Impact of model physics on estimating the surface mass balance of the Greenland ice sheet

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[1] Long-term predictions of sea level rise from increased Greenland ice sheet melting have been derived using Positive Degree Day models only. It is, however, unknown precisely what uncertainties are associated with applying this simple surface melt parameterization for future climate. We compare the behavior of a Positive Degree Day and Energy Balance/Snowpack model for estimating the surface mass balance of the Greenland ice sheet under a warming climate. Both models were first tuned to give similar values for present-day mass balance using 10 years of ERA-40 climatology and were then run for 300 years, forced with the output of a GCM in which atmospheric CO_2 increased to 4 times preindustrial levels. Results indicate that the Positive Degree Day model is more sensitive to climate warming than the Energy Balance model, generating annual runoff rates almost twice as large for a fixed ice sheet geometry. Roughly half of this difference was due to differences in the volume of melt generated and half was due to differences in refreezing rates in the snowpack. Our results indicate that the modeled snowpack properties evolve on a multidecadal timescale to changing climate, with a potentially large impact on the mass balance of the ice sheet; an evolution that was absent from the Positive Degree Day model. **Citation:** Bougamont, M., J. L. Bamber, J. K. Ridley, R. M. Gladstone, W. Greuell, E. Hanna, A. J. Payne, and I. Rutt (2007), Impact of model physics on estimating the surface mass balance of the Greenland ice sheet, *Geophys. Res. Lett.*, *34*, L17501, doi:10.1029/2007GL030700.

1. Introduction

[2] For the 21st century, the predicted sea level contribution from the Greenland ice sheet (GrIS) is +0.5 ± 0.4 mm/year, for all climate scenarios and a range of climate models [*Alley et al.*, 2005; *Church et al.*, 2001]. However, these predictions used a Positive Degree Day Model (PDDM) to determine the surface mass balance (SMB) [e.g., *Huybrechts and De Wolde*, 1999; *Huybrechts et al.*, 2002; *Ridley et al.*, 2005], which determines the amount of melt using a temperature threshold only. A more physically-based approach is to use an energy balance and snowpack model (EBSM), which takes into account all the fluxes of heat at the surface but requires considerably more inputs to drive it. The main reason for using a PDDM is the limited data required to force it. Both methods can give similar results for present-day surface mass balance when appropriately tuned [e.g., *Box et al.*, 2004; *Hanna et al.*, 2005], but are known to have different sensitivities to climate forcing [*van de Wal*, 1996]. Changes in cloud cover, for example, have a direct impact on the radiative balance of an EBSM but only indirectly influence a PDDM through their effect on surface temperature. The only study that compared the behaviour of each approach indicated that the mass balance sensitivity of a PDDM to a 1°C warming is 20% higher than that of an EBSM [*van de Wal*, 1996]. Here, we investigate the potential impact on estimates of the GrIS SMB that rely on just one highly parameterized scheme. We compare a PDDM and an EBSM to calculate the SMB of the GrIS in a warming climate as prescribed by a transient run of the Hadley Centre Climate Model version 3 (HadCM3). While we examine the differences between the two models to a future climate forcing scenario, assessing which model performs ''best'' is not the purpose of this study.

2. Methods

[3] The PDDM used in this study is the daily degree day scheme similar to the annual one described by *Reeh* [1991], and takes into account ice and snow melt, the diurnal cycle, liquid precipitation and refreezing of meltwater based on a fraction of the total snow deposited. The EBSM used here is validated and described by *Bougamont et al.* [2005]. Physically-based equations are used to estimate the energy available for melt, and refreezing is evaluated using a scheme that models the evolution of the snowpack through time. The model runs with a time step of 2 hours.

[4] Each model was first tuned to produce annual runoff rates close to estimates by *Hanna et al.* [2005]. To this end, they were forced with 6-hourly European Centre for Medium-range Weather Forecast (ECMWF) reanalysis (ERA-40) data for the period 1991–2000. The PDDM was driven with precipitation and 2 m -air temperature fields. The latter was corrected for biases using empirically-derived lapse rates at a 0.5° by 0.5° resolution [*Hanna et al.*, 2005]. The additional input required to drive the EBSM includes downward shortwave and longwave radiation, surface pressure, wind field and 2 m-atmospheric humidity. All fields were resampled to match the model resolution of 20 km, using bilinear interpolation. For the PDDM, the degree-day factors for ice and snow (PDD_{ice} and PDD_{snow} respectively), as well as the fraction of snow cover to be exceeded before

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Table 1. Summary of the Tuned Variables Used in This Study

Model	Tuned Variables	Value
PDDM	PDD_{ice}	0.007 mm °C^{-1} day^{-1}
	PDD_{snow}	0.003 mm °C^{-1} day^{-1}
	$P_{\max}$	0.6
EBSM	α_{ice}	0.4
	α_{old}	0.3
	w*	150 mm
	c_2	35
	c_3	48.6

runoff occurs ($P_{\max}$), were used as tuning parameters. The values adopted (Table 1) are within the range of commonly used values determined based on observations [*Braithwaite*, 1995; *Braithwaite et al.*, 1994; *Lefebre et al.*, 2002]. The list of tunable parameters is longer for the EBSM. Parameters have identical values to *Bougamont et al.* [2005], with the exception of ice and old snow albedo (α_{ice} and α_{old} respectively), the characteristic scale for surficial water (w*), and two constants used to calculate the timescale for runoff to occur (c_2 and c_3 in equation 13, *Bougamont et al.* [2005]). New values are summarized in Table 1. The mean annual runoff production for the period 1991–2000 are within about 10% of the *Hanna et al.* [2005] estimates (which have a measurement of interannual variability of 10%), with a high correlation coefficients of 0.85 and 0.92 when calculated with the PDDM and EBSM, respectively.

[5] Both models were then run for a period of 300 years, forced with HadCM3 output, for a simulation where the initial CO_2 level matches present-day conditions and increased by 1% every year for 110 years (until it reached four times pre-industrial levels). This resulted in a mean temperature increase over Greenland of ~11°C and an ~55% increase in precipitation. For the remaining 190 years, the climate was kept constant by repeating the last 10 warmest years. Monthly anomalies were applied to the temperature field to avoid a known winter cold bias of up to 10°C in the HadCM3 climate [*Ridley et al.*, 2005]. For consistency, we also used monthly anomalies for all other required fields. Our reference climate is identical to the one used in the tuning phase.

[6] We present model results for an idealized configuration, with a fixed geometry ice sheet corresponding to that of the present-day throughout the run. Here, feedbacks from changes in elevation have purposefully been removed so that the response of the two mass balance schemes to changes in surface forcing can be isolated from other effects. For similar reasons we have not included ice dynamics, and restrict the analysis to the behaviours of the SBM models. We do not, therefore, attempt to predict the future behaviour of the ice sheet.

3. Results and Discussion

[7] Figure 1a displays the time-series of the annual net SMB, total melt and refreezing rates, averaged over a 10-year period. The net SMB diverges during the warming period, reaching a maximum difference at year 110 of up to ~900 Gt. The annual runoff production at year 110 is almost twice as much for the PDDM compared with the EBSM (2050 Gt versus 1250 Gt). Under a constant forcing (i.e. after year 110), the net SMB and all its components remain unchanged for the PDDM, while the EBSM net SMB becomes increasingly negative as the annual runoff rates continue to rise. Likewise, the surface area in which runoff occurs in the EBSM continues to expand after year 110, while the PDDM runoff area remains constant (Figure 1b). Whereas the PDDM calculates the mass balance as a direct response to temperature change, the EBSM mass balance depends strongly on the surface albedo value, and the expansion of the runoff limit inland can be explained for the most part by surface albedo feedbacks. These depend on the snowpack and surface properties [*Brun et al.*, 1992; *Oerlemans and Knap*, 1998; *Warren*, 1982; *Zuo and Oerlemans*, 1996], as well as on the ice sheet geometry (which affects the speed of meltwater transport) [*Bougamont et al.*, 2005; *Knap and Oerlemans*, 1996; *Zuo and Oerlemans*, 1996]. The surface albedo value drops as melt increases, removing snow from the surface. The inland migration of the EBSM runoff limit (Figure 1b) supports the inference that surface albedo feedbacks are important controls on the SMB.

[8] As the runoff volume is determined by both the total melt and refreezing volumes generated, we compare these

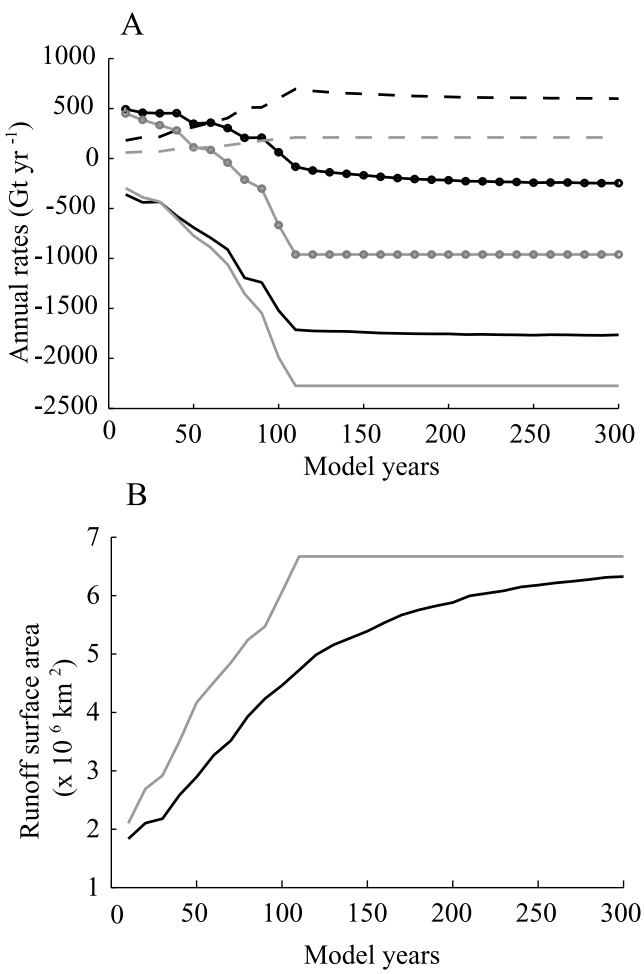

Figure 1. (a) Annual net surface mass balance (circles), total melt rates (solid), and refreezing rates (dashed) for the EBSM (black) and the PDDM (gray). (b) Runoff surface area for the EBSM (black) and the PDDM (gray).

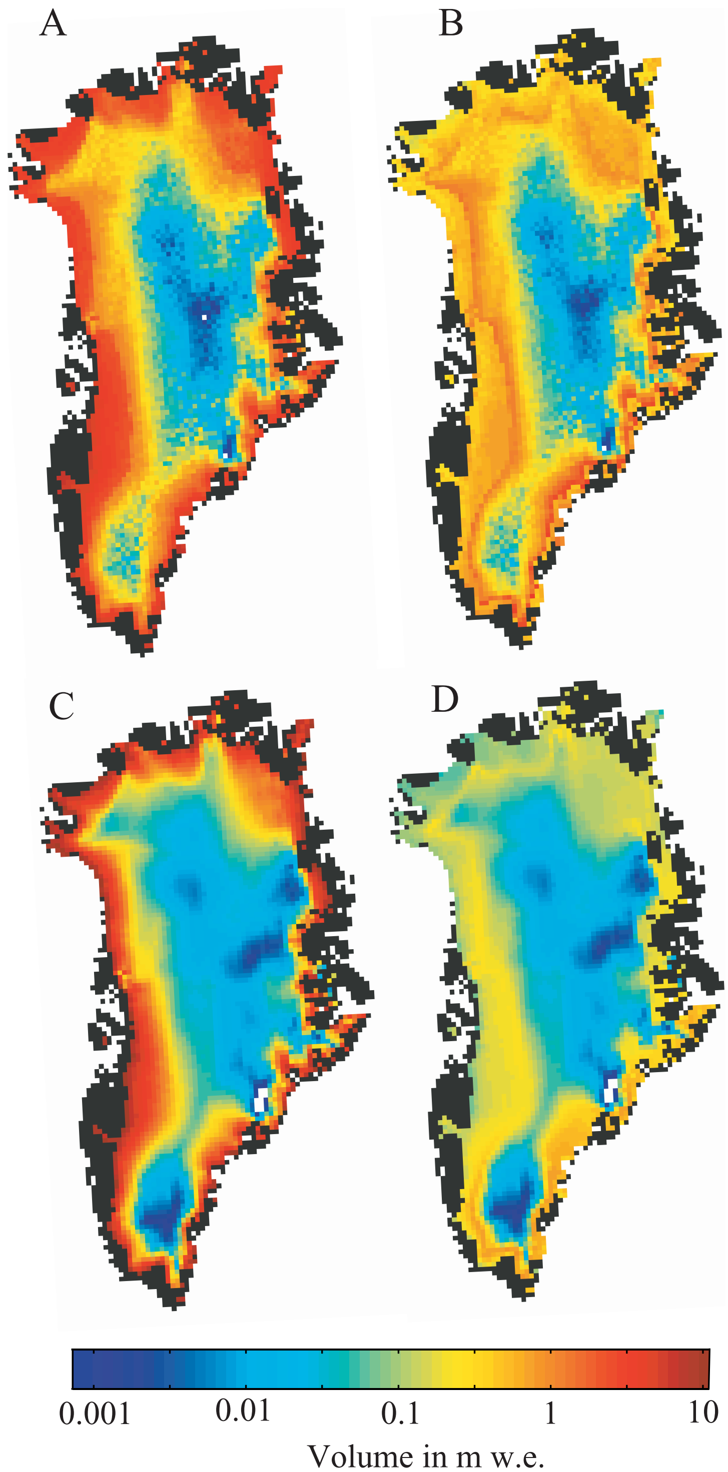

Figure 2. Total melt (left) and refreezing (right) volumes averaged for decade 11 (i.e., at the end of the warming period) in meters of water equivalent. Results for the EBSM are presented in Figures 2a and 2b, while results for the PDDM are presented in Figures 2c and 2d.

for each model in Figure 2. The cumulated volume of total melt, refreezing and runoff generated by year 110 and 300 are summarized in Table 2. The variation in cumulated refreezing volume is larger than the variation in cumulated total melt volume. At year 110, refreezing alone accounts for 88% of the cumulated runoff difference, versus 50% for the total melt (Table 2). While some differences in total melt production are evident (e.g. higher PDDM coastal melt rate, higher EBSM rates near the ELA), the difference in refreezing volume and pattern appears much more significant (Figure 2). The EBSM refreezing volume is consistently greater than the PDDM one. Moreover, the EBSM refreezing rates are generally highest near the ELA, while the PDDM rates are the highest in the south and southeast of

Table 2. Cumulated Volume of Total Melt, Refreezing, and Runoff Produced by the EBSM, and Difference With the PDDM Results, at Years 10 (Runoff Only), 110, and 300 in Centimeters of Sea Level Rise[a]

	Total Melt		Total Refreezing		Runoff		
Model	Year 110	Year 300	Year 110	Year 300	Year 10	Year 110	Year 300
EBSM	26.9	120.0	11.7	44.6	0.6050	18.6	90.5
PDDM-EBSM	+4.6	+31.8	−8.0	−29.7	+0.0496	+9.1	+46.4

[a]Note that while the relationship between the total melt, refreezing, and runoff volume is straightforward in the PDDM used here (the runoff is equal to total melt minus total refreezing), it is not the case in the EBSM, where meltwater can also be stored in the EBSM subsurface layers.

the ice sheet. Strong refreezing also occurs near the ELA on the west side of the ice sheet (although to a lesser degree compared to the EBSM case), but no such pattern can be seen in the northeast.

[9] Figure 3 displays the volume of refreezing per unit area of ice sheet where melt occurs. The EBSM refreezing rate per unit area greatly exceeds the PDDM value at all times. In both cases, the refreezing volume per unit area increases during the first 110 years because the melt volume (Figure 1a) and area increase significantly (the ELA migrates inward as the climate warms up). By the end of the warming period, the EBSM (PDDM) refreezing volume per unit area increases by 61% (22%), confirming a greater sensitivity of the EBSM refreezing scheme to climate change.

[10] The evolution of the refreezing under constant climate (Figure 3) reveals another key difference between the EBSM and the PDDM, in that the EBSM refreezing scheme continues to respond to the changed forcing while the PDDM refreezing scheme is static. Using the EBSM, the peak in refreezing occurs at the end of the warming period. After the climate is kept constant, the refreezing volume decreases markedly near the ELA, along the south eastern coast, and to a lesser degree in the northeast part of the ice sheet. As the snowpack warms up, the melt water percolating down the layers will refreeze less and less efficiently. The EBSM refreezing volume decreases because the effect of the warming snowpack dominates the slight increase of melt volume (Figure 1a) and area. This suggests that the modeled snowpack has a multi-decadal memory that can impact on the mass balance. This effect is absent from the PDDM, which has no "thermal inertia".

[11] It is possible that alternative model tuning could lead to closer agreement between the model estimates of mass balance. However, the PDDM parameters used here have been derived from field observations and are relatively realistic [*Braithwaite*, 1995; *Lefebre et al.*, 2002]. The EBSM was originally tuned to match in-situ observations of mass balance along the K-Transect [*Bougamont et al.*, 2005] and ETH-Camp [*Greuell and Konzelmann*, 1994] in southwest Greenland. Moreover, the EBSM tunable parameters expected to have the greatest impact on mass balance affect mostly the melt generation (via the surface albedo as well as the timescale for runoff formation), and less so the refreezing processes. The latter is controlled by (1) the water availability, (2) the space availability, and (3) the temperature within the snowpack [*Bougamont et al.*, 2005; *Greuell and Konzelmann*, 1994]. Sensitivity experiments on the mass balance model indicate that the englacial parameterization is most affected by uncertainties in the equation used for conductivity and for energy penetration [*Greuell and Konzelmann*, 1994]. However, the effects of those on the net SMB remain limited compared to the effect of uncertainties in albedo and precipitation [*Greuell and Konzelmann*, 1994]. Finally, even if the refreezing schemes had been tuned to give the same initial values, they would soon diverge due to the effect of changing snowpack properties on the EBSM refreezing calculations in long-term simulations.

4. Conclusion

[12] We find that the PDDM has a larger response to the simulated climate warming than the EBSM (concurring with *van de Wal* [1996]), translating into more than a factor 2 difference in the cumulative net surface mass. First, the PDDM does not include a parametrization for a change in lapses rates, specific humidity, winds and cloud cover associated with climate change. Second, important albedo feedbacks are not explicitly incorporated into a PDDM. Third, with larger EBSM refreezing rates, a cumulative divergence over time would be expected up to the point where the snow can admit no more water for refreezing. Relatively little work has been done on determining a robust and accurate refreezing scheme for Greenland, partly due to the lack of in-situ observational data to validate such a scheme, yet it is clear from this study that (1) refreezing is an important component of the SMB (concurring, for example, with *Janssens and Huybrechts* [2000]), (2) there

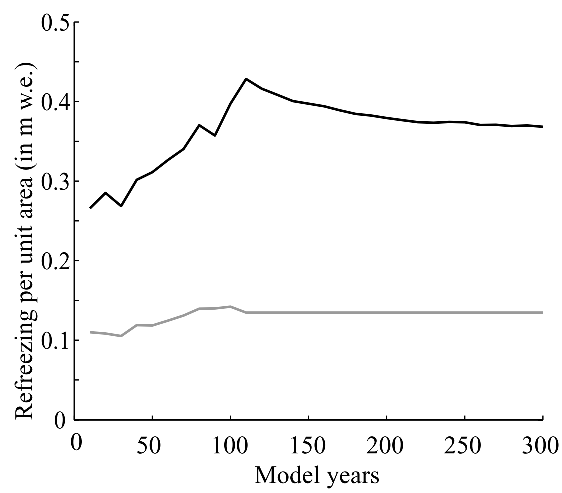

Figure 3. Total refreezing volume (in meters of water equivalent) divided by the area experiencing melt for the EBSM (black) and PDDM (gray).

are large discrepancies between different methods that are being used, and (3) it is, at present, without adequate in-situ observations, difficult to determine whether one refreezing scheme is significantly "better" than another.

[13] Furthermore, the type of scheme used is constrained by the "surface melt" model chosen. PDDMs must employ relatively simple refreezing schemes as there is no way of calculating the sub-surface temperature and energy budget in the snowpack with a PDDM. It should be noted, however, that more sophisticated PDDM refreezing schemes than the one used here exist [e.g., *Huybrechts and De Wolde*, 1999; *Pfeffer et al.*, 1991]. They were tested against each other, with the conclusion that the more complex refreezing schemes generated runoff volumes comparable to the simpler ones, and had similar sensitivities to warming scenarios [*Janssens and Huybrechts*, 2000], which appears to be at odds with the findings of this study. The main reason for this, we believe, lies in the multi-decadal response of the modelled EBSM snowpack to a past change in climate. Long term predictions of sea level rise from increased GrIS runoff have so far been derived using a PDDM. In view of the results presented here, we conclude that large uncertainties in estimates of the future surface mass balance response of the ice sheet remain. Substantial increases in ice velocity have recently been observed in Greenland [e.g., *Joughin et al.*, 2004; *Rignot and Kanagaratnam*, 2006]. As a consequence, there has been growing interest in the role of changes in ice dynamics on the mass balance of the GrIS and the inability of numerical models to reproduce these dynamic changes [*Joughin*, 2006]. The observed increased loss due to ice dynamics amounts to $\sim$100 Gt a^{-1} [*Rignot and Kanagaratnam*, 2006] or about 15% of the annual mass turnover. By contrast, the impact of model physics on the prediction of future surface mass balance amounts to $\sim$800 Gt a^{-1} within a century. We suggest, therefore, that our ability to predict the future behavior of the GrIS is constrained not only by uncertainties in modeling ice dynamics but equally by our ability to adequately model the surface mass balance.

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