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Short-term volume changes of the Greenland ice sheet in response to doubled CO_2 conditions

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ABSTRACT

This paper focuses on the rôle of accumulation and cloudiness changes in the response of the Greenland ice sheet to global warming. Changes in accumulation or cloudiness were often neglected, or coupled to temperature changes. We used model output on temperature, precipitation and cloudiness from a GCM (ECHAM4 T106). The GCM output was used to drive the Greenland model that exists of a vertically averaged ice flow model, coupled to a 1D surface energy balance model that calculates the ablation. Variables are temperature, accumulation and cloudiness. Sensitivity experiments with this model show that changes in accumulation are very important for the ice sheet mass balance, whereas cloudiness is of secondary importance. If the Greenland model is forced by the GCM output, the Greenland model is found to contribute 70% less to sea level rise after 70 years than is indicated by the results presented in the IPCC report. This large discrepancy is mainly due to the fact that the enhanced ablation is strongly compensated by increased accumulation. Comparing the result obtained here with changes in mass balance derived directly from the same general circulation model, indicates a 20% larger contribution to sea level. This increase is due to changes in ice flow, and a different method for the ablation calculation.

1. Introduction

Several ice dynamical model studies have estimated the response of the Greenland ice sheet to global warming (Huybrechts et al., 1991; Van de Wal and Oerlemans, 1994; Fabre et al., 1995; Greve, 1995; Van de Wal and Oerlemans, 1997; Huybrechts and De Wolde, 1999). These studies calculate the ice sheet response to an atmospheric temperature perturbation. This temperature perturbation is often prescribed or derived from zonally mean climate models. Most of these models calculate the mass balance as a function of temperature, whereas the models presented by Van de Wal and Oerlemans (1994, 1997) take the entire energy balance of the surface into account.

Little attention has been paid to the rôle that accumulation and cloudiness play in the change of volume of the ice sheet on the short time scale. Previously attempts have been made to link the accumulation change to the temperature change. This idea is based on the increase in the saturation vapour pressure with temperature. However, it is an open question whether this process describes the accumulation changes on the Greenland ice sheet in response to global warming. It might be that changes in the general circulation pattern lead to positive or negative changes in the accumulation at specific sites on the ice sheet.

General circulation models are useful tools to study the rôle of changes in precipitation patterns in more detail. In this paper we use output from the

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ECHAM4 T106 atmospheric GCM, at high resolution. The high resolution is necessary to obtain realistic simulations of the accumulation distribution (Ohmura et al., 1996). More specifically, T106 (1.1°) experiments with ECHAM4 were carried out for both present day and $2 \times CO_2$ conditions with associated sea surface temperature and sea-ice distributions derived from a transient scenario run with ECHAM4 at T42 (2.8°) resolution coupled to the OPYC ocean model (Roeckner et al., 1998). This scenario run takes into account a gradual increase in CO_2 and other greenhouse gases according to the IPCC Scenario IS92a (Kattenberg et al., 1996). In this scenario CO_2 concentration doubles after 70 years. The T106 experiment for present-day conditions uses the AMIP Sea Surface Temperature (SST) climatology (Gates, 1992), on which are superimposed detrended SST variabilities from the coupled T42 experiment representative for the decade 1971–1980. The experiment under $2 \times CO_2$ conditions is representative for the decade 2041–2050 and uses the SST obtained through a superposition of the AMIP SST climatology with the mean SST changes between the periods 1971–1980 and 2041–2050 and the SST variabilities for 2041–2050, both taken from the coupled T42 experiment.

The model results, of the present-day accumulation over Greenland show a distribution pattern which is in agreement with the observations and better than previous results obtained with an earlier version of the model (Wild and Ohmura, 2000). The main improvement is the disappearance of the overestimation of the accumulation along the southeastern side. Besides accumulation changes, the GCM output provides changes in atmospheric temperature near the surface, the key parameter used in degree-day models and 1D surface energy balance models to calculate the ablation. One might therefore try to obtain changes in the mass balance over Greenland directly from GCM output, as did Ohmura et al. (1996) and Wild and Ohmura (2000).

However, GCM models have a few limitations. Firstly, the length of the runs is limited due to the available computer resources, implying that output is available for only two time slice windows and not for the continuous period. This implies that with a GCM one can calculate the change in mass balance at a certain time, but not the time integrated sea level change. A second limitation is the spatial resolution. Only 10% of the ice sheet is ablation area (Reeh, 1989 and Van de Wal and Oerlemans, 1994). This means for the current geometry (length is twice to three times the width) that the ablation area has an average width of 30 km. The T106 model has a grid size of 120 km in meridional direction and 20–60 km in longitudinal direction. This implies that the spatial resolution is too limited for accurate calculation of the ablation. A third limitation is that GCM models do not take into account the changing ice sheet geometry in the course of years.

The limitations mentioned lead to the conclusion that the best method at present is to use GCM output as input to a 1D surface energy balance model which is coupled to an ice sheet model that calculates the changing geometry. An additional advantage of our approach is that we could use a 1D surface energy balance model that was validated against available observational mass balance data (Van de Wal, 1996). Following the proposed approach we compared the effect of accumulation changes on the mass balance with the effect of temperature changes. This paper can therefore be considered as an extension of the results obtained by Ohmura et al. (1996) and Wild and Ohmura (2000); the differences arise from a more detailed ablation calculation (not only a function of temperature) and changes in ice sheet geometry.

From now on the combined 1D surface energy balance model and the ice sheet model will be referred to as the Greenland model. We start the paper with some explanations about the Greenland model. The results are split into two sections. First, some sensitivity experiments are presented, which use as input, temperature changes derived from a zonal mean climate model. In these experiments accumulation changes are coupled to temperature changes. These experiments illustrate the potential importance of the changes in accumulation and cloudiness and provide an opportunity for comparisons with the IPCC results, which focus on temperature change only (Warrick et al., 1996). The second part of the results is dedicated to experiments based on the ECHAM4 T106 output for changes in temperature, accumulation and cloudiness.

2. General concept of the Greenland model

The Greenland model is composed of an ice sheet model coupled to a 1D surface energy balance model that calculates the ablation. It should be noted that the version used here is identical to the one used for the reference experiment described by Van de Wal and Oerlemans (1997). First of all, we present an overview of the 1D surface energy balance model (Van de Wal and Oerlemans, 1994), and secondly, we explain the coupling to the ice sheet model.

The amount of energy available for melting is based on a calculation of the radiation budget and the turbulent transfer between the surface and the atmosphere. Climatological input variables for the model is 2 m temperature, accumulation and cloudiness. The vertical structure of the atmosphere is not taken into account in the calculation of the energy fluxes. Cloudiness is based on observational evidence from coastal stations, which shows a monotonic decrease of 40% going from South Greenland to North Greenland. Furthermore we assume a 33% reduction in the cloud cover between the margin and the central part of the ice sheet. Increased cloud cover reduces the shortwave radiation, but increases the longwave radiation. Annual accumulation is taken from Ohmura and Reeh (1991), who made a compilation of measurements in the period 1913–1989. Accumulation changes are expressed relative to the Ohmura and Reeh (1991) distribution. The turbulent energy flux is taken to be proportional to the difference between the 2-m temperature and the surface temperature. The exchange coefficient does not explicitly depend on surface roughness, wind speed or stability and can be considered as the crucial tuning parameter of the model.

A crucial part of the 1D surface energy balance model is the albedo parameterization. Tracking the type of surface simulates the physical characteristics of the albedo. New snow, old snow, ice and water have their own characteristic value. Processes which are taking into account are snow aging, the presence of meltwater at the surface and snowfall events. This means that if the GCM output initiates increased ablation, more ice will be exposed which will result in lower average albedos. This introduces a positive feedback for the ablation. Van de Wal and Oerlemans (1994) presented a detailed scheme.

This type of 1D surface energy balance models can be used for climate change experiments, which involve changes in 2 m temperature, accumulation and cloudiness only. It is not possible to prescribe a radiative forcing and generate an adjusted climate. Van de Wal (1996) showed that this model is capable of describing the sparsely available observed mass balance profiles.

The ablation calculated with the 1D surface energy balance model serves as input for the ice sheet model. The 2D vertically averaged ice sheet model includes internal deformation and sliding of ice, and bedrock adjustment. No thermodynamics of ice or bedrock are included. The solid earth component is simply divided into a lithosphere and a viscous asthenosphere. The viscosity of the asthenosphere determines the time-dependent response of the bedrock. The lithosphere depression is a result of local hydrostatic equilibrium. Calving is defined as the ice volume flux at the land-sea transition. The ocean is considered as an infinite sink for ice. If ice reaches the coast, thickness is set to zero. This is the poor man's approach. The lateral scale of most outlet glaciers is smaller than the grid-point distance, which means that no real physical description can be made.

Changes in mass balance lead to changes in the geometry of the ice sheet, which change the ice flow and ice thickness. Changing surface elevation on the other hand also changes the ablation rate. This means that a change in one of these processes will cause a time-dependent response leading to a new equilibrium state.

3. Sensitivity experiments

Before we describe the results of the experiments with the GCM output we draw attention to some sensitivity experiments. These sensitivity experiments provide the framework for judging the results based on the GCM output. In order to judge the importance of accumulation changes compared to temperature changes for the response of the Greenland ice sheet, we first calculated changes in ice volume for a range of temperature scenarios. In these experiments, the accumulation was kept constant. The temperature scenarios were obtained from a 2D climate model (De Wolde et al., 1997) which was forced by 12 radiative forcing scenarios (A–F) described in the IPCC report, 6 for constant 1990 aerosols (subscript n) and 6 for increasing aerosol concentrations after

1990 (subscript f) (Kattenberg et al., 1996). The time-dependent zonal mean atmospheric temperature changes calculated by the 2D climate model were used to force the Greenland model. As a starting point for our sensitivity experiments we considered an equilibrium state which resembles the present state of the ice sheet, as described by Van de Wal and Oerlemans (1997). The resulting changes in ablation and volume of the Greenland ice sheet were expressed in terms of global mean sea level change (SLC). It should be stressed here that all sensitivity experiments use the 2D-climate model to calculate the change in atmospheric temperature. Experiments based on GCM output will be discussed in the next section.

3.1. Sensitivity to temperature changes

The radiative forcing scenarios described in the IPCC report (Warrick et al., 1996) are used here to demonstrate the range of ice volume changes as a result of an atmospheric temperature change. The calculated contribution of the Greenland ice sheet to sea level rise is 10.4 cm for the An-scenario, see Fig. 1, which is considered here as the *reference* scenario (Warrick et al., 1996). For the different temperature scenarios used, we observe a range of calculated sea level rises between 6 and 14 cm after 110 years.

The calculated range of sea level rise increases with time. Sea level rise relative to that of the reference scenario ranges from 57%–131% after 110 years, whereas it is only 67–117% after 70 years (the period of the GCM results in the next section). We now turn to the question of whether this range is sensitive to variations in accumulation and cloudiness.

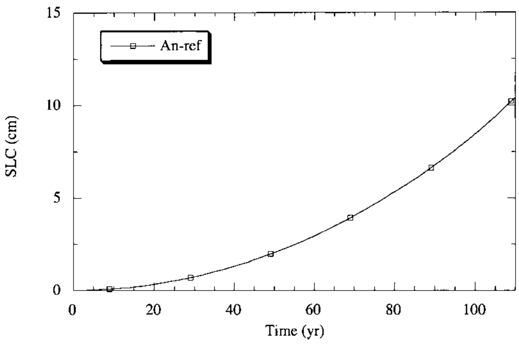

Fig. 1. The contribution from the Greenland ice sheet to global sea level change (SLC) for the reference climate scenario An (no aerosols) (Van de Wal and Oerlemans, 1997).

3.2. Sensitivity to accumulation changes as a function of temperature

To study the rôle of accumulation we start by relating accumulation changes to temperature changes. It has been suggested that for the Greenland ice sheet snow accumulation may increase uniformly by 5% per degree warming (Reeh and Gundestrup 1985), which is roughly equal to what is expected if accumulation is proportional to the amount of precipitable water in a saturated atmospheric column. On the other hand more recent results based on analyses of ice cores show that the increase in accumulation might even be 10% per degree warming (Kapsner et al., 1995). This number can be considered as an upper limit because part of the accumulation increase is probably due to changes in the atmospheric circulation, which might be different from place to place. Therefore we calculated the response of the ice sheet for three different cases (i) no increase in accumulation (see previous section), (ii) 5% increase per K, and (iii) 10% increase per K. Table 1 shows the results of these runs 70 years after the start.

To provide some insight into the evolution of the individual components of the mass fluxes, we present Fig. 2. The figure demonstrates the change in accumulation, ablation, calving and the net mass flux, for experiment (iii) (10% increase in accumulation per degree). The figure shows that there is a steady state (net mass flux zero) in 1990. The net mass flux decreases continuously over this period, which means that the ice sheet retreats.

Table 1. *The sea level change (SLC) for different experiments including a accumulation change related to a change in temperature; the results are scaled by the SLC which is due only to the temperature increase (SLC_{ref}). This increase is 4.1 cm after 70 years*

Accumulation change	SLC/SLC_{ref} (%)
0% per K	100
+5% per K	75
+10% per K	52

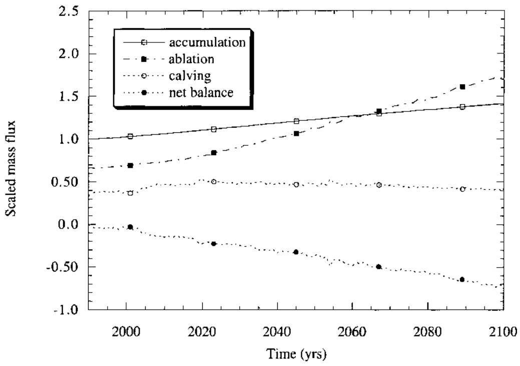

Fig. 2. The evolution of the different mass fluxes (ablation (ABL), accumulation (ACC), calving (CAL) and net mass flux (NMF), calculated from the change in volume over time. Results are scaled by the accumulation in 1990. Results are for experiment (iii) (10% increase in accumulation per degree).

Adjustment is not fast enough to re-establish a new steady state within a period of 100 years. Since temperature increases more or less linearly and accumulation is a linear function of temperature, we observe a linear trend in accumulation. On the other hand, the figure shows that the ablation increases non-linearly, which means that the sensitivity of the ice sheet increases in the case of larger temperature perturbations (Van de Wal 1996). Because of this, the relative reduction of the sea level rise as a result of increased accumulation as presented in Table 1 decreases on a time scale of a few hundred years. The effect of changes in accumulation is large in view of the ranges for different temperature scenarios presented in the previous section.

3.3. Change in cloudiness

Since the 1D surface energy balance model is forced by temperature, accumulation and cloudiness, it is worthwhile performing a few experiments relating to changed cloudiness only. Although not much is known about changes in cloudiness during climate change, one could speculate that increased cloudiness might lead to increased accumulation. We calculated the response of the ice sheet in 3 different cases (i) no increase in cloudiness, (ii) a linear increase of 5% over 70 years, and (iii) a linear 10% increase over 70 years. Table 2 shows the results of these runs 70 years after the start.

Table 2. *The sea level change for different experiments including a change in cloudiness; the results are scaled by the SLC which is due to the temperature increase only after 70 years*

Experiment	SLC/SLC_{ref} (%)
0% per 70 years	100
5% per 70 years	98
10% per 70 years	96

Apparently cloudiness has only a slight effect on the 1D surface energy balance model. Increased cloudiness not only reduces the shortwave radiation, but it also increases the longwave radiation. The net effect of these two processes depends on the surface albedo. In general, the change in shortwave radiation dominates. For an ice sheet with a relatively high surface albedo the two processes cancel each other out (see e.g., Ambach 1974). The limited sensitivity for changes in cloudiness can therefore be understood by realizing that the albedo of ice in Greenland is typically 0.55. This high albedo value for ice means that the accuracy of cloudiness distribution from a GCM is not important for the ablation calculations which is fortuitous because the accuracy of cloudiness is low along the ice sheet margins. It should be noted that combinations of perturbations in cloudiness and accumulation are simply the sum of the individual perturbations; no non-linear effects could be observed.

Summarising the results of the sensitivity experiments one might conclude that changes in accumulation are potentially important for the calculation of sea level changes. A reduction in sea level rise of up to 50% cannot be ruled out. After some time the non-linear increase in ablation will reduce the importance of the linear increase in accumulation. The additional effect of changes in cloudiness is expected to be marginal.

4. Experiments including changes in temperature, accumulation and cloudiness based upon GCM output

Now we focus on the experiments with the GCM output instead of the zonal mean climate model. The resolution of the ECHAM4 T106 model used is roughly $1.125° \times 1.125°$. The

Greenland model has an equidistant grid resolution of 20×20 km. GCM data are therefore bilinearly interpolated to the 20×20 km grid with a weighting proportional to the distance between original point and interpolated point. This is done for the control run and the doubled CO_2 scenario experiment of the GCM.

Figs. 3a–d show the differences in GCM output between the doubled CO_2 climate and the present climate for the three climatological variables interpolated on the 20×20 km grid. It can be observed that the temperature change increases going higher on the ice sheet. The annual mean temperature increase over the ice sheet is 3.4°C which is slightly more than the mean increase of the zonal mean climate model (3.0°C). Summer temperatures are thought to be more important for ablation calculations. Fig. 3b shows the increase in the July temperature. The July temperature change shows a more pronounced temperature change with a smaller increase along the margins and a higher increase in the central parts of the ice sheet. The average July temperature increase is 2.7°C. The smaller increase in the temperature change lower on the ice sheet is probably due to the damping of the temperature change in the marginal areas because the surface temperature of the ice in the summer reaches zero and prevents further temperature increase in these zones. A thorough meteorological explanation however is beyond the scope of this paper, more details of the ECHAM results can be found in Wild and Ohmura (2000).

The mean increase in accumulation is 30%. It is predicted that the accumulation will increase everywhere on the ice sheet. This is a substantial revision of earlier estimates (Ohmura et al., 1996), which showed nearly no change in precipitation.

The mean increase in cloudiness is 2%. Higher up on the ice sheet the increase is largest and the Southern parts even show areas with a small decrease in cloudiness.

In order to use the differences in temperature, accumulation and cloudiness for both GCM climate simulations as input for the Greenland model we have to define a time-dependent experiment. This is necessary because in the Greenland model ice dynamics are involved as well as a time-dependent albedo feedback mechanism. Increased ablation will decrease the snow layer and therefore result in a lower albedo. The lower albedo will increase the ablation leading to a positive albedo feedback mechanism. We linearly interpolated in time between the doubled climate state and the reference climate and used this scenario to drive the Greenland model. The results in terms of sea level change are presented in Table 3. The temperature and accumulation changes dominate the sea level rise. Increased accumulation compensates to a large extent for the increased ablation. It is obvious that the integrated effect of a change in cloudiness on the volume of the ice sheet is negligible for the GCM experiment.

Table 3. *The sea level change for different experiments for the doubled CO_2-scenario; results are presented after 70 years; ΔT means including the change in temperature, ΔP including the change in accumulation and ΔN including the change in cloudiness*

Experiment	SLC after 70 years (cm)	SLC scaled (%)
$\Delta T + \Delta P + \Delta N$	1.3	100
$\Delta T + \Delta P$	1.3	100
ΔT	3.2	246

5. Discussion

This paper presents results relating to the short-term response of the Greenland ice sheet. In terms of sea level change we observe a range of predictions from 6–14 cm for the year 2100 for the different temperature scenarios used. After 70 years, the range is 67%-117%, where 100% is the sea level rise resulting from the AN-scenario as presented by Warrick et al. (1996). The sensitivity experiments show that for an increase of 10% in the accumulation per degree temperature increase, the sea level rise is reduced by about 47%, (Table 1). Two mechanisms are responsible for the increased mass balance. Primarily the mass balance increases due to increased accumulation. A secondary effect is that more accumulation means more snow and more reflection of energy due to higher values for the albedo. This means that there is a feedback mechanism which, in the case of more accumulation, leads to an additional decrease in the ablation. Although not shown explicitly it can be shown that the primary effect

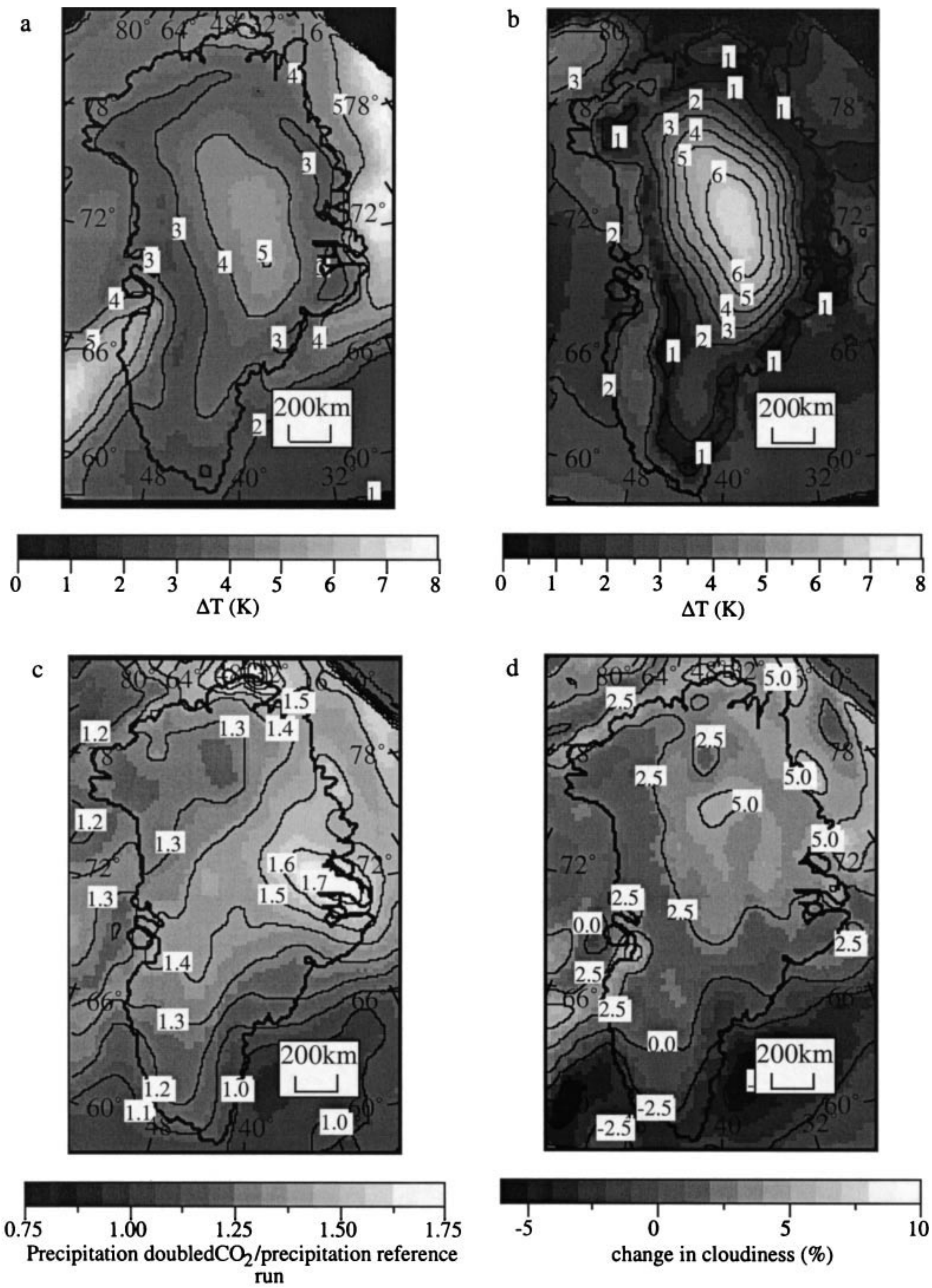

Fig. 3. The difference between the doubled CO_2 climate and the reference climate in the mean annual temperature (a), July temperature (b), accumulation (c) and cloudiness (d) for an area from 60°N to 80°N and from 0°W to 60°W. The thick contour line is the margin of the modelled Greenland ice sheet.

of the increased accumulation is larger than the effect of the decreased ablation.

On the basis of the sensitivity experiments only, one might conclude that the uncertainty resulting from accumulation scenarios is as large as the uncertainty arising from temperature scenarios. The reduction of the SLC due to increased accumulation (10% per °C) is estimated to be 50%. The prescribed accumulation increase in the sensitivity experiment, however, is based upon information that is derived from ice core records from central Greenland, which focuses on longer time scales. It is questionable whether the assumption that the increase in accumulation is coupled to the temperature change is valid for the short term time scale. We believe that the results based on the output of a GCM are far more representative and not in contradiction with the ice core record. Kapsner et al. (1995) also suggested that changes in large scale circulation are the driving force for changes in accumulation.

Results obtained in this study should be compared with estimates of changes in the surface mass balance derived directly from GCM results (Wild and Ohmura 2000). They calculated changes in ablation with a parameterization based on summer temperature changes on the GCM grid (T106) for fixed ice sheet geometry for the present-day climate and a doubled CO_2 climate. Here we used the same GCM data but we used the Greenland model (20*20 km grid resolution) composed of a 1D surface energy balance model and ice flow model to calculate changes in volume between the present-day climate and the doubled CO_2 climate. Results of this comparison are presented in Table 4. Apparently, the projected change in ablation between the two approaches is considerable. Although the two methods of calculating the ablation are entirely different one can give an explanation for the observed difference. The 1D surface energy balance model includes an albedo feedback mechanism. More accumulation leads to lower ablation here even if the temperature remains constant, because the albedo of snow is higher than that of ice. However, the difference in ablation in the two approaches is compensated by the increased calving flux in the Greenland model, so the net mass flux change presented in Table 4 is nearly identical for both approaches. This implies that a fixed geometry approach cannot be used. The Greenland model would predict almost no change in mass for a fixed geometry because increased accumulation and ablation compensate each other. The results indicate that higher resolution modelling including a physically based calving flux is a must for future modelling work.

Table 4. *Change in mass flux between the doubled CO_2 climate and the present-day climate; values are expressed in mm/yr averaged over the ice sheet; because the surface area is not a constant in this study, we used the average surface area over the integrated 70 years*

Mass flux	Wild and Ohmura (2000) (mm/year)	This study (mm/year)
accumulation	+92	+96
ablation	−155	−114
calving	—	−44
total	−63	−61

As this model integrates the changes in mass fluxes forward in time we can calculate the contribution that the Greenland ice sheet will make to global sea level. Table 3 showed that the predicted sea level change is only 1.3 cm due to the fact that increased accumulation will compensate for the increased ablation. This is approximately 20% more than expected from a linear interpolation between doubled CO_2 climate and present-day climate as estimated directly from GCM output by (Wild and Ohmura, 2000). However, our results are difficult to compare with these results because of the difference in ablation calculation and the fact that Wild and Ohmura (2000) neglect the effect of ice flow. The most striking result is the very small contribution of 1.3 cm compared to previous estimates, for instance the results obtained with the An-forcing scenario (4.0 cm after 70 years) presented by (Warrick et al., 1996). This difference can be explained partly by changes in spatial and temporal temperature forcing. In Table 3 we observe that the temperature forcing by ECHAM output results in 3.2 cm. However, the main difference is due to the increased accumulation, which lowers this 3.2 cm to 1.3 cm global sea level rise.

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