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Deglacial radiocarbon history of tropical Atlantic thermocline waters: absence of CO₂ reservoir purging signal

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ABSTRACT

A current scenario to explain much of the atmospheric CO₂ increase during the Glacial to Holocene climate transition requires the outgassing of a deep, old oceanic CO₂ reservoir thought to be located in the Southern Ocean. In this scenario, CO₂-rich and ¹⁴C-depleted subsurface Antarctic-sourced water, ventilates the thermocline where it is purged to the atmosphere in the equatorial regions, a view that has been met with conflicting results. Using a novel approach (paired surface and deep-dwelling planktonic foraminifer radiocarbon analyses), we document that the equatorial Atlantic thermocline did not see old, ¹⁴C-depleted water, which would be characteristic of the proposed isolated deep ocean CO₂ reservoir. Data from several studies concur that, during the deglaciation, Antarctic intermediate waters were contributing to Atlantic thermocline waters even more than today, therefore, our observations challenge the current purging hypothesis. Together with other studies, these results suggest that the mechanism responsible for the deglacial CO₂ rise cannot invoke contemporary circulation modes and/or thermocline ventilation pathways.

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1. Introduction

Atmospheric CO₂ concentrations recorded in ice cores show a two-step increase from Glacial to Holocene levels near 17 and 12 ka BP, respectively (Monnin et al., 2001). At these same times, radiocarbon (Δ¹⁴C) measured in corals and planktonic foraminifera show a large decreases unsupported by ¹⁴C production changes alone (Hughen et al., 2006). These two steps in atmospheric CO₂ and radiocarbon anomalies are associated with the Heinrich stadial 1 (ca 18–15 ka BP) and the Younger Dryas (ca 13–11 ka BP) cooling events. The idea that the ocean influences CO₂ atmospheric level goes back to Broecker (1982) and Siegenthaler and Wenk (1984) and is currently favored over other hypotheses, such as the influence of productivity and nutrient utilization changes (Sarmiento and Toggweiler, 1984). Broecker and Barker (2007) used foraminiferal radiocarbon ages to propose that CO₂ was stored in a deep oceanic reservoir during the glacial period, isolated from the atmosphere for several thousand years. The study of Adkins et al. (2002) postulate that this old, CO₂-rich reservoir may have been near the Southern Ocean where pore water results indicate strongly

stratified, very salty bottom waters during the last glacial, a view supported by benthic-planktonic foraminiferal radiocarbon evidence (Sikes et al., 2000; Skinner et al., 2010) and modeling studies (Tschumi et al., 2010). The conventional purging hypothesis suggests that during the deglaciation, vigorous upwelling around Antarctica (Anderson et al., 2009) opened up the reservoir, allowing the CO₂ and the ¹⁴C-depleted water to spread in the ocean and the atmosphere.

This hypothesis remained unverified until two pulses of very low Δ¹⁴C water were identified at intermediate depth off Baja (California) (Marchitto et al., 2007) and in the eastern equatorial Pacific (EEP) (Stott et al., 2009), coincident with the atmospheric CO₂ increases near the Heinrich stadial 1 and the Younger Dryas cooling events. The modern EEP is ventilated by southern-source intermediate waters (Antarctic Intermediate Water AAIW or SubAntarctic Mode Water SAMW) which is believed to have extended much farther northward during the deglaciation relative to the present in both the Atlantic and the Pacific basins (Anderson et al., 2009; Brattmiller et al., 2007; Pahnke et al., 2008) and up to Baja, California (Marchitto et al., 2007). Current views on the purging mechanism invoke the ventilation of the deep oceanic CO₂ reservoir by Antarctic intermediate water masses via the thermocline ventilation waters and outgassing in the low latitude upwelling regions, but inconsistencies remain. This scenario is

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challenged by the lack of any deglacial ^{14}C anomaly in deep water $\Delta^{14}\text{C}$ series in the regions off Chile (De Pol-Holz et al., 2010) and New Zealand (Rose et al., 2010) where AAIW/SAMW is subducted. Also, the 3000 years lag between the occurrence of ^{14}C -depleted water in the Southern Ocean (Skinner et al., 2010) and in the equatorial Pacific (Marchitto et al., 2007; Stott et al., 2009) is difficult to explain. The aim of this paper is to test the hypothesis that an old (low $\Delta^{14}\text{C}$), southern-source intermediate water mass ventilated the tropical thermocline during the deglaciation near 17 ka and 12 ka, when CO_2 levels increased. AAIW/SAMW presently ventilates all three oceans, so if these southern-sourced water masses drained the radiocarbon-depleted CO_2 reservoir during the deglaciation, then the age difference between surface and thermocline waters in the equatorial Atlantic should increase during the evacuation period of this reservoir.

2. Material and method

2.1. Oceanographic context

Piston core RC24-08 is located in the Atlantic equatorial upwelling region ($1^\circ 20'\text{S}$, $11^\circ 54'\text{W}$, 3885 m). In the Atlantic Ocean, AAIW/SAMW circulates in the interior south Atlantic, joins the Western Boundary current along the Brazilian margin, shoals eastward along the equator as the Equatorial Under Current (EUC) and then upwells to the surface in the eastern equatorial Atlantic. Modeling experiments confirm observations that about 5 Sv ($\text{Sv} \equiv 10^6 \text{ m}^3 \text{ s}^{-1}$) of the 19 Sv of southern-sourced water exported northward into the three oceans, reaches the equatorial Atlantic (Sen Gupta and England, 2007). High dissolved silica contents, inherited in the AAIW/SAMW formation regions, trace the northward expansion of these water masses (Fig. 1). At the core location, AAIW/SAMW is found around 600 m depth under modern condition. The bomb-corrected $\Delta^{14}\text{C}$ profile from the closest GLODAP station (Key et al., 2004) shows a steep gradient compared to mid-latitude profiles as ^{14}C -depleted water of southern origin is upwelled in the equatorial region (Fig. 2).

2.2. Age model

The age model for core RC24-08 was based on linear interpolation between twelve ^{14}C dates on *Globigerinoides ruber* calibrated to calendar age B.P. using the CALIB 6.0 program (Reimer et al., 2009). At the core site, pre-anthropogenic (pre-1850) ocean reservoir age is estimated at 335 years (Butzin et al., 2005) (<http://radiocarbon.LDEO.columbia.edu>). Many studies looking at changes in productivity of foraminifera (Mix, 1989) or diatom (Bradt  miller et al., 2007), sea surface temperature (Farmer et al., 2005), nutricline/thermocline depth (Molfin   and McIntyre, 1990) or upwelling diatoms counts (Abrantes, 2000) in the tropical Atlantic suggest intensified equatorial upwelling and trade winds during glacial and deglacial periods. The enhancement of deep-water upwelling might have resulted in larger reservoir ages. We used 600 years as a maximum estimate for the reservoir age (Butzin et al., 2005) and built a model age taking into account these two reservoir age estimates (Fig. 3, Table 1). Sedimentation rate of core RC24-08 is not constant; it is high over the deglaciation (about 12 cm/1000 years) but lower over the Holocene (4 cm/1000 years) and the glacial (7 cm/1000 years). A possible explanation is the enhanced upwelling and productivity over the deglaciation. Such sedimentation rate and the high CaCO_3 content all along the core (Fig. 6), reduce bioturbation and dissolution impacts on ^{14}C dates (Barker et al., 2007).

2.3. Stable isotope and trace element analysis

We measured the oxygen and carbon stable isotopic composition ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) and trace element ratio (Mg/Ca) of three foraminifer species living at different water depth: *G. ruber*, *Neoglobobulimina dutertrei* and *Globobulimina crassaformis*. *G. ruber* was selected in the 250–355 μm size fraction, *G. crassaformis* and *N. dutertrei* were selected in the 355–425 μm size fraction. Stable isotope compositions were measured with Optima VG instruments at The State University of New York at Albany or at LDEO. Both labs use NBS19 as the reference standard with a long term external reproducibility of 0.05‰ on $\delta^{18}\text{O}$. Trace element ratios were

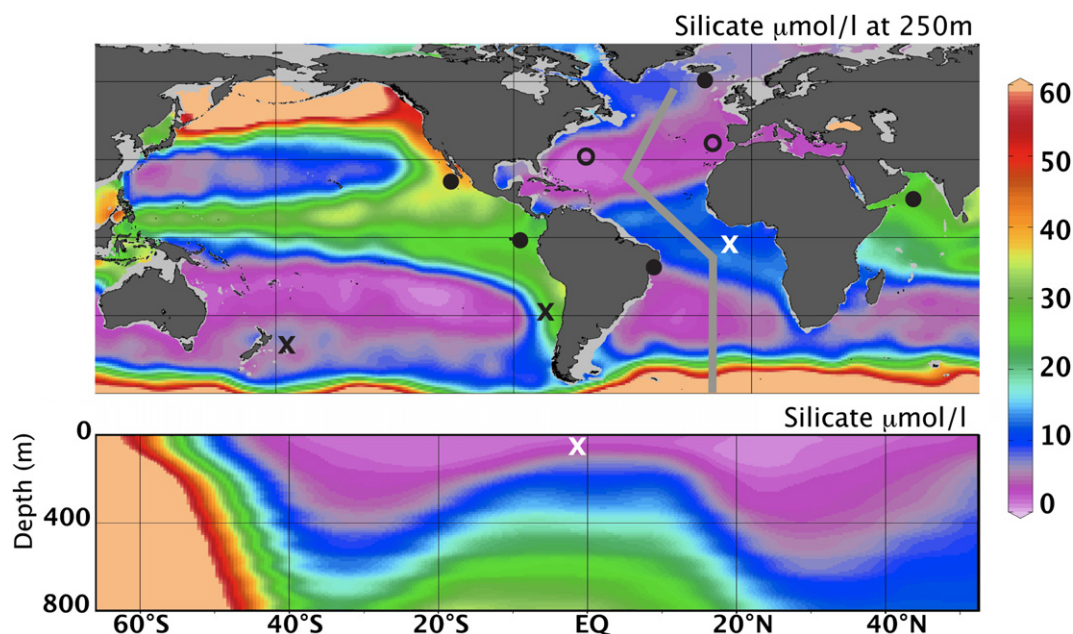


Fig. 1. Silicate content at 250 m depth (top) and along a meridional Atlantic profile (bottom). White cross shows RC24-08 location. Location of studies with evidence for ^{14}C -depleted water during deglaciation are drawn with dots (filled dots for shallow sites, and empty dots for deep sites), black crosses show location of sites with no deglacial ^{14}C -depleted water. See Table 3 for references. The silicate production zone, around Antarctica is shown in clay color, the silicate is then exported with AAIW/SAMW and upwelled in the equatorial region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

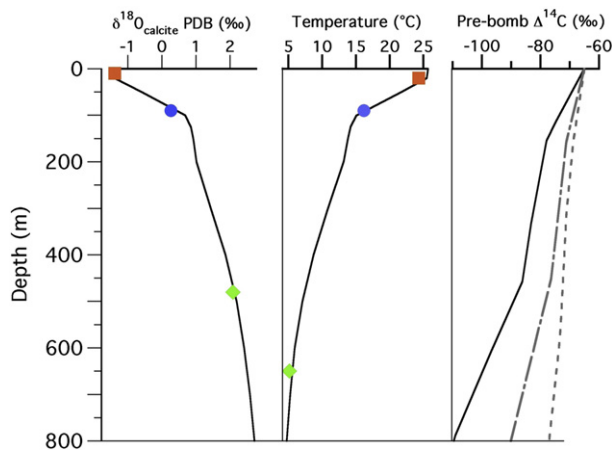


Fig. 2. Modern oceanographic data at the core site and comparison with coretop foraminifera geochemical data (*G. ruber* in orange, *N. dutertrei* in blue and *G. crassaformis* in green). From left to right: $\delta^{18}\text{O}$ calcite in equilibrium with $\delta^{18}\text{O}$ water composition extracted from the GISS Database (Schmidt et al., 1999); temperature of seawater extracted from World Ocean Atlas (Conkright et al., 2002) and calculated calcification temperature from Mg/Ca ratio; Pre-bomb $\Delta^{14}\text{C}$ ‰ extracted from the closest GLODAP station (Key et al., 2004) to RC24-08 core site (black line), in the mid-latitude North Atlantic (short dotted line) and in the mid-latitude South Atlantic (long dotted line). Error on GLODAP $\Delta^{14}\text{C}$ value is estimated at $\pm 15\%$ (Rubin and Key, 2002). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

measured with an Ultima-C Jobin Yvon ICP-OES at LDEO using the full reductive and oxidative cleaning protocol (Boyle and Keigwin, 1987). Long-term measurement of international standard routinely measured is within 1% of the reported value with standard deviation of ± 0.04 mmol/mol (Greaves et al., 2008).

We performed $\delta^{18}\text{O}$ and Mg/Ca ratio measurements for these species from the coretop to confirm the habitat depth of these foraminifera. We measured $\delta^{18}\text{O}$, $\delta^{13}\text{C}$ and Mg/Ca ratio on *G. ruber* and *G. crassaformis* downcore RC24-08 to monitor surface and thermocline conditions and check for calcification depth change.

2.4. Coretop results and species calcification depth

Coretop data agree well with the expected values at the known habitat depth of these species (Fig. 2). Coretop Mg/Ca data for

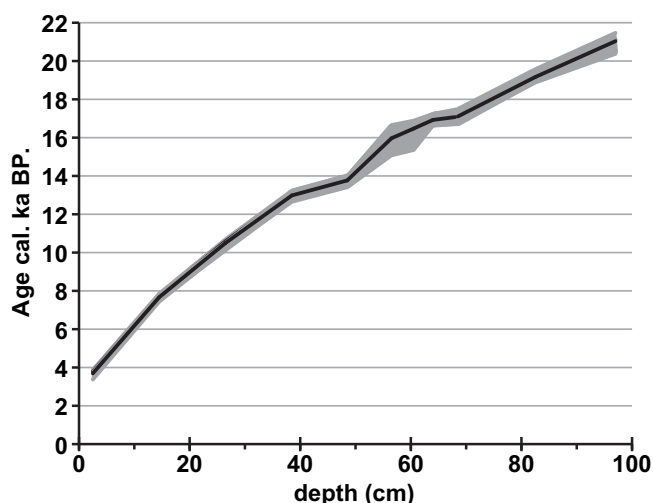


Fig. 3. Age model for core RC24-08. Black line represents the calibrated ages using a reservoir age of 355 years, grey envelope is the maximum deviation from this model age taking into account ^{14}C measurement errors, calibration into calendar age error (2σ) and a reservoir age of 600 years.

G. ruber, *G. crassaformis* and *N. dutertrei* are from RC24-07 (13°S , 11.9°W , 3899 m) located very close to RC24-08 ($1^{\circ}20\text{S}$, $11^{\circ}54\text{W}$, 3885 m). *G. ruber* Mg/Ca ratios were converted to temperature using a new Atlantic basin calibration equation: $\text{SST} = 16.06 + 4.62 \times \ln(\text{Mg/Ca}) - (3.42 \times \delta^{18}\text{O}_{G. ruber}) - 0.1 \times \Delta\text{CO}_3^{2-}$ (Arbuszewski et al., 2010). Where $\delta^{18}\text{O}_{G. ruber}$ is corrected for the ice volume storage change and ΔCO_3^{2-} is the bottom water carbonate saturation, the modern value ($13 \mu\text{mol/kg}$) was used for the calculation. Coretop temperature values of *G. crassaformis* and *N. dutertrei* were calculated by using the equation $\text{Mg/Ca} = 1/0.78 \exp(0.052 \times \text{temperature})$ (Cléroux et al., 2008) and applying a 10% correction on Mg/Ca ratio to take into account the different cleaning protocol (Barker et al., 2003). *G. ruber* represents surface ocean conditions, confirming its known calcification depth within the surface mixed layer (0–40 m). *N. dutertrei* calcifies at the base of the upper thermocline, around 100 m depth (Steph et al., 2009; Farmer et al., 2007). *G. crassaformis* is a deep-dwelling foraminifera species, whose bulk shell $\delta^{18}\text{O}$ values indicate calcification around 500–600 m depth (Steph et al., 2009). A series of $\delta^{18}\text{O}$ measurements on a transect of coretop samples between 35°N and 25°S , covering very different oceanographic regions in the Atlantic, shows that *G. crassaformis* consistently calcifies over this depth range (Cléroux et al., 2009).

2.5. $\Delta^{14}\text{C}$ calculation

We calculated deglacial $\Delta^{14}\text{C}$ variations in the upper thermocline and deep-thermocline water using paired radiocarbon analyses on *G. ruber*/*N. dutertrei* and paired radiocarbon analyses on *G. ruber*/*G. crassaformis*, respectively (Fig. 4, Table 2). We selected *G. ruber* specimens larger than $250 \mu\text{m}$, *G. crassaformis* and *N. dutertrei* specimens larger than $355 \mu\text{m}$ to avoid any juveniles that might calcify at shallower depth. Prior to graphitization about 5 mg of foraminifera were gently crushed and cleaned by ultrasonication with methanol and dilute acid leach (0.001 N HCl). Samples were graphitized and analyzed at Lawrence Livermore National Laboratory. Age-corrected $\Delta^{14}\text{C}$ were calculated using the following equation (Adkins and Boyle, 1997):

$$\Delta^{14}\text{C} = \left[\left(\frac{e^{-^{14}\text{C}_{\text{age}}/8033}}{e^{-\text{cal. age}/8266}} \right) - 1 \right] \times 1000$$

where cal. age is the calendar age derived from *G. ruber* ^{14}C age and calibrated using IntCal 2009 with a reservoir age of 335 years (Reimer et al., 2009).

$\Delta^{14}\text{C}$ calculation is dependant on the age model. To evaluate the impact of the age model on our $\Delta^{14}\text{C}$ results, we performed the calculation for the two extreme age models constrained by error on ^{14}C ages, error on calendar ages and a reservoir age of 600 years (see supplementary material). The uncertainty associated with the choice of the model age increases with time. The uncertainty on $\Delta^{14}\text{C}$ is about 100‰ over the deglaciation (Fig. 5). Increasing the reservoir age (to 600 years) for the calculation decreases the thermocline $\Delta^{14}\text{C}$ but not to the extent expected from the pacific records (Fig. 4). On the contrary, the $\Delta^{14}\text{C}$ gradient between species is independent of the age model.

3. Results

3.1. Downcore records

SSTs reconstructed from Mg/Ca ratio on *G. ruber* show a warming of about 2°C between the early deglaciation and the Holocene (Fig. 6). Accordingly, the $\delta^{18}\text{O}$ composition, corrected for ice volume change (Waelbroeck et al., 2002), decreases of about

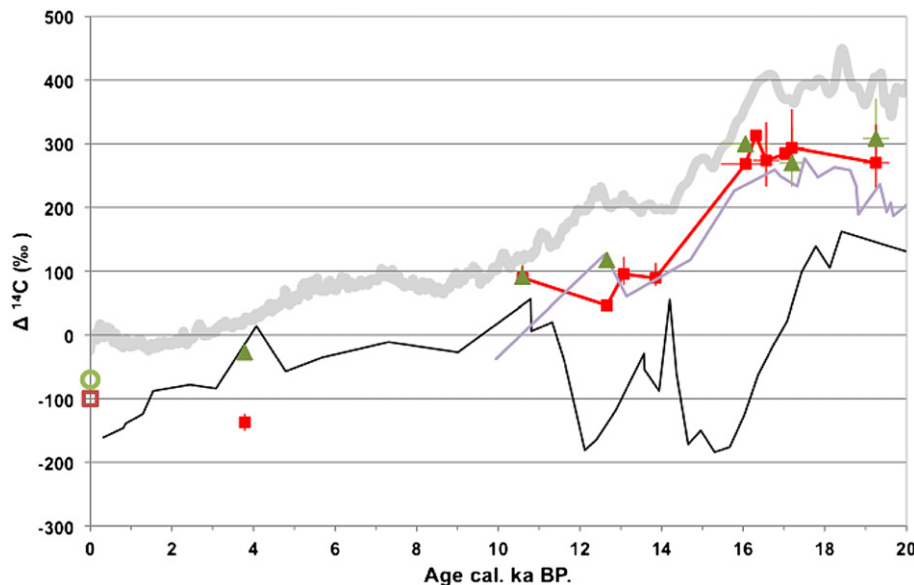


Fig. 4. Atmospheric and oceanic radiocarbon activity over the last 20 ka. Atlantic equatorial $\Delta^{14}\text{C}$ of the upper thermocline (green) and the deep-thermocline (red) follows the atmospheric signal (light thick grey) with an offset similar to the modern offsets, represented by the green circle and the red square for 100 m and 600 m depth respectively. To be on the same time scale than atmospheric and Atlantic reconstruction, $\Delta^{14}\text{C}$ signal off Chile (light purple blue) (De Pol-Holz et al., 2010) have been recalculated using the IntCal09. These two AAIW/SAMW records contrast with $\Delta^{14}\text{C}$ reconstruction off Baja, California (Marchitto et al., 2007) (black). Around 16 ka, large error bars associated with deep-thermocline $\Delta^{14}\text{C}$ reconstruction results from large uncertainties on the ^{14}C age – calendar age calibration curve (Reimer et al., 2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

0.5‰ over the same period, indicating no change in surface salinity (Duplessy et al., 1991). The $\delta^{13}\text{C}$ recorded by *G. ruber* increases from the early deglaciation (about 0.6‰) to the Holocene (about 1.6‰) as previously observed in many records (Spero and Lea, 2002). This increase is rather smooth as recorded in the Western Atlantic (Curry and Crowley, 1987), although the event at 13.8 ka might be similar to the event recorded in the Benguela region (Schneider et al., 1992). The worldwide occurrence of the $\delta^{13}\text{C}$ minimum is interpreted as the re-establishment of deep mixing

south of the Arctic polar front as Antarctica began to warm and low $\delta^{13}\text{C}$ water spread in AAIW/SAMW source region. This is in agreement with the opal records for the core RC24-08, high opal content in the equatorial region has been interpreted either as enhanced equatorial upwelling or Si leaking from the southern ocean during the deglaciation (Bradtmeier et al., 2007). After removing the ice volume component, the $\delta^{18}\text{O}$ composition of *G. crassaformis* shows no variation over the last 18 ka and its $\delta^{13}\text{C}$ increases by about 0.5‰ which is almost the mean ocean change between glacial and late Holocene periods (Duplessy et al., 1988). We also looked at foraminifera assemblage changes in a nearby core RC28-07 (1.34°S, 11.9°W, 3899 m) (Mix, 1986). All surface-dwelling species and deep-dwelling species reach their modern-like abundances near 17 ka (supplementary material). From geochemical measurements on RC24-08 and abundance counts of foraminifera species with different ecology, habitat depth and seasonality in the core RC24-07, we conclude that, at the core site, the water column remained very stable and similar to the present-day over the last 17 ka. Since the water column structure and the $\delta^{18}\text{O}$ of *G. crassaformis* did not change since the deglacial period, we are confident that this species kept its calcification depth. *G. crassaformis* can therefore be used to monitor past variations in the radiocarbon content of deep thermocline water (AAIW/SAMW) in the equatorial Atlantic.

3.2. $\Delta^{14}\text{C}$ gradient in the equatorial Atlantic during the last 20 ka

Deglacial changes in the upper water column $\Delta^{14}\text{C}$ gradient are assessed by comparing radiocarbon content of the different foraminifera species (Fig. 4). A potential caveat for our method is that, if the upwelling was considerably stronger it could have reduced the $\Delta^{14}\text{C}$ gradient between species. As discussed above, the constant $\delta^{18}\text{O}$ offset between *G. ruber* and *G. crassaformis*, and the other downcore records give confidence that the gradient between the thermocline and the surface levels did not noticeably change since 17 ka and that the water column structure was not markedly

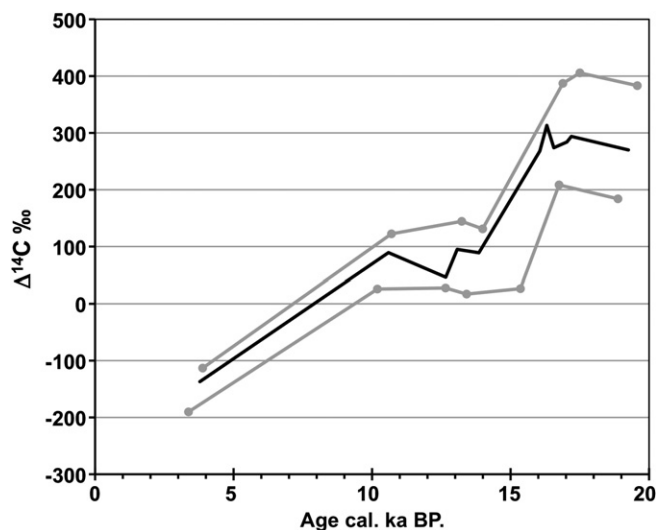


Fig. 5. influence of the model age on $\Delta^{14}\text{C}$ calculation. The black curve represents mean $\Delta^{14}\text{C}$ calculated with the mean calendar age using 335 years as a reservoir age (Table S2). The upper grey curve represents the max $\Delta^{14}\text{C}$ calculated with the younger calendar age limit (2σ) using 355 years as a reservoir age (Table S2, column 8). The lower grey curve represents the min $\Delta^{14}\text{C}$ calculated with the older calendar age limit (2σ) using 600 years as a reservoir age (Table S3, column 9). These two grey curves draw the largest envelop taking into account all the uncertainty associated with this calculation.

Table 1

^{14}C dates on *G. ruber*, calibrated into calendar age B.P. using the CALIB 6.0 program with a reservoir age of 335 years ($\Delta R = -65$) and a reservoir age of 600 years ($\Delta R = +200$). The model age was calculated by linear interpolation between 12 radiocarbon dates. Data with asterisk* was performed on *N. dutertrei*. Reference 1 is LLNL, this study; Reference 2 is McIntyre and Molino, 1996.

Lab no.	Depth (cm)	^{14}C age (years)	\pm Error	CALIB6.0, $\Delta R = -65$		Marine mean age cal. (years)	Curve \pm Error	CALIB6.0, $\Delta R = +200$		Marine mean age cal. (years)	Curve \pm Error	Δ age	Reference
				-2 sigma	+2 sigma			-2 sigma	+2 sigma				
144051	2.5	3770	30	3683	3883	3783	100	3372	3551	3462	90	322	1
OS-6804	14.5	7230	40	7659	7856	7758	99	7433	7588	7511	78	247	2
144054	26.5	9655	50	10483	10699	10591	108	10191	10444	10318	127	274	1
144060	38.5	11535	35	12909	13237	13073	164	12652	12930	12791	139	282	1
144062	48.5	12325	50	13720	13992	13856	136	13412	13736	13574	162	282	1
OS-6805	56.5	13550	50	15453	16658	16056	603	15074	16143	15609	535	447	2
144067	60.5	13790	50	16235	16888	16562	327	15356	16616	15986	630	576	1
OS-3935	64	14300	70	16789	17241	17015	226	16640	17023	16832	192	184	2
OS-3930	68	14400	70	16860	17463	17162	302	16725	17098	16912	187	250	2
144070	68.5	14440	70	16888	17501	17195	307	16750	17134	16942	192	253	1
144073	82.5	16570	100	18931	19575	19253	322	18876	19405	19141	265	113	1
OS-3934*	97	18050	100	20780	21470	21125	345	20374	21243	20809	435	317	2

different from today. It is therefore unlikely that the subsurface upwelled water reached the surface at any time. The modern $\Delta^{14}\text{C}$ differences between the atmosphere and seawater at 100 m and 600 m depth in the Eastern equatorial Atlantic are -70‰ and -100‰ respectively (Key et al., 2004). Antarctic Bottom Water (AABW) has a modern $\Delta^{14}\text{C}$ value of -160‰ . In the western North Atlantic, $\Delta^{14}\text{C}$ between 4000 and 4700 m depth has been estimated at -50‰ around 12.5 ka, $+50\text{‰}$ around 13.5 ka and about $+100\text{‰}$ around 18 ka (Robinson et al., 2005). These values may reflect past AABW composition and are therefore potential baseline values for deep-ocean $\Delta^{14}\text{C}$.

Upper thermocline $\Delta^{14}\text{C}$ reconstructions based on *N. dutertrei* measurements follow the atmospheric composition (Reimer et al., 2009) with an average offset of 72‰ . This offset varies by $\pm 27\text{‰}$. We conclude that over the last 20 ka, the age offset between the

upper thermocline and the atmosphere remained consistent with the modern value.

Between the glacial period and the early Holocene, the $\Delta^{14}\text{C}$ of the deep thermocline reconstructed from *G. crassaformis* dating is on average 102‰ ($\pm 36\text{‰}$) lower than the $\Delta^{14}\text{C}$ of the atmosphere. Through the deglaciation and over the periods with very depleted $\Delta^{14}\text{C}$ recorded off Baja, the $\Delta^{14}\text{C}$ difference between *G. crassaformis* and *G. ruber* is remarkably constant and follows atmospheric $\Delta^{14}\text{C}$. We conclude that during the early deglaciation the deep-thermocline of the eastern equatorial Atlantic does not show an incursion of "old water". Our Atlantic thermocline $\Delta^{14}\text{C}$ records are very similar to the benthic-planktonic $\Delta^{14}\text{C}$ reconstruction measured off Chile at 1000 m depth, i.e. within the modern formation area of AAIW/SAMW (De Pol-Holz et al., 2010), suggesting that both sites may have been influenced by the same water mass.

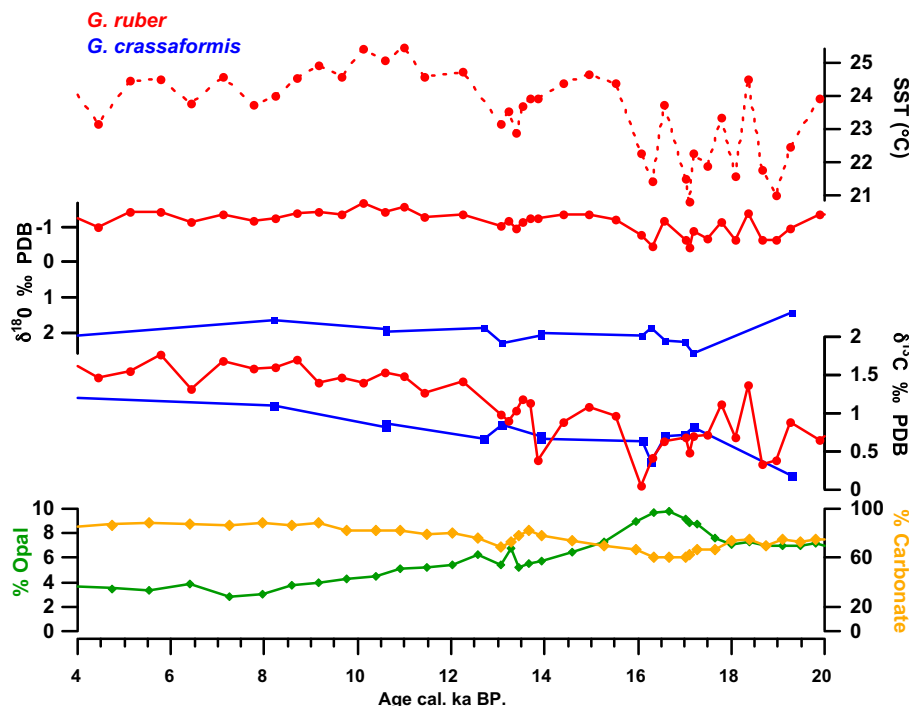


Fig. 6. RC24-08 downcore reconstruction from *G. ruber* (red), *G. crassaformis* (blue) and sediment composition. From top to bottom: SST from Mg/Ca measurement, ice volume corrected oxygen isotopic composition, carbon isotopic composition, opal percent (green) and carbonate percent (orange). SST and $\delta^{18}\text{O}$ data show very little change, we infer that temperature and salinity water column structure remained very stable over the last 20 ka. $\delta^{13}\text{C}$ and opal data both indicates enhanced influence of southern-sourced water and/or enhanced upwelling. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2

Age-corrected $\Delta^{14}\text{C}$ data calculated with the mean calendar age using 335 years as a reservoir age. Calendar ages in red are estimated by interpolation between two dated levels, there is no error associated with these calendar ages.

Taxa	Middle depth (cm)	^{14}C age yr (BP)	^{14}C age error (yr)	Cal. age (yr BP)	Calendar age error (kyr)	$\Delta^{14}\text{C}$ (per mil)	$\Delta^{14}\text{C}$ max	$\Delta^{14}\text{C}$ min
G. crassaformis	2.5	4860	25	3783	100	–137	–124	–150
G. crassaformis	26.5	9605	30	10591	108	89	108	79
G. crassaformis	36.5	11940	40	12659		46		
G. crassaformis	38.5	11975	35	13073	164	95	122	78
G. crassaformis	48.5	12780	40	13856	136	89	113	77
G. crassaformis	56.5	13695	45	16056	603	268		
G. crassaformis	58.5	13660	45	16309		313		
G. crassaformis	60.5	14150	50	16562	327	274	334	232
G. crassaformis	64.5	14545	45	17033		284		
G. crassaformis	68.5	14640	70	17195	307	294	355	258
G. crassaformis	82.5	16790	60	19253	322	270	330	231
N. dutertrei	2.5	3895	25	3783	100	–27	–12	–36
N. dutertrei	26.5	9590	30	10591	108	91	110	81
N. dutertrei	36.5	11410	35	12659		118		
N. dutertrei	56.5	13495	50	16056	603	300		
N. dutertrei	68.5	14790	50	17195	307	270	326	231
N. dutertrei	82.5	16550	60	19253	322	309	371	268

Around 4 ka, the $\Delta^{14}\text{C}$ difference between *G. crassaformis* and *N. dutertrei* is about 110‰, i.e. larger than the modern value. As the modern $\Delta^{14}\text{C}$ of intermediate water in the South Atlantic has an end-member value of about 140‰ (Key et al., 2004), this observation could suggest enhanced upwelling or aging of the thermocline water around 4 ka. Interpretation would require further investigation, and the timing and amplitude of this data point is not relevant for the conclusions of this paper.

4. Discussion

4.1. Deglacial intermediate circulation in the Atlantic

Several lines of evidence indicate that southern-sourced intermediate water invaded the North Atlantic intermediate depths during the glacial and deglacial periods. Neodymium isotopes in the tropical Atlantic (Pahnke et al., 2008), Cd/Ca ratio and $\delta^{13}\text{C}$ measurement in the North Atlantic (Rickaby and Elderfield, 2005) and opal flux reconstructions from 231 Pa/230Th ratio in the equatorial Atlantic (Bradt et al., 2007) have all been interpreted as AAIW replacing a weak North Atlantic Deep Water over the glacial period. Several studies also showed increased upwelling conditions in the equatorial region during glacial and cold events (Abrantes, 2000; Kim and Schneider, 2003; Farmer et al., 2005; Bradt et al., 2007). Despite some disagreements over the

precise timing of the upwelling changes, all these studies indicate that equatorial upwelling was greater during the last glacial than the late Holocene. Downcore measurements of opal concentration and foraminiferal $\delta^{13}\text{C}$ at site RC24-08 confirm the influence of water coming from the Southern Ocean and increased active upwelling during the deglaciation (Fig. 6). Even with the mean ocean change (Duplessy et al., 1988), the $\delta^{13}\text{C}$ increase of *G. crassaformis* from core RC24-08 favors a water mass with a South Atlantic origin as glacial $\delta^{13}\text{C}$ values were heavier in the North Atlantic (Marchitto and Broecker, 2006). RC24-08 data corroborates the array of evidence for a greater influence of AAIW/SAMW, or its deglacial equivalent, in the Atlantic equatorial thermocline over the last glacial and deglacial interval. Our $\Delta^{14}\text{C}$ calculations using *G. crassaformis* show that the basal tropical Atlantic thermocline never recorded the characteristic ^{14}C -depleted signature indicative of ventilation by an old southern reservoir, as required by the purging hypothesis.

4.2. Search for glacial CO_2 reservoir; deglacial evacuation route

Efforts to constrain the glacial CO_2 reservoir and its deglacial oceanic ventilation path have produced confounding results, available deep- and surface ocean radiocarbon records are summarized in Table 3. Fig. 1 plots ^{14}C evidences for the deglaciation only.

Table 3

Sites investigated for ^{14}C -depleted water during deglaciation and plotted on Fig. 1.

Location	Latitude	Longitude	Depth dated	Deglacial ^{14}C -depleted water?	Reference
Baja California	23°5 N	111°6 W	705 m	Yes	Marchitto et al., 2007
Arabian Sea	18°15 N	57°39 E	596 m	Yes	Bryan et al., 2010
	17°59 N	57°35 E	820 m		
Pacific equatorial	1°13 S	89°41 W	617 m	Yes	Stott et al., 2009
Off Brazil	~ 22° S	~ 40° W	621 m	Possibly	Mangini et al., 2010
	~ 24° S	~ 43° W	781 m		
Chile	36°13 S	73°40 W	1000 m	No	De Pol-Holz et al., 2010
New Zealand	37°22 S	177°00 E	651 m	No	Rose et al., 2010
	43°32 S	174°55 E	1210 m		
Equatorial Atlantic	1°20 S	11°54W	~ 600 m	No	This study
South Iceland	~ 62°N	~ 18°W	1237–2303 m	Yes	Thornalley et al., 2011
Western North Atlantic	~ 35°N	~ 60°W	>2000 m	Yes	Robinson et al., 2005 and Keigwin, 2004
East North Atlantic	37°48 N	10°10W	3146 m	Yes	Skinner and Shackleton, 2004
New Zealand	Bay of Plenty and Chatham Rise		>3000 m	Yes	Sikes et al., 2000

During the last glacial period, ^{14}C -depleted waters have been found in the deep South Atlantic (Skinner et al., 2010), deep Western South Pacific (Sikes et al., 2000), below 2500 m depth in the North Western Atlantic (Keigwin, 2004; Robinson et al., 2005) and possibly off Brazil (Mangini et al., 2010). Both southern ocean sites are believed to identify the location of the old, deep carbon reservoir whereas old ages found off Brazil and in the northern Sargasso Sea are interpreted as a purging signal or a ventilation slowdown. All attempts to locate the reservoir in the Pacific have failed so far (Broecker and Clark, 2010 and reference therein).

During the deglaciation, old waters have been identified at 23°N in the Eastern Pacific (Marchitto et al., 2007), in the EEP region (Stott et al., 2009) and in the Arabian Sea (Bryan et al., 2010). All these sites reside between 600 and 800 m depth, putatively representing paleo-AAIW/SAMW water masses, and the timing of the events is consistent at each location with the purging hypothesis, although the amplitude of the various signals remains enigmatic (Bryan et al., 2010). However, two $\Delta^{14}\text{C}$ reconstructions from sediment cores off Chile (De Pol-Holz et al., 2010) and New Zealand (Rose et al., 2010) do not exhibit these deglacial radiocarbon depletion events, yet they are also situated within the modern AAIW/SAMW formation region or pathway.

In the North Atlantic, very old ventilation ages have been found both in the Western and the Eastern mid-latitudes (Robinson et al., 2005; Skinner and Shackleton, 2004) below 2000 m depth and possibly off Brazil (Mangini et al., 2010). Mostly interpreted as southern-sourced water invasion versus NADW during the deglaciation, the $\Delta^{14}\text{C}$ recorded in both mid-latitudes Atlantic studies are compatible with the very-depleted ^{14}C water found off Baja. Recently, very old ventilation ages have been reported in sediment cores south of Iceland and interpreted as incursions of ^{14}C -depleted water mass of Antarctic origin (Thornalley et al., 2011). It is challenging to reconcile these incursions of old deep/intermediate waters off Iceland with the results of our study showing that the equatorial thermocline did not see any anomalously old water during the deglacial. This may indicate that the intermediate circulation in the Atlantic during the deglaciation was very different than today but the presence of Antarctic-sourced intermediate water south of Iceland remains to be confirmed. We note that the timing of these incursions is different than those observed in the Pacific sites. Also, other ^{14}C anomalies have been reported for a core north of Iceland (core PS2644, $67^\circ 52.02'\text{N}$, $21^\circ 45.92'\text{W}$, 777 m water depth (Voelker et al., 1998)), with benthic foraminiferal ages being up to 1500 years younger than planktic foraminifera. Influence of southern sourced water at PS2644 site is even less probable than south of Iceland. These results could be explained either by large reservoir age caused by the sea-ice or we can hypothesize that another ^{14}C -depleted reservoir may still need to be discovered in the Arctic region.

Taken together, the deglacial ocean ventilation picture that emerges from this compilation is considerably more complex than initially envisioned. To reconcile all the observations in the different oceans, the deglacial intermediate circulation must have been quite different from today, with different formation areas and pathways. If we assume that the sites in the North Atlantic, where ^{14}C -depleted water were found, were bathed by southern-source water, the fact that we don't detect this signal at all in our study of the equatorial Atlantic upwelling region implies that a strong ^{14}C gradient with depth existed in the Atlantic. The data compilation also hints that there may have been multiple isolated old, carbon-rich reservoirs in the North Atlantic and Pacific during the last glacial. Initially ruled out in the North Pacific (Broecker et al., 2004; Shackleton et al., 1988), recent studies indicating poorly ventilated water during the last glacial (Galbraith et al., 2007) and major reorganization in the

North Pacific circulation during the deglaciation (Okazaki et al., 2010) may reinvigorate interest in this hypothesis.

5. Conclusion

This study tests the hypothesis that intermediate water ventilation to tropical upwelling regions was a purging pathway for the ^{14}C -depleted CO_2 reservoir putatively located in the glacial Southern Ocean. We reconstructed the upper water column $\Delta^{14}\text{C}$ gradient in the eastern equatorial Atlantic upwelling region using three planktonic foraminifer species. We present evidence that deep-dwelling foraminifera in the equatorial Atlantic maintained their habitat in the thermocline since the deglaciation, the observed $\Delta^{14}\text{C}$ gradients can therefore be reliably interpreted as radiocarbon content changes of subsurface and thermocline depth water masses on the equator. This study, and others, showed that Atlantic equatorial thermocline water was fed by subsurface Antarctic water during the deglaciation. Finally, our thermocline ^{14}C data do not record any abnormally old water over this period, contradicting the purging hypothesis. If we assume that the current evidence for the ^{14}C -depleted water in the Southern Ocean, Eastern Pacific and North Atlantic reflect the Antarctic reservoir and its purging, then the intermediate circulation must have been quite different from today.

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Appendix. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.quascirev.2011.04.015.

References

- Abrantes, F., 2000. 200 000 yr diatom records from Atlantic upwelling sites reveal maximum productivity during LGM and a shift in phyto- plankton community structure at 185 000 yr. *Earth and Planetary Science Letters* 176, 7–16.
- Adkins, J., Boyle, E., 1997. Changing atmospheric D^{14}C and the record of deep water paleoventilation ages. *Paleoceanography* 12, 337–344.
- Adkins, J., McIntyre, A., Schrag, D.P., 2002. The salinity, temperature and $\delta^{18}\text{O}$ of the glacial deep ocean. *Science* 298, 1769–1773.
- Anderson, R.F., Ali, S., Bradtmiller, L.L., Nielsen, S.H.H., Fleisher, M.Q., Anderson, B.E., Burckle, L.H., 2009. Wind-Driven upwelling in the southern Ocean and the deglacial rise in atmospheric CO_2 . *Science* 323, 1443–1448.
- Arbuszewski, J.J., deMenocal, P.B., Kaplan, A., Farmer, C.E., 2010. On the fidelity of shell-derived $\delta^{18}\text{O}$ seawater estimates. *Earth and Planetary Science Letters* 300, 185–196.
- Barker, S., Broecker, W., Clark, E., Hajdas, I., 2007. Radiocarbon age offsets of foraminifera resulting from differential dissolution and fragmentation within the sedimentary bioturbated zone. *Paleoceanography* 22.
- Barker, S., Greaves, M., Elderfield, H., 2003. A study of cleaning procedures used for foraminiferal Mg/Ca paleothermometry. *Geochemistry Geophysics Geosystems* 4, 10. 1029/2003GC000559.
- Boyle, E., Keigwin, L.D., 1987. North Atlantic thermohaline circulation during the past 20,000 years linked to high-latitude surface temperature. *Nature* 330, 35–40.
- Bradtmiller, L.L., Anderson, R.F., Fleisher, M.Q., Burckle, L.H., 2007. Opal burial in the equatorial Atlantic Ocean over the last 30 ka: implications for glacial-interglacial changes in the ocean silicon cycle. *Paleoceanography* 22.
- Broecker, W., 1982. Glacial to interglacial changes in ocean chemistry. *Progress in Oceanography* 11, 151–197.
- Broecker, W., Barker, S., 2007. A 190 ‰ drop in atmosphere's $\Delta^{14}\text{C}$ during the 'Mystery Interval' (17.5–14.5 kyr). *Earth and Planetary Science Letters* 256, 90–99.
- Broecker, W., Clark, E., 2010. Search for a glacial age ^{14}C depleted ocean reservoir. *Geophysical Research Letters* 37.
- Broecker, W., Clark, E., Hajdas, I., Bonani, G., 2004. Glacial ventilation rates for the deep Pacific Ocean. *Paleoceanography* 19.

- Bryan, S.P., Marchitto, T.M., Lehman, S.J., 2010. The release of ^{14}C -depleted carbon from the deep ocean during the last deglaciation: evidence from the Arabian Sea. *Earth and Planetary Science Letters* 298, 244–254.
- Butzin, M., Prange, M., Lohmann, G., 2005. Radiocarbon simulations for the glacial ocean: the effects of wind stress, Southern Ocean sea ice and Heinrich events. *Earth and Planetary Science Letters* 235, 45–61.
- Cléroux, C., Cortijo, E., Anand, P., Labeyrie, L., Bassinot, F., Caillon, N., Duplessy, J.C., 2008. Mg/Ca and Sr/Ca ratios in planktonic foraminifera: proxies for upper water column temperature reconstruction. *Paleoceanography* 23.
- Cléroux, C., deMenocal, P.B., Arbuszewski, J.J., Kaplan, A., 2009. Monitor the Past Subsurface Subtropical Cells Activity by Upper Ocean Temperature and Salinity Gradients Reconstruction. *PAGES OSM*, Corvallis.
- Conkright, M.E., Locarnini, R.A., Garcia, H.E., O'Brien, T.D., Boyer, T.P., Stephens, C., Antonov, J.I., 2002. *World Ocean Atlas 2001: Objective Analyses, Data Statistics, and Figures CD-ROM Documentation*, 17 p.
- Curry, W.B.C., Crowley, T.J., 1987. The $\delta^{13}\text{C}$ of equatorial Atlantic surface waters: implications for ice age pCO_2 levels. *Paleoceanography* 2, 489–517.
- De Pol-Holz, R., Keigwin, L.D., Southon, J., Hebbeln, D., Mohtadi, M., 2010. No signature of abyssal carbon in intermediate waters off Chile during deglaciation. *Nature Geoscience* 3, 192–195.
- Duplessy, J.-C., Labeyrie, L., Juillet-Leclerc, A., Maitre, F., Duprat, J., Sarnthein, M., 1991. Surface salinity reconstruction of the north Atlantic Ocean during the last glacial maximum. *Oceanologica Acta* 14, 311–324.
- Duplessy, J.-C., Shackleton, N.J., Fairbanks, R.G., Labeyrie, L., Oppo, D.W., Kallel, N., 1988. Deepwater source variations during the last climatic cycle and their impact on the global deepwater circulation. *Paleoceanography* 3, 343–360.
- Farmer, C.E., deMenocal, P.B., Marchitto, T.M., 2005. Holocene and deglacial ocean temperature variability in the Benguela upwelling region: Implications for low-latitude atmospheric circulation. *Paleoceanography* 20.
- Farmer, E.C., Kaplan, A., deMenocal, P.B., Lynch-Steiglitz, J., 2007. Corroborating ecological depth preferences of planktonic foraminifera in the tropical Atlantic with the stable oxygen isotope ratios of core top specimens. *Paleoceanography* 22.
- Galbraith, E.D., Jaccard, S.L., Pedersen, T.F., Sigman, D.M., Haug, G.H., Cook, M., Southon, J.R., Francois, R., 2007. Carbon dioxide release from the North Pacific abyss during the last deglaciation. *Nature* 449, 890–893.
- Greaves, M., Caillon, N., Rebaubier, H., group, a.i., 2008. Interlaboratory comparison study of calibration standards for foraminiferal Mg/Ca thermometry. *Geochemistry Geophysics Geosystems* 9.
- Hughen, K., Southon, J., Lehman, S.J., Bertrand, C., Turnbull, J., 2006. Marine-derived ^{14}C calibration and activity record for the past 50,000 years updated from the Cariaco Basin. *Quaternary Science Reviews* 25, 3216–3227.
- Keigwin, L.D., 2004. Radiocarbon and stable isotope constraints on last glacial maximum and younger Dryas ventilation in the western north Atlantic. *Paleoceanography* 19.
- Key, R.M., Kozyr, A., Sabine, C.L., Lee, K., Wanninkhof, R., Bullister, J.L., Feely, R.A., Millero, F.J., Mordy, C., Peng, T.-H., 2004. A global ocean carbon climatology: results from global data Analysis Project (GLODAP). *Global Biogeochemical Cycles* 18.
- Kim, J.-H., Schneider, R., 2003. Low-latitude control of interhemispheric sea-surface temperature contrast in the tropical Atlantic over the past 21 kyears: the possible role of SE trade winds. *Climate Dynamics* 21, 337–347.
- Mangini, A., Godoy, J.M., Godoy, M.L., Kowsmann, R., Santos, G.M., Ruckelshausen, M., Schroeder-Ritzrau, A., Wacker, L., 2010. Deep sea corals off Brazil verify a poorly ventilated 1 southern pacific Ocean during H2, H1 and the younger Dryas. *Earth and Planetary Science Letters* 293, 269–276.
- Marchitto, T.M., Broecker, W., 2006. Deep water mass geometry in the glacial Atlantic Ocean: a review of constraints from the paleonutrient proxy Cd/Ca. *Geochemistry Geophysics Geosystems* 7.
- Marchitto, T.M., Lehman, S.J., Ortiz, J.D., Fluckiger, J., van Geen, A., 2007. Marine radiocarbon evidence for the mechanism of deglacial atmospheric CO_2 rise. *Science*.
- McIntyre, A., Molino, B., 1996. Forcing of Atlantic equatorial and subpolar millennial cycles by precession. *Science* 274, 1867–1870.
- Mix, A.C., 1986. Late Quaternary Paleoceanography of the Atlantic Ocean: Foraminiferal Faunal and Stable-isotopic Evidence. Columbia University, New York.
- Mix, 1989. Influence of productivity variations on long-term atmospheric CO_2 . *Nature* 337.
- Molino, B., McIntyre, A., 1990. Nutricline variation in the equatorial Atlantic coincident with the Younger Dryas. *Paleoceanography* 5, 997–1008.
- Monnin, E., Indermühle, A., Dällenbach, A., Flückiger, J., Stauffer, B., Stocker, T.F., Raynaud, D., Barnola, J.-M., 2001. Atmospheric CO_2 concentrations over the last glacial Termination. *Science* 291, 112–114.
- Okazaki, Y., Timmermann, A., Menviel, L., Harada, N., Abe-Ouchi, A., Chikamoto, M.O., Mouchet, A., Asahi, H., 2010. Deepwater formation in the north pacific during the last glacial Termination. *Science* 329, 200–204.
- Pahnke, K., Goldstein, S.L., Hemming, S.R., 2008. Abrupt changes in Antarctic Intermediate Water circulation over the past 25,000 years. *Nature Geoscience* 1, 870–874.
- Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T., Hajdas, I., Heaton, T., Hogg, A., Hughen, K., Kaiser, K., Kromer, B., McCormac, F., Manning, S., Reimer, R., Richards, D., Southon, J., Talamo, S., Turney, C., van der Plicht, J., Weyhenmeyer, C., 2009. *INTCAL09 and MARINE09 Radiocarbon age calibration curves, 0–50,000 years cal BP*. *Radiocarbon* 51, 1111–1150.
- Rickaby, R.E.M., Elderfield, H., 2005. Evidence from the high-latitude North Atlantic for variations in Antarctic Intermediate water flow during the last deglaciation. *Geochemistry Geophysics Geosystems*.
- Robinson, L.F., Adkins, J., Keigwin, L.D., Southon, J., Fernandez, D.P., Wang, S.-L., Scheirer, D.S., 2005. Radiocarbon variability in the western north Atlantic during the last deglaciation. *Science* 310, 1469–1473.
- Rose, K.A., Sikes, E.L., Guilderson, T.P., Shane, P., Hill, T.M., Zahn, R., Spero, H.J., 2010. Upper-ocean-to-atmosphere radiocarbon offsets imply fast deglacial carbon dioxide release. *Nature* 466.
- Rubin, S.I., Key, R.M., 2002. Separating natural and bomb-produced radiocarbon in the ocean: the potential alkalinity method. *Global Biogeochemical Cycles* 16.
- Sarmiento, J.L., Toggweiler, J.R., 1984. A new model for the role of the oceans in determining atmospheric PCO_2 . *Nature* 308, 621–624.
- Schmidt, G.A., Bigg, G.R., Rohlin, E.J., 1999. *Global Seawater Oxygen-18 Database*. <http://data.giss.nasa.gov/o18data/>.
- Schneider, R., Dahmke, A., Kölling, A., Müller, P.J., Schulz, H.D., Wefer, G., 1992. Strong deglacial minimum in the $\delta^{13}\text{C}$ record from planktonic foraminifera in the Benguela upwelling region: palaeoceanographic signal or early diagenetic imprint? In: Summerhayes, C.P.P., Prell, W.L., Emeis, K.C. (Eds.), *Upwelling Systems: Evolution Since the Early Miocene*. Geological Society, Vol. 64, pp. 285–297.
- Sen Gupta, A., England, M.H., 2007. Evaluation of interior circulation in a high-Resolution global Ocean model. Part II: southern Hemisphere intermediate, mode, and thermocline waters. *Journal of Physical Oceanography* 37, 2612–2636.
- Shackleton, N.J., Duplessy, J.-C., Arnold, M., Maurice, P., Hall, M.A., Cartlidge, J., 1988. Radiocarbon age of the last glacial Pacific deep water. *Nature* 335, 708–711.
- Siegenthaler, U., Wenk, T., 1984. Rapid atmospheric CO_2 variations and the ocean circulation. *Nature* 308.
- Sikes, E.L., Samson, C.R., Guilderson, T.P., Howard, W.R., 2000. Old radiocarbon ages in the southwest Pacific Ocean during the last glacial period and deglaciation. *Nature* 405, 555–559.
- Skinner, L.C., Fallon, S., Waelbroeck, C., Michel, E., Barker, S., 2010. Ventilation of the deep southern Ocean and deglacial CO_2 rise. *Science* 328, 1147–1151.
- Skinner, L.C., Shackleton, N.J., 2004. Rapid transient changes in northeast Atlantic deep water ventilation age across Termination I. *Paleoceanography* 19.
- Spero, H.J., Lea, D.W., 2002. The cause of carbon isotope minimum events on glacial Terminations. *Science* 296, 522–525.
- Steph, S., Regenberg, M., Tiedemann, R., Mulitz, S., Nurnberg, D., 2009. Stable isotopes of planktonic foraminifera from tropical Atlantic/Caribbean coretops: implications for reconstructing upper ocean stratification. *Marine Micropaleontology* 71, 1–19.
- Stott, L., Southon, J., Timmermann, A., Koutavas, A., 2009. Radiocarbon age anomaly at intermediate water depth in the Pacific Ocean during the last deglaciation. *Paleoceanography* 24.
- Thornalley, D.J.R., Barker, S., Broecker, W., Elderfield, H., McCave, I.N., 2011. The deglacial evolution of north Atlantic deep convection. *Science* 331, 202–205.
- Tschumi, T., Joos, F., Gehlen, M., Heinze, C., 2010. Deep ocean ventilation, carbon isotopes, marine sedimentation and the deglacial CO_2 rise. *Climate of the Past Discussion* 6, 1895–1958.
- Voelker, A.H.L., Sarnthein, M., Grootes, P.M., Erlenkeuser, H., Laj, C., Mazaud, A., Nadeau, M.-J., Schleicher, M., 1998. Correlation of marine ^{14}C ages from the Nordic seas with the GISP2 isotope records: implications for ^{14}C calibration beyond 25 ka BP. *Radiocarbon* 40, 517–534.
- Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K., Balbon, E., Labracherie, M., 2002. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. *Quaternary Science Reviews* 21, 295–305.