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Application of a Degree-Day Mass Balance Model to the Qamanârssûp Sermia Outlet Glacier, West Greenland

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1. ABSTRACT

A degree-day glacier mass balance model is applied to the Qamanârssûp sermia outlet glacier, West Greenland. Degree-day factors for snow and ice are found using an automatic calibration procedure. The best fit degree-day factors found using mass balance data from 1979/80-1986/87 in the elevation range 370-1410 m a.s.l. are in relatively good agreement with previously published values which were computed directly from mass balance measurements close to the location of the temperature station at 760 m a.s.l. The best fit degree-day factors are found to be about 0.0073 $m_{w.e.}$/°C/d for ice, and about 0.0028 $m_{w.e.}$/°C/d for snow. For comparison, degree-day factors computed by Braithwaite and Olesen (1989) from mass balance measurements at 790 m a.s.l. were 0.0077 $m_{w.e.}$/°C/d for ice, and 0.0025 $m_{w.e.}$/°C/d for snow.

The best fit degree-day factor for ice found by the calibration procedure is lowered significantly and the agreement with the previously found values becomes poorer when mass balance data below 370 m a.s.l. are included in the data set. This is caused by very low and even negative mass balance gradient with elevation below this altitude, which is not accounted for in the model computations in a satisfactory manner.

Model results in the elevation range 370-1410 m a.s.l. are in fair agreement with the measured variation in the average mass balance with elevation. In addition, the model explains about 70% of the year to year variance in the average mass balance of each year using a single parameter set. When data below 370 m a.s.l. are included, the model explains about 60% of the year to year variance in the average mass balance of each year using a single parameter set.

The increase in glacier ablation on Qamanârssûp sermia due to a warming of 2 °C is predicted to range from about 1.2 $m_{w.e.}$ per year at the highest elevations to 2.5 $m_{w.e.}$ at the lowest elevations. Predicted changes in the accumulation are small or negligible even if the the warming is accompanied by a 10% increase in the precipitation.

2. INTRODUCTION

This report is an addendum to the NHP report "Degree-day mass balance modelling with applications to glaciers in Iceland and Norway" by Tómas Jóhannesson, Oddur Sigurðsson, Tron Laumann and Michael Kennett (1993). The degree-day mass balance model *mbt*, which is described in the NHP report, is applied to mass balance data from Qamanârssûp sermia, West Greenland, and the estimated degree-day factors are compared with degree-day factors which have been directly estimated from mass balance and temperature measurements.

Mass balance data from glaciers and ice sheets contain implicit information about the dependence of glacier mass balance on climate. The measured mass balance varies with elevation and from year to year, mainly as a consequence of the fall of temperature with altitude and as a consequence of yearly temperature fluctuations. It is therefore possible to use measured variations in the mass balance together with meteorological data to parametrize the relation between glacier mass balance and climate using a suitable glacier mass balance model. The mass balance model may then be used to estimate likely glacier mass balance changes resulting from hypothetical climatic changes, *e.g.* climatic warming caused by increasing concentration of greenhouse gasses in the atmosphere. In this way, measured mass balance variations with elevation and time can be used to estimate the sensitivity of glaciers to climate changes. This approach was used in the abovementioned NHP report using data from the glaciers Sátujökull (part of Hofsjökull), central Iceland and Nigardsbreen (part of Jostedalsbreen) southern Norway.

The mass balance data from Qamanârssûp sermia, which are analyzed below, have the advantage over the data from Iceland and Norway that detailed measurements of summer ablation and temperature at a single elevation have been used to estimate degree-day factors for melting of ice and snow directly. These direct estimates of the degree-day factors can be used to verify the result of the calibration of the glacier mass balance model, which is predominantly derived from the measured mass balance gradient with elevation.

The degree-day glacier mass balance model involves a number of parameters which are described in detail in the NHP report. This description will not be repeated here, but the reader is referred to the NHP report.

The mass balance model is derived for temperate glaciers and ice caps. The Greenland ice sheet is of course not temperate. However, the mass balance data from Qamanârssûp sermia come from the ablation area of the ice sheet where special considerations related to cold ice sheets (*e.g.* superimposed ice) are not needed.

3. MASS BALANCE AND METEOROLOGICAL DATA

The mass balance data from Qamanârssûp sermia are from 14 "center-line" stakes from the mass balance years 1979/80-1986/87 and span the elevation range 110-1410 m a.s.l. Missing mass balance data are estimated by a statistical procedure using data from the other stakes (Braithwaite, personal communication). The mass balance year is defined to extend from 1 September to 31 August. The model computations are based on monthly temperature averages computed from temperature measurements at Qamanârssûp sermia base camp (64°29'N, 49°29'W, 760 m a.s.l., a few hundred meters from Stake 751 at 790 m a.s.l. on the glacier). Missing temperature values are estimated from temperatures at Nuuk/Godthåb, about 150 km away from Qamanârssûp sermia (Braithwaite, personal communication). The mass balance and temperature measurements were carried out by the Geological Survey of Greenland (Grønlands geologiske undersøgelse, GGU) (Olesen and Braithwaite, 1989, Braithwaite and Olesen, 1989).

The degree-day computations are based on monthly temperature averages assuming temperature deviations from the monthly mean to be normally distributed with a standard deviation σ (Braithwaite, 1984), which is given as a model parameter. The standard deviation of the temperature deviations was chosen to be $\sigma = 3.5$ °C, which is between the values of σ used in the NHP report for Iceland and Norway (3.3 and 3.1 °C) and the value used by Braithwaite (1984) for Qamanârssûp sermia (4.0 °C). This difference in the value of σ has insignificant effect on the degree-day sum and on the corresponding computed ablation. The degree-day computations in the NHP report were mainly based on daily temperature data. It is shown in the NHP report that degree-day sums computed from daily temperature data with the *mbt* model are consistent with degree-day sums computed from monthly temperature data.

Accumulation or winter balance at the stakes on Qamanârssûp sermia is not available. Winter balance measurements for stakes at 1200 and 1410 m a.s.l. together with measured precipitation at Nuuk/Godthåb and measured summer precipitation at the Qamanârssûp sermia base camp indicates that the yearly precipitation on the glacier is between 0.5-1.0 $m_{w.e.}$, with little gradient with elevation. A fixed value of 0.7 $m_{w.e.}$ for the yearly precipitation with uniform distribution between the months of the year is used in the model computations. Other values of the precipitation did not affect the model calibration significantly except for the degree-day factor for snow, which is highly dependent on the value chosen for the precipitation as would be expected. Varying the precipitation from year to year based on variation in the measured precipitation at Nuuk/Godthåb turned out to have little effect on the model calibration. Wind correction for snow or rain is not used and no precipitation gradient with elevation is specified.

The 14 center-line stakes do not include Stake 751 which was used by Braithwaite and Olesen (1989) for estimating degree-day factors. The calibration performed below may therefore be considered independent of the previously estimated degree-day factors. The mass balance measurements exhibit considerable local deviations from a smooth variation with elevation (*cf.* Figure 1 below). Above about 370 m a.s.l., the local deviations can in most cases be explained by local conditions which lead for example to increased snow accumulation in local depressions and decreased accumulation on topographic ridges in the glacier landscape (Braithwaite, personal communication). Below about 370 m a.s.l., the measurements show essentially no mass balance gradient with elevation over an elevation range of about 300 m. This feature of the mass balance profile is difficult to explain (it might to some extent be caused by local advection of cold air from adjacent areas to the lower parts of the glacier according to Braithwaite, personal communication) and it cannot be adequately modelled by a simple glacier mass balance model as employed here.

The mass balance measurements from Qamanârssûp sermia are yearly or net balance measurements, whereas the measurements from from Sátujökull and Nigardsbreen are both winter balance and summer balance measurements. The winter balance depends primarily on the precipitation and the summer balance is most sensitive to summer temperature. Therefore, measurements of both winter and summer balance make it easier to derive estimates of model parameters which affect the yearly mass balance in a similar way. As a consequence, the model parameters for Qamanârssûp sermia are not as well constrained as for Sátujökull and Nigardsbreen.

4. MODEL CALIBRATION

The fixed model parameters for Qamanârssûp sermia are given in Table I (for explanation of the meaning of the parameters, see the Appendix in the NHP report).

TABLE I: Fixed model parameters for Qamanârssûp sermia.

Parameter	Name	Value	Unit
Standard deviation of temperature deviations	*sgm*	3.5	°C
Snow/rain threshold	*tsn*	1.0	°C
Precipitation/elevation gradient	*grp*	Not used	1/100m
Rain correction factor	*rko*	Not used	1
Snow correction factor	*sko*	Not used	1
Precipitation correction factor	*pko*	Not used	1
Snow thickness used in degree-day computations	*sis*	0.3	$m_{w.e.}$
Refreezing ratio	*rfr*	0.07	1
Elevation of temperature station	*elt*	760	m a.s.l.
Elevation of precipitation station	*elp*	Not used	m a.s.l.
Starting elevation for precipitation gradient	*elq*	Not used	m a.s.l.

The remaining model parameters, *i.e.* the degree-day factors for ice and snow and the temperature gradient, are found by calibrating the model against the mass balance measurements using a non-linear least squares procedure (Chambers and Hastie, 1992).

The calibration was carried out firstly for the mass balance data in the entire elevation range 110-1410 m a.s.l. The results of this calibration using the mass balance measurements from the years 1979/80-1986/87 are given in Table II.

TABLE II: Best fit parameter values (Parameters I) determined from the measured yearly balance in the elevation range 110-1410 m a.s.l. on Qamanârssûp sermia.

Parameter	Name	Value	Unit
Degree-day factor for ice	*ddi*	0.0065	$m_{w.e.}$/°C/d
Degree-day factor for snow	*dds*	0.0035	$m_{w.e.}$/°C/d
Temperature lapse rate	*grt*	0.52	°C/100m
Residual variance	σ_δ^2	0.7	$m_{w.e.}^2$
Residual standard error	σ_δ	0.9	$m_{w.e.}$

Figure 1A below shows the average of the mass balance measurements at each elevation (symbols) together with the model results (dashed curves) corresponding to the calibration in Table II (Parameters I). There are systematic differences between the measurements and the model results such that the mass balance gradient above about 370 m a.s.l. is greatly underestimated. This is caused by mass balance measurements below 370 m a.s.l. where the mass balance gradient is essentially zero over an elevation range of about 300 m. As discussed in the previous section, this feature of the mass balance profile is difficult to explain, but it might be caused by some local meteorological conditions which cannot be taken into account in the mass balance model in the absence of more detailed meteorological information. The parameter values in Table II are not in particularly good agreement with the degree-day factors estimated from measurements at 790 m a.s.l. (Braithwaite and Olesen, 1989) which are 0.0077 $m_{w.e.}$/°C/d for ice and 0.0025 $m_{w.e.}$/°C/d for snow. This is perhaps not surprising as the parameter values may be expected to be highly influenced by data below 370 m a.s.l. which are not adequately modelled. In addition, the estimated temperature lapse rate appears to be somewhat lower than expected (Braithwaite, personal communication).

Since the overall shape of the mass balance profile above 370 m a.s.l. is characterized by a relatively monotonic increase of the mass balance with elevation, the calibration procedure was repeated for data in the elevation range 370-1410 m a.s.l. The results of this calibration using the mass balance measurements from the years 1979/80-1986/87 are given in Table III.

TABLE III: Best fit parameter values (Parameters II) determined from the measured yearly balance in the elevation range 370-1410 m a.s.l. on Qamanârssûp sermia.

Parameter	Name	Value	Unit
Degree-day factor for ice	*ddi*	0.0073	$m_{w.e.}$/°C/d
Degree-day factor for snow	*dds*	0.0028	$m_{w.e.}$/°C/d
Temperature lapse rate	*grt*	0.66	°C/100m
Residual variance	σ_δ^2	0.5	$m_{w.e.}^2$
Residual standard error	σ_δ	0.7	$m_{w.e.}$

Figure 1A below shows the average of the mass balance measurements at each elevation (symbols) together with the model results (solid curves) corresponding to the calibration in Table III (Parameters II). The modelled mass balance is clearly in much better agreement with the data above 370 m a.s.l. compared with the previous results, although there are significant local deviations from the smooth model prediction. The parameter values in Table III are in fairly good agreement with the degree-day factors estimated by Braithwaite and Olesen (1989) (see above) and the estimated temperature lapse rate is not unreasonable. The difference between the parameter values in Table III and the degree-day factors estimated by Braithwaite and Olesen (1989) is in fact less than the statistically estimated uncertainty in the parameter estimates corresponding to the misfit between the modelled results and the measurements (±0.0005 $m_{w.e.}$/°C/d for *ddi* and ±0.001 $m_{w.e.}$/°C/d for *dds* corresponding to 1 σ). The parameter values in Table III will be used below for estimating the effect of climatic warming on the mass balance of Qamanârssûp sermia.

The correlation matrix determined by the calibration procedure for the parameters in Table III is shown in Table IV and shows a relatively high correlation between all the parameters.

TABLE IV: Correlation matrix for the model parameters for Qamanârssûp sermia.

	ddi	*dds*	*grt*
ddi	1.00	-0.94	-0.87
dds	-0.94	1.00	0.89
grt	-0.87	0.89	1.00

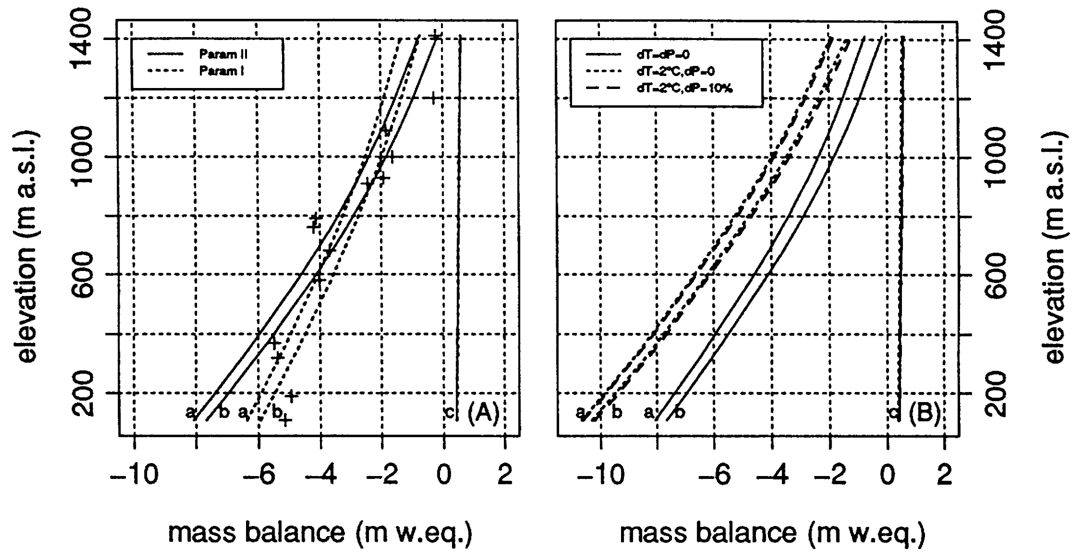

FIGURE 1: A: Measured (symbols) yearly mass balance and modelled (solid and dashed curves) yearly ablation (labeled "a"), mass balance (labeled "b") and accumulation (labeled "c") on Qamanârssûp sermia. The curves for the modelled accumulation are so close that they overlap. The solid curves (labeled Param II) correspond to the parameter set in Table III derived from mass balance data in the elevation range 370-1410 m a.s.l. The dashed curves (labeled Param I) correspond the parameter set in Table II derived from the data set with points below 370 m a.s.l. included.

B: Modelled yearly ablation (labeled "a"), mass balance (labeled "b") and accumulation (labeled "c") on Qamanârssûp sermia under present climate (solid curves) and warmer climates (dashed curves). The curves for the accumulation are so close that they overlap and also the curves for ablation and mass balance in the warmer climates. Model parameters are given in tables I and III.

5. CLIMATE CHANGES AND GLACIER MASS BALANCE

The main purpose of the glacier mass balance modelling described here and in the NHP report is to estimate the effect of climate changes on glaciers in the Nordic countries. Figure 1B shows the average modelled mass balance of Qamanârssûp sermia together with the predicted mass balance for 2 °C warmer climate with the same precipitation (short dashed curves) and for 2 °C warmer climate with 10% more precipitation (long dashed curves) using the parameter values in tables I and III. The increase in glacier ablation due to a warming of 2 °C is predicted to range from about 1.2 $m_{w.e.}$ per year at the highest elevations to 2.5 $m_{w.e.}$ at the lowest elevations. Predicted changes in the accumulation are small even if the warming is accompanied by a 10% increase in the precipitation. This is similar to the predicted effect of climatic warming on the mass balance of Sátujökull in Iceland and Nigardsbreen in Norway as described in the previously mentioned NHP report.

Increased summer ablation (June to August) on Qamanârssûp sermia due to climatic warming has been estimated by Braithwaite and Olesen (1990) (see also Braithwaite (1992)) using an energy balance model. For a warming of 2 °C, their computations predict an increase of 1.14 $m_{w.e.}$ in the summer ablation at Stake 751 at 790 m a.s.l. The increase in the summer ablation predicted by the degree-day model used here is 1.5 $m_{w.e.}$ and the predicted increase in the yearly ablation is 1.9 $m_{w.e.}$. The difference between the predicted increase in the yearly ablation and in the June to August ablation is mainly due to a longer ablation season under a warmer climate (under present climate conditions, essentially all ablation at Stake 751 takes place during the months June to August). The increase in the summer ablation found here (1.5 $m_{w.e.}$) is somewhat higher than the increase computed by Braithwaite and Olesen (1.14 $m_{w.e.}$). This difference is probably related to a fundamental difference between energy balance and degree-day models. In a degree-day model, all melting is assumed to be proportional to the sum of positive degree-days and therefore melting is predicted to increase more or less proportional to the temperature increase relative to the degree-day threshold. In an energy balance model, only some of the energy balance components are proportional to the temperature. Therefore, a climatic warming does not affect all components of the energy balance equally and the increased energy available for melting in a warmer climate is not necessarily proportional to the temperature increase relative to zero degrees Celcius.

It is not possible to arrive at a firm conclusion about energy balance versus degree-day models based on the limited study presented here. The predicted increase in the summer ablation on Qamanârssûp sermia is about 30% higher for the degree-day model than for the energy balance model. If the degree-day model is incorrect to this extent, then one would expect predicted year to year variations in the mass balance to be considerably higher than measured variations. This does not appear to be the case for Qamanârssûp sermia where the standard deviation of modelled year to year variations in the average mass balance is only about 10% higher than the standard deviation of the measured variations. One would also expect the model calibration to be highly dependent upon the mean temperature of the years used for calibration such that degree-day factors derived using data from cold years would be significantly higher than degree-day factors derived from data from warmer years. According to the analysis in the NHP report, this is not the case for Nigardsbreen where the calibrated degree-day factors are relatively independent of the average temperature of the calibration period in spite of temperature changes of almost 2 °C.

6. CONCLUSIONS

Best fit degree-day factors found from mass balance measurements above 370 m a.s.l. on Qamanârssûp sermia are in relatively good agreement with previously published values which are computed directly from mass balance measurements at 790 m a.s.l. Best fit degree-day factors found with mass balance measurements below 370 m a.s.l. included in the data set are, however, not in as good agreement with the previously published values. The mass balance data below 370 m a.s.l. show essentially no mass balance gradient with elevation and cannot be adequately explained by the model (*cf.* Figure 1). This indicates that automatic calibration of the model leads to realistic parameter values when the model fits the data reasonably, but systematic discrepancy between model output and measurements can lead to misleading parameter values. Since systematic discrepancy between model output and measurements was not present to such a degree on Sátujökull and Nigardsbreen that the modelled mass balance gradient was significantly different from the measured gradient on average, this indicates that the parameter values found in the NHP report for these glaciers are valid.

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