Implications of changes in freshwater flux from the Greenland ice sheet for the climate of the 21st century

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[1] Two simulations of the 21st century climate have been carried out using, on the one hand, a coarse resolution climate general circulation model and, on the other hand, the same model coupled to a comprehensive model of the Greenland ice sheet. Both simulations display a gradual global warming up to 2080. In the experiment that includes an interactive ice sheet component, a strong and abrupt weakening of the North Atlantic thermohaline circulation occurs at the end of the 21st century. This feature is triggered by an enhanced freshwater input arising mainly from a partial melting of the Greenland ice sheet. As a consequence of the circulation decline, a marked cooling takes place over eastern Greenland and the northern North Atlantic. This result underlines the potential role of the Greenland ice sheet in the evolution of climate over the 21st century. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1635 Global Change: Oceans (4203); 4255 Oceanography: General: Numerical modeling; 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes. **Citation:** Fichefet, T., C. Poncin, H. Goosse, P. Huybrechts, I. Janssens, and H. Le Treut, Implications of changes in freshwater flux from the Greenland ice sheet for the climate of the 21st century, *Geophys. Res. Lett.*, *30*(17), 1911, doi:10.1029/2003GL017826, 2003.

1. Introduction

[2] Deep convective mixing is an essential ingredient of the ocean thermohaline circulation (THC). In particular, sinking of surface water in the Greenland-Iceland-Norwegian (GIN) Seas and in the Labrador Sea leads to the formation of North Atlantic Deep Water (NADW) and initiates an overturning circulation cell on the meridional plane in which the northward transport of upper ocean warm water is balanced by a deep return flow of cold water, imposing a strong northward heat flux in both the North and South Atlantic Oceans [*Gordon*, 1986]. Due to this transport, the northern North Atlantic is about 4°C warmer than the Pacific at similar latitudes. Changes in NADW circulation therefore have the potential to cause significant climate change over the North Atlantic region. The pioneering work by *Stommel* [1961] and other more recent studies [e.g., *Rahmstorf*, 1995] suggest that the THC is a non-linear system which is highly sensitive to changes in freshwater forcing. It may collapse if a certain threshold is exceeded and can show hysteresis behavior. There is also growing evidence that some of the glacial climate shifts recorded in proxies were associated with changes in NADW flow due to hydrological interactions with continental ice sheets [e.g., *Ganopolski and Rahmstorf*, 2001; *Wang and Mysak*, 2001; *Schmittner et al.*, 2002].

[3] A likely consequence of global warming is a partial melting of the Greenland ice sheet, resulting in a positive contribution to sea level change and a larger freshwater flux into the surrounding ocean. Over the past decade, various studies were conducted with ice sheet models to quantify the ice volume alterations under specified climate change scenarios for the 21st century and beyond [e.g., *IPCC*, 2001]. In the most comprehensive assessments, the Greenland ice sheet is projected to be able to contribute up to 9 cm to global sea level rise by 2100, with the potential of a larger contribution afterward if the warming were sustained beyond the 21st century. As the Greenland ice sheet lies close to the two main areas of NADW formation, one can anticipate that it will play a role in modulating the future strength of the THC. In the present work, this effect is evaluated over the 21st century with a coarse resolution climate general circulation model (CGCM) coupled to a comprehensive model of the Greenland ice sheet (GISM).

2. Model Description and Experimental Design

[4] Apart from some improvements made to the river routing scheme, the CGCM used here is identical to that of *Huybrechts et al.* [2002]. The atmospheric component is based on version 5.3 of the LMD atmospheric general circulation model (AGCM) [*Grenier et al.*, 2000]. It is a grid point model with 64 points evenly spaced in longitude, 50 points evenly spaced in sine of latitude, and 15 sigma levels. The direct effect of sulfate aerosols is simulated by increasing the surface albedo as in *Mitchell et al.* [1995]. The ocean-sea ice component is the CLIO model [*Goosse and Fichefet*, 1999]. This model is made up of a primitive equation, free surface ocean general circulation model coupled to a thermodynamic-dynamic sea ice model with viscous-plastic rheology. Its horizontal resolution is of 3° × 3°, and there are 20 vertical levels. No flux correction is applied to the coupled CGCM.

[5] The GISM consists of a high resolution (20 km, 31 levels) thermomechanical ice dynamics model coupled to a visco-elastic bedrock model [*Huybrechts and de Wolde*, 1999]. It also includes a surface mass balance model that distinguishes between snow accumulation, rainfall, and

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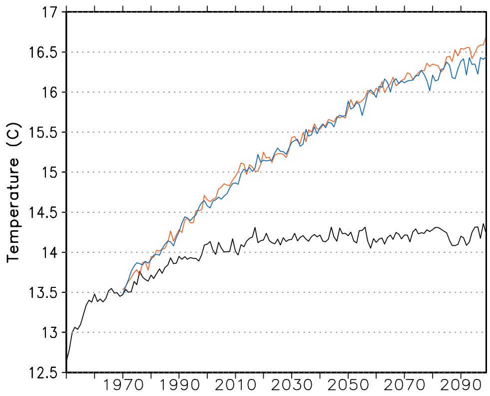

Figure 1. Time series of globally averaged annual mean SAT from CONTROL (in black), SRESB2 (in red), and SRESB2G (in blue).

runoff. The melt and runoff scheme is based on the positive degree-day method and accounts for meltwater retention in the snow pack and formation of superimposed ice [*Janssens and Huybrechts*, 2000].

[6] The key atmospheric variables needed as input for the GISM are surface temperature and precipitation. Because the details of the surface climate of Greenland are not well captured on the coarse AGCM grid, these boundary conditions consist of a present-day component as represented on the much finer GISM grid to which climate change anomalies from the CGCM are superimposed. The present-day surface temperature over Greenland is parameterized as a function of latitude and surface elevation, and the current precipitation rate is prescribed from observations (see *Huybrechts et al.* [2002] for details). Temperature differences and precipitation ratios (climate change versus control) produced by the CGCM are interpolated from the AGCM grid onto the GISM grid and respectively added or multiplied with the reference surface temperatures and precipitation rates. Temperature perturbations are applied monthly, but precipitation ratios are only imposed annually because reliable information on the monthly distribution of precipitation over Greenland is missing for the reference climate. The GISM in turn provides CLIO with the geographical distribution of the annual mean freshwater flux resulting from ice sheet runoff, iceberg calving, runoff from ice-free land, and basal melting below the ice sheet. The AGCM does not accommodate changes in the geometry of the Greenland ice sheet (elevation and extent) as these would be hardly detectable on the coarse AGCM grid on the century time-scale that is the subject of this paper.

[7] A control simulation (CONTROL) of 150-yr duration was first performed with the CGCM. The initial state consisted of outputs from equilibrium experiments conducted with the stand-alone AGCM and CLIO model. In this run, the atmospheric greenhouse gas and sulfate aerosol amounts were held fixed at the 1970 values. The model was then integrated from the beginning of year 21 of CONTROL for 130 years (corresponding to the period 1971–2100) with the greenhouse gas and sulfate aerosol concentrations increasing with time according to the IPCC SRES B2 scenario [*IPCC*, 2001]. This run will be hereafter referred to as SRESB2. In both experiments, the freshwater flux from Greenland was prescribed to annual mean values taken from the GISM initial state decribed below. Note that this prevents a strict conservation of mass in the model. A third simulation (SRESB2G), similar to SRESB2, was carried out with the CGCM coupled to the GISM. Because of the long response time of the Greenland ice sheet, the GISM has been first run over the last two glacial-interglacial cycles up to the year 1970 with forcing from ice core data to derive initial conditions for coupling with the CGCM (see *Huybrechts and de Wolde* [1999] for details). A second control run with an interactive Greenland ice sheet was not performed because the GISM does not evolve much under a fixed 1970 climate [*Huybrechts et al.*, 2002], and therefore such a coupled experiment would have been very similar to CONTROL with a fixed Greenland ice sheet.

3. Results

[8] Figure 1 displays the temporal evolution of the globally averaged annual mean surface air temperature (SAT) for CONTROL, SRESB2, and SRESB2G. A warming of 0.8°C occurs during the first decade of CONTROL. After this initial phase, the temperature continues to rise at a slower rate (0.15°C per decade) for 50 years before finally stabilizing. In the Southern Ocean, only a reduced sea ice cover remains after a strong initial melting (6×10^6 km^2 at the time of the maximum ice area, to be compared with the observed 16×10^6 km^2). By contrast, there is too extensive a sea ice cover in the GIN Seas. Associated with this feature is a regional shift in deep convection, from the GIN Seas to a location east of the southern tip of Greenland. CONTROL is also characterized by a gradual decrease in the maximum value of the North Atlantic annual mean meridional overturning streamfunction (which is an index of the strength of the NADW circulation) from 21 Sv (1 Sv = 10^6 m^3 s^{-1}) around year 20 to 13 Sv at the end of the experiment. Drifts of this type are commonly found in other non-flux corrected CGCMs [e.g., *IPCC*, 2001]. To take the drift into account, the signal of climate change in SRESB2

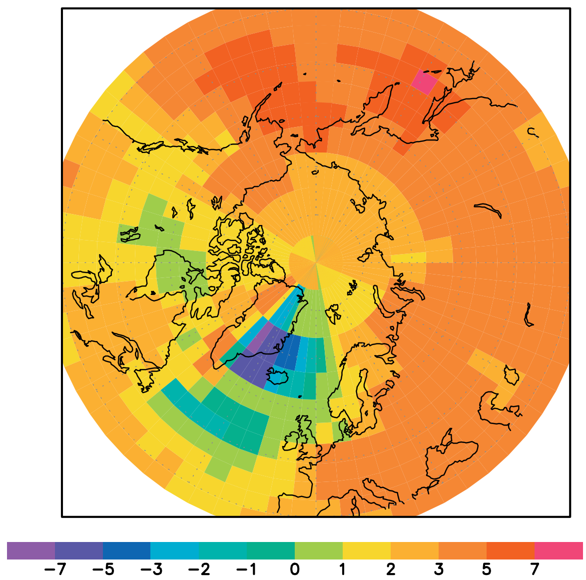

Figure 2. Differences in annual mean SAT (in °C) between SRESB2G and CONTROL averaged over years 2096–2100.

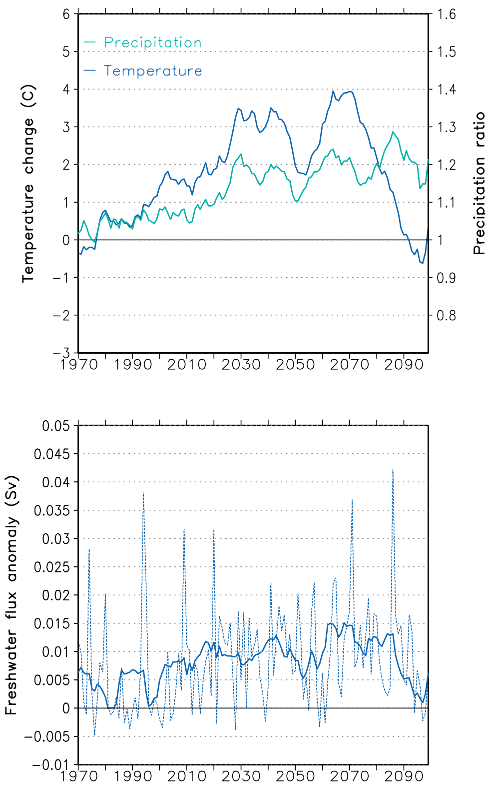

Figure 3. Time series of the differences in annual mean SAT and precipitation rate averaged over Greenland between SRESB2G and CONTROL (upper panel) and of the difference in annual mean total freshwater flux from Greenland between SRESB2G and CONTROL (lower panel). Solid curves: 10-year running average; dashed curve: no running average.

and SRESB2G is determined by subtracting corresponding years of CONTROL from the SRESB2 and SRESB2G integrations, respectively.

[9] By the end of SRESB2, the annual mean SAT is enhanced by 2.5°C on a global average. An intensification of the hydrological cycle is also simulated, with a 3.3% increase in globally averaged, annual mean precipitation. These changes are within the range of those obtained with other CGCMs [e.g., *IPCC*, 2001]. The temperature response from SRESB2G closely follows that from SRESB2 up to 2080 but is somewhat weaker afterward, thus leading to a global warming of only 2.2°C at the end of the experiment. This behavior is mostly attributable to a strong cooling that takes place over eastern Greenland and the northern North Atlantic during the last 20 years of SRESB2G (Figure 2).

[10] Averaged over Greenland, the annual mean SAT increases by 4°C over 1970–2080 in SRESB2G, and the annual mean precipitation heightens by 20% (Figure 3, upper panel). The ice sheet response during this period shows a clear decrease in area and volume. The total area shrinks by 1%, and the total volume is reduced by an amount equivalent to 5.5 cm of global sea level rise. The lower panel of Figure 3 indicates that the annual mean total freshwater flux from Greenland increases by 0.015 Sv over 1970–2080. Superimposed on this overall increasing trend are pronounced interannual variations, with magnitude exceeding occasionally 0.035 Sv. Those freshwater flux perturbations can be compared to the one that induced the Great Salinity Anomaly observed at the end of the 1960s and the early 1970s in the high latitude North Atlantic [*Dickson et al.*, 1988]. This event, that had a significant impact on deep water formation [e.g., *Dickson et al.*, 1988], was associated with an excess freshwater of about 2300 km^3. With a freshwater flux from Greenland enhanced by 0.015 Sv, such an anomaly can be built in less than 5 years. During pulses, less than 2 years are necessary. Beside these perturbations, the annual mean surface freshwater flux due to precipitation, evaporation, and river runoff is increased by 0.017 Sv during 2070–2080 in SRESB2G (compared to CONTROL) over the oceanic area extending from 50°N to 80°N and from 60°W to 30°E. This means that Greenland contributes to about 50% of the long-term change in total freshwater flux simulated by the model over this region.

[11] Figure 4 depicts the time series of the change in the maximum value of the annual mean meridional overturning streamfunction in the North Atlantic for SRESB2 and SRESB2G. The NADW formation weakens similarly in both runs up to 2080, as it does in most comparable CGCM experiments [e.g., *IPCC*, 2001]. After 2080, the two scenarios diverge. A strong and abrupt decline in the North Atlantic THC is observed in SRESB2G together with a displacement of the main sites of deep convection to a region situated just south-west of Iceland. These features are caused by the freshening of the high latitude North Atlantic resulting from the increased inflow of freshwater from Greenland, especially the two strong anomalies that occur between 2070 and 2090 (see lower panel of Figure 3). Given the model uncertainties, the change in convection location should be seen more as a demonstration that such a change is possible in principle, rather than as a specific prediction, as discussed in *Rahmstorf* [1999].

[12] The breakdown of the THC during the last decades of SRESB2G yields a significant cooling over eastern Greenland and the northern North Atlantic, which is amplified by the albedo and insulation feedbacks related to the expansion of the sea ice cover in the GIN Seas (see Figure 2). As a consequence, the total freshwater flux from Greenland starts to decrease and comes back to its reference value by the year 2100 (see lower panel of Figure 3). It would have been

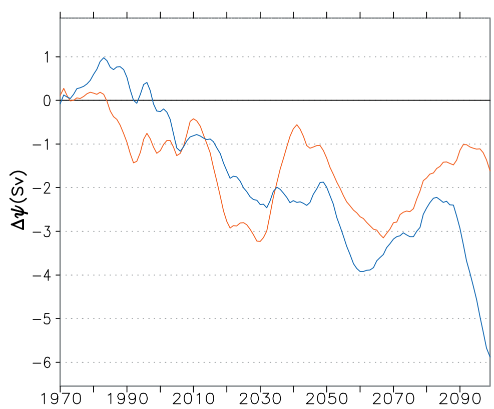

Figure 4. Time series of the differences in maximum value of the annual mean meridional overturning streamfunction in the North Atlantic between SRESB2 and CONTROL (in red) and between SRESB2G and CONTROL (in blue). A 10-year running average has been applied.

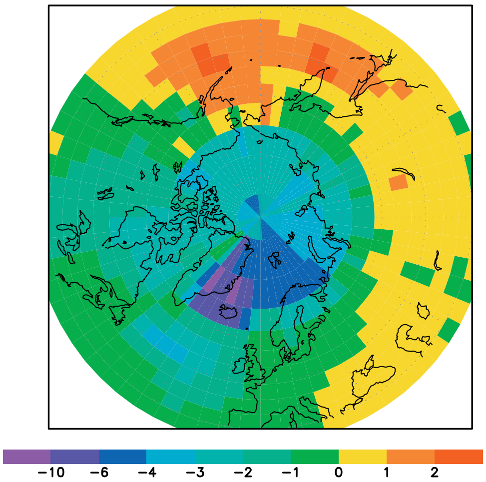

Figure 5. Differences in annual mean SAT (in °C) between SRESB2G and SRESB2 averaged over years 2096–2100.

interesting to extend the simulation over the 22nd century to check if this reduction in freshwater input cannot lead to a resumption of the North Atlantic THC in the model afterward. Unfortunately, this was not possible because of a lack of CPU time. Figure 5 shows the differences in annual mean SAT between SRESB2G and SRESB2 averaged over the last 5 years of integration. Coolings ranging from 2 to 12°C are noticed over most of the northern North Atlantic and Arctic Oceans, in eastern Greenland, and over parts of northern Canada, Alaska, Siberia, and Scandinavia. In contrast, the northern North Pacific exhibits a slight warming, which is associated with a reduced sea ice areal coverage in this sector.

4. Discussion and Conclusion

[13] The evolution of climate during the 21st century has been simulated using a coarse resolution CGCM coupled to a comprehensive model of the Greenland ice sheet. Because of the warming that enhances melting at the surface of the ice sheet, the total freshwater flux from Greenland increases during the simulation. At the end of the 21st century, this flux appears large enough to induce a strong and abrupt weakening of the North Atlantic THC and a subsequent cooling over eastern Greenland and the northern North Atlantic.

[14] Such a breakdown of the THC does not occur in a simulation that does not include an interactive ice sheet component, which highlights the major role played by the freshwater flux from Greenland. Nevertheless, caution must be exercised when drawing conclusions from our experiments. First, the present-day climate is not perfectly reproduced by our CGCM. In particular, the main sites of deep convection are located east of the southern tip of Greenland and not in the GIN Seas and Labrador Sea as observed. This has certainly an influence on the sensitivity of the model to changes in the freshwater flux from Greenland. Second, only one experiment has been conducted with an interactive ice sheet component and one without this component. Recent studies performed with Earth system models of intermediate complexity [e.g., *Schaeffer et al.*, 2002] have shown that the evolution of the THC close to a transition point is quite unpredictable. Therefore, a large number of experiments would be necessary to demonstrate that the difference of behavior between our two simulations is robust and does not arise by chance. In any case, the magnitude of the freshwater perturbation originating from Greenland and its potential impact stress the urgent need to couple ice sheet models to CGCMs in order to provide reliable projections of the climate evolution over the 21st century and beyond.

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