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Response of South Atlantic deep waters to deglacial warming during Terminations V and I

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ABSTRACT

New deep-sea core data from the Atlantic sector of the Southern Ocean, covering MIS12 to MIS10 and the last deglaciation, show a clear lag of the changes in deep water properties with respect to changes in surface conditions. The development of a chronology based on the correlation of Southern Ocean sea surface temperature with air temperature over Antarctica allows the quantification and comparison of phase lags within the marine records during Termination V (TV) and Termination I (TI).

Deglacial changes in the South Atlantic are interpreted as the response to changes in the state of the Atlantic meridional ocean circulation (AMOC). The warming of South Atlantic surface waters and air temperature over Antarctica at the beginning of both TV and TI is attributable to a reduction in interhemispheric heat transport due to the weakening of the AMOC. Comparison of our results with CLIMBER-2 simulations indicates that the response of bottom waters seen in the benthic isotopic records, delayed with respect to South Atlantic surface warming, can be explained by the increased inflow of North Atlantic Deep Water (NADW) to the South Atlantic site at the time of the AMOC recovery.

Reconstructed sea surface temperature at our South Atlantic site exhibits a cold spell at the end of TV, resembling the Antarctic Cold Reversal of the last deglaciation. The presence of cold spells during TV and TI may be explained by the fact that the recovery of the AMOC took place early during the termination in both cases. The sequence of events is similar during both terminations; however, the magnitude of the phase shifts between South Atlantic surface and deep waters conditions differs from one termination to the other, suggesting variations in the magnitude and duration of the AMOC perturbation.

1. Introduction

The bipolar seesaw mechanism has been widely invoked to explain the phase difference between the evolution of Antarctica and Greenland temperatures during the last deglaciation (Crowley, 1992; Broecker, 1998). This theory proposes that variations in the strength of the Atlantic meridional overturning circulation (AMOC) affect the distribution of heat between the North and South Atlantic. Many modeling studies have suggested that a shutdown or a slowdown of the thermohaline circulation in the North Atlantic promotes a cooling in this region, and a concomitant warming in the Southern Hemisphere. The different nature of the signals recorded in ice cores of the two hemispheres (abrupt changes in Greenland, and gradual, more moderate temperature rises over Antarctica) have been explained by the thermal inertia of the Southern Ocean, a large water body without lateral boundaries (Stocker and Johnsen, 2003). The prevailing view is that large bursts of less dense fresh water from melting Northern Hemisphere ice sheets are a key factor in the periodic collapses of the AMOC (Ganopolski and Rahmstorf, 2001). Heinrich Stadial 1 (HS1) has been identified as the cold interval in the North Atlantic happening early in the last deglaciation (~18.0–14.6 ky), associated with a slowdown of the circulation (Broecker et al., 1992; Waelbroeck et al., 2001). It was followed by the Bølling–Allerød (B–A) between ~14.6 and 12.8 ky, the warm period in the North Atlantic region when the AMOC recovered. Recent studies have focused on the response of the Southern Ocean to this interhemispheric seesaw mechanism over the last deglaciation (Bianchi and Gersonde, 2004; Lamy et al., 2007; Barker et al., 2009), showing a direct link between changes in this region and the Northern Hemisphere.

However, a number of unresolved questions remain with respect to the exact timing and mechanisms involved in the response of both

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hemispheres to the deglaciation. Among them, the response of surface and deep waters of the Southern Hemisphere to changes in the AMOC is still not completely understood. A phase shift of sea surface temperature (SST) and planktic oxygen isotope records with respect to benthic oxygen isotopic records, has been observed in several marine records of the Southern Ocean (Waelbroeck et al., 1995; Labeyrie et al., 1996; Mashiotta et al., 1999; Becquey and Gersonde, 2003; Cortese et al., 2007). Many of these proxy-based studies however, have focused only on the last deglaciation. When they have explored several terminations, it has usually been by means of time series analysis in the Milankovitch frequency domain, which does not allow the comparison of different glacial-interglacial transitions. Moreover, the influence of changes in the AMOC on this surface/ bottom water phasing has been little explored in data-based studies.

This study compares two important terminations: Termination V (TV), the glacial-interglacial transition between marine isotopic stage (MIS) 12 and MIS11, and Termination I (TI), the transition between MIS2 and the Holocene. MIS11 is the interglacial period dated around 400 ka ago, and has been the subject of great attention as a possible "analogue" to the Holocene due to its orbital configuration, close to that of the present period (Berger and Loutre, 2003). However, the exact phasing of changes in surface properties with respect to changes in deep water properties during Termination V has remained difficult to quantify, because of the uncertainty associated with the current dating methods applied to this period. The objective of this study is to evaluate deep water circulation changes in this area of the Southern Ocean with respect to surface hydrology evolution during both TV and TI. The first changes induced by the deglaciation in surface waters of this area (as recorded by the SST warming) will be compared with the first deglacial changes happening in deep waters of the site, as registered in the benthic $\delta^{18}O$ and $\delta^{13}C$. Benthic $\delta^{18}O$ depends on changes in bottom water temperature and $\delta^{18}O$, so the signal can be used to track variations in deep water properties. The carbon isotopic ratio of *Cibicides* spp. has been shown to register the $\delta^{13}C$ of the total dissolved CO_2 of bottom waters due to its epifaunal habitat (Duplessy et al., 1984). Assuming that the principal factor affecting the seawater $\delta^{13}C$ is the global deep water circulation, *Cibicides* $\delta^{13}C$ is used as a proxy for deep water ventilation. TI serves here as a reference interval, since it has been extensively studied thanks to the availability of well dated records.

The present study is based on new, high resolution marine records from the Atlantic sector of the Southern Ocean. A new age scale for the sediment core, consistent with Antarctica ice core records, is proposed for MIS12 to MIS10. This age scale allows the comparison between marine and ice records with a precision of ~1700 y, and between marine records and greenhouse gases trapped within the ice with a precision of ~2100 y. The new chronostratigraphical framework is used to quantify the phasing of changes in SST and planktic foraminifera isotopic records with respect to benthic isotopic records during TV. The records from TV are then compared with records of the last deglaciation, in order to evaluate the similarities and differences between the mechanisms acting during both periods, and to clarify the influence of changes in the AMOC on phase shifts of terminations.

2. Study area

The evolution of surface and deep waters in the Atlantic sector of the Southern Ocean from MIS12 to MIS11 and the last 40 ka is reconstructed using new high-resolution data from cores MD07-3077 and MD07-3076 CQ (44°09′ S, 14°13′ W, 3770 m) (Fig. 1). Core MD07-3077 is a 49.5 m long piston core that covers approximately the last 500 ky, whereas core MD07-3076 is a 10.9 m long square-section core that allows the sampling of large quantities of undisturbed sediment over the last 110 ky.

The cores were recovered from the eastern flank of the mid-Atlantic ridge at 3770 m depth; this site is presently bathed in a mix of modified North Atlantic Deep Water (NADW) and Lower Circumpolar Deep Water (LCDW) (Saunders and King, 1995; Siedler et al., 1996; Stramma and England, 1999). At present, the sampling site lies below the Subantarctic zone of the Southern Ocean, between the Subtropical and Subantarctic Fronts (STF and SAF, respectively) (Fig. 1). The STF separates subtropical from subantarctic waters; its position is defined by the northward temperature increase from 10 °C to 12 °C at 100 m depth (Orsi et al., 1995). The position of the SAF corresponds to the deepening of the Antarctic Intermediate Water (AAIW) salinity minimum from near the surface in the polar frontal zone, to depths greater than 400 m in the Subantarctic zone (Orsi et al., 1995).

One centimeter thick samples were taken each 4 cm in core MD07-3077, allowing an average resolution of 413 y. In core MD07-3076, sampling was conducted each 2 cm, leading to an average resolution of 226 y. Benthic isotope and SST records from this core are being published elsewhere (Skinner et al., 2010; Waelbroeck et al., submitted for publication).

3. Methods

3.1. Isotopic analyses

Planktic and benthic foraminiferal $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios ($\delta^{18}O$ and $\delta^{13}C$ respectively, expressed in ‰ versus Vienna Pee-Dee Belemnite, VPDB) were measured at LSCE (Gif-sur-Yvette) on Finnigan Δ+ and Elementar Isoprime mass spectrometers. VPDB is defined with respect to NBS-19 calcite standard ($\delta^{18}O = -2.20$‰ and $\delta^{13}C = +1.95$‰). The mean external reproducibility (1σ) of carbonate standards is ±0.05‰ for $\delta^{18}O$ and ±0.03‰ for $\delta^{13}C$; measured NBS-18 $\delta^{18}O$ is −23.2±0.2‰ VPDB and $\delta^{13}C$ is −5.0±0.1‰ VPDB.

Planktic (*Globigerina bulloides* and *Neogloboquadrina pachyderma* left) and benthic (*Cibicides* sp.) foraminiferal specimens were handpicked in cores MD07-3077 and MD07-3076. Planktic species were picked in a narrow size range to minimize size effects on isotopic ratios (250–315 μm size fraction for *G. bulloides*, and 200–250 μm size fraction for *N. pachyderma* left). The samples were cleaned in a methanol ultrasonic bath for a few seconds and roasted under vacuum at 380 °C for 45 min prior to analysis, in order to eliminate impurities (Duplessy, 1978).

The need to use two different planktic species for the isotopic analysis results from the position of the core site, which lies in a "transition zone" *sensu* Bé and Tolderlund (1971) where the distribution of cold-water and warm-water species overlaps. The sub-polar species *G. bulloides* is more abundant at this site during interglacial periods, whereas *N. pachyderma* left abundances decrease dramatically when temperature increases. The two species coexist during glacial-interglacial transitions. Both *G. bulloides* and *N. pachyderma* left showed similar measured isotopic values in sections where they are both abundant (pooled standard deviation of 0.14‰ for $\delta^{18}O$ over these periods, Supplementary Material Fig. S1). Therefore, a mean planktic $\delta^{18}O$ signal was built from the composite record of both species.

Regarding benthic foraminifera of core MD07-3077, pure *Cibicides wuellerstorfi* samples were analyzed in many levels; when the material was not sufficient, *C. ungerianus*, *C. pachyderma*, *C. kullenbergi* and one unidentified *Cibicides* species were also measured. Replicated analyses of different species from the same level were performed in order to discard species-specific isotopic differences. The pooled standard deviation for replicated measures of *C. wuellerstorfi* was 0.11‰ for $\delta^{18}O$ and 0.27‰ for $\delta^{13}C$ (for 23 levels, with a total of 49 replicates). The isotopic values of the other species were compared to the values of *C. wuellerstorfi*, and only the $\delta^{13}C$ values of the unidentified *Cibicides* species were found to deviate from them. This species was thus removed from the dataset; the resultant mixed *Cibicides* $\delta^{18}O$ and $\delta^{13}C$ standard pooled deviations were 0.09 and 0.22‰, respectively (87 levels, 222 replicates), therefore supporting the choice of using a composite curve.