# Changes in Sea-Level associated with Modifications of the Mass Balance of the Greenland and Antarctic Ice Sheets over the $21^{st}$ Century

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**Abstract**

Changes in runoff from Greenland and Antarctica are often cited as one of the major concerns linked to anthropogenic changes in climate. The changes in mass balance, and associated changes in sea-level, of these two ice sheets are examined by comparing the predictions of the six possible combinations of two climate models and three methods for estimating melting and runoff. All models are solved on 20 and 40 km grids respectively for Greenland and Antarctica. The two temperature based runoff parameterizations give adequate results for Greenland, less so for Antarctica. The energy balance based approach, which relies on an explicit modelling of the temperature and density structure within the snow cover, gives similar results when coupled to either climate model. The Greenland ice sheet, for a reference climate scenario similar to the IPCC's IS92a, is not expected to contribute significantly to changes in the level of the ocean over the $21^{st}$ century. The changes in mass balance in Antarctica are dominated by the increase in snowfall, leading to a decrease in sea-level of $\sim 4$ cm by 2100. The range of uncertainty in these predictions is estimated by repeating the calculation with the simpler climate model for seven climate change scenarios. Greenland would increase the level of the oceans by 0 – 2 cm, while Antarctica would decrease it by 2.5 – 6.5 cm. The combined effect of both ice sheets lowers the sea-level by 2.5 – 4.5 cm over the next 100 years, this represents a $\sim 25\%$ reduction of the sea-level rise estimated from thermal expansion alone. This surprisingly small range of uncertainty is due

to cancellations between the effects of the two ice sheets. For the same reason, the imposition of the Kyoto Protocol has no impact on the prediction of sea-level change due to changes in Greenland and Antarctica, when compared to a reference scenario in which emissions are allowed to grow unconstrained.

# 1 Introduction

Greenland and Antarctica contain together almost all of the glacier ice on Earth, which if fully melted could add over $75\,m$ to the level of the oceans. For time scales of a century or less, the response of the ice sheets to changes in climate is governed by surface processes, the accumulation of snow and meltwater formation, percolation, refreezing and runoff. Because of the very high surface reflectivity of snow and the dramatic changes in albedo which take place at the onset of melting, these regions can be expected to respond quite sensitively to changes in the climatic forcing, and to changes in temperature in particular. It is in fact in large part because of the snow/ice albedo feedback effect and changes in sea-ice extent that General Circulation Models predict that above average warming will take place in the Arctic and Antarctic regions (Houghton et al., 1996).

The snow which accumulates on the Greenland and Antarctic ice sheets is for the most part gradually transformed into ice which then takes millenia to return to the ocean in the form of icebergs or meltwater. By providing this long term storage site for freshwater, the mass balance of Greenland and Antarctica also depends on the atmospheric circulation, and will be sensitive to changes in precipitation patterns.

Progress in estimating changes in accumulation and runoff has been slowed by two factors: the low resolution of most climate models which does not allow an accurate representation of the climatology over the ice sheets, and the lack of reliability in the calculation of meltwater formation and runoff. Both issues are addressed in this paper. A hierarchy of models which will be used to estimate the amount of melting and runoff from meteorological parameters is presented in section 2, with particular focus on a model of the snow cover developed for that purpose. The climate models and climate change scenarios used as forcing for the melt models are described in section 3. By comparing in section 4 the results obtained with different combinations of climate and melt models for the current climate and at the time of $CO_2$ doubling, the objective was to assess the reliability of the projected changes in mass balance and sea-level obtained with transient climate change scenarios. These results are discussed in section 5. The impact of the Kyoto protocol in reducing changes in sea-level is discussed in section 6.

## 2 Snow melt models

The three snow melt models which will be used in the following calculations were described more extensively in a paper about the current state of the mass balance of the Greenland and Antarctic ice sheets (Bugnion, 1999); a brief summary is presented here:

- The linear model uses the apparent linear correlation between the average summer temperature, for $T_{avg} > -2°C$, and the ablation observed at a few measurement stations in Greenland as the basis for the parameterization (Ohmura et al., 1996; Wild and Ohmura, 1999).

- The degree-day model uses the sum of temperatures above the melting point as a "melting potential". Snow and ice are melted successively at different rates to account for the change in albedo between these two surfaces. A prescribed fraction of the meltwater refreezes to form superimposed ice (Braithwaite and Olesen, 1989; Huybrechts et al., 1989; Braithwaite, 1995).

- The snowpack model developed at M.I.T. relies on a representation of the physical processes which occur in the snow cover to obtain an estimate of runoff. The uppermost $15\,m$ of the snow, firn and ice are divided into a maximum of 12 layers. Each layer settles under the weight of the overlying snow until it is compressed into ice. The temperature distribution is calculated from a heat diffusion equation which includes the effect of the latent heat released or absorbed by the changes of phase of water. Melt- and rainwater percolation is modeled by prescribing the maximum volume fraction of water which saturates the firn, the excess filtering down layer by layer until it reaches ice, at which point it is assumed to contribute to runoff. The surface energy balance provides the boundary condition at the surface and a vanishing heat flux is imposed at $15\,m$ depth. Many components of the surface energy balance are calculated internally by the snowpack model, notably the surface albedo, the upwelling longwave radiation and the turbulent fluxes of latent and sensible heat. This model allows an explicit calculation of the formation of meltwater, of the fraction of meltwater which refreezes and of runoff in the ablation region. This was not the case in past modelling efforts (Thompson and Pollard, 1997; Ohmura et al., 1996; DeWolde et al., 1997; Wild and Ohmura, 1999) which neglected the effect of latent heating on the temperature and density structure of the snow cover which was not modelled explicitely.

The model is computationally sufficiently efficient to be solved on a $20\,km$ grid on the Greenland ice sheet and $40\,km$ on Antarctica. The resolution used for Greenland has been shown by Glover (1999) to be sufficient to resolve the features of the melt zone on the margins of that ice sheet. The model is allowed to equilibrate with the 1990 climate by developing temperature and density structures appropriate for each location on the ice sheet before proceeding with the transient climate change calculations.

The conditions at Qamanârssûp Sermia on the Greenland ice sheet, as predicted by the MIT climate model (see the next section for details about the model), provide an example of the differences in behavior of the three models. The average summer temperature is 5.4° which leads the linear model to predict $0.51 \cdot 5.4 + 0.93 = 3.68\,m.$ of runoff. This location experiences 4 months with temperatures above the melting point for a total of 527 positive degree-days (PDD). Melting the winter's snow accumulation uses only 19 PDDs and 60% of that meltwater is assumed to refreeze. The remaining PDDs are used to melt ice for a total runoff of 4 $m$. The snowpack model relies on the surface energy balance to generate 3.27 $m$ of meltwater, 8 $cm$ of liquid water is added in the form of rain, 4 $cm$ refreezes within the snow cover and 3.31 $m$ contribute to the runoff from the ice sheet. The potential for refreezing is for the most part eliminated between July, when the winter's snow is melted and bare ice outcrops, and September, when temperatures drop below the melting point.

Because the snowpack model is based on well established physical principles, it can be expected to respond in a believable way to substantial changes in atmospheric forcing. The results obtained with the simpler temperature based models will therefore be assessed by comparison to those obtained with the snowpack model.

Because of the size of the ice sheets, the response of the internal ice dynamics of Greenland and Antarctica to changes in the surface forcing will take place on time scales greater than a century and will therefore be neglected (Greve, 1997; Huybrechts, 1990a). Dynamic changes which could take place over less than a century, such as the partial collapse of the West Antarctic ice sheet (M.Oppenheimer, 1998) or rapid local changes in glacier dynamics (Krabill et al., 1999) are still difficult to model accurately and will be neglected in this analysis.

# 3 Climate Models

The climatological input to the snow melt models is derived from the simulations performed with two climate models. Both model outputs are interpolated with a distance weighted scheme onto a 20 $km$ grid for Greenland and a 40 $km$ grid for Antarctica.

Because of the high resolution required to capture adequately the topography and climate of Greenland and Antarctica, the simulations performed with the $\sim 1.1° \times 1.1°$ resolution (T106) version of the ECHAM 4 GCM could not be performed in transient mode with a time varying forcing over the $21^{st}$ century (Wild and Ohmura, 1999). These authors chose instead to use the sea surface temperature and sea ice distribution provided by a lower resolution simulation of the IS92a transient scenario (Houghton et al., 1996), with the same model (Roeckner et al., 1999), for the current climate and at the time of doubling of the equivalent carbon dioxide level (i.e. allowing for increases in $CO_2$ and other trace gases), as boundary conditions for 10 year integrations of the high resolution model. The terminology "time-slice experiment" will be used to decribe these simulations.

The MIT model is a zonally averaged version of the GISS GCM which does however distinguish between land, ocean, land-ice and sea-ice (Sokolov and Stone, 1998). This model's main advantage is its computational efficiency, it allows the simulation of the climate's transient response to a large set of emissions scenarios. By making what are thought to be reasonable assumptions about the emissions rate of greenhouse gases and by varying key model parameters, the objective was an assessment of the range of sea-level change which can be expected to accompany changes in the mass balance of Greenland and Antarctica over the next century. The scenarios are described in detail in section 5.2. Although one could assume that a zonally averaged model would be unable to give reliable estimates of the mass balance of an ice sheet, the MIT model's performance in reproducing the known features of the current state of the mass balance of Greenland and Antarctics was respectable (Bugnion, 1999). The temperature distribution over the ice sheets is reconstructed from the air temperatures at the sea-level by using known lapse rates (Ohmura, 1987; Schwerdtfeger, 1970) and the incoming longwave radiation is interpolated to the altitude of the grid point. The precipitation distribution is obtained by weighting the zonally averaged precipitation with an array representing the observed accumulation normalized in order to conserve the amount of snow- and rainfall predicted by the model; all other variables are left unaltered.

# 4 1 vs. $2 \times CO_2$ simulations

The following results were derived from time-slice experiments with the ECHAM 4 model for 1 and $2 \times CO_2$ conditions (Wild and Ohmura, 1999), and a transient integration of the MIT model (the $REF$ case described in section 5.2) in 1990 and at the time of $CO_2$ doubling. These runs are not equilibrium simulations and the ocean has not been given sufficient time to fully adjust to the changes in the overlying atmosphere. A more moderate warming than in a doubled $CO_2$ equilibrium simulation can therefore be expected a priori.

The following results show the differences in response of the three melt models when they are subject to a forcing different from the current climate. Detailed results for the current climate and their comparison to observations can be found in Bugnion (1999).

## 4.1 Accumulation

The snowfall, evaporation and accumulation (snowfall - evaporation) values predicted by the MIT and ECHAM models for Greenland and Antarctica are summarized in Table 1. Both models predict similar accumulation totals for Greenland in 1990 and both are sufficiently close to the value of $553 \cdot 10^{12}\, kg\, a^{-1}$ derived from observations (Houghton et al., 1996) for the estimates to be adequate for our modelling purposes. The current accumulation over Antarctica is however overestimated by both models, and by the MIT model in particular. It is also highly likely that these models will overestimate the changes in precipitation accompanying changes in the climatic forcing. Because snow accumulation is critical in determining the evolution of the mass balance of the ice sheets over the coming century, the precipitation amounts predicted by the MIT and ECHAM climate models for Antarctica which were used to calculate changes in sea-level were scaled by factors of 0.62 and 0.72 respectively in order to reproduce the best guess of the current total accumulation of $1810 \cdot 10^{12} kg\, a^{-1}$ (Vaughan et al., 1999). This scaling is justified by the following simple argument: The air temperatures predicted by the climate models are generally too warm because the model's topography underestimates the true elevation, this is the case in particular for the MIT model which has no topography. This bias in temperature leads to an excessive moisture holding capacity of the atmosphere and too much precipitation. The increase in saturation water vapor pressure in a changing climate, and to some degree the increase in precipitation, will therefore be too large because the baseline is wrong. The drawback of this approach is that it neglects the effect of changes in atmospheric circulation on the precipitation patterns, this effect can however be expected to be smaller for Antarctica than for Greenland. Alternatively, one could assume that, although the current precipitation is overestimated, this will not be the case for changes in precipitation; this was the approach taken by most past modelling efforts (Thompson and Pollard, 1997; Ohmura et al., 1996; Wild and Ohmura, 1999).

The unscaled changes in accumulation in Greenland and Antarctica between the current climate and the time of $CO_2$ doubling as well as the increase between those two dates are summarized in Table 1.

The ECHAM model predicts a more rapid increase in the amount of snowfall over Greenland during the next century than the MIT model. This discrepancy cannot be linked to differences in the evolution of the annual mean air temperature (summarized in Table 3) since both models predict the same increase ($+3.8°C$) over that region. Dividing the increase in accumulation by the change in temperature gives a 2.6 % increase in accumulation per degree of temperature change for the MIT model and a 6.4 % increase for the ECHAM model.

| | MIT | | | ECHAM | | | Observations |
|---|---|---|---|---|---|---|---|
| | Snow | Evap. | Accum. | Snow | Evap. | Accum. | Accum. |
| Greenland $1 \times CO_2$ | 649 | 95 | 554 | 585 | 46 | 540 | $553^{\dagger}$ |
| Greenland $2 \times CO_2$ | 727 | 118 | 609 | 739 | 67 | 672 | |
| Greenland - Change | 78 | 23 | 55 | 153 | 21 | 132 | |
| Antarctica $1 \times CO_2$ | 3121 | 246 | 2875 | 2732 | 241 | 2491 | $1810^{\ddagger}$ |
| Antarctica $2 \times CO_2$ | 3553 | 313 | 3240 | 3087 | 288 | 2799 | |
| Antarctica - Change | 432 | 67 | 365 | 355 | 47 | 308 | |

Table 1: Snowfall, evaporation and accumlation over the Greenland and Antarctic ice sheets for 1 and $2{\times}CO_2$ conditions. Units are $10^{12} kg\, a^{-1}$. Source for the observed is †: Houghton et al. (1996), ‡: Vaughan et al. (1999).

These numbers bracket the value which would have been expected, had the precipitation been controlled by local thermodynamics and the change in saturation vapor pressure associated with changes in temperature ($\sim +5.3\frac{\%}{^{\circ}C}$), an assumption often made by glaciologists (Huybrechts et al., 1989; Huybrechts, 1990b).

| | MIT | | | ECHAM | | |
|---|---|---|---|---|---|---|
| | $1 \times CO_2$ | $2 \times CO_2$ | Change | $1 \times CO_2$ | $2 \times CO_2$ | Change |
| Greenland | -23.0 | -19.2 | +3.8 | -20.7 | -17.3 | + 3.4 |
| Antarctica | -33.2 | -29.5 | + 3.8 | -34.4 | -32.6 | + 1.7 |

Table 2: Annual average temperature over Greenland and Antarctica for 1 and $2{\times}CO_2$ conditions and the temperature difference between the current climate and the time of $CO_2$ doubling. Units are $^{\circ}C$

The ECHAM model also predicts a larger increase in accumulation in Antarctica than the MIT model, but a smaller change in both the annual mean and summer temperatures. The absence of a strong correlation between the patterns of change in the accumulation and temperature fields point to large scale modifications of the atmospheric circulation and of the poleward flux of moisture as the cause of the increase in snowfall. These dynamic effects and changes in the storm track location in the Atlantic have been pointed out by Ohmura et al. (1996) in simulations of the climate change over Greenland with the ECHAM 3 GCM.

### 4.2 Runoff

The total runoff originating from the Greenland and Antarctic ice sheets for both current and doubled carbon dioxide conditions are sumarized in Table 2.

| | MIT | | | ECHAM | | | Observations |
|---|---|---|---|---|---|---|---|
| | Snowpack | PDD | Linear | Snowpack | PDD | Linear | |
| Greenland $1 \times CO_2$ | 162 | 172 | 299 | 122 | 353 | 568 | $237^{\dagger}$ |
| Greenland $2 \times CO_2$ | 306 | 291 | 448 | 295 | 515 | 832 | |
| Greenland - Change | 148 | 119 | 149 | 173 | 162 | 264 | |
| Antarctica $1 \times CO_2$ | 0 | 63 | 620 | 0 | 18 | 122 | |
| Antarctica $2 \times CO_2$ | 29 | 146 | 1029 | 0 | 10 | 112 | |
| Antarctica - Change | 29 | 83 | 409 | 0 | -8 | -10 | |

Table 3: Runoff from the Greenland and Antarctic ice sheets for 1 and $2\times CO_2$ conditions. Units are $10^{12}\,kg\,a^{-1}$. Source for the observed is †: Houghton et al. (1996).

The estimates produced by the MIT/snowpack and the MIT/degree-day models for Greenland for the current climate are similar and 25–30% lower than the value of $237 \cdot 10^{12}\,kg\,a^{-1}$ derived by Reeh (Houghton et al., 1996) from measurements. The MIT/snowpack model estimates total melting at $176 \cdot 10^{12}\,kg\,a^{-1}$, $\sim$ 20% of the total melt- and rainwater ($35 \cdot 10^{12}\,kg\,a^{-1}$) is predicted to refreeze in-situ. The ablation at individual stations and the extent of the melt zone predicted by these model combinations are generally in excellent agreement with observations in the Southern two-thirds of the ice sheet, the extent and intensity of melting along the Northern coast is however underestimated. The linear model overestimates the source area of runoff. The three models do however predict similar increases in runoff over the $21^{st}$ century, $+119$ – $+149 \cdot 10^{12}\,kg\,a^{-1}$. The ablation region is shown in Fig.1 for both single and double $CO_2$ conditions and for the MIT/snowpack model combination. An increase in both the intensity and extent of the source area of runoff can be observed.

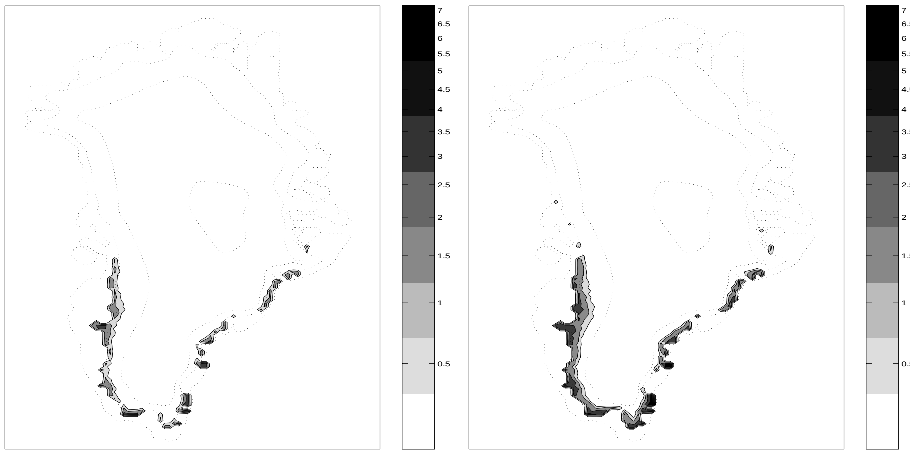


Figure 1: Runoff in $m\,year^{-1}$ predicted by the MIT/snowpack model combination. Left column: $1 \times CO_2$, Right column: $2 \times CO_2$. Dotted lines are the $1000\,m$. topographic height contours.

The discrepancy bewteen the results obtained with the three melt models is much larger for the estimates produced with the ECHAM model input for Greenland. The snowpack model underestimates melting in the Southern half of the ice sheet because the climate model's summer temperatures are lower than observed, and the temperature dependence of the albedo parameterization does not allow the energy balance to become sufficiently positive to generate large amounts of meltwater. It does compensate by capturing melting and runoff in the Northern third of the ice sheet. The amount of refreezing taking place is however larger than was the case for the MIT model, $49 \cdot 10^{12}\,kg\,a^{-1}$ or $\sim 40\%$ or the melt- and rainwater input and the aggregate estimate of runoff is, at $122 \cdot 10^{12}\,kg\,a^{-1}$, lower than the MIT model's. The Degree-Day and in particular the linear model produce very intense melting in the Northern half of the ice sheet. The difference between 1 and $2 \times CO_2$ conditions is shown in Fig.2 for the ECHAM/snowpack combination. The larger increase in runoff associated with the ECHAM model is due to a more rapid increase in summertime temperatures than in the MIT model, up to $5°C$ over the central portion of the ice sheet and $\sim 1.7°C$ in the coastal areas source of runoff. The MIT model predicts a warming of the average summer temperature of $1.2°C$ between the current climate and the time of $CO_2$ doubling with the largest warming $\sim 1.5°C$ taking place in the Southern third of the ice sheet where most of the melting takes place. This distribution of the temperature change in that model is closely linked to modifications in the sea-ice distribution and associated albedo changes.

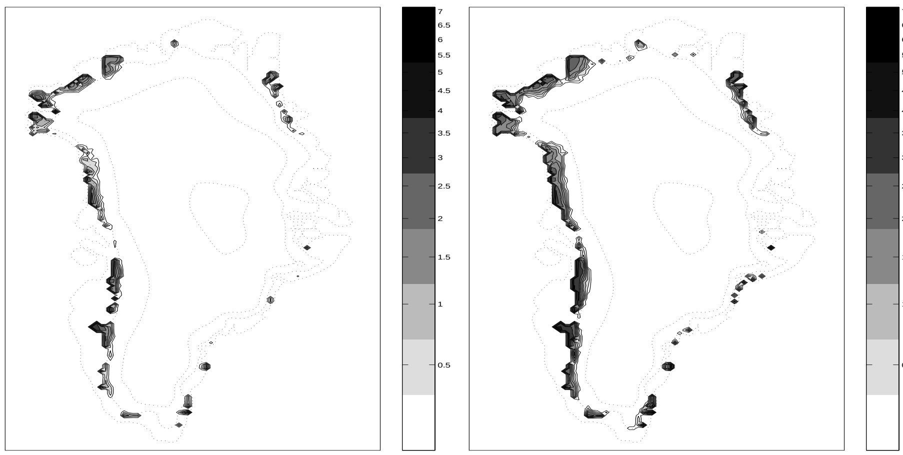


Figure 2: Runoff in $m\,year^{-1}$ predicted by the ECHAM/snowpack model combination. Left column: $1 \times CO_2$, Right column: $2 \times CO_2$. Dotted lines are the $1000\,m$. topographic height contours.

The substantial increase in runoff which is predicted by the melt models for rather small changes in summer temperatures ($+1.5 - 1.7°C$) are a clear illustration of the high sensitivity of the mass balance of Greenland to changes in climate.

The differences in response of the melt models can in part be traced back to the runoff parameterizations. The runoff predicted by the linear model is a linear function of temperature. This is also the case for the degree-day model after the initial fraction of meltwater is refrozen. The albedo parameterization built into the snowpack model will however lead to a non-linear response to changes in air temperature: Once temperatures pass the melting point, the albedo drops very rapidly, as a cubic function of temperature. After the snow is melted away however, the albedo stabilizes at the constant value chosen for the reflectivity of ice and the amount of melting and runoff taking place depends entirely on the net surface energy balance.

The snowpack model, whether forced with the MIT or the ECHAM climate data, does not predict any runoff originating from Antarctica for the current climate and only minimal runoff at the time of $CO_2$ doubling (Table 2). The input of liquid water in the form of rain ($\sim 250 \cdot 10^{12}$ and $\sim 35 \cdot 10^{12}\, kg\, a^{-1}$ for the MIT and ECHAM models respectively) or meltwater ($\sim 25 \cdot 10^{12}$ resp. $\sim 2.5 \cdot 10^{12}\, kg\, a^{-1}$) refreezes entirely in-situ. The temperature based methods predict small to moderate amounts of runoff, all of which is taking place on the Antarctic Peninsula. Although the source area of runoff is not inconsistent with the observed extent of the melt zone derived from satellite microwave remote sensing by Zwally and Fiegles (1994), the linear model's prediction of $620 \cdot 10^{12}\, kg\, a^{-1}$ of ablation for the current climate would have led to a rapid depletion of ice in that region. The warming of air temperatures predicted by the ECHAM model is entirely concentrated in the fall, winter and spring seasons, leaving summertime temperatures, and therefore melting, unchanged between the current climate and the time of $CO_2$ doubling.

# 5 Sea-Level Rise

## 5.1 ECHAM Model

Translating changes in the mass balance of an ice sheet into changes in sea-level requires either a transient integration or an assumption about the time evolution of the changes in accumulation and runoff between the time-slice experiments. The assumption used here is that the changes between 1990 and 2100 will proceed linearly. This assumption may not be justified in light of the preceeding discussion on the effects of non-linearities in the evolution of the surface albedo on the formation of meltwater and runoff, yet the transient integrations performed with the MIT model and described below do not give a clear indication that an alternate fit would clearly be more appropriate. Integrating the changes in mass balance based between the two runs of the ECHAM model yields the estimates of sea-level change shown in Fig.3. It is unclear which, if any, of those results is more reliable since all three estimates of runoff for the current climate were quite different and far from observations. The $173/163 \cdot 10^{12} kg\, a^{-1}$ increase in runoff predicted by the snowpack and degree-day models respectively for Greenland are to a large degree offset by the $132 \cdot 10^{12} kg\, a^{-1}$ increase in accumulation, and the resulting sea-level rise is negligible. The linear model predicts an increase of 2.8 $cm$ but that model was already substantially overestimating the current runoff. The decrease in sea-level associated with changes in the mass balance of the Antarctic ice sheet is entirely determined by the increase in accumulation. Therefore, because the ECHAM model provided the best estimate of accumulation of the two climate models over that ice sheet, the decrease in the level of the oceans by $5.5 - 6.5$ $cm$ by the end of the next century is the main conclusion to retain from these examples.

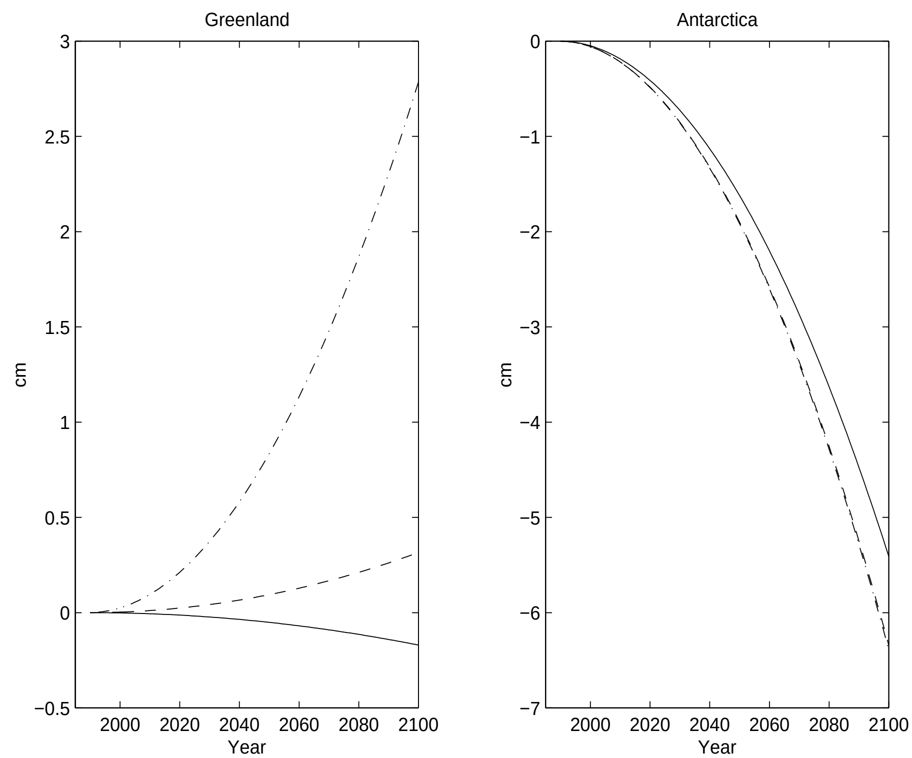


Figure 3: Prediction of changes in sea-level from 1990 to 2100 associated with changes in the mass balance of the Greenland (left) and Antarctic (right) ice sheets (Note that the scales are different), ECHAM 4 climate model Wild and Ohmura (1999). solid line: snowpack model, dashed line: degree-day model and dash-dotted line: linear model

## 5.2 MIT Model

The main advantage of a simpler climate model such as the MIT model is that it allows one to not only estimate the change in sea-level resulting from a reference climate change transient scenario similar to the IPCC's IS92A (Houghton et al., 1996), but it also allows an assessment of how various assumptions about the emissions of greenhouse gases and the uncertainty in key parameters in the climate model affect the estimate. The scenarios which are used in this study are characterized by a three letter code (Prinn et al., 1997):

- The first letter represents high, standard and low estimates for the increase in emissions of greenhouse gases.
- The middle letter gives an indication of the rate of warming. By taking lower/higher values for the aerosol optical depth and the oceanic heat uptake, the rate of warming will be faster/slower than for the reference case.
- The last letter gives the sensitivity of the model to greenhouse forcing. By tuning the cloud feedback, higher and lower sensitivities than the reference case can be obtained.

The $HHH$ scenario combines high emissions, a strong rate of warming and a large climate sensitivity, it therefore exhibits the largest warming of the runs, globally $+5.5°C$ degrees by 2100. The $LLL$ scenario has the smallest warming, $+1°C$ degrees in 2100. The reference scenario, which mimics the IPCC's IS92a scenario, and which was used to derive the melting and runoff at the time of carbon dioxide doubling in the preceeding section, has a global average increase in temperature of $+2.5°C$ by 2100. The scenarios are considered as being equally probable, and the results obtained by driving the snowpack model with this input data can be regarded as a first estimate of the range of uncertainty in the contribution of Greenland and Antarctica to sea-level change in the $21^{st}$ century.

The evolution from 1990 to 2100 of the individual contributions to the mass balance of the Greenland ice sheet, as estimated by the snowpack model for the $REF$, $HHH$ and $LLL$ scenarios, is shown in Fig.4.

Snow- and rainfall increase steadily over the next century, and the rate of increase is closely linked to rate of warming of the atmosphere, as shown by the differences between the

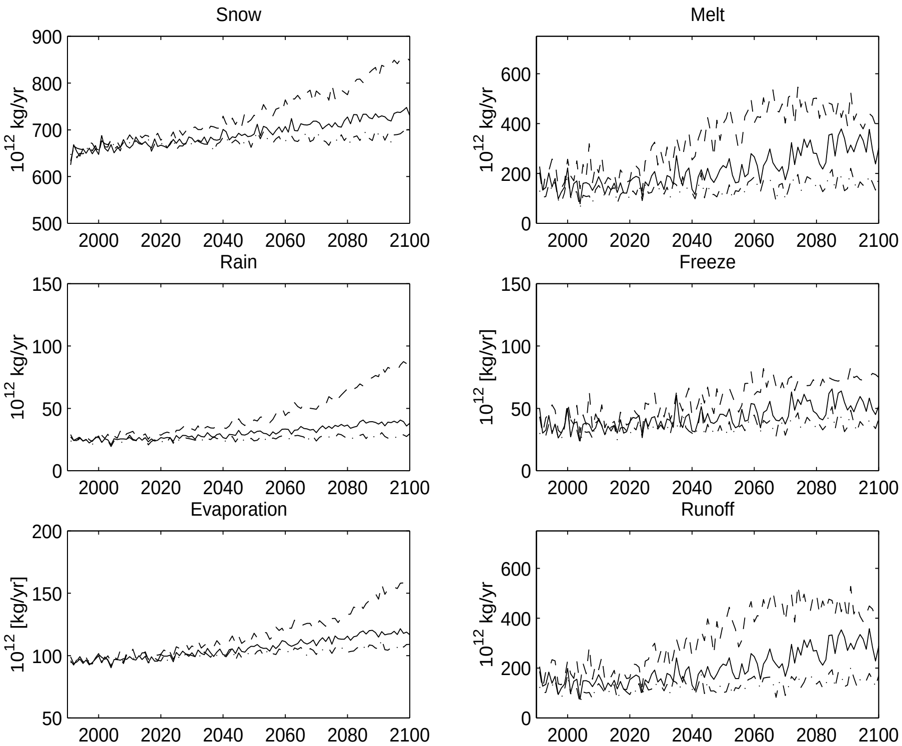


Figure 4: Time evolution from 1990 to 2100 of the amount of snowfall, rainfall, evaporation, melting, freezing and runoff over the Greenland ice sheet. Units are $10^{12}\, kg\, a^{-1}$. MIT model. Solid line: REF, dahed line: HHH, dash-dotted line: LLL scenarios.

three curves. As noted previously, this does not however mean that temperature changes control the increase in precipitation, the latter is determined by the modifications in atmospheric circulation which are associated with the changes in temperature. The slow changes in summer air temperatures have an important impact on the evolution of melting and runoff, these quantities do not increase beyond their 1990 values until 2050 in the $REF$ scenario, increase most rapidly between 2030 and 2070 in the $HHH$ scenario and do not show any visible change in the $LLL$ run. This delay is closely linked to the role of oceanic convection which limits the heating of the ocean surface in high latitudes, thereby increasing the time the atmosphere takes to adjust to the changes in forcing in transient simulations. Note that the warming predicted for the Arctic is still larger than the global average because of the ice-albedo feedback effect. The refreezing of rainfall and meltwater remains an important component of the mass balance throughout the integrations, but the capacity of the snow cover to refreeze liquid water diminishes as the warming accelerates and more meltwater is produced. The ratio of melting/freezing in the $HHH$ run is $\sim 4$ at the start of the integration and increases to $\sim 6$ by 2100. These changes are closely linked to the density structure of the snow cover in the ablation region: Once the newly deposited snow of the previous winter is melted away and bare ice is exposed, the capacity to refreeze water is lost until new snow is deposited, the meltwater contributes therefore rapidly to the total runoff. The albedo of bare ice is set to a constant value and the melting becomes largely independent of the surface air temperature once ice is exposed, which explains why runoff in the $HHH$ scenario levels off after 2070. Refreezing does however retain an important role in delaying the formation of runoff in areas which were previously not exposed to melting: The small amounts of rain- or meltwater which are added at the surface in the summer immediately refreeze in the snowpack to form superimposed ice layers, thereby delaying the onset of runoff.

The equivalent projections for the Antarctic ice sheet are shown in Fig.5. The most striking difference to Greenland is the amount of refreezing taking place. The very cold winter temperatures combined with large negative values in the energy balance lead to firn temperatures which are much colder than on Greenland, and which represent a sufficient storage of energy to refreeze any meltwater which percolates into the snowpack during the summer. With the exception of the $HHH$ scenario which does show substantial melting taking place in Antarctica by the end of the $21^{st}$ century, runoff remains a negligible quantity in the $REF$ and $LLL$ scenarios. Note that most of the melting occurs on the Antarctic Peninsula, an area characterized by strong topographic gradients. It is far from certain that the $40\,km$ grid which was used is sufficiently fine to capture the changes in mass balance in that region adequately.

The impact on the sea-level of the changes in the individual components which form the mass balance are shown as an example for the case of the $REF$ scenario and Greenland in Fig.6. Changes in rainfall and evaporation contribute almost equally but in opposite directions to the sea level change, both effects are also very small. The increase in accumulation is balanced by the increase in melting, and the net sea level change is very small. This is to a certain extent also the case for the other six scenarios, shown in Fig.7; the $+1.7\,cm$ increase

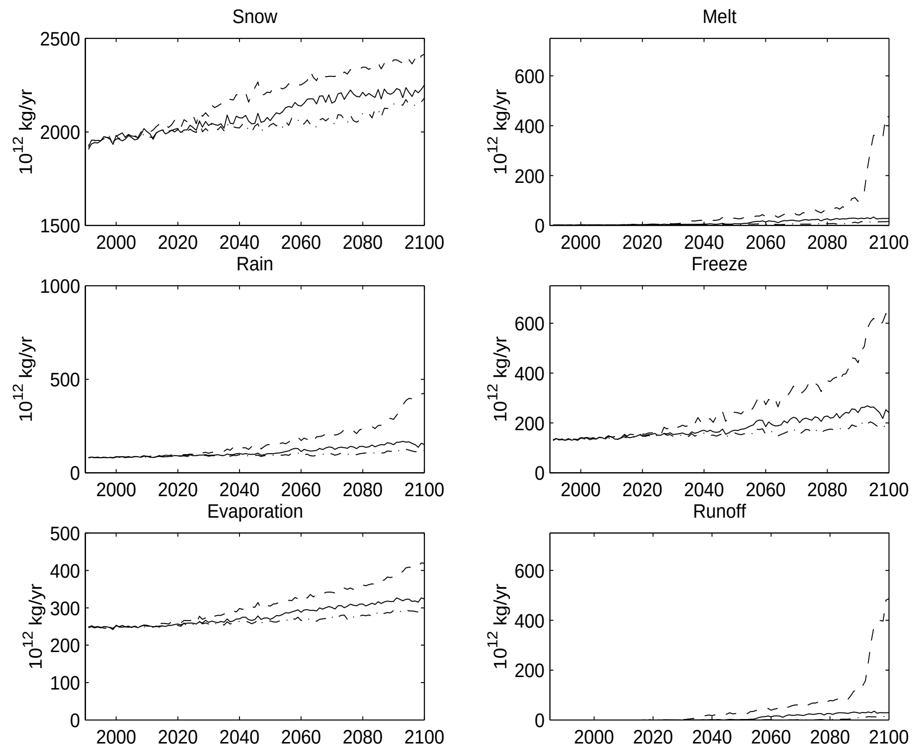


Figure 5: Evolution from 1990 to 2100 of the amount of snowfall, rainfall, evaporation, melting, freezing and runoff over the Antarctic ice sheet. Units are $10^{12}\,kg\,a^{-1}$. MIT model. Solid line: REF, dahed line: HHH, dash-dotted line: LLL scenarios.

in sea-level from Greenland associated with the HHH run is the result of a $4.2\,cm$ rise due to increased runoff and of a $2.5\,cm$ drop due to increased accumulation. As the climatic forcing strengthens, increasingly large changes in accumulation and ablation are to a large degree offsetting each other, giving the impression that the mass balance of the Greenland ice sheet is relatively insensitive to changes in climate when in fact the amount of meltwater runoff has doubled or tripled by 2100. The contribution of Greenland to sea-level rise can nevertheless be expected to be in the -0.5 – +1.7 $cm$ range by 2100.

It is worth noting that the dominant factor in determining the range of uncertainty in the prediction of sea-level rise is not the rate of increase in emissions of greenhouse gases, but the assumption made about two climate model parameters: the aerosol optical depth and the deep ocean heat uptake. The latter factor is particularly important in high latitudes. The runs which have a low ocean heat uptake (middle letter $H$) exhibit a larger sea level rise than

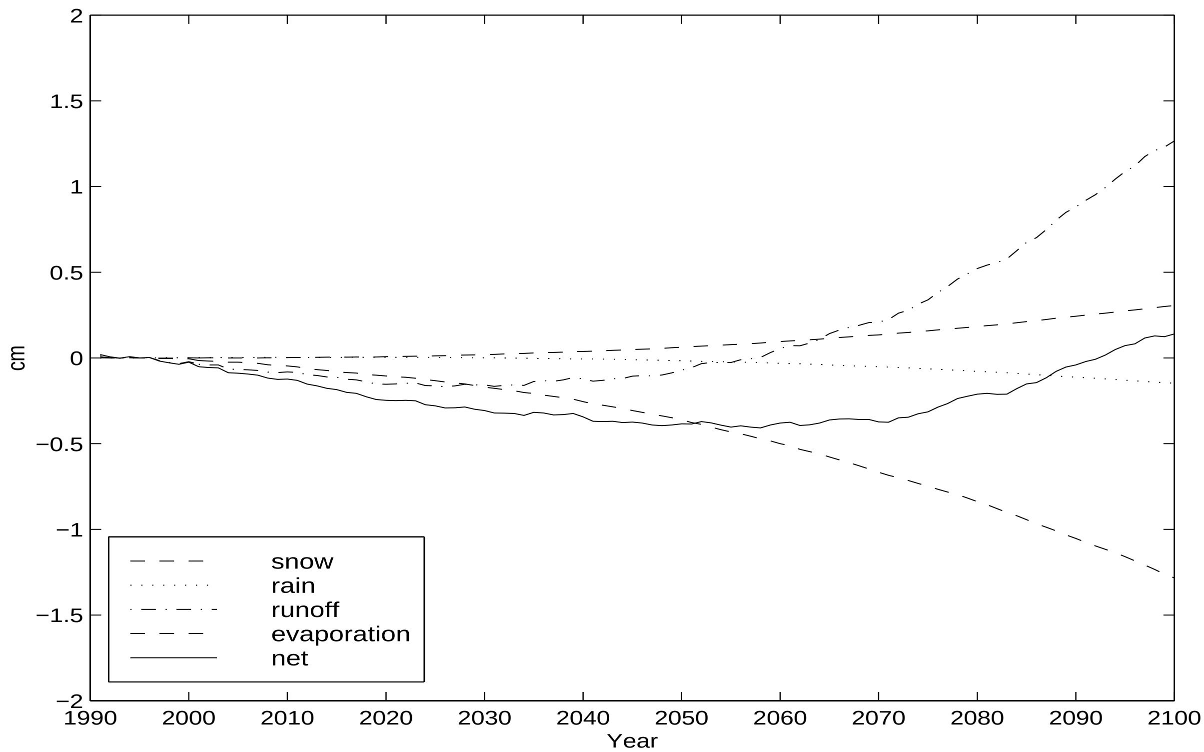


Figure 6: Individual contribution to sea level change from Greenland, in *cm*. Reference transient scenario, MIT model.

those with high heat uptake (middle letter $L$). By mixing the water column and transporting heat from the surface to the deep ocean, convective overturning in high latitudes is the main mechanism which delays the warming of the atmosphere. In a simplifying assumption, oceanic heat uptake is modeled as a diffusive process below the mixed layer ocean model which is coupled to the MIT atmospheric model for the transient runs (Sokolov and Stone, 1998).

The situation in Antarctica is dominated by the increase in accumulation. The small increase in snowfall in the $LLL$ scenario leads to a 2.6 $cm$ decrease in sea-level. The substantial increase in runoff observed during the last 20 years of the $HHH$ integration is sufficient to begin a reversal of the downward trend in sea-level. This leads to a range of uncertainty of -6.2 – -2.6 $cm$ for Antarctica.

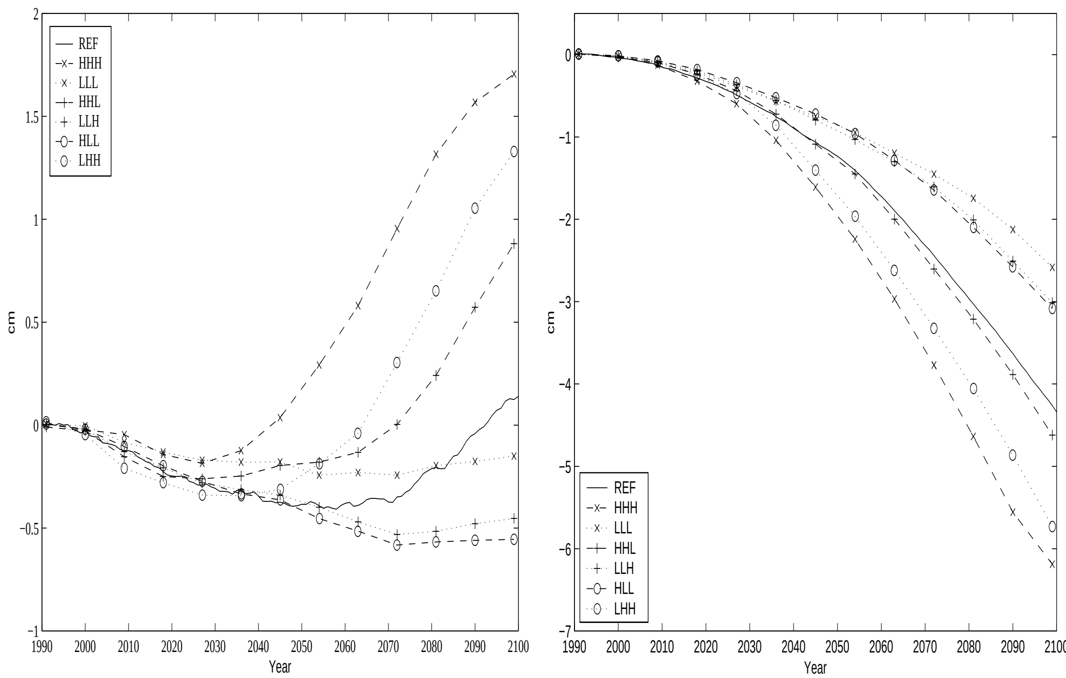


Figure 7: Sea level rise induced by the change in mass balance for 7 transient runs for the Greenland (left) and the Antarctic ice sheet (right), MIT model. Units are cm.

The scaling applied to the precipitation field in Antarctica, which reduces current total accumulation to the observed value, has an important impact on the estimates of sea-level rise, without it, the decrease in the level of the oceans would be in the -12.2 – -4.3 $cm$ range.

The combined effects of Greenland and Antarctica on sea-level changes predicted by the MIT/snowpack model is summarized in Table 4 and is in the -4.5 – -2.7 $cm$ range. This is a surprisingly small range of uncertainty when considering the large spread in temperature changes associated with the various scenarios, but it follows logically from the offsetting effects of the two ice sheets.

The estimates of runoff derived with the three melt models for Greenland were all within a reasonable range of observations for the current climate. It is therefore particularly interesting to observe how they respond to the range of forcing provided by the $HHH - LLL$ scenarios. The evolution of the runoff from the Greenland ice sheet is shown as the left-hand column of Fig.8, the changes in sea-level in 2100 are summarized as the first three columns of Table 4. The three models are generally in good agreement over a broad range of forcing.

| | Greenland | | | Antarctica | | | Net | | |
|---|---|---|---|---|---|---|---|---|---|
| | SP | PDD | LM | SP | PDD | LM | SP | PDD | LM |
| $REF$ | 0.2 | 0.1 | 0.3 | -4.3 | 0.4 | 2.6 | -4.1 | 0.5 | 2.9 |
| $HHH$ | 1.7 | 2.0 | 2.8 | -6.2 | 24.6 | 6.5 | -4.5 | 26.6 | 9.3 |
| $LLL$ | -0.1 | -0.1 | 0.0 | -2.6 | -1.1 | 1.1 | -2.7 | -1.2 | 1.1 |

Table 4: Sea-level change predicted by the MIT model for the $REF, HHH, LLL$ scenarios and the snowpack (SP), Positive Degree-Day (PDD) and Linear models (LM). Left-hand column: Greenland, Middle column: Antarctica, Right-hand column: Net sea-level change. Units are $cm$

The discrepancy which occurs during the last 20–30 years of the $HHH$ integration does however point to a limitation of the degree-day model and to the crucial role of the albedo parameterization in detemining melting. Beyond a certain threshold which is reached once ice outcrops during the ablation season, increasing temperatures will no longer have much impact on the rate of meltwater formation in the snowpack model (they have an indirect effect through the sensible and latent heat fluxes), the amount of runoff predicted by the degree-day model will however continue to increase. The linear model predicts a slightly larger amount of runoff in all scenarios and suffers from the same flaw as the degree-day model, most likely because the range of temperatures over which the model was originally calibrated has been exceeded by the end of the $HHH$ run.

The equivalent results for Antarctica are shown in the right-hand column of Fig.8 and are summarized as the central three columns of Table 4, they do not have the consistency of the results presented for Greenland. The temperature based methods, and the degree-day method in particular, are much more sensitive to the changes in climate which are taking place. This is in large part due to their inability to refreeze large amounts of meltwater (refreezing in the snowpack model reduces the amount of runoff by $615 \cdot 10^{12}\, kg\, a^{-1}$ in the $HHH$ scenario in 2100 and offsets a large part of the increase in rainfall and melting) and to the fact that they were not calibrated to the conditions prevailing in that part of the world.

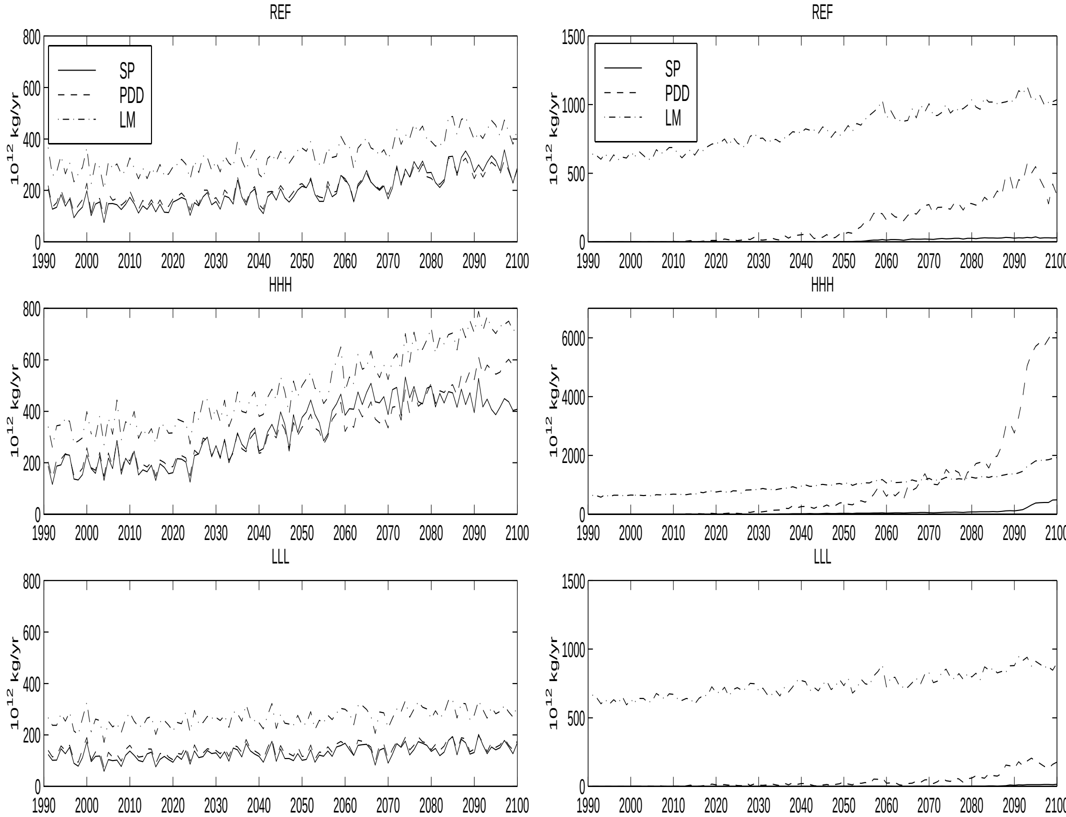


Figure 8: Evolution of the runoff from 1990 to 2100. Left column: Greenland, Right column: Antarctica. MIT climate model. Snowpack Model: solid line, Degree-Day Model: dashed line, Linear Model: dash-dotted line. Top panels: $REF$, Middle panels: $HHH$, Lower panels: $LLL$. Units are $10^{12}\,kg\,a^{-1}$

# 6 Effect of the Kyoto Protocol on Sea-Level Change

As part of an international effort to mitigate the potential human-induced climate change, the so-called Annex I countries agreed to reduce their emissions of carbon dioxide and other greenhouse gases at the Third Conference of the Parties to the United Nations Framework Convention on Climate Change held at Kyoto, Japan in December, 1997. The terms of this Protocol call for industrialized nations to reduce their emissions of six greenhouse gases below 1990 levels by 5.2% on average by 2008-2012. In particular, the United States agreed to a 7% reduction, while the European Union agreed to an 8% reduction, and Japan a 6% reduction. If the Protocol is ratified, these nations will be committed to legally-binding restrictions.

The impact of the Kyoto Protocol on changes in sea-level is calculated here in Fig. 9 by contrasting the results derived from a simulation in which no restrictions are imposed on the emissions of greenhouse gases which are allowed to grow unconstrained (note that because of assumptions about emission rates of greenhouse gases, this scenario has slight differences from the $REF$ run used in the previous section) and a simulation in which the terms of the Kyoto protocol are implemented and emissions by the industrialized nations are held constant after the 2008-2012 compliance period (Reilly et al., 1999). The global mean warming is reduced to $2°C$ when the Kyoto Protocol is imposed, from $2.4°C$ in the unconstrained case. The difference is however twice as large in polar regions where the Protocol reduces the warming from $4.6°C$ to $3.8°C$ by 2100. The protocol reduces the increase in sea-level due to increased melting on the Greenland ice sheet by $\sim 1\,cm$, it however also reduces the decrease in sea-level linked to increasing accumulation over Antarctica by little more than the same amount. The Kyoto protocol thus leaves the prediction of sea-level change due to modifications in the mass balance of the ice sheets virtually unchanged at $-3\,cm$ by the end of the $21^{st}$ century. This effect is however only one of numerous contributions to sea-level rise, the contributions from thermal expansion, the melting of small glaciers and ice caps and changes in surface and ground water uses are not included in this estimate.

# 7 Discussion

The combined effect of increasing accumulation and runoff from the Greenland and Antarctic ice sheets on the level of the oceans are summarized in Table 4. The range obtained with the MIT / snowpack model combination is -4.5 – -2.5 $cm$, with a best guess of -4 $cm$. At -5.5 $cm$, the number obtained with the ECHAM climate input, when coupled to the snowpack model, is not very different. The reasonable agreement between the results obtained for both Greenland and Antarctica by the ECHAM and MIT-$REF$ gives some confidence in the results obtained with the MIT model for the other climate change scenarios and the Kyoto runs. The thermal expansion associated with the $REF$ run is 17 $cm$ (Prinn et al., 1997), thus the contribution of Greenland and Antarctica represents a 25 % reduction, bringing

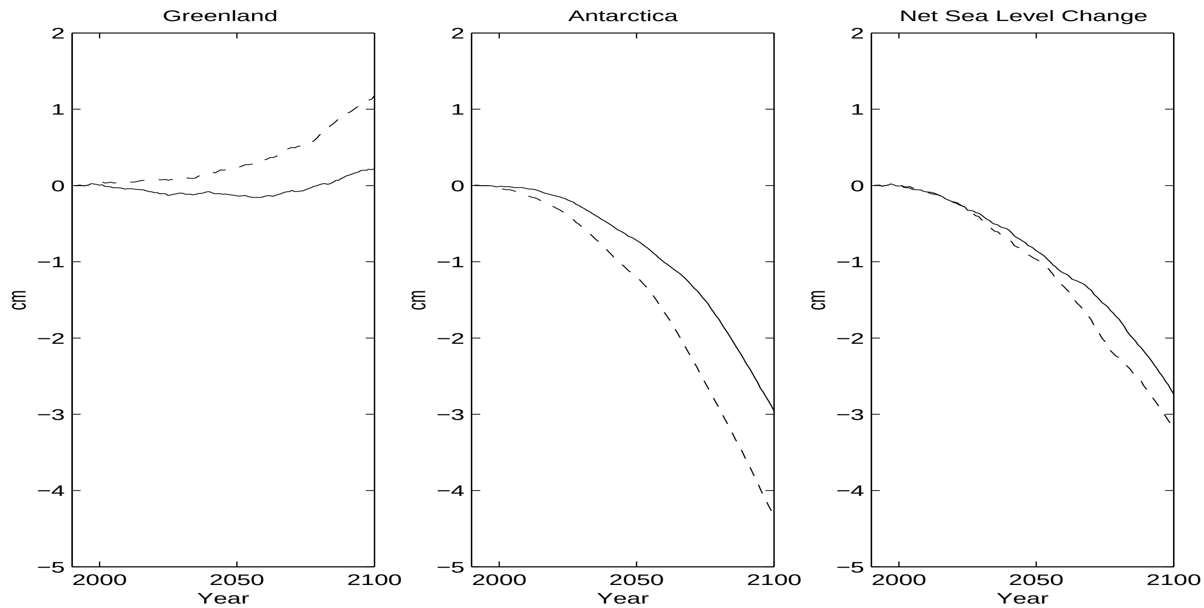


Figure 9: Changes in sea level calculated for the reference scenario (dashed line) and for a scenario implementing the Kyoto protocol (full line) for Greenland (left), Antarctica (middle) and net sea-level change (right). Units are *cm*.

this number down to 13 *cm*. The small changes over the next century which are estimated with the snowpack model stand in sharp contrast with the conclusions from previous studies (Ohmura et al., 1996; Thompson and Pollard, 1997; DeWolde et al., 1997) which were as large as $+10\,cm$ for Greenland and $-10\,cm$ for Antarctica. The discrepancies between these projections can however be explained by differences in climate models, in the use of transient vs. equilibrium simulations, by differences in the resolution at which melting is calculated and in the models used to estimate runoff. The scaling factor used to obtain a realistic total accumulation over the Antarctic ice sheet also has an important effect in reducing the contribution to sea-level change from that continent.

The results obtained with the snowpack model certainly have more credibility than those derived with simple parameterizations. Temperature based methods such as the degree-day and linear models are calibrated to the range of temperatures and conditions observed in southern Greenland and are prone to failure outside of that range, as can be seen from the results obtained in Antarctica. As could be expected in snow or ice covered areas, the parameterization of the surface albedo has a determining influence on the results, and both the non-linear dependence of snow albedo on surface temperature and the absence of dependence of the ice albedo on temperature critically affects the results obtained with the snowpack model. The importance of the surface energy balance and of the temperature and density structures within the snow cover in determining runoff is highlighted by the ability of the snowpack in Antarctica to refreeze most of the melt- and rainwater which is added at the surface, thereby adding an important delay in the onset of melting. Significant changes can however be expected to take place on the Antarctic Peninsula for a warming of more than a few degrees.

In order to avoid excessive computation requirements, simplifications in climate models are however required to perform many transient simulations. The weakness of this study lies in the inability of the MIT climate model to capture regional climate changes, for example the changes in location and intensity of the Atlantic storm track which would affect the accumulation of snow on the Greenland ice cap. Local climate changes could also affect the temperature structure of the atmosphere and the lapse rates which were assumed to remain constant in this study. The zonal model does however capture global scale changes in the atmospheric circulation and in the moisture transport.

The assumptions made about the intensity of oceanic heat uptake are shown to play a dominant role in determining melting on the Greenland ice sheet. The constant ocean diffusion coefficient which is used below the mixed layer ocean model does not allow to capture the changes in the thermohaline circulation which could accompany the modifications of the atmospheric circulation, as reported by Cubasch et al. (1992), Manabe and Stouffer (1994) or Wood et al. (1999). A reduction in the intensity of the thermohaline circulation would induce a relative cooling in the region around Greenland which would further reduce, or reverse the direction of the changes in melting and runoff. However, comparisons with coupled A/O-GCM results have shown that the global effect is small for 100 year projections (Sokolov and Stone, 1998).

The freshwater flux from Greenland increases from $\sim 0.0015\,Sv$ in 1990 to $\sim 0.003\,Sv$ at the end of the $21^{st}$ century in the reference run. This is only a fraction of the freshwater flux which occurred during the Younger Dryas and peaked at $0.44\,Sv$ Fairbanks (1989), and which is thought to have been sufficient to lead to the temporary collapse, or at least to a transition to a different state of overturning, of the thermohaline circulation (Broecker et al., 1985; Lehman and Keigwin, 1992). It is also much less than the freshwater pulses artificially added to the North Atlantic basin in model simulations aimed at switching the state of the thermohaline circulation away from its current equilibrium (Marotzke and Willebrand, 1991; Manabe and Stouffer, 1995; Rahmsdorf and Willebrand, 1995). Enhanced poleward atmospheric moisture transport also leads to a weakening of the thermohaline circulation in simulations of future climate changes in coupled atmosphere-ocean GCM's. The contribution of Greenland to the freshwater forcing is smaller by a factor of 5–10 than the increase over the North Atlantic basin due to atmospheric transport ($0.15\,Sv$ North of $50°N$ with the assumption of a geographically uniform increase) reported by Manabe and Stouffer (1994) after the first hundred years of their 1% per year increase in $CO_2$ experiment. Because the freshwater produced by the melting of snow and ice on the Greenland ice sheet flows into the Labrador and Greenland Seas very close to the sites of deep water formation, a small increase in runoff may not have a negligible impact on the convective overturning. The assesment of effects such as these would however require an interactive coupling between the snowpack model and an atmosphere-ocean GCM.

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