Deglacial sea surface temperature and salinity increase in the western tropical Atlantic in synchrony with high latitude climate instabilities

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Abstract

A sediment core from the western tropical Atlantic covering the last 21,000 yr has been analysed for centennial scale reconstruction of sea surface temperature (SST) and ice volume-corrected oxygen isotopic composition of sea water ($\delta^{18}O_{ivc-sw}$) using Mg/Ca and $\delta^{18}O$ of the shallow dwelling planktonic foraminifer *Globigerinoides ruber* (white). At a period between 15.5 and 17.5 kyr BP, the Mg/Ca SST and $\delta^{18}O_{ivc-sw}$, a proxy for sea surface salinity (SSS), reveals a warming of around 2.5 °C along with an increase in salinity. A second period of pronounced warming and SSS increase occurred between 11.6 and 13.5 kyr BP. Within age model uncertainties, both warming intervals were synchronous with air temperature increase over Antarctica and ice retreat in the southern South Atlantic and terminated with abrupt centennial scale SSS decrease and slight SST cooling in conjunction with interglacial reactivation of the meridional overturning circulation (MOC). We suggest that during these warm intervals, production of saline and warm water of the North Brazil Current resulted in pronounced heat and salt accumulation, and was associated with warming in the southern Atlantic, southward displacement of the intertropical convergence zone and weakened MOC. At the termination of the Younger Dryas and Heinrich event 1, intensification of cross-equatorial heat and salt transport caused centennial scale cooling and freshening of the western tropical Atlantic surface water. This study shows that the western tropical Atlantic served as a heat and salt reservoir during deglaciation. The sudden release of accumulated heat and salt at the end of Younger Drays and Heinrich event 1 may have contributed to the rapid reinvigoration of the Atlantic MOC.
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1. Introduction

Understanding the paleoclimatic history of the tropics is essential due to their role as a heat and salt reservoirs for both the southern and northern high latitudes. During the last deglaciation and marine iso-tope stage 3, ice core [1] and marine sediments from the northern high latitudes [2,3] reveal climate instabilities denoted as Dansgaard–Oeschger (D–O) cycles and Heinrich events (the marine equivalent to the pronounced cold D–O events of the ice core records). These events were associated with instabilities of continental ice sheets, calving of icebergs in the North Atlantic, and perturbations of the global thermohaline circulation [2–4]. In contrast, both Antarctic ice core records [5] and marine records from the southern Atlantic Ocean [6–8] reveal warming during Heinrich

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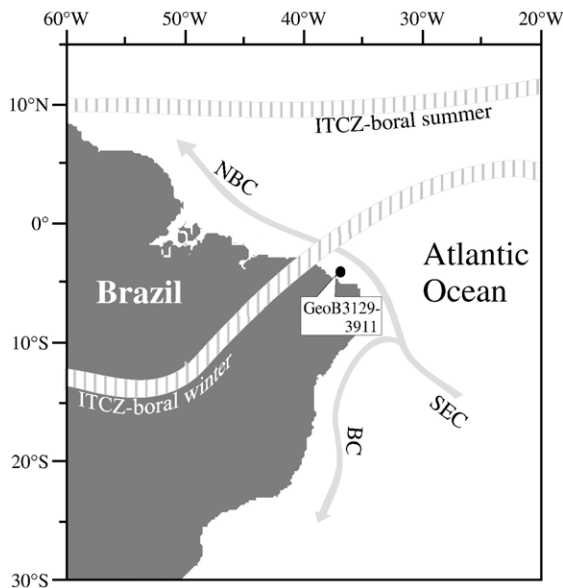*E-mail address:* sweldeab@geol.ucsb.edu (S. Weldeab).

Fig. 1. Map showing location of GeoB3129-3911, seasonal position of the ITCZ, and main surface and near surface current systems: BC: Brazil Current; NBC: North Brazil Current; SEC: South Equatorial Current.

event 1 (H1) and the Younger Dryas (YD) [9]. The role of, and impact upon, the tropical Atlantic Ocean during the "bipolar see-saw" behaviour [10] of the high latitudes is, however, not well understood. SST records from the Tobago Basin [11,12], Caribbean Sea [13] and Gulf of Mexico [14] reveal warming during the H1 and YD, though significant differences exist with respect to the timing and magnitude of SST changes. In contrast, SST reconstructions from the Cariaco Basin show cooling in synchrony with northern high latitudes [15].

In this study we present a reconstruction of sea surface conditions from a part of the western tropical Atlantic that is fully under the influence of the North Brazil Current, one of the main suppliers of saline and warm water masses from the tropical and subtropical South Atlantic to the North Atlantic [16–18]. Thus, a marine climate archive from the western tropical Atlantic under the direct influence of the North Brazil Current is ideal for providing insight into the thermal history of the western tropical Atlantic and cross-equatorial heat flow during the last deglaciation.

2. Material and methods

GeoB3129/3911 was recovered from the continental margin of northeastern Brazil (4°36.8′S, 36°38.2′W; 830 m water depth), during the *Victor Hensen* Cruise

JOP-SII and *Meteor* Cruise M34/4 (Fig. 1). Modern annual mean SST and SSS above the core location are 27.3 °C and 36‰, respectively [19]. The strongest seasonal SST contrast occurs between January–March (28.5 °C) and July–September (26.5 °C) [19]. There is very little seasonal SSS contrast showing 0.3‰ difference [19]. The Rio Piranhas River drains a semi-arid catchment area of 22.875 km^2 resulting in a mean annual discharge of 2.6 km^3 [20]. Though it enters into the western tropical Atlantic around 60 km southwest of the core location, its current effect on ocean salinity variation is negligible [19]. Thus, hydrographic conditions of the near surface layer at the core site are entirely determined by the North Brazil Current that predominantly originates from low latitudes [16–18] and shows little variation throughout the year over the core site [21].

Results of sedimentological and bulk geochemical analyses, as well as details regarding AMS ^{14}C-data of GeoB3129-3911 are provided in previous studies [22–24]. For this study, the age model has been recalculated (Table 1) using CALIB v. 5.01 [25] and Marine04 data set [26]. The chronology of the two combined sediment cores (GeoB3129-3911) was established by 16 AMS datings of *Globigerinoides sacculifer* (250–400 m) samples [23] covering the last 20.5 thousand years before present (kyr, BP). For the Mg/Ca and δ^{18}O analyses, the shallow

Table 1
AMS datings obtained using monospecific foraminifers (*G. sacculifer*) [23]

Core	Core depth (cm)	^{14}C–AMS ± error (yr, BP)	Calibrated age (yr, BP)	2σ ranges (yr, BP)
GeoB 3129-1	22	2230 ± 30	1825	1731–1919
GeoB 3129-1	52	4010 ± 50	4019	3865–4172
GeoB 3129-1	62	4220 ± 30	4315	4217–4413
GeoB 3129-1	90	6280 ± 40	6741	6632–6849
GeoB 3129-1	119	6910 ± 60	7423	7303–7542
GeoB 3129-1	207	9560 ± 80	10398	10234–10561
GeoB 3129-1	241	10050 ± 60	10990	10797–11182
GeoB 3129-1	307	10310 ± 60	11427	11321–11532
GeoB 3129-1	329	10830 ± 60	12393	12255–12530
GeoB 3129-1	452	11010 ± 70	12593	12376–12809
GeoB 3129-1	491	12000 ± 70	13459	13288–13629
GeoB 3129-1	523	12440 ± 70	13898	13751–14044
GeoB 3129-1	548	12780 ± 50	14423	14101–14745
GeoB 3911-3	543	13080 ± 80	14924	14586–15261
GeoB 3911-3	648	14560 ± 110	16901	16410–17391
GeoB 3911-3	665	17320 ± 90	20069	19869–20268

Calibrated age model is calculated using Calib v. 5.0.1 [25] and Marine04 data set [26]. Intervals between the age control points are linearly interpolated.

dwelling planktonic foraminifer *Globigerinoides ruber* white (250–300 μm) was selected using 30–50 and 15 individuals, respectively. Sample cleaning for foraminiferal Mg/Ca analysis was conducted using reductive and oxidative steps following of the established Mg/Ca cleaning protocols [27,28]. To minimise selective dissolution of lattice-bound Mg in the foraminiferal calcite, the alkaline chelation step using puffered DTPA (di-ethylene-triamine-penta-acetate) has been omitted. Before weak acid leaching, a microscopic check was conducted to remove any foreign material and strongly discoloured foraminiferal fragments [27]. The Mg/Ca measurements were conducted by ICP-OES (Perkin Elmar Optima 3300 R). For stabilization and minimizing the matrix effect, an internal standard (yttrium) was added and samples were diluted to equal Ca concentration depending on the Ca concentration from a preliminary ICP-OES measurement. Standards and replicate runs of the samples show a mean reproducibility of ± 0.07 Mg/Ca mmol/mol. Each point of Mg/Ca SST estimate presents an average of three replicate Mg/Ca analyses. In conjunction with the Mg/Ca ratios, Sr/Ca, Fe/Ca, Mn/Ca, and Ba/Ca ratios were analysed. The Fe/Ca and Mn/Ca values were utilised for monitoring the cleaning efficiency of the samples. The range of Fe/Ca and Mn/Ca varies between 0.03–0.2 and 0.02–0.09 mmol/mol, respectively, and show no co-variation with Mg/Ca. Two samples showing anomalously high Mg/Ca values and accompanying high Fe/Ca (>0.2) and/or Mn/Ca (>0.1) ratios were rejected. Mg/Ca-SST was calculated using the calibration equation developed by Anand et al. [29]. Oxygen isotope composition ($\delta^{18}O_c$) of *G. ruber* w. was analysed using a Finnigan MAT 252 mass spectrometer and long-term precision for $\delta^{18}O$ account for 0.05‰. Variation of ice-volume-corrected, local oxygen isotope composition of sea water ($\delta^{18}O_{ivc-sw}$), a proxy for SSS, was computed applying the temperature—$\delta^{18}O_c-\delta^{18}O_{sw}$ relationship proposed by Shackleton [30] and subtracting the change in $\delta^{18}O$ of sea water due to reduction of global ice volume associated with the deglaciation [31]. Last Glacial Maximum enrichment of the ocean mean oxygen isotope is estimated about ~1‰ [31,32]. Error of the calculated $\delta^{18}O_{ivc-sw}$ values is assessed taking into account: 1) uncertainty in the Mg/Ca SST estimation of ± 1 °C that corresponds to ~0.2‰ oxygen isotope change [33] and 2) analytical error in the oxygen isotope analyses of 0.05‰ resulting in cumulative error estimation of $\delta^{18}O_{sw}$ of ± 0.25‰. This is close to error estimation of $\delta^{18}O_{sw}$ (± 0.22‰) reported by Schmidt et al. [13].

3. Modern $\delta^{18}O_{sw}$–SSS relationship in the western tropical/subtropical Atlantic

Modern $\delta^{18}O_{sw}$–SSS relationship in the tropical western Atlantic (31°W to 2°E and 21°N to 15°S; water depth 2–50 m) is obtained using best fit of least squares regression (Fig. 2) and data compilation [34,35] available at the database of the Goddard Institute for Space Studies (http://data.giss.nasa.gov/o18data). SSS obtained using core top data (Mg/Ca SST, $\delta^{18}O_{ivc-sw}$ and modern $\delta^{18}O_{sw}$–SSS relationship (Fig. 2)) and annual SSS [19] over the core site are in excellent agreement showing values of 36‰ and 35.95‰, respectively. However, application of the modern $\delta^{18}O_{sw}$–SSS relationship for estimate of paleo-salinity variation assumes temporal invariance of the linearity of the $\delta^{18}O_{sw}$–SSS relationship. This assumption is likely valid for salinity change due to precipitation–evaporation cycles only, whereas changes in the origin of surface water, significant change in fresh water input (riverine or glacial), and /or advection may change the $\delta^{18}O_{sw}$–SSS relationship in a manner somehow different than the assumption based on the modern correlation [36]. Significant change in fresh water input and change in source of surface sea water over our study area are assumed to be negligible for the following
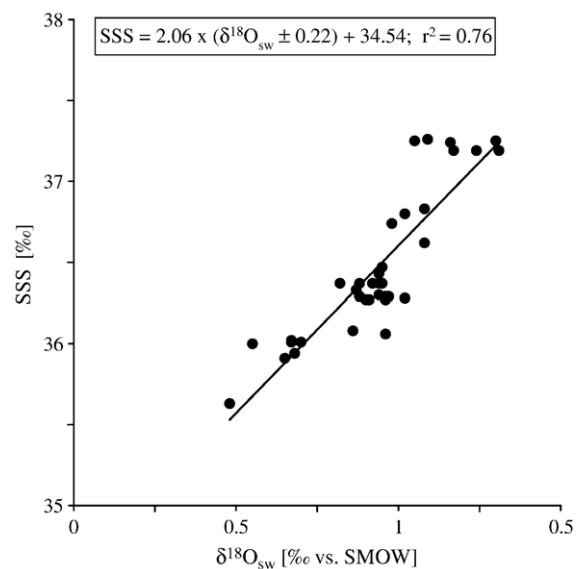

Fig. 2. Modern $\delta^{18}O_{sw}$–salinity relationship in the western tropical Atlantic. $\delta^{18}O_{sw}$ and salinity are from data compilation [34,35] available at the database of the Goddard Institute for Space Studies (http://data.giss.nasa.gov/o18data). Standard error estimate for SSS accounts for ± 0.45‰. However, standard error estimate of ± 1‰ is assessed for paleosalinity reconstruction due to error propagation related to uncertainties of local $\delta^{18}O_{sw}$ calculation (see also Materials and methods section).

reasons: 1) The small catchment area of river system (see above) and, thus, the small amount of fresh water input, is not likely to significantly affect the salinity at our core site 2) The North Brazil Current, which is the source of sea water over our core site, may have experienced phases of weakening or strengthening. However, a continuous northward flow of the North Brazil Current over the investigated time interval can be assumed in all likelihood. Thus, change in SSS could be mainly attributed to change in evapo-precipitation balance. Hence, along the local $\delta^{18}O_{sw}$ variation, the modern $\delta^{18}O_{sw}$–SSS relationship may be applied for rough estimation for implied SSS change.

4. Results and discussion

The Mg/Ca–SST estimation shows that the last part of the Last Glacial Maximum (23–19 cal kyr [37]) was 3 °C cooler than the average Holocene value of about 27.5 °C over the last 11 cal. kyr BP (Fig. 3). This is consistent with the growing line of evidence that in the tropical Atlantic, the Last Glacial Maximum SST was 2.5–3 °C cooler relative to the Holocene [11–13,15].

At 17.5 kyr BP, SST and $\delta^{18}O_{ivc-sw}$ reconstructions reveal a pronounced warming and SSS increase, with SST rising from glacial temperatures of around 24 to 26.2 °C and a $\delta^{18}O_{ivc-sw}$ increase of 0.5‰ within
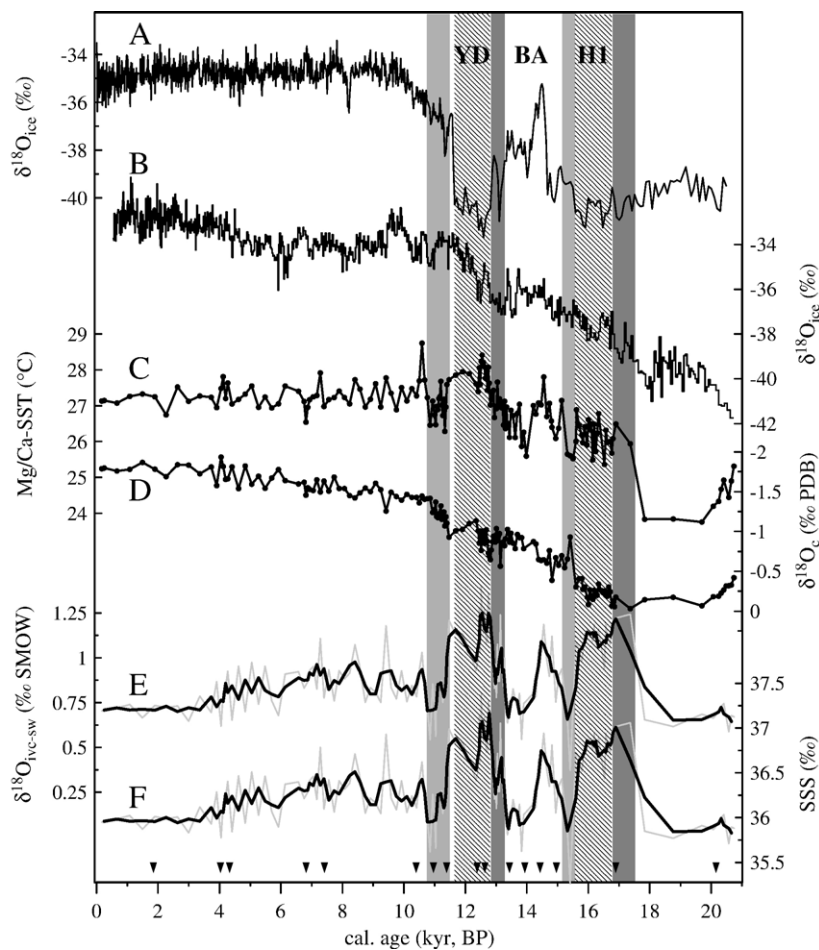

Fig. 3. Climate records of GeoB3129-3911 core over the last 21 kyr compared to the high latitude ice core records. A) and B) $\delta^{18}O_{ice}$ records of GISP2 (Greenland) [1] and Byrd station (Antarctica) [5], respectively. C) GeoB3129-3911: Mg/Ca–SST record of *G. ruber* w. (size fraction: 250–300 μm) converted using the calibration equation: Mg/Ca [mmol/mol]=0.38 * exp(0.09 * T [°C] [29], D) $\delta^{18}O_c$ of *G. ruber* w. in GeoB3129-3911 core. E) GeoB3129-3911: ice volume free isotope composition of the local sea water ($\delta^{18}O_{ivc-sw}$), bold line indicates three point running average. F) A rough estimated of the implied SSS change reconstructed using modern $\delta^{18}O_{sw}$-salinity relationship in the Western tropical/subtropical Atlantic. Bold line indicates three point running average. Age control points (AMS datings) of the age model are indicated by triangles. Hatched areas show intervals of YD and H1. YD, B–A, and H1 denotes Younger Dryas (12.9–11.6 cal. kyr), Bølling–Allerød (15.4–12.9 cal. kyr), and Heinrich events 1 (16.9–15.4 cal. kyr), respectively. Light and dark grey areas indicate cooling (after the YD and H1) and the onset of warming (before the YD and H1) in the western tropical Atlantic, respectively.

around 500 yr, indicating profound changes in oceanic conditions (Figs. 3 and 4). Within the uncertainties of the age model, this warming interval is synchronous with the air temperature increase over Antarctica [5] as well as with sea-ice retreat and SST increase in the southern Atlantic Ocean [6–8] (Fig. 4). Although the marked $\delta^{18}O_{ivc-sw}$ decrease and slight SST cooling at 15.5–15.2 kyr falls within error estimate of Mg/Ca SST, this transition indicates the termination of the first deglacial phase and intensified cross-equatorial heat and salt transport. This is concurrent with increased ice rafted detritus (IRD) in the southern Atlantic [7], indicating a northward advance of Antarctic sea ice (Fig. 4). However, the termination of salinity SST increase leads the reinvigoration of meridional overturning circulation by approximately 500 yr [4] (Fig. 4). Whether this discrepancy in the timing of the events is related to uncertainties in the age models or is related to different oceanic processes is difficult to assess.
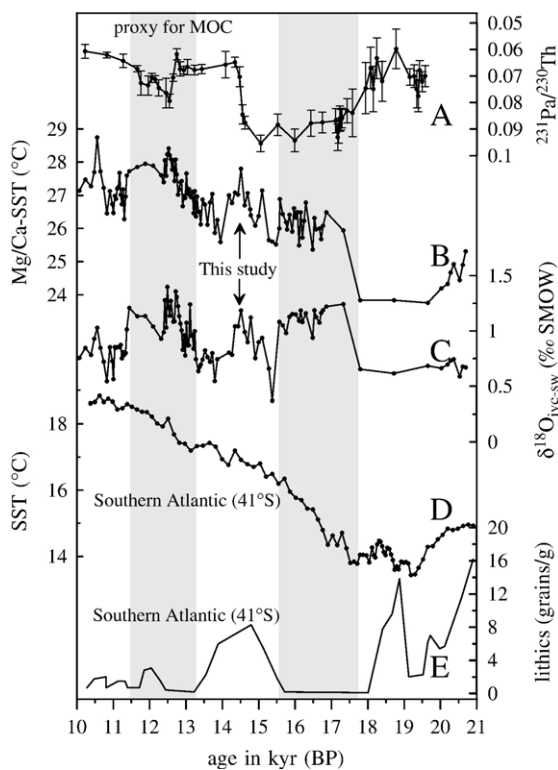

Fig. 4. Climate records from the western tropical Atlantic in comparison with records from southern high latitude and the activity of the MOC during the time interval 10–21 kyr (BP). A) Radiogenic isotope ratios indicating the activity of the MOC [39]. B) Mg/Ca SST and C) local $\delta^{18}O_{ivc-sw}$ (‰) of the GeoB3129-3911 core. D) $U^{K'}_{37}$ based SST reconstruction from the southern Atlantic (41°S) [6]. E) IRD record the southern Atlantic (41°S) indicating retreat and advance of Antarctic sea ice [7]. Gray bars indicate warm and saline intervals in the western tropical Atlantic.

In contrast to these warming phases which are synchronous with Antarctica ice records, North Brazil Current oceanic conditions during the Bølling–Allerød (B–A) and the time period from 20 to 17.5 kyr BP reveal similarities between the northern and southern high latitudes. For instance, between 15.2 and 14.1 kyr, warm saline surface waters in the western tropical Atlantic correspond with a warm phase in both northern and southern high latitudes (Figs. 3 and 4). This is followed by a brief cooling of less than 100-yr duration (~14.1–14.0 kyr BP) that is also documented in the Greenland ice core and, to lesser degree, in the Antarctic ice core (Fig. 3). During the Antarctic Cold Reversal (ACR: 12.4–14 kyr) [38], SST and SSS in the western tropical Atlantic were relatively low and gradually increased towards the end of the ACR. During the YD (12.8–11.5 kyr BP), SST within the North Brazil Current showed an increase of 1.7 °C (Fig. 3 C). Although the onset (~12.8 ky) of SST increase was concordant with the weakening of the MOC [39] (Fig. 4), $\delta^{18}O_{ivc-sw}$ increase, started at 13.3 kyr BP. The YD was terminated by an SST and $\delta^{18}O_{ivc-sw}$ decline of 1.5 °C and 0.7‰, respectively, and coincided (within the uncertainties of the age models) with the reinvigoration of the MOC [39] (Fig. 4). In general, the North Brazil Current SST pattern during the YD shows a similar trend to that of the Antarctic ice core (Fig. 3). However, warm conditions in Antarctica continued until 11 kyr, whereas cooling and SSS decrease in the North Brazil Current had already begun by 11.5 kyr. The Holocene period was characterised by a remarkably stable SST ranging between 27 and 27.7 °C. However, $\delta^{18}O_{ivc-sw}$ continuously decreased until 3 cal. kyr, reaching its present day value of 0.75 ‰ [34,35].

Our results clearly demonstrate that the sea surface warming trends in the North Brazil Current region were synchronous with air temperature over Antarctica as reflected by the Byrd ice core $\delta^{18}O$ record, as well as with South Atlantic SST during the H1 and YD periods (Figs. 3 and 4), indicating a close relationship between low and southern high latitude climate change. However, close comparison reveals that changes in sea surface temperatures in the southern Atlantic [6] and the $\delta^{18}O_{ice}$ of the Byrd ice core in Antarctica [5], particularly during H1, were characterized by a gradual temperature increase, while SST and SSS increases in the North Brazil Current were more abrupt and the termination of salinity build up phases more pronounced. The western tropical Atlantic deglacial warming and salinity increase occurred parallel to the weakening of the MOC [39] (Fig. 4). The termination

of H1 represents an exception to this more or less anti-phased relationship between the MOC and the SSS/SST in the western tropical Atlantic (Fig. 4). At the termination of H1, the western tropical Atlantic showed a salinity decrease and slight SST cooling, supporting model-predicted heat and salinity release [40]. At the same time, the $^{231}Pa/^{230}Th$ ratios [4] remained high, indicating weakened MOC. In addition, the salinity increase started approximately 500 yr prior to the onset of the YD and slowdown of the MOC [4]. This may suggest that the onset and termination of the salt build up in the western tropical Atlantic may be favoured by sea surface conditions of the southern Atlantic (Fig. 4E), as sea ice retreat and advance in the southern Atlantic is coincident with salinity increase and decrease, respectively. A possible mechanism that may explain the salt build up in the western tropical Atlantic before the onset of YD is that a warm southern Atlantic sea surface during and before the onset of YD and H1 (Fig. 3) [6,7] induced a weakening of the temperature gradient between the western tropical Atlantic and the southern Atlantic, likely resulting in less a vigorous (due to the reduced intensity of the southeastern trade winds), but saline and warm North Brazil Current accumulating in the western tropical Atlantic. This may be seen as an additional mechanism for salt accumulation in the western tropical Atlantic due the slow down of the MOC [39] during the YD and H1. During the same time period, a southward shift of the intertropical convergence zone (ITCZ) along with an intensification of the NE trade winds, was suggested based on paleoclimate reconstructions implying reduced runoff in the Cariaco [15,41] and Amazonian basins [42], and wet conditions in northeastern Brazil (south of ~4°S) [43–45]. We suggest that the saline and warm North Brazil Current (supplied by the saline and warm South Equatorial Current), slow down of the MOC, and displacement of the ITCZ coupled with strengthened NE trade winds during the YD and H1, resulted in accumulation and stagnation of warm and saline water mass in the entire western tropical Atlantic.

The warm conditions terminated with abrupt SST and SSS declines that lasted approximately ~500 (YD) and ~300 (H1) yr. The onset of salinity decrease and slight cooling at the termination of YD, within the range of our age model error, is coincident with warming in the northern high latitudes [1] and reactivation of the MOC in its interglacial mode [4]. This opposite behaviour of the tropical Atlantic and northern high latitudes is consistent with the release of heat and salinity accumulated in the western tropical Atlantic during the YD and H1 and confirms modelling studies

that predict this anti-phased pattern in the tropical Atlantic [10,40,46]. Contemporaneous with the cooling and salinity decrease of the western tropical Atlantic, an increase of IRD content in the southern South Atlantic (Fig. 4) indicates a northward advance of sea ice [7]. We argue that the oceanic (warming in the northern and cooling in the southern high latitudes) and atmospheric (northward displacement of the ITCZ and strengthening of SE trade winds) changes in the northern and southern high latitudes at the end of the YD and H1 induced an intensification of cross-equatorial heat and salinity transport associated with the North Brazil Current.

Compared with available SST records from the tropical/subtropical western Atlantic, our findings reveal an opposite trend to the SST record from the Cariaco Basin [15] that show a pronounced SST drop in synchrony with the YD and, to lesser degree, H1 of the northern high latitudes. SST reconstructions from the Tobago Basin [11,12], and Caribbean Sea [13], and Gulf of Mexico [14], however, provide evidence that are in accordance with our SST record for the time intervals coeval to the YD and H1. There is, however, significant deviation in timing and magnitude of SST change in the records that show SST warming during the YD and H1. For instance, SST records from the Tobago Basin [11],
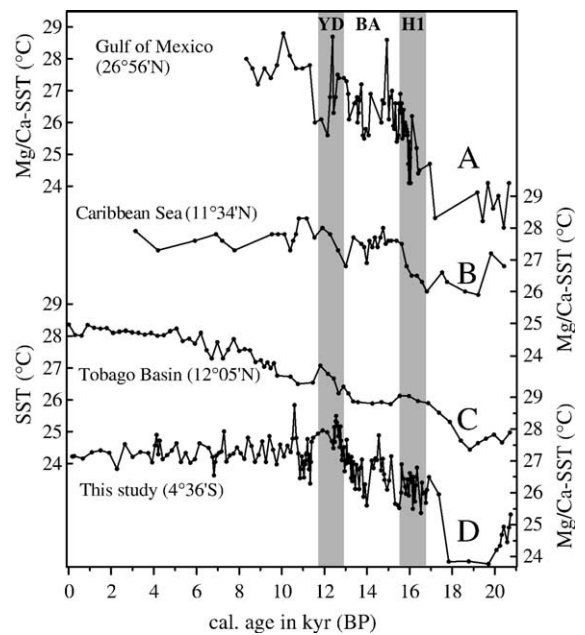

Fig. 5. A comparison of SST records from western tropical/subtropical Atlantic that show warming during the YD and H1. A) Mg/Ca SST reconstruction from the Gulf of Mexico (26°56′N/91°20′W) [14], B) Mg/Ca SST reconstruction from the Caribbean Sea (11°34′N/78°25′W) [13], C) alkenone unsaturation index based SST reconstruction from the Tobago Basin (12°25′N/61°15′W) [11], D) Mg/Ca SST record of this study (4°36′S/36°38′W).

the Gulf of Mexico [14], and this study show warming up to 2.5 °C that start before the onset of H1 in the northern high latitude (Fig. 5). A Mg/Ca record from the Caribbean Sea [13], however, documents an SST increase of 1.5 °C during the second half of H1. While the slight deviation in the timing of SST change could be attributed to uncertainty in the age models, the heterogeneous pattern of the available SST records during the YD and H1 within the tropical/subtropical western Atlantic may be mainly related to the route of water masses, the wind system to which the basin was exposed, and basin geometry and/or its exchange with the open ocean.

5. Conclusion

This study has shown that temperature and/or salinity increases in the western tropical Atlantic started approximately 500 yr before the onset of the YD and H1 in the northern high latitudes, and occurred in synchrony with warming in the southern high latitudes of the Atlantic sector, implying that the western tropical Atlantic sea surface conditions were amplified by southern Atlantic warming and associated heat and salt supply via the SEC. Collapse or slow down of the MOC in the northern Atlantic [4] and southward displacement of the ITCZ [15,44] during the YD and H1 may have led to stagnation and accumulation of heat and salt in the western tropical Atlantic [11,13,40]. Thus, during the YD and H1 sea surface conditions in the western tropical Atlantic were governed by interhemispheric processes. At end of the YD and H1, heat and salt release from the western tropical Atlantic to the northern high latitudes may have accelerated and amplified warming and pushed the thermohaline circulation into its interglacial mode.

This study documents the thermal history of the North Brazil Current, which appears to have played a crucial role in cross-equatorial heat and salt transport during the last 21 kyr. As such, it stresses the importance of the tropics and the western tropical Atlantic for their role in interhemispheric transmittance of climate signals and forcing mechanisms.

References

[1] P.M. Grootes, M. Stuiver, J.W.C. White, S. Johnsen, J. Jouzel, Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores, Nature 366 (1993) 552–554.

[2] G. Bond, W. Broecker, S. Johnsen, J. McManus, L. Labeyrie, J. Jouzel, G. Bonani, Correlations between climate records from North Atlantic sediments and Greenland ice, Nature 365 (1993) 143–147.

[3] G.C. Bond, R. Lotti, Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation, Science 267 (1995) 1004–1010.

[4] J.F. McManus, R. Francois, J.-M. Gherardi, L.D. Keigwin, S. Brown-Leger, Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes, Nature 428 (2004) 834–837.

[5] T. Blunier, E.J. Brook, Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period, Science 291 (2001) 109–112.

[6] J.P. Sachs, R.F. Anderson, S.J. Lehman, Glacial surface temperature of the Southeast Atlantic Ocean, Science 293 (2001) 2077–2079.

[7] S.L. Kanfoush, D.A. Hodell, C.D. Charles, T.P. Guilderson, P.G. Mortyn, U.S. Ninnemann, Millennial-scale instability of the Antarctic ice sheet during the last Glaciation, Science 288 (2000) 1815–1818.

[8] A. Shemesh, D.A. Hodell, X. Crosta, C.D. Charles, T. Guilderson, Sequence of the events during the last deglaciation in Southern Ocean sediments and Antarctic ice cores, Paleoceangraphy 17 (2002), doi:10.1029/2000PA000599.

[9] T. Sowers, M. Bender, Climate records covering the last deglaciation, Science 269 (1995) 210–214.

[10] T.F. Stocker, Climate change: the seesaw effect, Science 282 (1998) 61–62.

[11] C. Rühlemann, S. Mulitza, P.J. Müller, G. Wefer, R. Zahn, Warming of the tropical Atlantic Ocean and slowdown of thermohaline circulation during the last deglaciation, Nature 402 (1999) 511–514.

[12] M. Hüls, R. Zahn, Millennial-scale sea surface temperature variability in the western tropical North Atlantic from planktonic foraminiferal, Paleoceangraphy 15 (2000) 659–678.

[13] M.W. Schmidt, H.J. Spero, D.W. Lea, Links between salinity variation in the Caribbean and North Atlantic thermohaline circulation, Nature 428 (2004) 160–163.

[14] B.P. Flowers, D.W. Hasting, H.W. Hill, T.M. Quinn, Phasing of deglacial warming and Laurentide ice sheet meltwater in the Gulf of Mexico, Geology 32 (2004) 597–600.

[15] D.W. Lea, D.K. Pak, L.C. Peterson, K.A. Hughen, Synchrony of tropical and high-latitude Atlantic temperatures over the Last Glacial termination, Science 301 (2003) 1361–1364.

[16] I. Da Silveira, L.B. Miranda, W. Brown, On the origins of the North Brazil Current, J. Geophys. Res. 99 (1995) 22501–22512.

[17] L. Stramma, J. Fischer, J. Reppin, The North Brazil undercurrent, Deep-Sea Res. I 42 (1995) 773–795.

[18] F. Schott, L. Stramma, J. Fischer, The warm water inflow into western tropical Atlantic boundary regime, spring 1994, J. Geophys. Res. 100 (1995) 24745–24760.

[19] S. Levitus, T.P. Boyer, World Ocean Atlas 1994, vol. 4, Temperature, Washington, 1994.

[20] GRDC, Global Runoff Data Center, Germany: http://grdc.bafg.de.

[21] W.E. Johns, T. Lee, N.R.C. Beardsley, J. Candela, R. Limeburner, B. Castro, Annual cycle and variability of North Brazil Current, J. Phys. Oceanogr. 28 (1998) 103–128.

[22] H.W. Arz, J. Pätzold, G. Wefer, Correlated millennial-scale changes in surface hydrography and terrigenous sediment yield inferred from Last-Glacial marine deposits off northeastern Brazil, Quat. Res. 50 (1998) 157–166.

[23] H.W. Arz, J. Pätzold, G. Wefer, The deglacial history of the western tropical Atlantic as inferred from high resolution stable isotope records off northwestern Brazil, Earth Planet. Sci. Lett. 167 (1999) 105–117.

[24] H.W. Arz, J. Pätzold, G. Wefer, Climatic changes during the last deglaciation recorded in sediment cores from the northeastern Brazilian Continental Margin, Geo Mar. Lett. 19 (1999) 209–218.

[25] M. Stuiver, P.J. Reimer, Extended ^{14}C data-base and revised calib 3.0 C-14 age calibration program, Radiocarbon 35 (1993) 215–230.

[26] K.A. Hughen, M.G.L. Baillie, E. Bard, A. Bayliss, J.W. Beck, C. Bertrand, P.G. Blackwell, C.E. Buck, G. Burr, K.B. Cutler, P.E. Damon, R.L. Edwards, R.G. Fairbanks, M. Friedrich, T.P. Guilderson, B. Kromer, F.G. McCormac, S. Manning, C. Bronk Ramsey, P.J. Reimer, R.W. Reimer, S. Remmele, J.R. Southon, M. Stuiver, S. Talamo, F.W. Taylor, J. an der Plicht, C.E. Weyhenmeyer, Marine04 marine radiocarbon age calibration, 0–26 Cal Kyr BP, Radiocarbon 46 (2004) 1059–1086.

[27] S. Barker, M. Greaves, H. Elderfield, A study of cleaning procedures used for Mg/Ca paleothermometry, Geochem. Geophys. Geosyst. 4 (2003), doi:10.1029/2003GC000559.

[28] P.A. Martin, D.W. Lea, A simple evaluation of cleaning procedures on fossil benthic foraminiferal Mg/Ca, Geochem. Geophys. Geosyst. 3 (2002), doi:10.1029/2001GC000280.

[29] P. Anand, H. Elderfield, M.H. Conte, Calibration of Mg/Ca thermometry in planktonic foraminifera from a sediment trap time series, Paleoceanography 18 (2003), doi:10.1029/2002PA000846.

[30] N.J. Shackleton, Attainment of isotopic equilibrium between ocean water and the benthonic foraminiferal genus Uvigerina: isotopic changes in the ocean during the last glacial, Cent. Natl. Rech. Sci. Colloq. Int. 219 (1974) 203–209.

[31] C. Waelbroeck, Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records, Quat. Sci. Res. 21 (2002) 295–305.

[32] D.P. Schrag, G. Hampt, D.W. Murray, Pore water constraints on the temperature and oxygen isotopic composition of the glacial ocean, Science 272 (1996) 1930–1932.

[33] S.-T. Kim, J. O'Neil, Equilibrium and non-equilibrium oxygen isotope effects in synthetic carbonate, Geochim. Cosmochim. Acta 61 (1997) 3461–3475.

[34] G.R. Bigg, J. Rohling, An oxygen isotope data set for marine water, J. Geophys. Res. 105 (2000) 8527–8535.

[35] G.A. Schmidt, Forward modeling of carbonate proxy data from planktonic foraminifera using oxygen isotope tracers in a global ocean model, Paleoceanography 14 (1999) 482–497.

[36] E.J. Rohling, G.R. Bigg, Paleosalinity and δ^{18}O: a critical assessment, J. Geophys. Res. 103 (C1) (1998) 1307–1318.

[37] A.C. Mix, E. Bard, R. Schneider, Environmental processes of the ice age: land, oceans, glaciers (EPILOG), Quat. Sci. Rev. 20 (2001) 627–657.

[38] T. Blunier, J. Schwander, B. Stauffer, T. Stocker, A. Dällenbach, A. Indermühle, J. Chappellaz, D. Raynaud, J.-M. Barnola, Timing of the Antarctic cold reversal and the atmospheric CO_2 increase with respect to the Younger Dryas event, Geophys. Res. Lett. 24 (1997) 2683–2686.

[39] J.F. McManus, R. Francois, J.-M. Gherardi, L.D. Keigwin, S. Brown-Leger, Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes, 428 (2004) 834-837.

[40] D. Pailard, L. Labeyrie, Role of the thermohaline circulation in the abrupt warming after Heinrich events, Nature 372 (1994) 162–164.

[41] L.C. Peterson, G.H. Haug, K.A. Hughen, U. Rohl, Rapid changes in the hydrologic cycle of the tropical Atlantic during the last glacial, Science 290 (2000) 1947–1951.

[42] M.A. Maslin, S.J. Burns, Reconstruction of the Amazon Basin effective moisture availability over the past 14,000 years, Science 290 (2000) 2285–2287.

[43] H. Behling, H.W. Arz, J. Pätzold, G. Wefer, Late Quaternary vegetational and climate dynamics in northeastern Brazil: inferences from marine core GeoB 3104-1, Quat. Sci. Rev. 19 (2000) 981–994.

[44] T. Jennerjahn, V. Ittekkot, H. Arz, H. Behling, J. Pätzold, G. Wefer, Asynchrony of preserved terrestrial and marine signals of climate change in the tropics during the Heinrich events, Science 306 (2004) 2236–2239.

[45] X. Wang, A.S. Auler, R.L. Edwards, H. Cheng, P.S. Cristalli, P.L. Smart, D.A. Richards, C.-C. Shen, Wet periods in northern Brazil over the past 210 kyr linked to distant climate anomalies, Nature 432 (2004) 740–743.

[46] R. Knutti, J. Fluckiger, T.F. Stocker, A. Timmermann, Strong hemispheric coupling of glacial climate through freshwater discharge and ocean circulation, Nature 430 (2004) 851–856.