Saline Indian Ocean waters invade the South Atlantic thermocline during glacial termination II

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ABSTRACT

Salty and warm Indian Ocean waters enter the South Atlantic via the Agulhas leakage, south of Africa. Model simulations and proxy evidence of Agulhas leakage strengthening during glacial terminations led to the hypothesis that it was an important modulator of the Atlantic Ocean circulation. Yet, the fate of the leakage salinity and temperature anomalies remains undocumented beyond the southern tip of Africa. Downstream the leakage, new paleoceanographic evidence from the central Walvis Ridge (southeast Atlantic), shows that salinity increased at the thermocline, and less so at the surface, during glacial termination II. Thermocline salinity change coincided with higher frequency of Agulhas rings passage at the core location and with salinity maxima in the Agulhas leakage area, suggesting that leakage waters were incorporated in the Atlantic circulation through the thermocline. Hydrographic

changes at the Walvis Ridge and in the leakage area display a distinct two-step structure, with a reversal at ~134 ka. This matched a wet interlude within the East Asia weak monsoon interval of termination II, and a short-lived North Atlantic warming. Such concurrence points to a Bølling-Allerød-like recovery of the Atlantic circulation amidst Termination II, with a northward shift of the intertropical convergence zone and Southern Hemisphere westerlies, and attendant curtailment of the inter-ocean connection south of Africa.

INTRODUCTION

The South Atlantic subtropical gyre is a main component of the Atlantic meridional overturning circulation (AMOC), acting as a conduit for the warm and saline upper waters that flow northward across the equator (Gordon, 1986; Garzoli and Matano, 2011). Most of those waters originate in the subtropical Indian Ocean and are transported by the Agulhas Current to the southern tip of Africa, where they “leak” into the South Atlantic (Agulhas leakage, AL, Fig. 1A), increasing its heat and salinity (Gordon et al., 1992; Biastoch et al., 2009; Beal et al., 2011). Numerical models point to a correlation of AL intensity with North Atlantic salinity and with AMOC strength (Biastoch et al., 2009; Biastoch and Böning, 2013). Advancing on indications by Gordon et al. (1992), others suggested a role for the AL in Pleistocene glacial terminations (e.g., Weijer et al., 2002; Knorr and Lohmann, 2007). Paleooceanographic reconstructions indeed reveal that AL maxima were a persistent feature of terminations (Peeters et al., 2004), whereby AL intensifications resulted from deglacial reorganizations of the southern hemisphere westerlies (Toggweiler et al., 2006), due either to their southern shift (Sijp and England, 2009; Biastoch et al., 2009; Biastoch and Böning, 2013), or to the redistribution of momentum associated with their intensification (Durgadoo et al., 2013). The so-called AL hypothesis

contends that enhanced salt input from the AL into the upper branch of the AMOC may have helped to overcome the glacial density stratification that impeded deep convection in the northern North Atlantic (Knorr and Lohmann, 2007), thereby nudging the AMOC from a shallower and potentially slower glacial mode to a stronger interglacial one. During terminations, however, the AMOC underwent major reductions (McManus et al., 2004; Denton et al., 2010). This appears in contradiction with the link between AL strengthening and AMOC intensification, as derived from modern climate models (Biaosoch and Böning, 2013), and as formulated in the AL hypothesis. Lack of data tracking the Atlantic propagation of salinity anomalies coupled with past AL intensifications (Marino et al., 2013) casts further doubts on the AL hypothesis.

Here we document the incorporation of AL heat and salt anomalies into the South Atlantic subtropical gyre during glacial termination II (T-II), which featured the most prominent intensification in AL volume of the last 640 k.y. (Caley et al., 2014).

METHODS

Core 64PE-174P13 (29°45.7'S, 2°24.1'E, 2912 m water depth) is located on the central Walvis Ridge, in the eastern sector of the South Atlantic gyre (Fig. 1A), directly in the path of present and past Agulhas rings (Gordon et al., 1992; Scussolini et al., 2013). We generated stable isotope ($\delta^{18}\text{O}$) and trace element (Mg/Ca) time series from two planktic foraminiferal species: *Globigerinoides ruber* (sensu lato) and *Globorotalia truncatulinoides* (sinistral), which dwell close to surface (within the upper ~100 m) and in the subsurface (within the permanent thermocline at ~500 m, hereafter referred to as thermocline), respectively (cf. Scussolini and Peeters, 2013). The $\delta^{18}\text{O}$ measurements were conducted as reported in Scussolini and Peeters (2013). Mg/Ca ratios were analyzed by ICP-OES at the VU University Amsterdam on

cleaned foraminiferal samples (cf. Barker et al., 2003). We converted Mg/Ca to calcification temperatures using the calibration by Anand et al. (2003) for *G. ruber* and by Regenberg et al. (2009) for *G. truncatulinoides*. Paired Mg/Ca- $\delta^{18}\text{O}$ and coeval sea-level records yield ice-volume corrected seawater $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{\text{sw-ivc}}$), a proxy for local salinity changes (e.g., Marino et al., 2013). The chronology adopted here for the 165–95 ka interval is consistent with the one of the ^{230}Th -dated speleothems (Cheng et al., 2009; Barker et al., 2011). See the Data Repository for details about the methods.

RESULTS

The $\delta^{18}\text{O}$ values of *G. ruber* and *G. truncatulinoides* from 64PE-174P13 display distinct decreases during T-II that are synchronous but different in magnitude: $\sim 1.5\text{‰}$ in *G. truncatulinoides* and $\sim 1.1\text{‰}$ in *G. ruber* (Fig. 1B; Table DR4). The Mg/Ca-temperatures feature millennial-scale variations superimposed upon a longer-term glacial-interglacial warming (Fig. 1C). Surface temperatures exhibit sub-orbital oscillations of $\sim 1\text{ }^{\circ}\text{C}$ during glacial MIS 6 and two distinct warming shifts of up to $2.5\text{ }^{\circ}\text{C}$ between ~ 142 and 126 ka , interspersed with a $\sim 3\text{ k.y.}$ return to near-glacial values. Glacial thermocline temperatures show larger fluctuations (up to $3\text{ }^{\circ}\text{C}$) and a two-phase warming ($2\text{--}4\text{ }^{\circ}\text{C}$) at ~ 142 and 130 ka . The $\delta^{18}\text{O}_{\text{sw-ivc}}$ (Fig. 1D) increased at both surface ($\sim 0.7\text{ ‰}$) and thermocline ($\sim 1.2\text{ ‰}$) from $\sim 140\text{--}142\text{ ka}$, decreased gradually from 125 ka , and remained at relatively low levels afterwards.

DISCUSSION

Agulhas Leakage Control on the Walvis Ridge Salinity

Several lines of evidence indicate that multi-millennial changes, starting at $\sim 142\text{ ka}$, in upper ocean temperature and $\delta^{18}\text{O}_{\text{sw-ivc}}$ (hence salinity) in the central Walvis Ridge reflected the hydrographic response of the South Atlantic subtropical

gyre to the AL strengthening of T-II (Fig. 2 B-F). First, the thermocline $\delta^{18}\text{O}_{\text{sw-ivc}}$ anomaly, which is $\sim 70\%$ larger than the simultaneous $\delta^{18}\text{O}_{\text{sw-ivc}}$ change at surface, correlates with the enhanced propagation of Agulhas rings to the Walvis Ridge, as inferred from a proxy registered in the same core and foraminiferal species (*G. truncatulinoides*) (Fig. 2C; Table DR2; Scussolini et al., 2013). An increase in the advection of Indian Ocean saline waters transported by anticyclonic Agulhas rings would depress the South Atlantic isohalines (van Aken et al., 2003) and increase the salt content of the subsurface, thus explaining the prominent salinification of the thermocline during T-II. Second, the thermocline waters at the Walvis Ridge, contrary to their counterpart from the Agulhas Plateau (core MD02-2588; Ziegler et al., 2013), lacked the “carbon isotope minimum” (Fig. DR2) that fingerprinted deglacial Subantarctic Mode Water (Spero and Lea, 2002). This indicates that the Walvis Ridge subsurface hydrography was not controlled by fresh and low- $\delta^{13}\text{C}$ Subantarctic Mode Water but by saltier and more nutrient-depleted AL waters. Third, both surface and thermocline $\delta^{18}\text{O}_{\text{sw-ivc}}$ from the Walvis Ridge covaried with their surface counterpart from the Agulhas Bank (Marino et al., 2013), where warm and saline Indian Ocean waters “leak” into the South Atlantic (Beal et al., 2011) (Fig. 2 D-F; Table DR2). Finally, the upper ocean $\delta^{18}\text{O}_{\text{sw-ivc}}$ maxima of T-II at the Walvis Ridge coincided, within chronological uncertainties (Table DR1), with maximum transport of AL planktic foraminifera to the South Atlantic (Peeters et al., 2004) (Fig. 2B).

Marino et al. (2013) found that an increase of saline waters transport via the AL during T-II coincided with the Heinrich event 11 in the North Atlantic and with the profound interhemispheric reorganization of the ocean-atmosphere system coupled with a weakening of the AMOC (Stocker and Johnsen, 2003; Lee et al., 2011). Likewise the temperature relationship between bipolar ice cores across the last

glacial cycle (Stocker and Johnsen, 2003), the Agulhas salt-leakage developed in response to North Atlantic cooling and peaked prior to (or in step with) North Atlantic warming (Marino et al., 2013). Our Walvis Ridge thermocline $\delta^{18}\text{O}_{\text{sw-ivc}}$ record indicates a strong similarity in timing and magnitude with the Agulhas Bank surface $\delta^{18}\text{O}_{\text{sw-ivc}}$ over the whole 160–100 ka interval. One example is the glacial salinification at 152–147 ka, also tied to a North Atlantic cold phase (Marino et al., 2013). This suggests that the efficient transmission of the AL salt to the thermocline was a persistent millennial-scale feature of the South Atlantic gyre circulation and of the interhemispheric climate linkages.

Although salinification of the wider South Atlantic may have stemmed from salt retention in this sector of the basin, due to deglacial AMOC slowdown (Lohmann, 2003), the surface $\delta^{18}\text{O}_{\text{sw-ivc}}$ anomaly at the Walvis Ridge during T-II is smaller in amplitude than its counterpart from the Agulhas Bank (Fig. 2D-E). Consequently, enhanced AL was likely a more important driver of the salinity increase at the Walvis Ridge, at least during Heinrich event 11. Accordingly, the surface salinity anomaly associated with the AL would attenuate downstream in the South Atlantic, as observed in the data.

Modern AL and rings propagating in the South Atlantic are characterized by elevated heat and salinity at the thermocline (Arhan et al., 2011). Still, at the Walvis Ridge, thermocline temperature mirrors the proxy for Agulhas rings (Scussolini et al., 2013) less closely than the $\delta^{18}\text{O}_{\text{sw-ivc}}$ proxy, indicating that salinity was a more persistent property of the AL waters. This, along with the lower correlation between the surface temperature profiles at the Walvis Ridge and Agulhas Bank (Fig. 2F), suggests that the AL heat dissipated faster than the salinity anomaly in the Cape Basin, probably due to convection and air-sea interaction (Arhan et al., 2011; Beal et

al., 2011). Hence, cooling would reduce buoyancy, and sink the AL waters in the South Atlantic to the thermocline.

South Atlantic Evidence for a Climate Reversal During T-II

Our new Walvis Ridge records reveal a brief, mid-termination return to low surface temperature and $\delta^{18}\text{O}_{\text{sw-ivc}}$ values (Fig. 2 D and F) interjecting the long-term temperature and salinity increases of T-II. This millennial-scale, relatively cold and fresh episode corresponded, within age uncertainties (Table DR1), to analogous temperature and $\delta^{18}\text{O}_{\text{sw-ivc}}$ drops centered at ~134 ka in the AL area (Marino et al., 2013). Although the uncertainties in the South Atlantic chronology are relatively large (see Data Repository), such timing appears to agree with the brief interruption of the weak monsoon interval of T-II in East Asia (Fig. 2G; see also Fig. DR3 and Table DR3), and with a distinct warm phase in the wider North Atlantic region (Barker et al., 2011; Martrat et al., 2014) (Fig. DR3 F-G). It has been recently proposed that both South Atlantic (Barker et al., 2009) and AL (Marino et al., 2013) responded to interhemispheric reorganizations of the ocean-atmosphere system on a millennial-scale. The South Atlantic “reversal” punctuating T-II likely reflected the effect of a short-lived reduction in Indian-to-Atlantic heat and salt transport. This reversal may arise from: (i) A northward shift of the tropical and subtropical, and weakening of the subtropical wind fields. This could have affected the mesoscale processes at the oceanic fronts south of Africa (Biaosoch et al., 2009; Durgadoo et al. 2013), in turn reducing the AL (Peeters et al., 2004), and is further consistent with the more northerly position of the intertropical convergence zone inferred from Chinese speleothems (Wang et al., 2008; Cheng et al., 2009); (ii) A transient resumption of the AMOC, which may have restored the “piracy” of heat from the upper layers of the South Atlantic (Crowley, 1992) and contributed to decrease upper ocean salinity. As

the AMOC and the latitudinal arrangement of atmospheric circulation appear mutually dependent (Sijp and England, 2009; Toggweiler, 2009; Frierson et al., 2013), both mechanisms together may account for the South Atlantic reversals of T-II. This reinforces the analogy with events amidst termination I (Martrat et al., 2014), when cold conditions in the South Atlantic corresponded to the Bølling-Allerød interval (Barker et al., 2009).

CONCLUSIONS

New paleoceanographic data from the Walvis Ridge document that enhanced Agulhas leakage raised the salinity and heat content of surface and, more prominently, of thermocline layers of the South Atlantic gyre during T-II. AL waters seem to have sunk upon entrance in the South Atlantic. The salinification of the South Atlantic did not seem to entail the resumption of the AMOC envisaged by the AL hypothesis. Reconstructions of thermocline salinity further downstream should determine whether the salinity anomalies also impacted the North Atlantic, or were retained in the South Atlantic, potentially by the severing of the oceanic bottleneck of the North Brazil Current, produced by the deglacial southern shift in the easterlies position (Wilson et al., 2011).

The T-II increase of surface temperature and salinity at the Walvis Ridge and in the AL area occurred in two-steps, with a return to cold and fresh conditions at ~134 ka. Comparison with records of Asian monsoon and of North Atlantic climate ascribe the reversal to a transient resumption of the AMOC, and attendant reduction of heat and salt transfer via the AL, potentially mediated by rearrangements of the southern hemisphere westerlies and associated oceanic fronts.

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- 337

FIGURES

Figure 1. A) Map of the Agulhas system, with the location of Walvis Ridge core 64PE-174P13 and other cores discussed in the text. Contoured sea surface height

343 anomalies (seasonal climatological mean: www.aviso.altimetry.fr) indicate the
344 transmission of Agulhas rings into the Atlantic Ocean. B, C, D) Geochemical results
345 from core 64PE-174P13 for *Globigerinoides ruber* and *Globorotalia*
346 *truncatulinoides*: B) calcite $\delta^{18}\text{O}$; C) Mg/Ca-derived temperatures; D) ice-volume
347 corrected seawater $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{\text{sw-ivc}}$). Vertical error bars are propagated.

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352 Figure 2. South Atlantic records of upper ocean hydrography compared with

353 Antarctic temperatures and time series of tropical precipitation across T-II. A)

354 Antarctic temperature from EPICA Dome C (Jouzel et al., 2007) on the speleothem

355 ^{230}Th chronology of Barker et al. (2011). B) AL fauna record, proxy for AL intensity,

356 from the Cape Basin (core GeoB3603–2; Peeters et al., 2004; age model adapted, see

357 Data Repository). C) Thermocline $\delta^{18}\text{O}_{\text{sw-ivc}}$ (proxy for salinity) from Walvis Ridge

358 core 64PE-174P13 (this study), compared to the proxy for Agulhas rings in the same

359 core (Scussolini et al., 2013). D) Surface and E) thermocline $\delta^{18}\text{O}_{\text{sw-ivc}}$ from Walvis
360 Ridge (this study), compared to surface $\delta^{18}\text{O}_{\text{sw-ivc}}$ from Agulhas Bank (core MD96–
361 2080; Marino et al., 2013). F) Surface temperatures from Walvis Ridge (this study)
362 and from Agulhas Bank (MD96–2080; Marino et al., 2013). G) East Asia speleothems
363 from the Sanbao cave (Wang et al., 2008; Cheng et al., 2009), and growth phases
364 from Brazil speleothems (Wang et al., 2004; 1 σ error bars). The white bar indicates
365 the South Atlantic reversals during T-II.
366 ¹GSA Data Repository item 2014xxx, xxxxxxxx, is available online at
367 www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or
368 Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.