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Modeling surface response of the Greenland Ice Sheet to interglacial climate

D. Rau and I. Rogozhina

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

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Correspondence to: I. Rogozhina (valmont@gfz-potsdam.de)

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Abstract

This study presents a new approach to parameterizing surface mass balance (SMB) of the Greenland Ice Sheet (GIS) under interglacial climate validated against recent satellite observations and the results of a high-resolution model on a regional scale. Based on detailed analysis of the modeled SMB, we conclude that existing parameterizations fail to capture either spatial pattern or amplitude of the observed surface responses of the GIS. This is due to multiple simplifying assumptions adopted by the majority of modeling studies within the framework of a positive degree-day method. Modeled surface melting is found to be highly sensitive to a choice of daily temperature standard deviation (SD), which is generally assumed to have uniform distribution across Greenland. The range of commonly used SD values does not however receive support from climate datasets available. In this region, SD distribution is highly inhomogeneous and characterized by low values during summer months in areas where most surface melting occurs. Our approach is to make use of spatially variable SD and here we show that this leads to significant improvements in the modeled SMB over the instrumental record. Our findings necessitate evaluating potential consequences of the simplified SMB treatment for assessment of the history and future of glaciation on Earth.

1 Introduction

Over the last decades, observing climate and evolution of the cryosphere has received an 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 in understanding ice sheet and glacier dynamics (Budd and Jenssen, 1975; Calov et al., 2005; Oerlemans et al., 1998; Ritz et al., 1997; Rogozhina et al., 2011, 2012), deriving past climate variability (Huybrechts et al., 2007; Lhomme et al., 2005), and predicting possible responses of ice sheets to global climate changes (Greve, 2000; Huybrechts and De Wolde, 1999; 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 the 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 is losing its mass at an increasing speed (Joughin et al., 2010; Sasgen et al., 2012) and has experienced record high ice surface melt extents (Tedesco et al., 2012; Fettweis et al., 2011) 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 climate conditions at a time. 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 at a higher speed 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 retreating from the coasts (Fürst et al., 2013).

Two approaches are widely used for modeling ice loss through surface runoff in ice-covered regions, namely surface energy balance (SEB) and surface mass balance (SMB) models. Each of two approaches has its area of applicability and its limitations. SEB models are generally more physical than SMB models, since the former take into account a wide range of factors such as cloudiness, ice albedo and solar energy that exert an 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, SMB models make use of precipitation and temperature values that can be extrapolated into the past using local climate reconstructions.

In this study, we analyze existing parameterizations of ice surface melting and refreezing processes utilized by continental-scale ice-sheet models and present a new parameterization that enables significant improvements in the modeled surface responses of the GIS on a regional scale. We have designed a suite of transient simulations of the GIS evolution over the period of 1958 to 2009 in order to validate a number of existing SMB parameterizations and our new approach against the results of the high-resolution model RACMO2/GR (Ettema et al., 2009) and recent satellite observations (Sasgen et al., 2012).

2 Method

2.1 Modeling approach

In this study, the evolution of the GIS is simulated using the polythermal ice-sheet model SICOPOLIS (Greve, 1997) based on the rheology of an incompressible, heat conducting, power law fluid (Paterson, 1994) and the shallow ice approximation (Hutter, 1983; Morland, 1984). It is driven by external forcing including SMB (precipitation, evaporation and runoff), mean monthly surface air temperatures, eustatic sea level and geothermal heat flux.

Surface ice melting is specified with a positive degree-day (PDD) model (Calov and Greve, 2005) that parameterizes surface melt rates of snow and ice as a function of the number of days a year when mean daily air temperatures rise above 0 °C (Braithwaite, 1995). Braithwaite and Olesen (1984) suggested calculating the number of positive degree days using normal probability distributions around the long-term monthly mean temperatures as follows (Reeh, 1991)

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

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where t is the time, T is the air temperature, T_{acc} is the annual temperature cycle, and σ is the standard deviation of the daily temperatures from T_{acc} (= SD). To enable faster computations, we use the semi-analytical solution for the PDD integral (Eq. 1) introduced by Calov and Greve (2005). This is given by

$$\mathrm{PDD} = \int_0^A \left[\frac{\sigma}{\sqrt{2\pi}} \exp\left(-\frac{T_{acc}^2}{2\sigma^2}\right) + \frac{T_{acc}}{2} \mathrm{erfc}\left(-\frac{T_{acc}}{\sqrt{2}\sigma}\right)\right] \mathrm{d}t, \tag{2}$$

where

$$\mathrm{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty \exp(-\tilde{x}^2)\mathrm{d}\tilde{x}. \tag{3}$$

Conversion from precipitation data to snowfall and rainfall rates is done using a simple temperature dependent law of Calov and Marsiat (1998).

2.2 Simulation setup

In the period of 1958 to 2009, transient simulations with free evolution of ice surface have been driven by temperature, precipitation and evaporation monthly time series from the ERA-40 (1958–1988) and ERA-Interim (1989–2009) datasets. Gridded monthly precipitation, evaporation and temperature data used in this study are reanalysis products from the ERA-40 and ERA-Interim archives (Betts et al., 2009; Dee et al., 2011) given on a $0.5^\circ \times 0.5^\circ$ grid. From the monthly precipitation (P) and evaporation (E) data for the years 1958 to 2009, 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 difference between ice elevations corresponding to Cartesian and spherical grid cells using monthly temperature lapse rates (Fausto et al., 2009). The new monthly T and P-E fields have been derived on a 10 km × 10 km grid, the resolution adopted for all simulations.

Prior to short-term transient simulations (1958 to 2009), the ice-sheet model has been initialized over 200 thousand years using steady state present-day climate conditions (mean T and P-E fields from the ERA-Interim time series) in order to provide initial conditions at the beginning of the short-term transient simulations. The spin-up simulations with the fixed present-day GIS topography have been driven by different SMB parameterizations. In this study we analyze three existing SMB parameterizations, namely those of Greve (2005), Huybrechts (2002) combined with the retention model of Janssens and Huybrechts (2000) and Tarasov and Peltier (2002), and develop our own parameterization with spatially variable SD (see Sect. 3.2 for detail). All four parameterizations assume rainfall to contribute to the formation of superimposed ice. The details on the parameters adopted for each SMB parameterization are given in Table 1.

The resolution utilized by all simulations is 10 km × 10 km corresponding to 165 × 281 grid points in a stereographic plane. In vertical direction, 81 layers of varying thickness are used for a cold-ice column, with a vertical grid densifying towards the bedrock, and 11 equidistant grid points for the bedrock. Simulation setups are identical for all spin-up and transient simulations with the exception of parameterizations of melting and refreezing rates. Geothermal heat flux forcing data is that of Fox Maule et al. (2009) derived from satellite magnetic data.

3 Results and discussion

3.1 Daily temperature standard deviation as one of major parameters of the positive degree-day model

We derive the spatial distribution of SD across the Greenland region from the ERA-40 temperature time series (Fig. 1).

This reveals strong lateral gradients in the SD field, with the values decreasing dramatically towards the Greenland coasts and showing a clear dependence on surface

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elevation and proximity to the sea coast. Over the summer months, SD values in the areas characterized by the highest surface melting rates are found to 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, summer SD values do not exceed 3 °C, even at high elevations. If averaged over major drainage basins A–G (Figs. 1 and 2), rather low values of summer SD of 1.1 to 2 °C are contrasted by significantly higher values of 5.5 to 7.8 °C over the winter months. Depending on a particular area, mean annual SD values can thus be roughly estimated as about 3.3 to 4.9 °C, which are close to the range of traditionally used uniform values of SD across Greenland (Fig. 2). It is however obvious that these mean annual values are not suitable for modeling surface responses of the GIS in the summer period (Fig. 2), while surface melting rates in Greenland are negligibly low over the rest of the year (Rennermalm et al., 2009).

Over a generalization, the use of such values should result in largely exaggerated surface melt, even though surface runoff rates in different drainage basins show different degrees of sensitivity to a choice of regional SD values (Fig. 3). For instance, responses of modeled runoff rates to a doubling of SD values along the eastern and southern coasts are relatively insignificant (Fig. 3, areas C and D) as compared to the rest of Greenland. The highest sensitivity of the modeled runoff to regional SD values is found in the area B (northeastern Greenland) where runoff increases by 3.5 times (from around 77 to 270 $\mathrm{Gt\,yr^{-1}}$) in response to a doubling of a SD value.

3.2 New parameterization of surface mass balance of the Greenland Ice Sheet with spatially variable daily temperature standard deviation

Based on the summer spatial distribution of SD characteristic for Greenland in the second half of the 20th century (Sect. 3.1), we suggest a new approach to parameterizing SMB of the GIS under interglacial climate conditions. We derive a map of the summer SD distribution across Greenland (mean June, July and August months) and integrate it as a part of a PDD model. Then we design transient simulations of the GIS over the period of 1958 to 2009 driven by the new SMB parameterization with spatially variable

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SD and three existing SMB parameterizations using uniform SD values (see Sect. 2.2). Modeled SMB time series derived from four transient simulations are then averaged over the reference period (1958–2001) and region by region compared to the results of the high-resolution model RACMO2/GR (Ettema et al., 2009; Sasgen et al., 2012).

In the reference period, total SMB values calculated using existing SMB parameterizations with uniform SD values are largely underestimated (Fig. 4) as compared to the results of RACMO2/GR and a range of other independent SMB estimates (Vernon et al., 2012). Among the three existing parameterizations analyzed, the combined parameterization of Huybrechts (2002) and Janssens and Huybrechts (2000) gives the closest match with all independent estimates. The mean value of SMB resulting from this simulation deviates by 60 to 200 $\mathrm{Gt\,yr^{-1}}$ from the existing estimates as opposed to significantly larger deviations of 300 to 400 $\mathrm{Gt\,yr^{-1}}$ 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 the reference period. In contrast, total SMB from the simulation driven by the new SMB parameterization with spatially variable SD arrives at almost perfect agreement with the results of the RACMO2/GR model and falls within the range of other independent estimates close to the upper bound of the estimated range.

On a regional scale, modeled SMB values resulting from the 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). In these areas, the degree of fit between the modeled SMB may however originate from a low sensitivity of the modeled runoff rates to the choice of SD as discussed in Sect. 3.1. All three parameterizations fail to reproduce positive SMB values in the north of Greenland (areas A and B) as suggested by RACMO2/GR and thus underestimate regional SMB by 40 to 100 $\mathrm{Gt\,yr^{-1}}$. 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 the new SMB parameterization with spatially variable SD enables a high degree of agreement with the regional SMB values estimated from RACMO2/GR. Now we arrive at a nearly perfect fit with the values estimated within the areas A and F. Fitting the SMB value within the area F is especially important, since surface runoff from this area accounts for around 40 % of the total runoff in Greenland according to the results of RACMO2/GR (Ettema et al., 2009). Modeled SMB within the areas B and C is now slightly too high whereas it is still too low within the areas D, E and G but overall fit between the independent modeling approaches (SMB as in SICOPOLIS and SEB as in RACMO2/GR) has improved considerably as compared to the other existing SMB parameterizations analyzed in this study.

3.3 Validation of the new parameterization versus satellite observations

Finally we validate our modeling results derived using the new SMB parameterization by comparing them with the ice mass trends in Greenland estimated from recent satellite observations (Sasgen et al., 2012). To enable such comparison, one has to separate changes in ice mass induced by increased/decreased surface runoff from those due to acceleration/deceleration of ice discharge into the ocean. In the following we assume that relative trends in the observed ice mass changes induced by the two major sources of ice loss are relatively well captured by RACMO2/GR. In general, such assumption may be considered poorly justified, since the total trends in mass changes estimated from satellite data are not perfectly reproduced by the RACMO2/GR model (Sasgen et al., 2012). However, these are currently the most comprehensive estimates available on a regional scale, which are constrained by a wide range of in-situ measurements (Ettema et al., 2009). We therefore calculate trends in the SMB (the instrumental record (2003 to 2009) relative to the reference period) by subtracting the contribution of ice discharge provided by RACMO2/GR from the total mass trends derived from satellite observations (Fig. 5).

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Then we compare these with the corresponding trends in the modeled SMB from RACMO2/GR and our simulation driven by the new SMB parameterization. The comparison of SMB trends reveals that the use of the new SMB parameterization gives an excellent fit with the trends estimated within the areas B, C and E (falling within the range of estimated errors, Sasgen et al., 2012). Our simulation arrives at the same estimate of the trend obtained from RACMO2/GR within the area B, and results in a significantly better fit with the trends estimated in the areas C and E as compared to the results of RACMO2/GR. A slightly better fit has also been obtained within the area D ($-8\,\mathrm{Gt\,yr^{-1}}$ from our simulation versus $-19\,\mathrm{Gt\,yr^{-1}}$ from the satellite data analysis) where RACMO2/GR is likely to underestimate the regional SMB trend ($-6\,\mathrm{Gt\,yr^{-1}}$ from RACMO2/GR). Our simulated trends along the western and northern slopes of the GIS (areas A, F and G) are overall overestimated as compared to both the results of RACMO2/GR and estimates from satellite data. The use of the new SMB parameterization results in a large error in the SMB trend within the area F as compared to the trend from the satellite data analysis. However, our modeled trend within the area F is close to that obtained from RACMO2/GR, meaning that either both models equally fail to reproduce the observed trend or our assumption about the contribution of ice discharge to the observed mass trend does not hold in this area. Assuming that the SMB trends derived from the observed mass trends are not fully unrealistic, our simulated total SMB trend of $-168\,\mathrm{Gt\,yr^{-1}}$ falls within the range of estimated errors, although at its upper bound (Fig. 5).

4 Conclusions

This study aims to demonstrate that the use of more realistic values of major parameters within a PDD model leads to significant improvements in the modeled surface responses of the GIS on a regional scale. Here we mostly concentrate on assessing a specific role of spatial and seasonal variations of daily temperature standard deviation in driving ice surface evolution over time. Our findings point out that the common

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assumption about this parameter being spatially uniform across the entire Greenland region does not receive support from the climate datasets available. Summer SD values inferred from the ERA-40 climate dataset are four to six times lower than commonly used uniform values in the areas where most surface runoff occurs. Modeled surface runoff along the western and northern slopes of the GIS is found to be highly sensitive to a choice of regional SD values and is therefore, to a large extent, determined by strong lateral gradients in the SD distribution oriented towards the Greenland coasts. Efficiency of the new SMB parameterization with spatially variable SD parameter has been tested in application to the recent evolution of the GIS and has proven to give a high degree of agreement with the SMB trends extracted from satellite observations and the results of a state-of-the-art modeling approach based on an independent SEB method. Improvements in the modeled surface responses of the GIS induced by the use of more realistic SD values suggest that the current approach to a long- and short-term modeling of ice surface evolution under interglacial climate conditions (former, present and future) 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, a comprehensive analysis of this major parameter of a PDD model is needed to enable realistic modeling of the GIS history and its present-day state.

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Table 1. Description of SMB parameterizations analyzed in this study.

SMB parameterization	Ice specific heat capacity $[\mathrm{J\,(kg\,^{\circ}C)^{-1}}]$	Standard deviation, σ [°C]	Degree-day factors (snow), $[\mathrm{mm\,(^{\circ}C\,d)^{-1}}]$	Degree-day factors (ice), $[\mathrm{mm\,(^{\circ}C\,d)^{-1}}]$	Retention model
Greve (2005)/ New param.	$146.3 + 7.253T$	4.5/spatially variable[a]	$\beta^{\mathrm{b}}_{\mathrm{cold}} = \beta_{\mathrm{warm}} = 3$	$\beta^{\mathrm{b}}_{\mathrm{cold}} = 15$; $\beta_{\mathrm{warm}} = 7$	Greve (2005)
Tarasov and Peltier (2002)	$152.5 + 7.122T$	5.2	$\beta^{\mathrm{b}}_{\mathrm{cold}} = 2.65$; $\beta_{\mathrm{warm}} = 4.3$	$\beta^{\mathrm{b}}_{\mathrm{cold}} = 17.22$; $\beta_{\mathrm{warm}} = 8.3$	Tarasov and Peltier (2002)
Huybrechts (2002)	$2115.3 + 7.79T$ $[\mathrm{J\,(kg\,K)^{-1}}]$	5	$\beta_{\mathrm{cold}} = \beta_{\mathrm{warm}} = 3$	$\beta_{\mathrm{cold}} = \beta_{\mathrm{warm}} = 8$	Janssens and Huybrechts (2000)

[a] See Sects. 3.1 and 3.2 for detail. [b] Degree-day factors for cold conditions are only applied to the area north of 72° N (e.g., Greve, 2005).

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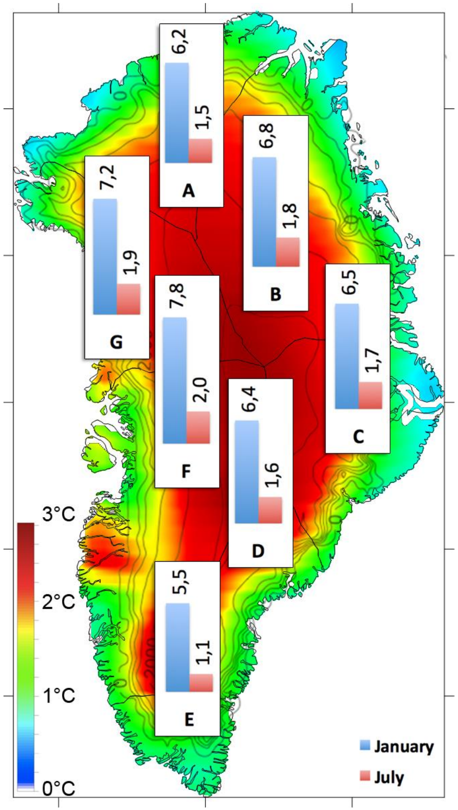

Fig. 1. Map of daily temperature standard deviation, σ (see Eqs. 1 and 2), derived for the July month using the ERA-40 climate dataset (1958–2001). The bars show the July and January values of SD averaged over major drainage basins A to G in Greenland.

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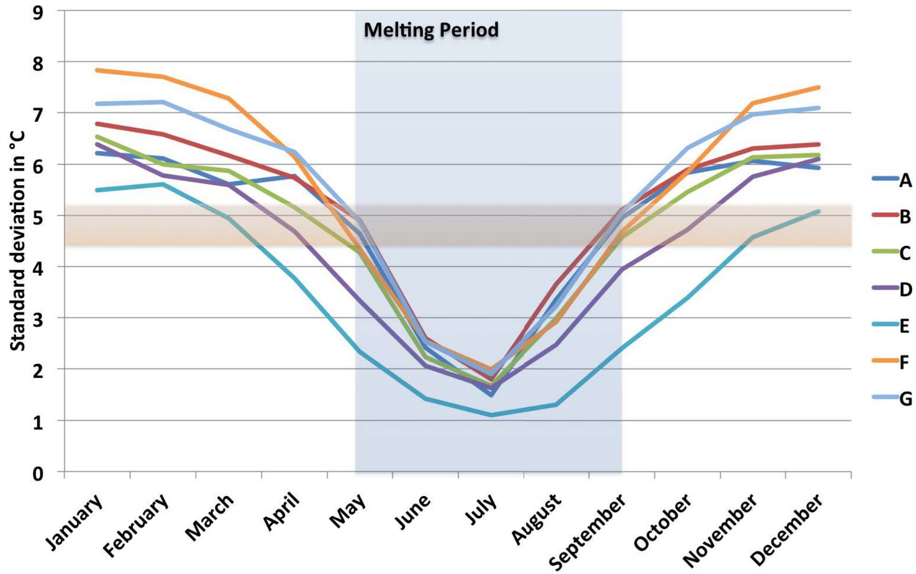

Fig. 2. Monthly values of SD derived from the ERA-40 temperature time series (1958–2001) and averaged over major drainage basins A to G (see Fig. 1 for area locations). The horizontal shaded area outlines commonly used uniform values of SD. The vertical shaded area shows the length of surface melting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

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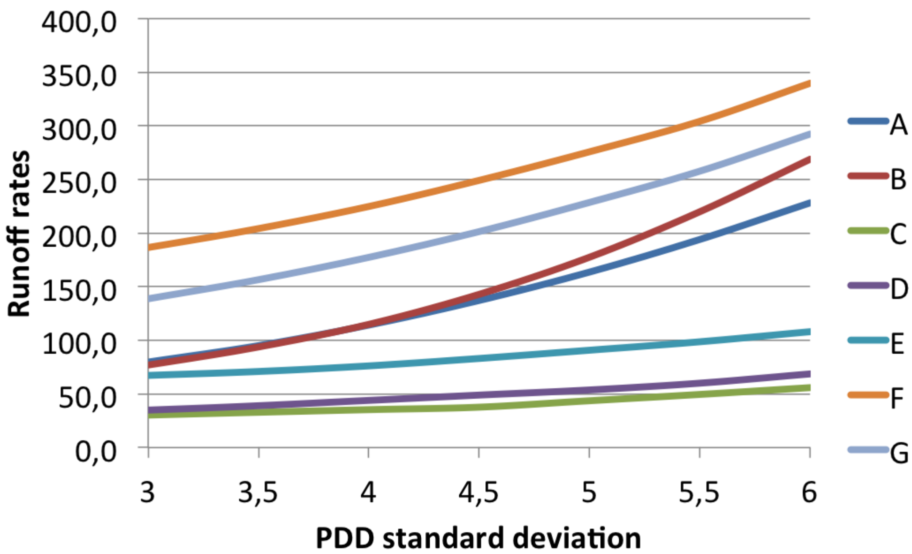

Fig. 3. Regional sensitivity of the modeled surface runoff rates ($\mathrm{Gt\,yr^{-1}}$) (mean annual values averaged over the reference period, 1958–2001, using the SMB parameterization of Greve, 2005) to a perturbation in SD values. Areas A to G are given in Fig. 1.

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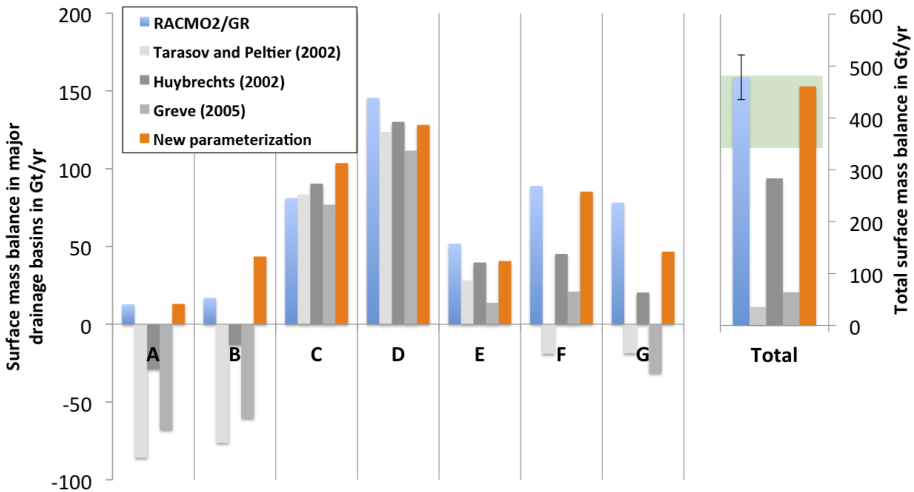

Fig. 4. Comparison of modeled values of regional and total SMB obtained from RACMO2/GR (blue), three SMB parameterizations of Tarasov and Peltier (2002), Huybrechts (2002) and Greve (2005) (grey), and the new SMB parameterization with spatially variable SD (orange). The SMB values are mean over the reference period, 1958 to 2001. Areas A to G are given in Fig. 1.

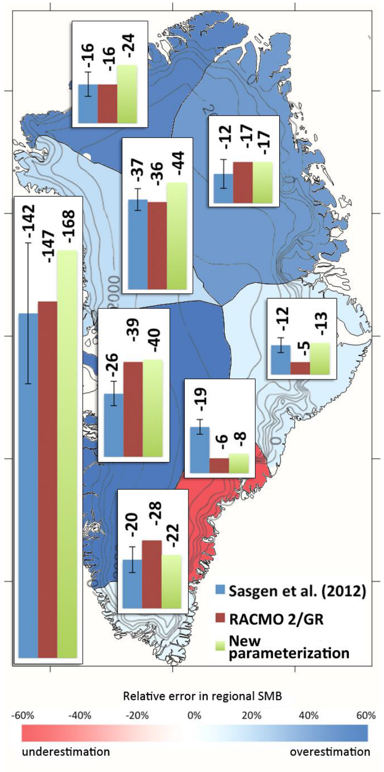

Fig. 5. SMB trends in Greenland (Gt yr^{-1}) (2003–2009 relative to the reference period) derived from ice mass trends in Greenland from satellite observations (Sasgen et al., 2012) corrected for ice discharge contribution (see Sect. 3.3 for detail). Error bars are those from Sasgen et al. (2012). Modeled SMB trends from RACMO2/GR and SICOPOLIS simulation using the new SMB parameterization with spatially variable SD. The color map provided in the background shows errors in our modeled SMB trends relative to the trends obtained from satellite data.

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