche, D. M., and Ritz, C.: Influence of ablation-related processes in the build-up of simulated Northern Hemisphere ice sheets during the last glacial cycle, The Cryosphere, 7, 681–698, doi:10.5194/tc-7-681-2013, 2013.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., Van De Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., De Rosnay, P., Tavolato, C., Thépaut, J. N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. Roy. Meteorol. Soc., 137, 553–597, 2011.

Ettema, J., Van Den Broeke, M. R., Van Meijgaard, E., Van De Berg, W. J., Bamber, J. L., Box, J. E., and Bales, R. C.: Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling, Geophys. Res. Lett., 36, 1–5, 2009.

Fausto, R. S., Ahlstrom, A. P., Van As, D., Johnsen, S. J., Langen, P. L., and Steffen, K.: Improving surface boundary conditions with focus on coupling snow densification and meltwater retention in large-scale ice-sheet models of Greenland, J. Glaciol., 55, 869–878, 2009a.

Fausto, R. S., Ahlstrøm, A. P., Van As, D., Bøggild, C. E., and Johnsen, S. J.: A new present-day temperature parameterization for Greenland, J. Glaciol., 55, 95–105, 2009b.

Fausto, R. S., Ahlstrøm, A. P., van As, D., and Steffen, K.: Present-day temperature standard deviation parameterization for Greenland, J. Glaciol., 57, 1181–1183, 2011.

Fettweis, X., Tedesco, M., van den Broeke, M., and Ettema, J.: Melting trends over the Greenland ice sheet (1958–2009) from spaceborne microwave data and regional climate models, The Cryosphere, 5, 359–375, doi:10.5194/tc-5-359-2011, 2011.

Goelzer, H., Huybrechts, P., Fürst, J. J., Nick, F. M., Andersen, M. L., Edwards, T. L., Fettweis, X., Payne, A. J., and Shannon, S.: Sensitivity of Greenland ice sheet projections to model formulations, J. Glaciol., 59, 733–749, doi:10.3189/2013JoG12J182, 2013.

Greve, R.: A continuum-mechanical formulation for shallow polythermal ice sheets, Philos. Trans. Math. Phys. Eng. Sci., 355, 921–974, 1997.

Greve, R.: On the Response of the Greenland Ice Sheet to Greenhouse Climate Change, Climatic Change, 46, 289–303, 2000.

Greve, R.: Relation of measured basal temperatures and the spatial distribution of the geothermal heat flux for the Greenland ice sheet, Ann. Glaciol., 42, 424–432, 2005.

Greve, R., Saito, F., and Abe-Ouchi, A.: Initial results of the SeaRISE numerical experiments with the models SICOPOLIS and IcIES for the Greenland ice sheet, Ann. Glaciol., 52, 23–30, 2011.

Huybrechts, P.: Sea-level changes at the LGM from ice dynamic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles, Quaternary Sci. Rev., 21, 203–231, 2002.

Huybrechts, P. and De Wolde, J.: The Dynamic Response of the Greenland and Antarctic Ice Sheets to Multiple-Century Climatic Warming, J. Climate, 12, 2169–2188, 1999.

Huybrechts, P., Rybak, O., Pattyn, F., Ruth, U., and Steinhage, D.: Ice thinning, upstream advection, and non-climatic biases for the upper 89 % of the EDML ice core from a nested model of the Antarctic ice sheet, Clim. Past, 3, 577–589, doi:10.5194/cp-3-577-2007, 2007.

Janssens, I. and Huybrechts, P.: The treatment of meltwater retention in mass-balance parameterisations of the Greenland ice sheet, Ann. Glaciol., 31, 133–140, 2000.

Joughin, I., Smith, B. E., Howat, I. M., Scambos, T., and Moon, T.: Greenland flow variability from ice-sheet-wide velocity mapping, J. Glaciol., 56, 415–430, 2010.

Larour, E., Morlighem, M., Seroussi, H., Schiermeier, J., and Rignot, E.: Ice flow sensitivity to geothermal heat flux of Pine Island Glacier, Antarctica, J. Geophys. Res., 117, F04023, doi:10.1029/2012JF002371, 2012.

Lhomme, N., Clarke, G. K. C., and Marshall, S. J.: Tracer transport in the Greenland Ice Sheet: constraints on ice cores and glacial history, Quaternary Sci. Rev., 24, 173–194, 2005.

Marsiat, I.: Simulation of the Northern Hemisphere continental ice sheets over the last glacial–interglacial cycle: Experiments with a latitude–longitude vertically integrated ice sheet model coupled to a zonally averaged climate model, Palaeoclimates, 1, 59–98, 1994.

Mote, T. L.: Greenland surface melt trends 1973–2007: Evidence of a large increase in 2007, Geophys. Res. Lett., 34, 1–5, 2007.

Oerlemans, J., Anderson, B., Hubbard, A., Huybrechts, P., Jóhannesson, T., Knap, W. H., Schmeits, M., Stroeven, A. P., Van De Wal, R. S. W., Wallinga, J., and Zuo, Z.: Modelling the response of glaciers to climate warming, Clim. Dynam., 14, 267–274, 1998.

Petrunin, A. G., Rogozhina, I., Vaughan, A. P. M., Kukkonen, I. T., Kaban, M. K., Koulakov, I., and Thomas, M.: Heat flux variations beneath central Greenland's ice due to anomalously thin lithosphere, Nat. Geosci., 6, 746–750, doi:10.1038/ngeo1898, 2013.

Pfeffer, W. T., Meier, M. F., and Illangasekare, T. H.: Retention of Greenland runoff by refreezing: implications for projected future sea level change, J. Geophys. Res., 96, 22117–22224, 1991.

Rahmstorf, S., Cazenave, A., Church, J. A., Hansen, J. E., Keeling, R. F., Parker, D. E., and Somerville, R. C. J.: Recent Climate Observations Compared to Projections, Science, 316, p. 709, doi:10.1126/science.1136843, 2007.

Rau, D.: Mass balance of the Greenland Ice Sheet: Ice-sheet modeling versus observations, bachelor thesis, Freie Universität Berlin, 2012.

Reeh, N.: Parameterization of Melt Rate and Surface Temperature on the Greenland lee Sheet, Polarforschung, 59, 113–128, 1991.

Rennermalm, A. K., Smith, L. C., Stroeve, J. C., and Chu, V. W.: Does sea ice influence Greenland ice sheet surface-melt?, Environ. Res. Lett., 4, 024011, doi:10.1088/1748-9326/4/2/024011, 2009.

Ridley, J. K., Huybrechts, P., Gregory, J. M., and Lowe, J. A.: Elimination of the Greenland Ice Sheet in a High CO_2 Climate, J. Climate, 18, 3409–3427, 2005.

Rignot, E. and Kanagaratnam, P.: Changes in the velocity structure of the Greenland ice sheet, Science, 311, 986–990, 2006.

Rignot, E., Velicogna, I., van den Broeke, M. R., Monaghan, A., and Lenaerts, J.: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, Geophys. Res. Lett., 38, L05503, doi:10.1029/2011GL046583, 2011.

Ritz, C., Fabre, A., and Letréguilly, A.: Sensitivity of a Greenland ice sheet model to ice flow and ablation parameters: consequences for the evolution through the last climatic cycle, Clim. Dynam., 13, 11–23, 1997.

Rogozhina, I., Hagedoorn, J. M., Martinec, Z., Fleming, K., Soucek, O., Greve, R., and Thomas, M.: Effects of uncertainties in the geothermal heat flux distribution on the Greenland Ice Sheet: An assessment of existing heat flow models, J. Geophys. Res., 117, 1–16, 2012.

Sasgen, I., Van Den Broeke, M., Bamber, J. L., Rignot, E., Sandberg Sørensen, L., Wouters, B., Martinec, Z., Velicogna, I., and Simonsen, S. B. Timing and origin of recent regional ice-mass loss in Greenland, Earth Planet. Sci. Lett., 333–334, 293–303, 2012.

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

Tarasov, L., and Peltier, W. R.: Greenland glacial history and local geodynamic consequences, Geophys. J. Int., 150, 198–229, 2002.

Tedesco, M., Fettweis, X., Mote, T., Wahr, J., Alexander, P., Box, J. E., and Wouters, B.: Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data, The Cryosphere, 7, 615–630, doi:10.5194/tc-7-615-2013, 2013.

Uppala, S. M., Kållberg, P. W., Simmons, A. J., Andrae, U., Da Costa, V., Bechtold, V., Fiorino, M., Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Van De Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., Mcnally, A. P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P., and Woollen, J.: The ERA-40 re-analysis, Q. J. Roy. Meteor. Soc., 131, 2961–3012, 2005.

van den Broeke, M., Bamber, J., Ettema, J., Rignot, E., Schrama, E., van de Berg, W. J., van Meijgaard, E., Velicogna, I., and Wouters, B.: Partitioning Recent Greenland Mass Loss, Science, 326, 984–986, 2009.

Vernon, C. L., Bamber, J. L., Box, J. E., van den Broeke, M. R., Fettweis, X., Hanna, E., and Huybrechts, P.: Surface mass balance model intercomparison for the Greenland ice sheet, The Cryosphere, 7, 599–614, doi:10.5194/tc-7-599-2013, 2013.