The glacial thermohaline circulation: Stable or unstable?

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[1] The stability of the glacial thermohaline circulation (THC) with respect to North Atlantic freshwater input is examined using a global ocean general circulation model. It is found that the quasi-equilibrium hysteresis behaviour is much less pronounced under glacial conditions than under present-day conditions, and the existence of multiple equilibria requires an anomalous freshwater inflow. The results may help to assess the effect of iceberg invasions and meltwater events, suggesting that the THC is prone to instability during a deglaciation phase when the Atlantic meridional overturning is weakened. Under full glacial conditions, however, the THC is mono-stable and even extreme freshwater pulses are unable to exert a persistentn effect on the conveyor. *INDEX TERMS:* 4255 Oceanography: General: Numerical modeling; 4267 Oceanography: General: Paleoceanography; 3220 Mathematical Geophysics: Nonlinear dynamics; 1635 Global Change: Oceans (4203). **Citation:** Prange, M., V. Romanova, and G. Lohmann, The glacial thermohaline circulation: Stable or unstable?, *Geophys. Res. Lett.*, *29*(21), 2028, doi:10.1029/2002GL015337, 2002.

1. Introduction

[2] The waxing and waning of continent-sized ice sheets was an important source for variability of the North Atlantic freshwater budget during the last glacial period (~100–10 kyr ago). Massive surges and melting of icebergs [e.g., *Heinrich*, 1988; *Broecker et al.*, 1992], so-called Heinrich events, caused abrupt changes in the freshwater budget [e.g., *Keigwin and Lehman*, 1994; *Bard et al.*, 2000]. There is clear geological evidence of a strong interconnection between ice-rafting events, fluctuations in the thermohaline circulation (THC), and climatic changes in the Atlantic realm [e.g., *Chapman and Shackleton*, 1999; *Broecker and Hemming*, 2001; *Clark et al.*, 2002]. Understanding the stability properties of the THC during glacial times is therefore of utmost importance for a proper interpretation of the geological record. Here, we study the sensitivity of the glacial THC with respect to variable North Atlantic freshwater input in a global ocean general circulation model (GCM), examining both the quasi-equilibrium hysteresis behaviour and the response to sudden freshwater pulses.

2. Model Design and Forcing

[3] The ocean model is based on the Hamburg large-scale geostrophic ocean model LSG [*Maier-Reimer et al.*, 1993]. The resolution is 3.5° with 11 levels. A third-order QUICK scheme [*Leonard*, 1979; *Schäfer-Neth and Paul*, 2001] for the advection of temperature and salinity has been implemented as described in *Prange et al.* [2002]. Depth-dependent horizontal and vertical diffusivities are employed ranging from 10^7 cm^2 s^{-1} at the surface to $5 \cdot 10^6$ cm^2 s^{-1} at the bottom, and from 0.6 cm^2 s^{-1} to 1.3 cm^2 s^{-1}, respectively.

[4] The model is driven by monthly fields of wind stress, surface air temperature and freshwater flux provided by a Last Glacial Maximum (LGM) simulation of the atmospheric GCM ECHAM3/T42. Forcing of the atmosphere comprises orbital changes, reduced concentration of CO_2 (200 ppm), and *CLIMAP* [1981] sea ice and surface temperatures with an additional cooling in the tropics (30°S–30°N) of 3 K. For a detailed description of the model run we refer to *Lohmann and Lorenz* [2000]. In order to close the hydrological cycle, a runoff scheme transports freshwater from the continents to the ocean. For the heat flux Q into the ocean we apply a boundary condition of the form $Q = (\lambda_1 - \lambda_2 \nabla^2)(T_a - T_s)$, where T_a and T_s denote air and sea surface temperatures, respectively. This thermal boundary condition allows an adjustment of surface temperatures to changes in the ocean circulation, based on an atmospheric energy balance model with diffusive lateral heat transports [*Rahmstorf and Willebrand*, 1995]. For λ_1 and λ_2 we choose 15 W m^{-2} K^{-1} and $2 \cdot 10^{12}$ W K^{-1}, respectively. In all model components the ice age paleotopography of *Peltier* [1994] is applied and a global sea level drop of 120 m is taken into account.

3. Glacial THC and Hydrographic Fields

[5] Starting from a present-day hydrography with a salinity anomaly of +1 psu imposed globally, the ocean model is integrated under glacial forcing for 5500 years to obtain an equilibrium circulation (Figure 1a). The simulated glacial Atlantic THC is weaker than the modern one, consistent with proxy data [e.g., *Boyle*, 1995; *Rutberg et al.*, 2000] and previous modelling studies [e.g., *Ganopolski et al.*, 1998; *Weaver et al.*, 1998]. The total volume flux of sinking water masses in the glacial North Atlantic amounts to 12 Sv, while 7 Sv are exported to the Southern Ocean. Compared to a present-day simulation with the same model [*Prange et al.*, 2002], this corresponds to a ~20% decrease of NADW flux into the circumpolar deep water. Due to an expanded sea ice cover in the North Atlantic, convection sites are shifted southward compared to the present-day circulation. Hence, the sinking branch of the glacial Atlantic meridional overturning circulation is located between 40°N and 60°N, and contributions from the Nordic Seas to North Atlantic Deep Water (NADW) are negligible (Figure 1a).

[6] In low latitudes, sea surface temperatures (Figure 1c) are about 4 K below modern values. Mean temperatures in the core of NADW are shown in Figure 1e. Salinities at that depth are relatively high (Figure 1d), exceeding mean sur-

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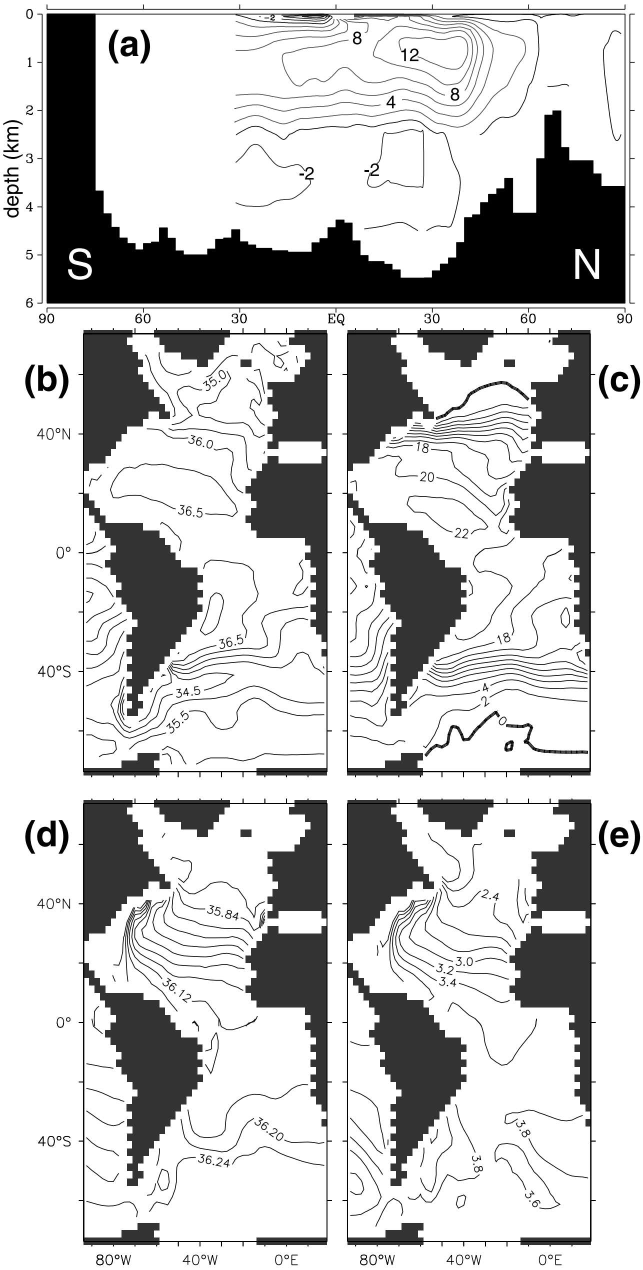

Figure 1. Glacial Atlantic Ocean in equilibrium: (a) meridional overturning streamfunction (Sv); (b) surface salinity; (c) surface temperature (°C); (d) salinity at 2000 m depth; (e) temperature at 2000 m depth (°C). 40 yr means are shown.

face salinities (Figure 1b) in mid and high latitudes. Similarly high deep water salinities were found in the LGM simulation of an Earth system model of intermediate complexity [*Ganopolski et al.*, 1998].

4. Hysteresis Behaviour

[7] Applying a slowly varying surface freshwater flux anomaly uniformly between 20°N and 50°N to the Atlantic Ocean, we analyse the quasi-equilibrium hysteresis behaviour of the glacial THC. The stability diagram is shown in Figure 2. For comparison, the hysteresis loop of the model with present-day forcing [*Prange et al.*, 2002] is displayed in the same figure. The present-day THC exhibits a pronounced hysteresis behaviour around the region of zero perturbation. For anomalous freshwater fluxes between -0.1 Sv and $+0.1$ Sv we identify two equilibrium modes of operation. By way of contrast, the stability diagram of the glacial THC reveals that multiple equilibria exist only in a narrow range in the area of positive anomalous freshwater input.

5. Freshwater Pulse Experiments

[8] In order to examine the destabilizing impact of abrupt meltwater perturbations in the glacial North Atlantic, we perform a series of freshwater pulse experiments (Figure 3). The pulses have a duration of 50 years and are uniformly applied to the North Atlantic between 20°N and 50°N. A first set of experiments deals with the stability of the glacial equilibrium circulation at point A in Figure 2. Freshwater fluxes of 0.2 Sv and 0.5 Sv cause a temporary weakening of the THC, while a perturbation of 1 Sv leads to zero overturning (Figure 3a). However, the THC recovers spontaneously after the perturbation, regaining its initial strength after about 1000 years. Due to the THC's mono-stability, freshwater pulses are unable to exert a persistent effect on the glacial conveyor, regardless of their magnitudes.

[9] Upper-ocean flow field and temperature distribution respond immediately to freshwater perturbations in the

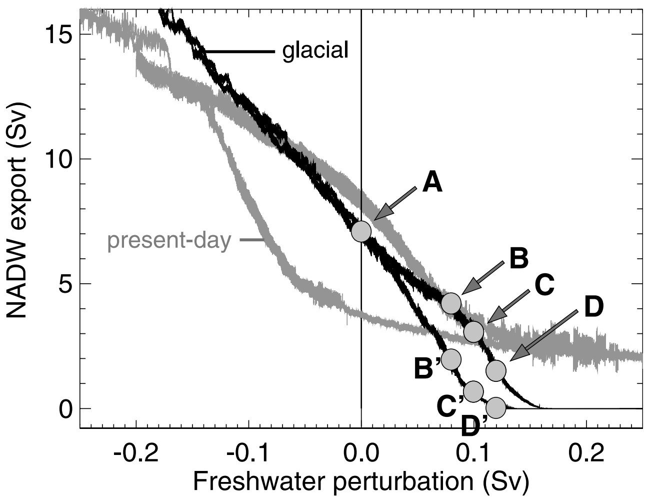

Figure 2. Maximum meridional Atlantic overturning streamfunction at 30°S (i.e., NADW export across 30°S) against North Atlantic surface freshwater flux anomaly for the last glacial and the present. Hysteresis loops are obtained as follows: Integration starts at the upper branch with zero freshwater perturbation. The freshwater input is then slowly increased until 0.3 Sv. The integration proceeds on the lower branch with freshwater input decreasing until -0.3 Sv. Then the freshwater input increases again to close the loop. Due to the slowly-varying nature of the surface forcing ($5 \cdot 10^{-5}$ Sv yr^{-1}) the model is in quasi-equilibrium during the integration [cf. *Rahmstorf*, 1995]. Curves are smoothed by a one-year boxcar-average. The stability of the states A, B, C, and D is examined in freshwater pulse experiments (see Figure 3).

Atlantic Ocean (Figure 4). After 50 years of 1 Sv freshwater input, when the overturning is zero (see Figure 3a), a modified circulation is directly linked to changes in oceanic heat transports and hence temperature distribution. In the upper ocean, the breakdown of the conveyor is reflected in an overall anomalous southward flow (Figure 4b), the main effect of which is a general warming in the South Atlantic and a cooling in the North Atlantic (Figure 4c), well-known as the "seesaw-effect" [e.g., *Stocker*, 1998; *Clark et al.*, 2002]. In addition to the north-south contrast, pronounced zonal differences in temperature change arise. For instance, an anomalous southward flow in the northeastern Atlantic (Figure 4b) causes particularly strong cooling off Southern Europe (Figure 4c). Similar North Atlantic temperature patterns, characterized by extreme coolings off France and Portugal, can be inferred from marine proxy data during Heinrich events [*Bard et al.*, 2000; *Broecker and Hemming*, 2001; *Clark et al.*, 2002].

[10] In a second set of pulse experiments, we investigate the stability of equilibrium states that reside within the hysteresis loop (states B, C, and D in Figure 2). A freshwater pulse of 1 Sv applied to state B causes the conveyor to collapse (Figure 3b). After 250 years some convection sites become reactivated, while others remain shut down (not shown) - the overturning restarts, but settles into a new

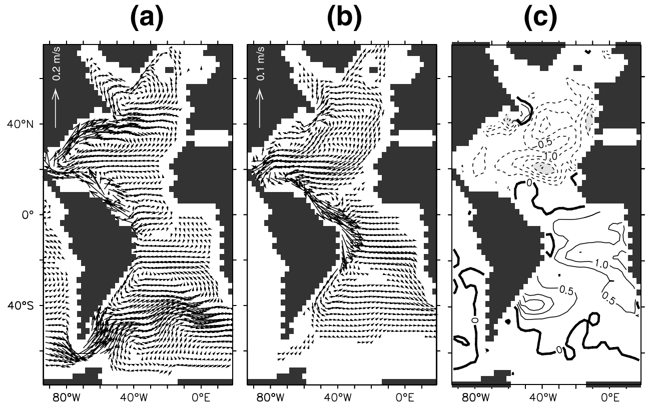

Figure 4. Response of the upper ocean to a 1 Sv-freshwater perturbation after 50 years of anomalous freshwater input when the overturning is zero: (a) unperturbed mean flow field of the glacial equilibrium (point A in Figure 2) averaged over the top 150 m; (b) annual mean velocity anomalies induced by the perturbation (averaged over the top 150 m); (c) annual mean sea surface temperature anomalies (K) induced by the perturbation; areas with temperature differences below −2 K are shaded.

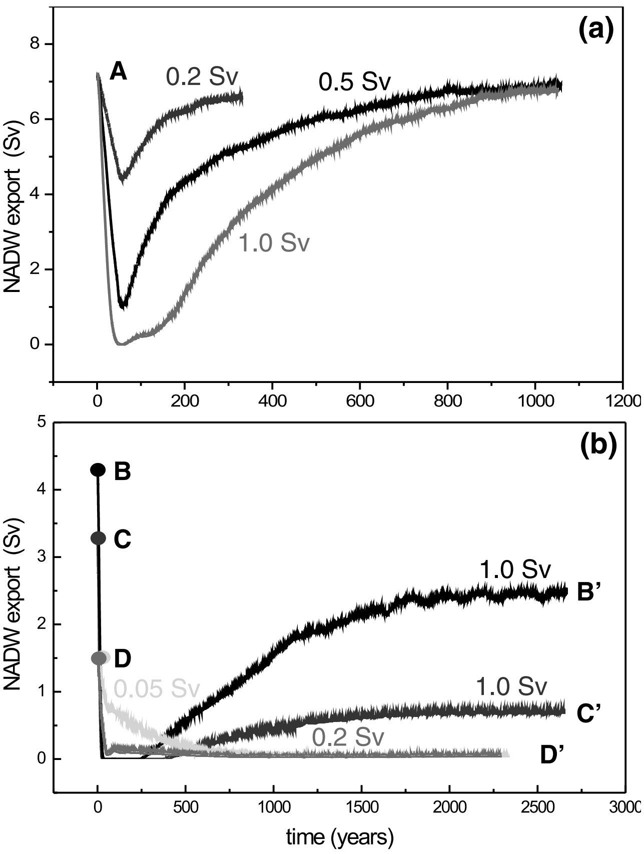

Figure 3. Temporal changes of the maximum Atlantic overturning streamfunction at 30°S (i.e., NADW export across 30°S) in consequence of 50 years-freshwater perturbations with different magnitudes: (a) perturbations of the glacial equilibrium at point A in Figure 2; (b) perturbations of the equilibrium states B, C, and D in Figure 2.

equilibrium with low NADW formation. This equilibrium state corresponds to point B′ on the lower branch of the hysteresis loop in Figure 2. Applying a perturbation of 1 Sv to state C, the THC behaves in a similar way and ends up in point C′. State D is much more vulnerable: a smooth transition to D′ can be induced by a weak perturbation of 0.05 Sv, while an abrupt change is triggered by a 0.2 Sv-pulse. The experiments reveal that the THC becomes increasingly unstable with reduced initial overturning strength.

6. Discussion and Conclusions

[11] Utilizing an oceanic GCM, we examined the stability of the glacial THC with respect to North Atlantic freshwater forcing. We found that the quasi-equilibrium hysteresis behaviour is much less pronounced than under present-day conditions, and multiple equilibria exist only when an anomalous freshwater input is applied. These results are consistent with a recent study of *Ganopolski and Rahmstorf* [2001], in spite of very different modelling approaches, i.e. one-way coupling of GCMs, as applied here, versus interactive coupling using a zonally averaged ocean model. In a model of intermediate complexity which employs a three-dimensional ocean GCM, a computationally inexpensive energy-moisture balance model of the atmosphere, and an ice sheet component, the glacial THC possesses different stability properties [*Schmittner et al.*, 2002]. In the absence of anomalous freshwater fluxes, the only stable glacial mode in that model is characterized by a conveyor shutdown, and the regime of bi-stability is shifted to the range of negative freshwater anomalies.

[12] How can the stability behaviour be understood? *Rahmstorf* [1996] pointed out that the stability properties of the Atlantic THC are linked to its freshwater budget. In our model set-up, the atmospheric moisture export out of the Atlantic catchment area (>30°S, Arctic Ocean included) is enhanced under glacial conditions by 0.08 Sv relative to

the present. An important process that contributes to the changed freshwater budget of the glacial Atlantic is a decrease of water vapour transport from the Pacific Ocean into the Arctic and into the northern Atlantic via Canada [*Lohmann and Lorenz*, 2000]. The lack of a low-saline Bering Strait throughflow, owing to a lowered sea level, lead to further reductions in the freshwater supply to the polar seas and hence to the convective regions in the glacial North Atlantic. Taking a reference salinity of 35 psu, this freshwater supply amounts to 0.05 Sv in our present-day simulation, which is in good agreement with observations [cf. *Aagaard and Carmack*, 1989]. The reduced freshwater input to the glacial North Atlantic results in relatively high salinities of deep water masses formed there during winter. High salinities in glacial NADW relative to the upper layers (Figures 1b, 1d) indicate a ''thermohaline flow regime'' of the THC [cf. *Rahmstorf*, 1996]. In this regime, freshwater is carried northward by the conveyor's upper limb into the regions of deep water formation. Consequently, a circulation with reduced overturning is unstable, since net evaporation and/or wind-driven oceanic salt transports would inevitably enhance North Atlantic surface salinities, driving NADW formation and the THC. By way of contrast, the present-day conveyor is driven by heat loss with freshwater forcing braking the overturning (''thermal flow regime''). As a result, multiple equilibria exist [*Stommel*, 1961; *Rahmstorf*, 1996].

[13] The results of our study may help to assess the effect of massive iceberg invasions and meltwater events documented in sediment records from the North Atlantic, suggesting the following conclusions: During a deglaciation phase, anomalous freshwater inflow may shift the THC into the regime of bi-stability (points B, C, D in Figure 2) where the conveyor is prone to instability and mode transitions. A mode transition results in a persistent slow-down of the THC, and the overturning does not recover until substantial changes in the North Atlantic freshwater budget occur. In the mono-stable regime of ''full glacial conditions'' (point A), even extreme freshwater pulses are unable to exert a persistent effect on the conveyor. As soon as the freshwater influx comes to an end the THC starts to recover spontaneously.

[14] The present study highlights the importance of the hydrological cycle for the stability properties of the THC. A correct representation of atmospheric moisture transports is crucial. A logical next step would be the inclusion of other climate components which may be important for the hydrological cycle, in particular land ice processes and the motion of sea ice.

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