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**Intermediate-depth warming in the low-latitude Atlantic related to weakened North Atlantic deep water production: combining palaeoclimate and modelling data for the last deglaciation**

Radioisotope records covering the last deglaciation show that two pronounced, abrupt climate events, Heinrich event H1 and the Younger Dryas, were associated with massive reductions in the rate of North Atlantic Deep Water formation [*Clark et al., 2002; McManus et al.*, 2004], possibly triggered by iceberg or meltwater discharge into the northern North Atlantic. Paleodata and simulations with ocean-climate general circulation models point out that the shifts in the strength of the meridional overturning circulation (MOC) induced a characteristic seesaw pattern of ocean temperature change. As a result of the decrease in Atlantic northward heat transport, the surface waters of the northern North Atlantic cooled by up to several degrees Celsius, whereas the South Atlantic surface waters slightly warmed by up to ~1°C. Climate models further predict a salient warming at intermediate depths that can reach up to several degrees Celsius in the tropical latitudes [*Manabe and Stouffer*, 1997].

In our presentation, we investigate the ocean's temperature response to large changes in the Atlantic THC, using model experiments in addition to two benthic foraminiferal oxygen isotope records from tropical latitudes covering the past 30,000 years and a time slice reconstruction of the change in the oxygen-18/oxygen-16 isotope ratio of planktic and benthic foraminifera ($\delta^{18}$Oc) from the Last Glacial Maximum (LGM) (19-23 ka BP) to Heinrich event H1 (15.4-16.8 ka BP) for the Atlantic Ocean between 30°S and 80°N.

The H1 time slice is derived from 30 benthic and 27 planktic high-resolution oxygen isotope records [*Paul and Mulitza, 2004*] and shows a strong decrease of $\delta^{18}$Oc from the surface down to a depth of about 1500 m in the tropical and subtropical South Atlantic Ocean as compared to the LGM (Figure 1a). In the North Atlantic Ocean, the situation is more complex: Between about 30° and 50°N, the surface water is characterized by a positive $\delta^{18}$Oc anomaly. North of about 45°N, a tongue of negative anomalies extends from the surface to the deep water along the southern flank of the Greenland-Scotland Ridge. To simulate the oxygen isotope change associated with a MOC change we employed the 'Hanse' model, a climate model of reduced complexity that follows the oxygen isotopes through all stages of the hydrological cycle [*Paul and Schulz*, 2002; *Paul and Mulitza*, 2004]. In accordance with the data, the freshwater experiment with the 'Hanse' model results in large negative anomalies in the upper 1500 m of the South Atlantic (Figure 1b), which was only weakly influenced by changes in the oxygen isotope ratio of the water ($\delta^{18}Ow$) (not shown here). In contrast, the $\delta^{18}Ow$ signature of the glacial meltwater was the main reason for the negative anomaly near the Greenland-Scotland Ridge at about 60°N. In our simulation, the deep water temperature in this region changed by 0.5°C at most. However, the isotopically light meltwater that had been stored at the surface during the stagnation of the MOC was released upon its recovery and advected downward to about 2000 m depth.

The two deglacial benthic isotope records show that the intense warming of the middepth tropical Atlantic is a recurrent feature of MOC slowdown (Figure 2). We corrected the benthic isotope data by subtracting the global $\delta^{18}O$ ice effect caused by the melting of continental ice and freshwater runoff during the last deglaciation. The residual $\delta^{18}O$ curves ($\Delta\delta^{18}O$) show rapid and pronounced decreases of 0.5 to 0.9‰ at the beginning of H1 and the Younger Dryas (Figures 2d and 2e, right panel) when deep water formation was greatly reduced (Figures 2b and 2c, right panel) and when the northern North Atlantic cooled (Figure 2a, right panel). These $\Delta\delta^{18}O$ shifts most probably reflect increases in temperature as indicated by the experiments with the 'Hanse' model. The temperature pattern of the tropical and South Atlantic in data and model results is in accordance with the bipolar temperature seesaw, a rapid cooling in the north accompanied by a warming in the south due to a weakened MOC and northward heat transport. In the model, the mid depth warming results from a reduced ventilation of cold intermediate and deep waters in conjunction with downward diffusion of heat. Meltwater experiments with a three-dimensional ocean general circulation model running under present-day and glacial conditions show that this intermediate-depth warming is a persistent feature of MOC slowdown, independent from the climatic background state (Figures 2 a and 2b, left panels). We thus propose that the distinctive ocean temperature pattern associated with MOC slowdown can help in tracing past and possibly future MOC changes. The next step in our work on intermediate depth temperature variability related to MOC change is the determination of benthic Mg/Ca ratios to separate the temperature from the oxygen isotope signal.

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# Figures

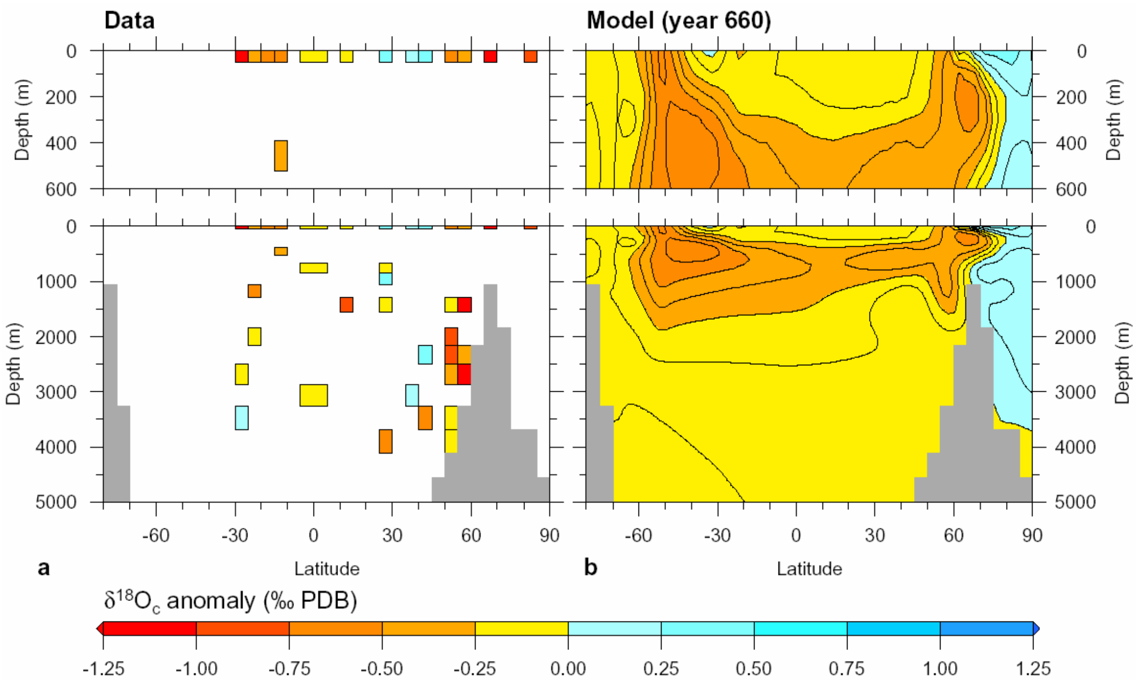
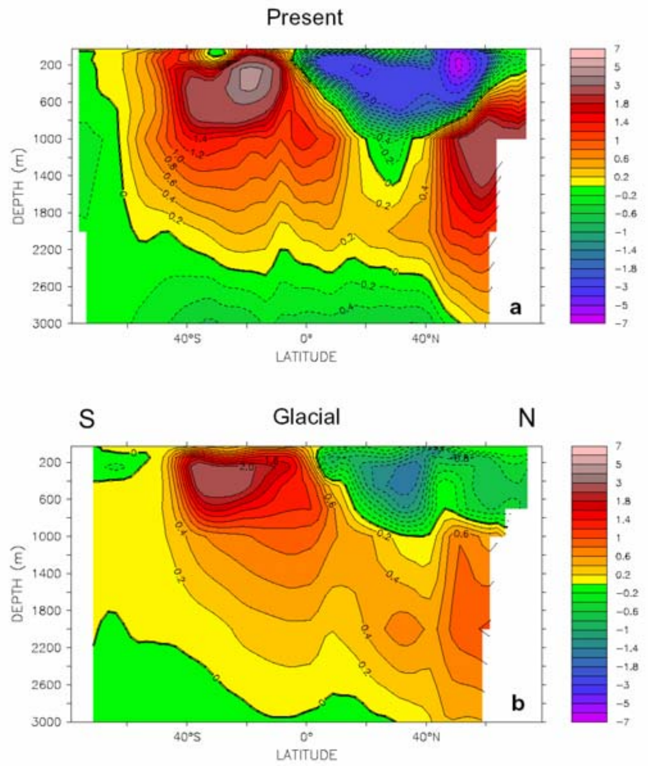



**Figure 1**: The zonal-mean $\delta^{18}O$ anomaly for carbonate ($\delta^{18}Oc$) in the Atlantic Ocean (H1 minus LGM, ‰ PDB) as found in (a) a collection of planktic and benthic high-resolution oxygen isotope records and (b) the ocean component of the 'Hanse' climate model. The planktic and benthic foraminiferal data were gathered from different publications [as given in *Paul and Mulitza*, 2004] and binned into the latitude-depth model grid cells. The 'Hanse' model is a zonally averaged, coupled climate model of reduced complexity, which includes an atmosphere-ocean isotopic cycle with fractionation of oxygen isotopes upon evaporation and precipitation [*Paul and Schulz*, 2002; *Paul and Mulitza*, 2004]. To account for the mean ocean $\delta^{18}Oc$ anomaly, 0.12‰ was added to the data and 0.03‰ to the model output. Starting from a cold climate state reminiscent of the LGM we applied a freshwater perturbation with a $\delta^{18}Ow$ signature of -40 ‰ for 100 years to mid-latitudes (40° to 50°N) at a rate of 0.1 Sv. After this perturbation, the 'Hanse' model was integrated until a quasi-steady state was reached. From the model output, we computed the equilibrium carbonate $\delta^{18}O$ using the paleotemperature equation of *Mulitza et al.* [2004].



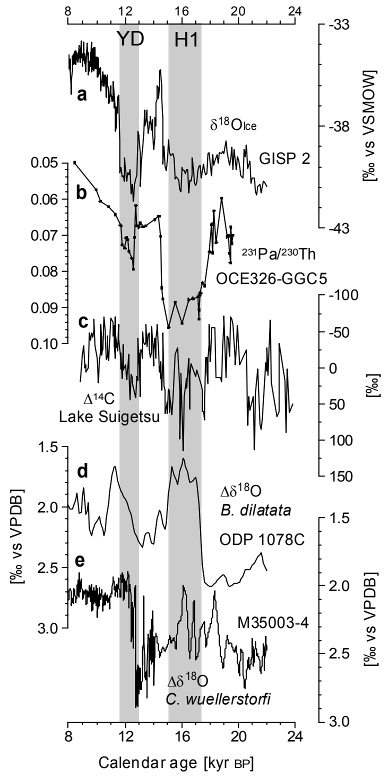


**Figure 2:** Left panels: Change of temperature in meltwater perturbation experiments using a hybrid-coupled model [*Prange et al.*, 2003] for present-day and glacial climate conditions. A meltwater input of 0.15 Sv is applied to the North Atlantic between 40°N and 55°N for 500 years. The model is designed as follows: The atmosphere model ECHAM3/T42 is forced by present-day observed or reconstructed (CLIMAP with 3°C additional cooling in the tropics) sea surface temperatures. Computed fields of surface air temperature, freshwater flux and wind stress are then used to drive an improved version of the ocean general circulation model LSG. (a) Zonally averaged temperature change (in °C) after 500 years (end of the meltwater perturbation) relative to the unperturbed state for the present-day Atlantic Ocean. Between -2°C and +2°C the contour interval is 0.2°C, for larger anomalies the interval is 1°C. (b) Same as in (a) but for the glacial Atlantic.

Right panel: Comparison of oxygen isotope ratios of (d) the benthic foraminifera *B. dilatata* [*Rühlemann et al.*, 2004] and (e) *C. wuellerstorfi* [*Hüls*, 2000] from sediment cores ODP 1078C (11°55' S, 13°24' E; 426 m water depth) and M35003-4 (12°05' N, 61°15' W; 1299 m water depth), respectively, indicating tropical Atlantic intermediate-depth temperatures, with (a) oxygen isotopes from the GISP2 ice core [*Stuiver and Grootes*, 2000] displaying air temperatures over Greenland, (b) $^{231}Pa/^{230}Th$ ratios [*McManus et al.*, 2004] and (c) atmospheric radiocarbon from sediments of Lake Suigetsu, Japan [*Kitagawa et al.,* 2000; adapted from *Clark et al.*, 2002]. Variations in $^{231}Pa/^{230}Th$ ratios and $\Delta^{14}C$ indicate changes in the rate of the Atlantic meridional overturning circulation.