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Geology 2008;36:919-922
doi:10.1130/G24979A.1

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Notes
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ABSTRACT

The North Atlantic Ocean underwent an abrupt temperature increase of 9 °C at high latitudes within a couple of decades during the transition from Heinrich event 1 (H1) to the Bølling warm event, but the mechanism responsible for this warming remains uncertain. Here we address this issue, presenting high-resolution last deglaciation planktic and benthic foraminiferal records of temperature and oxygen isotopic composition of seawater (δ¹⁸Osw) for the subtropical South Atlantic. We identify a warming of ~6.5 °C and an increase in δ¹⁸Osw of 1.2‰ at the permanent thermocline during the transition, and a simultaneous warming of ~3.5 °C with no significant change in δ¹⁸Osw at intermediate depths. Most of the warming can be explained by tilting the South Atlantic east-west isopycnals from a flattened toward a steepened position associated with a collapsed (H1) and strong (Bølling) Atlantic meridional overturning circulation (AMOC). However, this zonal seasaw explains an increase of just 0.3‰ in permanent thermocline δ¹⁸Osw. Considering that δ¹⁸Osw at the South Atlantic permanent thermocline is strongly influenced by the inflow of salty Indian Ocean upper waters, we suggest that a strengthening in the Agulhas leakage took place from transition from H1 to the Bølling, and was responsible for the change in δ¹⁸Osw recorded in our site. Our records highlight the important role played by Indian-Atlantic interocean exchange as the trigger for the resumption of the AMOC and the Bølling warm event.

INTRODUCTION

The increase in sea-surface temperature in the Southern Ocean, initial sea ice retreat around Antarctica, and atmospheric CO₂ rise began as early as 19 ka. In contrast, deglacial changes in the high latitudes of the North Atlantic did not commence until ca. 14.7 ka. This delay and the abrupt nature of the northern high latitudes deglacial response are usually linked to the variability of the Atlantic meridional overturning circulation (AMOC). After the last glacial maximum (LGM), a first short-lived meltwater pulse ca. 19 ka delivered to the Nordic Seas (Clark et al., 2004) and subsequent melting of icebergs from the Laurentide ice sheet (Heinrich event 1, H1) (Bond et al., 1992) generated a dramatic quasi-cessation of the AMOC (McManus et al., 2004). The slow down of the AMOC lasted until ca. 14.7 ka and cooled the North Atlantic. Concurrent to the resumption of the AMOC, the higher latitudes of the Northern Hemisphere underwent an abrupt warming of as much as 9 °C within a couple of decades, known as the Bølling warm event (Severinghaus and Brook, 1999). The transition from the H1 to the Bølling is probably the most striking climatic feature of the last deglaciation for the bottom of the water column ca. 15 ka (Fig. 2G). Not as clearly defined as the H1 to the Bølling transition, ice volume–corrected bottom ocean temperature due to the AMOC collapse. For further information on methods, see the Data Repository.

RESULTS AND DISCUSSION

The benthic δ¹⁸O record shows an abrupt change of 1.1‰ toward lower values ca. 15 ka and an excursion of ~0.6‰ toward higher values from 13.5 to 12 ka (Fig. 2H). The T_Mg/Ca reveals an increase of ~3.5 °C for the bottom of the water column ca. 15 ka (Fig. 2G). Not as clearly defined as the H1 to the Bølling change ca. 15 ka, ice volume–corrected bottom water δ¹⁸O (δ¹⁸Oice-bw) decreases 0.5‰ across the major step in benthic δ¹⁸O (Fig. 2F). Whereas the T_Mg/Ca change is highly significant (Lear et al., 2002), that is not the case for the decrease in δ¹⁸Oice-bw, which is smaller than the typical 2σ for δ¹⁸Oice-bw reconstructions (~0.8‰) (Schmidt, 1999). At the permanent thermocline, our planktic δ¹⁸O record is based on seven calibrated accelerator mass spectrometry radiocarbon measurements (GSA Data Repository Table DR1 and Fig. DR1). All ages are discussed in calibrated kiloanum B.P. (ka).

We measured Mg/Ca ratios and oxygen isotopic composition (δ¹⁸O) in the tests of deep-dweller planktic foraminifera Globorotalia inflata and benthic foraminifera Uvigerina bifurcata to estimate past temperature and δ¹⁸O of seawater (δ¹⁸Osw, a proxy for salinity) variation at the permanent thermocline and at the bottom of the water column, respectively. We converted Mg/Ca ratios to temperatures (T_Mg/Ca) using empirical equations for G. inflata (see the Data Repository) and Uvigerina spp. (Lear et al., 2002).

We used the University of Victoria (UVic) Earth System Climate Model (ESCM, version 2.8) (Weaver et al., 2001) to simulate a Bølling-like (BL, active AMOC) and a Heinrich-like (HL, collapsed AMOC) climate state. We compared both states focusing on the difference in ocean temperature due to the AMOC collapse. For further information on methods, see the Data Repository.

MATERIAL AND METHODS

We investigated the last deglaciation section of marine sediment core GeoB6211–2 recovered off southeastern South America (32.50°S, 50.24°W, 657 m water depth) (Fig. 1A). Our age model for GeoB6211–2

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shows centennial-scale oscillations superimposed on a long-term trend of decreasing values (0.6‰) for the whole period with relatively little change at 15 ka (0.2‰ decrease) and no clear trend during the interval from 13.5 to 12 ka (Fig. 2E). However, $T_{Mg/Ca}$ at the permanent thermocline shows an abrupt increase of ~6.5 °C ca. 15 ka followed by gradual cooling and an excursion of ~2.0 °C toward lower temperatures from 13.5 to 12 ka (Fig. 2D). Calculated $\delta^{18}O_{ivc-bsw}$ for the permanent thermocline ($\delta^{18}O_{ivc-ptsw}$) follows the trend of the $T_{Mg/Ca}$ record and shows an abrupt increase (~1.2‰) ca. 15 ka followed by a gradual decrease and an excursion of ~0.6‰ toward lower values from 13.5 to 12 ka (Fig. 2C). For the permanent thermocline, changes in $T_{Mg/Ca}$ and $\delta^{18}O_{ivc-bsw}$ are highly significant at least for the major steps ca. 15 ka (Schmidt, 1999).

The tilt of the contours of equal seawater density (isopycnals) in a latitudinal transect across the subtropical South Atlantic (Fig. DR2) is arguably clear evidence for the present-day relatively strong AMOC (e.g., Lynch-Stieglitz et al., 2006). The tilt is particularly steep in the upper ocean and reflects the northward-flowing upper branch of the AMOC, as the wind-driven component of the geostrophic flow is closed in the subsurface ocean. During periods of a slowdown in the AMOC, e.g., during H1,
one would expect a flattening of these contours, affecting the distribution of temperature and salinity (strengthening in the AMOC, e.g., during the Bolling, would result in steepening of the contours).

An abrupt strengthening in AMOC took place at the transition from the H1 to the Bolling, where it shifted from almost shutdown to near present-day values (e.g., McManus et al., 2004). Accordingly, a shift in the slope of the isopycnals at 32.5°S in the South Atlantic from a horizontal position (collapsed AMOC) toward the present-day situation (relatively strong AMOC) would alone cause a temperature increase at our core site of ~5 °C and 3 °C for the permanent thermocline and the bottom of the water column, respectively (Fig. DR3).

The temperature anomalies in an east-west transect at 35.1°S across the South Atlantic between our HL and BL climate states ran with the UVic ESCM support this interpretation (Fig. 1B; Fig. DR4). The east-west dipole pattern in temperature anomalies (zonal seesaw) shows positive (negative) values in the western (eastern) side of the basin and is most pronounced in the permanent thermocline. The vertical structure and the magnitude of the simulated temperature anomalies compare favorably with the present-day difference between two stations located at both extremes of the subtropical South Atlantic (Fig. DR3) and seem to be generated by a shift in the slope of the isopycnals.

A similar tilt in the isopycnals explains an increase of ~0.3‰ and 0.05‰ in δ¹⁸Osw for the permanent thermocline and the bottom of the water column, respectively (Fig. DR3). We estimated an increase as large as 1.2‰ in δ¹⁸Oivc-sw and a decrease of 0.5‰ in δ¹⁸Orec-bsw ca. 15 ka, although the latter value should be interpreted with caution since it is smaller than the associated error. The discrepancy of the observed and estimated changes in δ¹⁸Orec, especially for the permanent thermocline, clearly requires an additional process to have happened synchronous to the steepening in the isopycnals ca. 15 ka.

Interocean exchange is a key process controlling the properties of upper water masses in the South Atlantic (e.g., Poole and Tomczak, 1999). Gordon et al. (1992) calculated that ~60% of the Benguela Current central waters are relatively warm and salty waters drawn from the Indian Ocean via Agulhas leakage. For greater depths of the Benguela Current, You et al. (2003) estimated that ~80% of intermediate depth waters is composed of relatively cold and fresh waters from the Pacific Ocean that entered the Atlantic through the Drake Passage. These water masses entering the Atlantic help to balance the outflow of NADW at greater depths (e.g., Broecker, 1991; Gordon et al., 1992). In particular, the addition of salty Indian Ocean waters into the South Atlantic has been suggested to precondition the Atlantic for NADW formation (Gordon et al., 1992; Weijer et al., 2002). Past changes in magnitude and intensity of the Agulhas leakage affected the properties of upper water masses in the South Atlantic with possible consequences for the strength of the AMOC, as described for glacial-interglacial time scales (e.g., Peeters et al., 2004). Decreased Agulhas leakage is generally assigned to glacials.

Two high-resolution records of surface seawater δ¹⁸Oivc-sw (δ¹⁸Orec-bsw) show higher salinities along the route of warm and salty water transport from the Indian Ocean to the Atlantic Ocean between 18 and 14.5 ka and during the Younger Dryas (Levi et al., 2007) (Fig. 3C). These periods of increased salinity in the Indian Ocean coincide with the low-salinity periods recorded at the permanent thermocline at our site. The strengthening of the Agulhas leakage ca. 15 ka released the accumulated salty waters to the South Atlantic, controlling the changes in δ¹⁸Osw of both sites.

At 14.9 ka, the first appearance of Algoa fauna (warm temperate endemic bivalves from the Agulhas Bank and the southwest Indian Ocean) in the Benguela upwelling area (cool temperate) reflects the first strong inflow of Indian Ocean waters into the South Atlantic after the LGM (Fig. 3B) (Pether, 1994). This observation fits remarkably well with our explanation for the abrupt increase in δ¹⁸Oivc-sw recorded at our site.

The two better-resolved records (regarding temporal resolution and age model) of sea ice extent in the Atlantic sector of the Southern Ocean agree that ca. 15 ka maximum extension of winter sea ice retreated to the

![Figure 3. Comparison of deglacial changes in GeoB6211–2 permanent thermocline seawater (ptsw) δ¹⁸O with paleoclimate records from Indian and Southern Oceans. A: GeoB6211–2 continental ice volume–corrected (ivc) seawater δ¹⁸O for the permanent thermocline (see Fig. 2 caption). B: Occurrence of Algoa fauna in Benguela upwelling area (Pether, 1994). C: Continental ice volume–corrected sea surface (ssw, sea-surface water) δ¹⁸O from eastern tropical Indian Ocean MD98–2165 (gray trace) and from Mozambique Channel MD79–257 (black trace) (Levi et al., 2007). D: Sea ice duration in Atlantic sector of Southern Ocean; black shaded area (TN057–13)—sea ice presence estimated by transfer function (Shemesh et al., 2002); gray shaded area (PS2090/ODP1094)—sea ice extent assessed by relative abundance of Fragilariopsis curta and F. cylindrus, where a relative abundance >3% denotes recurrent presence of winter sea ice (Bianchi and Gersonde, 2004). Individual measurements (dots) and five-point running average (curve) are shown. Bar close to vertical axis of A depicts typical 2σ for continental ice volume–corrected seawater δ¹⁸O reconstructions (Schmidt, 1999). Age control points (black and gray coded triangles) are shown below each respective curve. Vertical dashed lines indicate major changes in our records. VSMOW—Vienna standard mean ocean water.](image-url)
south of 53°S for the first time during the deglaciation (Shemesh et al., 2002; Bianchi and Gersonde, 2004) (Fig. 3D). This marked retreat was probably associated with a southward shift in the meridional density gradient across the frontal zones around Antarctica. As the frontal zones shifted southward, the northern boundary of the Antarctic Circumpolar Current also retreated southward (Paul and Schäfer-Neth, 2003). Simultaneously, more Agulhas Current waters were able to reach the South Atlantic, and the Agulhas leakage recovered its interglacial strength. The high-salinity waters that formerly accumulated in the upper water column of the Indian Ocean (Levi et al., 2007) flooded the central depths of the South Atlantic and were clearly detected as a 0.9‰ anomaly in our δ18Oivc-pts record.

CONCLUSIONS

Our high-resolution records from the permanent thermocline of the western subtropical South Atlantic show a warming of ~6.5 °C and an increase in δ18Oivc-pts of 1.2‰ ca. 15 ka, while at intermediate depths we identify a warming of ~3.5 °C and no significant change in δ18Oivc-bsw. Most of the warming can be explained by tilting the South Atlantic east-west isopycnals from a horizontal position (collapsed AMOC, as during the Bolling). On the other hand, the same tilt explains just 0.3‰ change in δ18Oivc-pts, requiring an additional process to be responsible for the remaining 0.9‰. Salinity in the central water masses of the South Atlantic is strongly influenced by the inflow of salty Indian Ocean upper waters into the South Atlantic. We suggest that a strengthening in Agulhas leakage took place ca. 15 ka, and was responsible for the strong change in δ18Oivc-pts at the western subtropical South Atlantic. Our records are consistent with modeling results and highlight the important role played by Indian-Atlantic interocean exchange as the trigger for the resumption of the AMOC and the Bolling warm event.

ACKNOWLEDGMENTS

We thank M. Segi for help with the isotope analyses, J. Lynch-Stieglitz and J.R.E. Lutjeharms for discussions, and three anonymous reviewers for constructive comments. Work was funded through the DFG (Deutsche Forschungsgemeinschaft) Research Center/Excellence Cluster “The Ocean in the Earth System” and a CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) Brazil Fellowship granted to Chiessi.

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