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Evolution and Dynamics of the Greenland Ice Sheet over Past Glacial-Interglacial Cycles and in Future Climate-Warming Scenarios

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1. INTRODUCTION

The Greenland ice sheet is the second-largest ice body on today's Earth. Like the Antarctic ice sheet, it is an active component of the terrestrial climate system which interacts with the atmosphere, the ocean and the lithosphere by multiple processes. In this study, it is attempted to simulate the evolution of the Greenland ice sheet over the past glacial-interglacial cycles and in response to future climate change. To this end, dynamic/thermodynamic simulations of the Greenland ice sheet with an updated version of the model SICOPOLIS (SImulation COde for POLythermal Ice Sheets) are carried out for these two problems.

2. ICE-SHEET MODEL SICOPOLIS

The model SICOPOLIS simulates the large-scale dynamics and thermodynamics (ice extent, thickness, velocity, temperature, water content and age) of ice sheets three-dimensionally and as a function of time (Greve 1997). It is based on the shallow-ice approximation (Hutter 1983, Morland 1984) and the rheology of an incompressible, heat-conducting, power-law fluid [Glen's flow law, see Paterson (1994)]. The thermo-mechanical coupling is described by the temperature- and water-content-dependent rate factor in the form of Greve et al. (1998) which follows Paterson's (1994) recommendations. Isostatic depression and rebound of the lithosphere due to changing ice load is modelled by the local-lithosphere-relaxing-asthenosphere (LLRA) approach with an isostatic time lag (Le Meur and Huybrechts 1996, Greve 2001). External forcing is specified by (i) the mean annual air temperature at the ice surface, (ii) the surface mass balance (precipitation minus runoff), (iii) the global sea level which defines the land area available for glaciation and (iv) the geothermal heat flux prescribed at the bottom of a lithospheric thermal boundary layer of 5 km thickness. For all simulations, the resolution is 20 km, the time-step is 5 a, the geothermal heat-flux distribution is that of Greve (2005, Fig. 4) [based on the global heat-flow representation by Pollack et al. (1993) and heat-flow values of 60, 135, 50 and 20 mW m^{-2} for the ice-core locations GRIP, NGRIP, Camp Century and Dye 3, respectively], and the model parameters are those of Greve (2005, Table 1).

3. PALEOCLIMATIC SCENARIO

3.1 Set-up

As measure for the climate state at any time t during the last 422 ka, a glacial index $g(t)$ is used, which is based on the GRIP (from 105 ka BP until the present) and Vostok (prior to 105 ka BP) surface-temperature records. It is defined such that $g = 1$ denotes LGM conditions and $g = 0$ present conditions (Fig. 1). The climatic forcing fields (surface temperature, precipitation) over the ice sheet are then determined by interpolating between present conditions (as known from data) and LGM anomalies [results of GCM simulations with the

UKMO model by Hewitt and Mitchell (1997)], weighed by the glacial index. Surface melting is parameterised by a modification of Reeh's (1991) degree-day method. For details see Greve (2005).

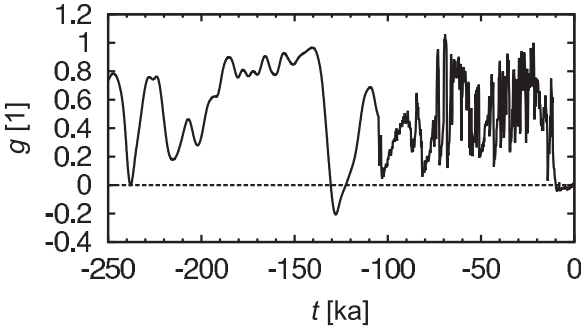

Figure 1: Glacial index $g(t)$ synthesized from the GRIP (from 105 ka BP until the present) and Vostok (prior to 105 ka BP) surface-temperature records (Greve 2005).

Model time for the simulation is from 250 ka BP until today. Initial conditions are provided by a spin-up simulation from 422 ka BP until 250 ka BP for which the thermal inertia of the lithosphere has been switched off.

3.2 Results

Figure 2 shows the evolution of the ice volume over the last 150 ka. As expected, the volume is larger during glacial and smaller during interglacial periods, and the Eemian ice retreat is much more pronounced than the retreat during the Holocene. The simulated Eemian ice-volume minimum at 123.5 ka BP ($2.026 \times 10^6\,\mathrm{km}^3$) corresponds to an equivalent sea-level rise of 2.75 m compared to the simulated present-day volume ($3.115 \times 10^6\,\mathrm{km}^3$). The LGM ice volume at 21 ka BP is $3.487 \times 10^6\,\mathrm{km}^3$ or 0.94 m of sea-level lowering.

The simulated present-day surface topography is shown in Figure 3. The ice volume ($3.115 \times 10^6\,\mathrm{km}^3$) is 6.2% too large compared to the observed value of $2.932 \times 10^6\,\mathrm{km}^3$. Most of this difference originates from simulated ice cover in areas where there is no ice in reality, in particular in Peary Land north of 82°N, and along the eastern ice margin between 68°N and

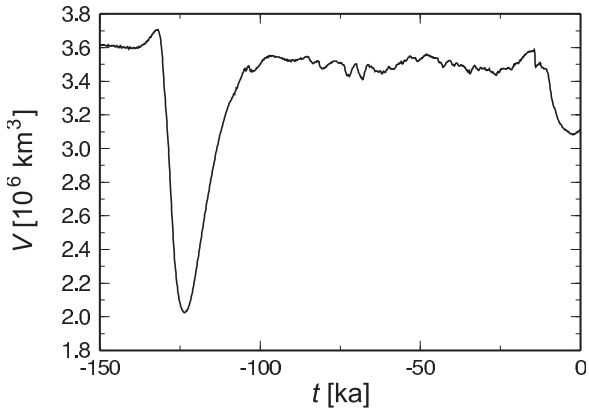

Figure 2: Paleoclimatic simulation: Ice volume V over the last 150 ka.

74°N. Nevertheless, the agreement with the observed topography (not shown) is very satisfactory, which is a good validation of the simulation results.

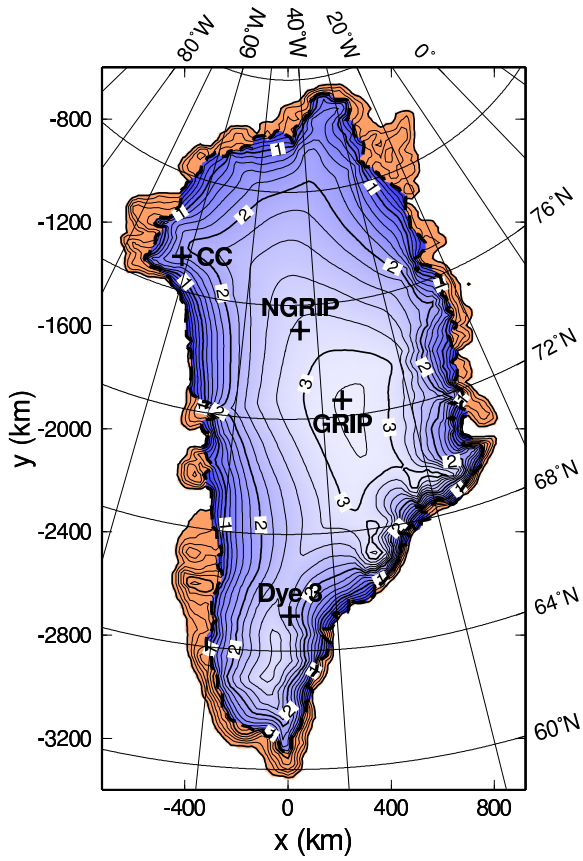

Figure 3: Paleoclimatic simulation: Present-day surface topography (contour spacing 200 m, labels in km a.s.l.). The heavy dashed line indicates the ice margin.

4. GREENHOUSE SCENARIOS

4.1 Set-up

The present-day ice sheet, which results from the paleoclimatic simulation and is shown in Fig. 3, is now used as initial condition for simulations over some hundred years into the future. It is assumed that the global mean temperature change results from the WRE profiles which assume stabilisation of the atmospheric CO_2 concentration at 450, 550, 650, 750 and 1000 ppm, respectively (Cubasch et al. 2001). The corresponding temperature scenarios are shown in Fig. 4.

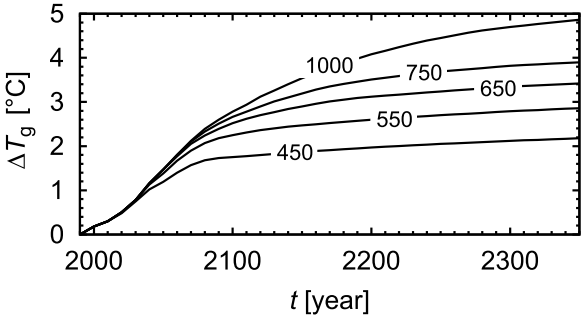

Figure 4: Global mean temperature change ΔT_g for the profiles WRE450, WRE550, WRE650, WRE750 and WRE1000 (stabilisation scenarios for atmospheric CO_2), by Cubasch et al. (2001).

Church et al. (2001, Table 11.13) report that nine different AOGCM experiments following the IS92a scenario for the 21st century provided a temperature change over the Greenland ice sheet in the range of 1.3 . . . 3.1 times the global mean change, with an average ratio of approx. 2. The increase in precipitation over Greenland was 2.7 . . . 7.8%/°C with an average of approx. 5%/°C. Here, these average sensitivities are transfered to the five simulations forced by the WRE scenarios. Consequently, the surface temperatures shown in Fig. 4 are amplified by a factor 2 and imposed as uniform increases over the ice sheet, and the precipitations are assumed to increase by 5% per degree of ice-sheet-surface-temperature change. Model time for the simulations is from the year 1990 (the "present") until the year 2350.

4.2 Results

The volume decreases of the Greenland ice sheet which result from the five scenarios are displayed in Fig. 5 (upper panel) as sea-level equivalents. In all cases, the volume decreases monotonically over time and does not stabilize within the modelled period. Therefore, the increased precipitation rates under warmer conditions are always outweighed by increased surface melting. In 2100, for the most optimistic WRE450 simulation the equivalent sea-level rise is 8.7 cm, whereas for the most extreme WRE1000 simulation it is 14.6 cm. During the 22nd century, the difference between the simulations becomes significantly larger, and in 2350 the sea-level rises vary by more than a factor 3.5, between 48.6 cm (for WRE450) and 1.78 m (for WRE1000).

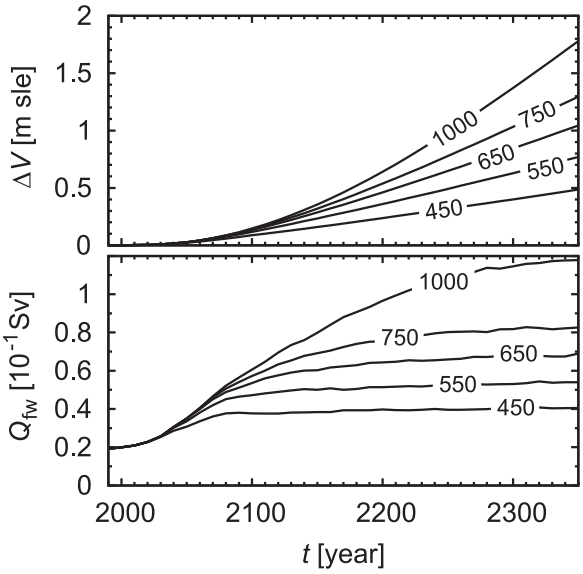

Figure 5: Volume change ΔV (in sea-level equivalents) and freshwater discharge Q_{fw} ($1\,\mathrm{Sv} = 10^6\,\mathrm{m}^3$ water equiv. s^{-1}) for the five simulations driven by the WRE surface-temperature scenarios shown in Fig. 4.

The freshwater discharge from the ice sheet into the surrounding sea (total of melting and calving) at present is 0.019 Sv, which corresponds to approx. $600\,\mathrm{km}^3$ water equiv. a^{-1}. Fig. 5 (lower panel) shows that even for the WRE450 simulation, it reaches twice that value by 2100, and stabilizes from then on. By contrast, for the WRE1000 simulation, the freshwater discharge doubles already in 2060, increases

further on and reaches almost 0.12 Sv in 2350, which is about six times the present value.

It is interesting to note that the shapes of the freshwater-discharge curves resemble closely those of the temperature-change forcings (Fig. 4). This is so because the increased freshwater discharge in global-warming scenarios for the Greenland ice sheet is almost entirely due to surface melting which is directly related to the increased surface temperatures.

5. CONCLUSION

The new simulations discussed here confirm (despite their inherent uncertainties) that the Greenland ice sheet underwent major changes over the past glacial-interglacial cycles and will most likely react significantly to future climate change. However, this is not a one-way road, because changes of the ice-sheet topography, albedo and freshwater discharge act back on the atmospheric and oceanic dynamics and thermodynamics. These feedback processes can lead to unexpected results in the coupled climate system, which can naturally not be captured by a pure ice-sheet model. This points out the necessity for future work on integrated climate-system modelling.

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