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Atlantic SST Signature of Heinrich Events

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Abstract

Different sea surface temperature (SST) reconstructions for the last glacial maximum are applied to a hybrid-coupled climate model. The resulting equilibria are perturbed by North Atlantic meltwater inputs in order to simulate the effect of Heinrich Events on Atlantic SSTs. The model results suggest that a breakdown of the present-day thermohaline circulation would induce a much stronger temperature drop in high northern latitudes than a Heinrich Event during the ice age. Important features of Heinrich Event SST signatures in the Atlantic Ocean, like extreme cooling off Portugal, can only be simulated by perturbing a *glacial* state of the ocean.

Zusammenfassung

Verschiedene Rekonstruktionen der Oberflächentemperatur (SST) für das letzte glaziale Maximum werden auf ein hybrid gekoppeltes Klimamodell angewandt. The resultierenden Gleichgewichte werden durch nordatlantische Schmelzwasser-Einträge gestört, um den Einfluss von Heinrich-Ereignissen auf die atlantische SST zu simulieren. Die Modellergebnisse legen nahe, dass ein Zusammenbruch der heutigen thermohalinen Zirkulation einen wesentlich stärkeren Temperaturabfall in hohen nördlichen Breiten hervorriefe als ein Heinrich-Ereignis während der Eiszeit. Wichtige Merkmale der atlantischen SST-Signatur von Heinrich-Ereignissen - wie eine extreme Abkühlung vor Portugal - können nur simuliert werden, wenn ein *glazialer* Zustand des Ozeans gestört wird.

1. Introduction

Transporting heat over large distances, the Atlantic thermohaline circulation (THC) plays a key role in the climate system. Geological records from the last glacial period suggest that enhanced abundances of ice-rafted debris in the North Atlantic (Heinrich Events) were associated with shutdowns of the THC and global-scale climatic changes (e.g., CLARK et al., 2002; BROECKER, 2003). The concept of THC fluctuations with global impact has motivated a large number of ocean and climate modellers to simulate THC disruptions by injecting freshwater to the North Atlantic (e.g., MANABE and STOUFFER 1995; SCHILLER et al., 1997; LOHMANN, 2003). The model results suggest that the THC is highly sensitive to changes in the North Atlantic freshwater budget, such that anomalous freshwater inputs can trigger a collapse of the circulation, thereby causing an abrupt temperature drop in the order of 5-10°C in the northern Atlantic realm.

Even though the combined efforts of paleoceanographers and climate modellers are well on the way to providing a consistent picture about the climatic impact of Heinrich Events and the important role of the THC, a closer inspection still reveals a number of discrepancies between geological data and model results. In the present study, we highlight the importance of the oceanic 'basic state' for the pattern of sea surface temperature (SST) change in response to a THC shutdown. In most previous model experiments, freshwater perturbations were applied to present-day states of the ocean. Here, we demonstrate that important features of the Heinrich Event SST signature in the Atlantic Ocean can only be simulated by perturbing a *glacial* state of the ocean.

2. Glacial climate simulations

We employ three different SST reconstructions for the last glacial maximum to force the atmosphere general circulation model ECHAM3/T42: 1) The CLIMAP (1981) reconstruction with an additional cooling of 3°C in the tropics (LOHMANN and LORENZ, 2000), 2) the North Atlantic reconstruction by WEINELT et al. (1996) merged with CLIMAP (SCHÄFER-NETH and PAUL, 2001), and 3) the new GLAMAP Atlantic reconstruction (SARNTHEIN et al., 2003) combined with CLIMAP (PAUL and SCHÄFER-NETH, 2003). The three experiments are denoted as experiment C, W and G, respectively. Orbital forcing, reduced concentration of carbon dioxide, and topographic changes (PELTIER, 1994) are taken into account. A fourth experiment, PD, is carried out with present-day SSTs. Fig. 1 shows simulated North Atlantic surface air temperatures for the three glacial experiments relative to experiment PD.

3. Meltwater perturbation experiments

Monthly outputs of the atmosphere model from experiments C, W, G and PD are applied to an improved version of the three-dimensional ocean model LSG, including a third-order QUICK advection scheme (SCHÄFER-NETH and PAUL, 2001; PRANGE et al., 2003). Forcing of the ocean model involves a runoff scheme and a surface heat flux formulation that allows for a scale-selective damping of temperature anomalies. For a detailed description of this hybrid-coupled model approach we refer to PRANGE et al. (2003), for a discussion of the resulting oceanic equilibrium circulations and hydrographies we refer to ROMANOVA et al. (2003). The equilibrium states are perturbed by a sudden 500-year freshwater input to the North Atlantic between 40°N and 55°N. A relatively high freshwater influx of 0.5 Sv (= $0.5 \cdot 10^6$ m^3s^{-1}) has been chosen to ensure a complete shutdown of the THC in all experiments, making direct comparison of the resulting temperature anomalies easier.

The temporal response of the Atlantic THC to the freshwater input is plotted in Fig. 2. After termination of the anomalous freshwater forcing, the present-day circulation remains in the 'off' mode, whereas the glacial circulations recover spontaneously. This mono-stable behaviour of the glacial THC has been attributed to enhanced atmospheric moisture exports out of the Atlantic catchment area (LOHMANN and LORENZ, 2000; PRANGE et al., 2002; ROMANOVA et al., 2003).

The response of Atlantic surface temperatures to the freshwater perturbation is displayed in Fig. 3 for the glacial and the present-day experiments. In experiment PD, the strongest cooling occurs in the northern North Atlantic and the Nordic Seas, where the SST decreases by more than 5°C, consistent with other meltwater experiments for the present-day climate (e.g., RAHMSTORF 1995; MANABE and STOUFFER 1995; SCHILLER et al., 1997). In the glacial experiments, the cooling is restricted to lower latitudes. A salient temperature drop appears in the eastern North Atlantic off Portugal in experiments C and W. Alkenone data suggest, that pronounced cooling off Southwest Europe in the order of 3-6°C is a typical feature of Heinrich Events (BARD et al., 2000; PAILLER and BARD, 2002; RÜHLEMANN, unpubl.). Comparing the model results with paleoceanographic data for Heinrich Event 1 (around 16,000 yr before present) reveals that the overall spatial signature of SST anomalies is captured much better in the glacial experiments than in experiment PD (Fig. 3).

4. Conclusions

The Atlantic SST response pattern with respect to meltwater perturbations strongly depends on the climatic background state. Compared to Heinrich Events of the ice age, a breakdown of the present-day THC would induce a much stronger temperature drop in high northern latitudes. Important features of Heinrich Event SST signatures in the Atlantic Ocean, like an extreme cooling off Portugal, can only be simulated by perturbing a *glacial* state of the ocean. Unlike the mono-stable glacial THC, the modern circulation can settle into a stable 'off' mode. Mono-stability may serve as an explanation for the recovery of the THC after Heinrich Event shutdowns during the last glaciation.

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FIGURE CAPTIONS

Figure 1: Differences between glacial and present-day annual mean surface air temperatures for experiments C, W and G in the Atlantic realm.

Figure 2: Temporal evolution of the Atlantic meridional overturning circulation (here: net export of North Atlantic deepwater at 30°S) in the experiments C, W, G and PD (present-day). A 500-yr meltwater perturbation is applied at year 0.

Figure 3: Atlantic SST response to the meltwater perturbation in experiments C, W, G and PD (present-day). Temperature anomalies relative to the unperturbed equilibria are plotted at the end of the meltwater period (i.e., year 500). For comparison, temperature changes suggested by proxy data from marine sediment cores (faunal and/or alkenone reconstructions) for Heinrich Event 1 are marked by dots as follows: warming (red), temperature changes less than 0.5°C (white), cooling (cyan), very strong cooling (dark blue). References: MASLIN et al. (1995), PATERNE et al. (1999), CHAPMAN and SHACKLETON (1998), BARD et al. (2000), RÜHLEMANN et al. (1999), KIM et al. (2002), SACHS et al. (2001).