AGU PUBLICATIONS

Paleoceanography

RESEARCH ARTICLE
10.1002/2016PA002953

Key Points:
- ^{14}C plateau tuning reveals surface water reservoir ages of 100-2500 years for glacial-deglacial times
- LGM reservoir ages compare favorably with ages simulated by a GCM with realistic boundary conditions
- Changing reservoir ages of surface waters depict local changes in meridional ocean circulation and local near-surface winds

Supporting Information:
- Supporting Information S1

Correspondence to:
S. Balmer,
balmer@gpi.uni-kiel.de

Citation:
Balmer, S., M. Sarnthein, M. Mudelsee, and P. M. Grootes (2016), Refined modeling and ^{14}C plateau tuning reveal consistent patterns of glacial and deglacial ^{14}C reservoir ages of surface waters in low-latitude Atlantic, *Paleoceanography*, *31*, 1030–1040, doi:10.1002/2016PA002953.

Received 19 MAR 2016
Accepted 5 JUL 2016
Accepted article online 11 JUL 2016
Published online 3 AUG 2016

Refined modeling and ^{14}C plateau tuning reveal consistent patterns of glacial and deglacial ^{14}C reservoir ages of surface waters in low-latitude Atlantic

Sven Balmer[1], Michael Sarnthein[1], Manfred Mudelsee[2,3], and Pieter M. Grootes[4]

[1]Institute of Geosciences, University of Kiel, Kiel, Germany, [2]Climate Risk Analysis, Bad Gandersheim, Germany, [3]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany, [4]Institute for Ecosystem Research, University of Kiel, Kiel, Germany

Abstract Modeling studies predict that changes in radiocarbon (^{14}C) reservoir ages of surface waters during the last deglacial episode will reflect changes in both atmospheric ^{14}C concentration and ocean circulation including the Atlantic Meridional Overturning Circulation. Tests of these models require the availability of accurate ^{14}C reservoir ages in well-dated late Quaternary time series. We here test two models using plateau-tuned ^{14}C time series in multiple well-placed sediment core age-depth sequences throughout the lower latitudes of the Atlantic Ocean. ^{14}C age plateau tuning in glacial and deglacial sequences provides accurate calendar year ages that differ by as much as 500–2500 years from those based on assumed global reservoir ages around 400 years. This study demonstrates increases in local Atlantic surface reservoir ages of up to 1000 years during the Last Glacial Maximum, ages that reflect stronger trades off Benguela and summer winds off southern Brazil. By contrast, surface water reservoir ages remained close to zero in the Cariaco Basin in the southern Caribbean due to lagoon-style isolation and persistently strong atmospheric CO_2 exchange. Later, during the early deglacial (16 ka) reservoir ages decreased to a minimum of 170–420 ^{14}C years throughout the South Atlantic, likely in response to the rapid rise in atmospheric pCO_2 and Antarctic temperatures occurring then. Changes in magnitude and geographic distribution of ^{14}C reservoir ages of peak glacial and deglacial surface waters deviate from the results of Franke et al. (2008) but are generally consistent with those of the more advanced ocean circulation model of Butzin et al. (2012).

1. Introduction

^{14}C reservoir ages of surface waters represent the difference between ^{14}C ages of the atmosphere and contemporaneous surface waters and reflect the balance between ocean-atmosphere CO_2 exchange and oceanic mixing. These reservoir ages are fundamental to derive any ^{14}C-based absolute chronology. Past reservoir ages can be derived from ^{14}C records of planktic foraminifers in comparison to past ^{14}C concentrations of the atmosphere that are rapidly reflected in the ^{14}C of dissolved inorganic carbon (DIC) in the ocean surface. Measured changes in reservoir age over time may thus form an important tracer of past changes in ocean circulation, such as upwelling of old subsurface waters and vice versa, and near-surface stratification [*Grootes*, 2015]. Reservoir ages can also be calculated by means of coupled ocean-atmosphere general circulation models (GCMs). *Franke et al.* [2008] based their model simulation of spatial and temporal variations in glacial reservoir age of the surface ocean on the assumption that these variations were controlled by changes in atmospheric ^{14}C concentration and a 30% reduction of Atlantic Meridional Overturning Circulation (AMOC). They found changes that were fairly modest in the low-latitude Atlantic during present and peak glacial times, at most rising from 400 to 500 ^{14}C years in high latitudes (Table 1). Later, *Butzin et al.* [2012] used similar assumptions in testing four meridional overturning circulation (MOC) scenarios of the Last Glacial Maximum (LGM). However, different from previous approaches (details of model design are listed in Table 2), their GCM employed a "self-consistent simulation" of ^{14}C, an LGM wind field controlled by LGM sea surface temperatures (SST), and a higher gas transfer velocity for the ^{14}C transfer from the atmosphere [*Sweeney et al.*, 2007]. On this basis, changes in simulated reservoir age were far more distinct reaching 500 in low and 2200 ^{14}C years in high latitudes.

It has been difficult to validate the different model-derived glacial reservoir ages and their spatial and temporal gradients, since centennial-to-millennial-scale records of empiric ^{14}C reservoir ages are widely lacking for both modern and past ocean surface waters in the Atlantic, a gap now reduced in this study. Yet some

Table 1. Changing ^{14}C Reservoir Ages (Years) of Surface Waters[a]

	South Atlantic West Wind Drift	Benguela Current	Brazilian Margin		Cariaco Basin	Azores C.
			South Brazil C.	Equatorial		
	MD07-3076[b] (44°4′S, 14°12′W) (3770 m w.d.)	GeoB 1711-4 (23°17′S, 12°23′W) (1976 m w.d.)	KNR 159-5-36GGC (27°31′S, 46°48′W) (1268 m w.d.)	GeoB 3910-1 (4°15′S, 36°21′W) (2361 m w.d.)	ODP 1002[c] (10°42′N, 65°10′W) (893 m w.d.)	MD08-3180[c] (38°N, 30°08′W) (3034 m w.d.)
No. of ^{14}C ages (23–12 cal. ka)	18	59 + 3[d,e]	26 + 37[f,g]	44 + 5[h]	179[i]	68
Sediment slice/sample		1 cm	1.5 cm	1−2 cm		
Planktic species	*G. bulloides/inflata/N. pachyderma* sinistral	*G. bulloides*	*G. ruber*	*G. sacculifer*	*G. bulloides/G. ruber*	*G. bulloides*
Number of tests/sample		318–944 (5–12 mg)	128–263 (1.6–5 mg)	66–299 (3–14 mg)		
Ø Sample resolution (cal. years)	~600	184	175/140[j]	134	104	105
Bolling/Allerod	700–1300	880	170–230	210–230	360	360–640
HS-1	700–1800	420–660	170–460	180–630	(−100–) 90	1460–2170
LGM	1300–2400	730–1080	540–870	–	20–700	320–600
LGM (model)[k]	400–500	500–600	500–600	500–600	500–600	400–500
LGM (model)[l]	At 50°S 2300–2700	1000–1300	800–1100	800–1100	500–800	600–900
LGM–PD[k] model anomaly	100	100	200	100	100	100
LGM–PD[l] model anomaly	At 50°S 1400–1800	400–600	400–600	200 – 400	200–400	200–400
LGM–B/A empiric anomaly	600–1700	−150–200	370–640	–	−340–340	−40

[a] ^{14}C reservoir ages present the difference in ^{14}C years between coeval paired ^{14}C ages of the atmosphere and ocean surface waters.
[b] *Skinner et al.* [2010].
[c] *Sarnthein et al.* [2015].
[d] *Little et al.* [1997].
[e] *Vidal et al.* [1999].
[f] *Came et al.* [2003].
[g] *Sortor and Lund* [2011].
[h] *Jaeschke et al.* [2007].
[i] *Hughen et al.* [2006].
[j] Including *Zoophycos* outliers. C. = current; PD = preindustrial; w.d. = water depth.
[k] *Franke et al.* [2008].
[l] *Butzin et al.* [2012].

authors already took a step forward and employed the reservoir ages simulated by either one of the two models—even though regarded as controversial—as database to reconstruct past distribution patterns of deepwater ventilation ages and related changes in AMOC [*Freeman et al*., 2015; *Huang et al*., 2015]. This highlights the importance of testing the significance of the results obtained by different models.

To allow testing of the model simulations, we now provide a synthesis of six partly published and partly new planktic ^{14}C reservoir age records from various key sectors of the low-latitude Atlantic (Figure 1). Most records were established by means of the ^{14}C plateau-tuning technique [*Sarnthein et al*., 2007, 2015]. Reservoir ages in Core MD07-3076 [*Skinner et al*., 2010] were generated by tuning of the temperature signal of local surface waters (SST) to the age-calibrated temperature record of Antarctic ice core EDML [*Lemieux-Dudon et al*., 2010]. For some core sections we added ^{14}C plateau tuning. In this way we generate a robust network of calendar age chronologies resolved at millennial-to-centennial age scales for last glacial and deglacial times: chronologies that may help in building global correlations of climate and atmospheric signals defined in ice cores, ocean sediments, and speleothems.

Our new records stem from three sites at the eastern and western continental margins of the South Atlantic (Table 1). Core GeoB 1711-4 was obtained off the coast of Namibia, where the intensity of the Benguela Upwelling System is linked to the strength of southeasterly trades [*Lütjeharms and Meeuwis*, 1987]. The upwelled waters in part consist of South Atlantic Central Water (SACW) [*Shannon and Nelson*, 1996]. Cores GeoB 3910-1 and KNR 159-5-36GGC stem from the Brazilian Margin, where modern surface waters are widely stratified and belong to the North Brazil and South Brazil Currents (Figure 1 and Table 1). Moreover, Site KNR 159-5 is partly influenced by a local cell of coastal upwelling of SACW, in particular during austral summer [*Castelao et al*., 2004].

The low-latitude and southern Atlantic are a major blank area in terms of ^{14}C reservoir ages. A prebomb average global reservoir age of ~400 years [*Stuiver et al*., 1986; *Broecker and Olson*, 1961] is often, for convenience, extrapolated as constant back in time beyond the Holocene. We therefore supplement our three new ^{14}C

Table 2. Description of Models Used for the Reconstruction of Changes in Surface Water Reservoir Age [*Franke et al.*, 2008; *Butzin et al.*, 2012]

Study	Model	Coupled to Other Models	Resolution	Forcing	Parameters for PD	Parameters for LGM
Franke et al. [2008]	UVic ESCM v.2.7	Two-dimensional energy-moisture balance model of the atmosphere[a]	3.8° × 1.8°; 19 levels	Solar insolation at top of the atmosphere over 1 year	Solar radiation (1950)	Solar radiation at 21 ka
		Dynamic thermodynamic sea ice model[b]		Wind stress at ocean surface; monthly climatology	Land ice distribution (1950)	Land ice distribution (21 ka)
					CO_2 = 280 ppmv	CO_2 = 200 ppmv
					Wind field: modern (NCEP/NCAR)	Wind field: modern (NCEP/NCAR)
Butzin et al. [2012]	Hamburg LSG ocean circulation model (improved[c])	ECHAM3/T42	3.5° × 3.5°; 22 levels	Ten year averaged monthly fields of wind stress	Present-day SST	GLAMAP SST as basis for ECHAM3/T42 simulation of AMOC
				Surface air temperature	$\Delta^{14}C$ = 0‰	$\Delta^{14}C$ = 350‰
				Freshwater flux	CO_2 = 280 ppmv	CO_2 = 200 ppmv
						Modified freshwater balance in Southern Ocean mimics sea ice transport to north

[a]*Fanning and Weaver* [1996].
[b]*Bitz et al.* [2001].
[c]Use of an updated relationship between wind speed and gas transfer velocity for $^{14}CO_2$ air-sea exchange following *Sweeney et al.* [2007].

records with the only planktic records of ^{14}C reservoir age published so far from the northern subtropical Atlantic (*Sarnthein et al*. [2015]) and the subantarctic South Atlantic (MD07-3076; *Skinner et al*. [2010]). In addition, we consider the Cariaco Basin record (OPD 1002; *Sarnthein et al*. [2015]) that formed in an almost isolated deep lagoon, when sea level dropped to the peak glacial and early deglacial low.

In total, these six empiric records provide a novel database for tracing changes in regional surface water circulation, stratification, and coastal upwelling with the transformation from the last glacial to the Bølling-Allerød episode that, in turn, have been controlled by past changes in seasonal wind strength and AMOC. In particular, the records help us to test the consistency of data for the last glacial simulated by two GCMs and thus the underlying assumptions regarding the coupled ocean-atmosphere system the models are based on.

2. Methods

Initial age control of all cores was based on planktic oxygen isotope ($\delta^{18}O$) records (supporting information Figures S1a–S1c), in GeoB 1711-4 also on a benthic $\delta^{18}O$ record [*Little et al*., 1997]. In GeoB 3910-1 we used an X-ray fluorescence (XRF) geochemical record to identify the Younger Dryas and Heinrich Stadial 1 (HS-1) by maxima in Ti/Ca that reflect humid conditions in nearby Eastern Brazil [*Jaeschke et al*., 2007] (Figure S2; details of method are in supporting information Text S1). The stratigraphic records served as a guideline to focus our sediment sampling for ^{14}C dates of peak glacial and deglacial sediments. In total, we analyzed 59 samples of GeoB 1711-4 and 44 samples of GeoB 3910-1. Samples of 20 cm^3 each were spaced at 2.5 and/or 5 cm and more closely near ^{14}C plateau boundaries (Tables 1 and S3). In core KNR 159-5-36GGC the glacial-to-deglacial section was first identified by wide-spaced ^{14}C ages of *G. ruber* [*Came et al*., 2003; *Sortor and Lund*, 2011] (Table 1), now supplemented by 26 ^{14}C ages between 60 and 200 cm core depth (Table S3).

Sediment samples were freeze dried, washed over a 63 μm sieve, and finally cleaned with deionized water. Monospecific planktic foraminifera tests for accelerator mass spectrometry (AMS) ^{14}C analyses were picked in the 150–400 μm size fraction as detailed in Table 1.

Radiocarbon samples were analyzed at the facility for accelerator mass spectrometry (AMS) of the Leibniz Laboratory, University of Kiel, Germany (KIA numbers), and the Keck Carbon Cycle AMS facility (UCIAMS numbers), University of California, Irvine, USA (Table S3). In the Leibniz Laboratory samples were cleaned with 15% H_2O_2 in an ultrasonic bath to remove dust and detrital carbonate as well as organic surface coatings. CO_2 was

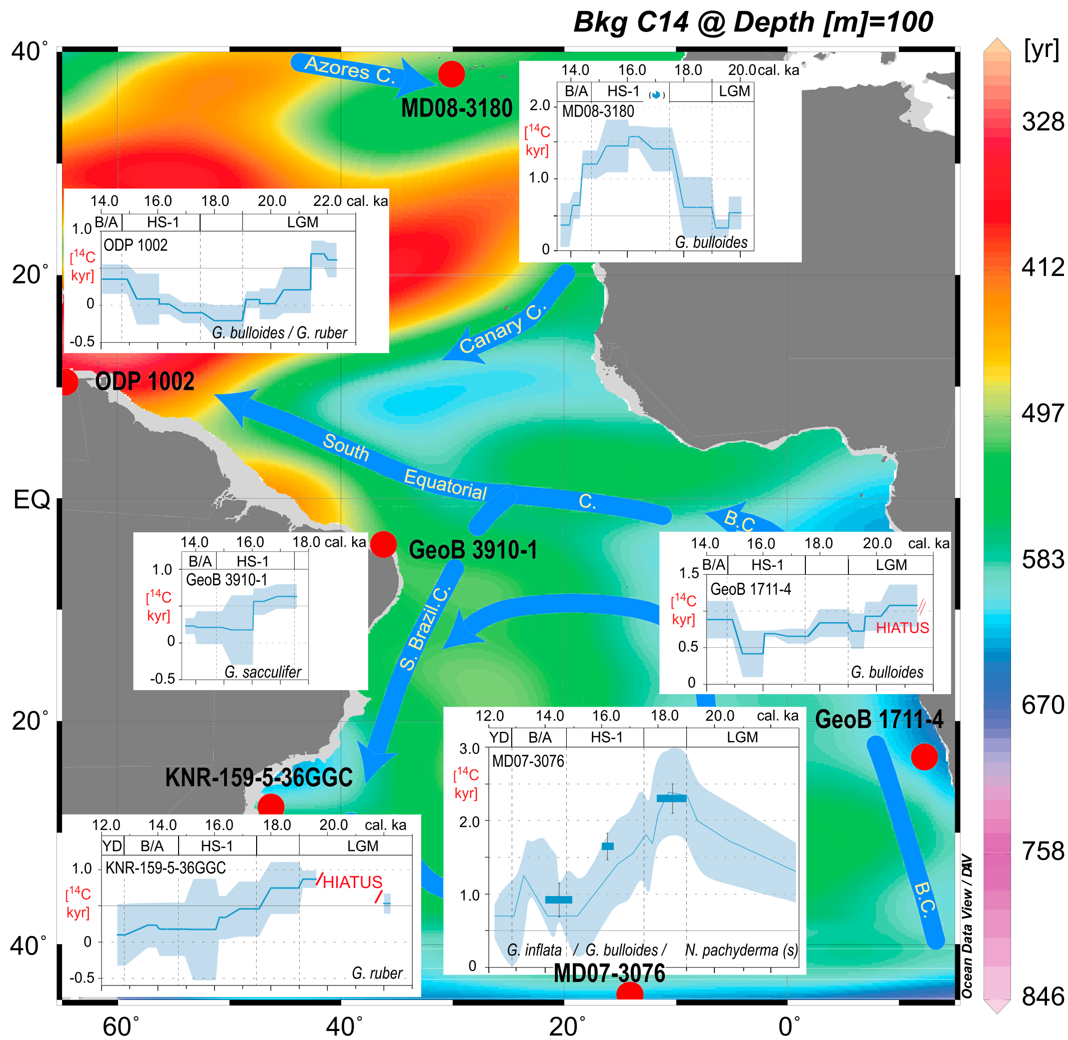

Figure 1. Glacial-to-deglacial ^{14}C reservoir ages (given in kyr) of surface waters and their uncertainty ranges (blue shading) at six core sites in the tropical and subtropical-to-midlatitude Atlantic and spatial variability of modern ^{14}C reservoir ages (given in years) in top 100 m water depth modeled by *Key et al*. [2004]. Bkg = Background. Blue arrows show major surface currents (C.). B. = Benguela. Records of ODP 1002 and MD08-3180 from *Sarnthein et al*. [2015], and MD07-3076 from *Skinner et al*. [2010]. Reservoir ages and uncertainties in MD07-3076 have been derived by tuning SST signals to EDML [*Lemieux-Dudon et al*., 2010]. These are compared to reservoir ages derived from ^{14}C plateau tuning (blue horizontal bars and black vertical uncertainty bars). Planktic foraminiferal species analyzed for ^{14}C ages are given near bottom of age diagrams. Map based on *Schlitzer* [2015].

released from the samples with 100% H_3PO_4 at 90°C and reduced with H_2 using Fe powder as catalyst. The ^{14}C concentration was measured by standard procedures, that is, by comparing the simultaneously collected ^{14}C, ^{13}C, and ^{12}C beams of each sample with those of oxalic acid standard CO_2 and those of pre-Eemian foraminifera [*Nadeau et al*., 1998]. Samples at the Keck AMS Laboratory were cleaned and leached prior to hydrolyzation in 70% H_3PO_4. The released CO_2 was graphitized under H_2 on an iron catalyst before ^{14}C analysis [*Vogel et al*., 1984]. All ^{14}C values were converted into conventional ^{14}C ages following *Stuiver and Polach* [1977], uncorrected for any reservoir age.

2.1. Derivation of Calendar Ages

Both absolute calendar (cal.) ages and surface water reservoir ages were derived by means of the ^{14}C plateau-tuning technique following the definitions and rules defined by *Sarnthein et al*. [2007, 2015]. In brief, a ^{14}C age plateau develops when the ^{14}C concentration in a reservoir (atmosphere or ocean) decreases at a rate close to the natural ^{14}C decay rate. Samples formed at successive points in time then show in measurement the same ^{14}C concentration, that is, the same ^{14}C age, for a section in a sediment core. Such a ^{14}C decrease may result from increased outgassing of old ^{14}C-depleted carbon from the ocean to the atmosphere or from a decrease in atmospheric ^{14}C production. Vice versa, if the global oceanic outgassing is significantly reduced or if atmospheric ^{14}C production increases, the atmospheric ^{14}C concentration shows a steep increase or "jump." Age plateaus in the atmosphere and surface ocean generally correlate on the scale of decades due to effective exchange of CO_2 across the ocean-atmosphere boundary layer [*Nydal et al.*, 1980]. Yet strong changes in local ocean mixing may break the ocean-atmosphere correlation. Planktic foraminifera tests archive these ^{14}C variations in the deep-sea sediment, which provides the basis of the IntCal approach beyond 14 cal. ka [*Reimer et al.*, 2013].

The suites of ^{14}C plateaus were identified in the planktic ^{14}C age-depth records by visual inspection and tuned to a suite of analogous plateaus in the atmospheric ^{14}C record of Lake Suigetsu between 22.5 and 12 cal. ka. We defined a plateau when two or more ^{14}C ages in a sediment section show no significant downcore rise over core depth. Suites of plateaus reflect analogous suites of short and long plateaus in the atmospheric ^{14}C record. For Suigetsu we choose the age scale based on varve counts [*Bronk Ramsey et al.*, 2012; *Sarnthein et al.*, 2015]. This scale is independent of the "official" Suigetsu model time scale that includes feedback of the Hulu and Bahama speleothem ^{14}C records that limits the unknown changes in the "dead carbon fraction" of these records to an extent we do not accept. The official time scale leads to absolute age estimates that exceed a purely varve-based estimate by up to 650 years during early HS-1. The identification of a plateau depends on the correlation of the full suite of plateaus in a sediment section with the atmosphere and is independent of the absolute age of the reference section. However, the absolute ages of the plateau boundaries are directly affected. The ^{14}C reservoir ages derived from the correlation of pertinent atmospheric and planktic ^{14}C plateaus do not suffer because ^{14}C ages are compared with ^{14}C ages only. The calculated shift in ^{14}C concentration between an atmospheric and the corresponding planktic ^{14}C plateau, however, varies with different Suigetsu age scales that control the back-calculated ^{14}C concentrations of the atmosphere.

The locations of planktic ^{14}C plateau boundaries were objectively confirmed by means of inflection points (short-lasting maxima and/or the half-height of steep slopes) in the first derivative record of all downcore changes in the ^{14}C age-depth relationship (details in supporting information Text S2). Within each core the range of resulting sedimentation rates and their short-term variability (Figures S1a–S1c) provides supportive information on the quality of plateau definitions.

For each ^{14}C plateau in each core, planktic average reservoir ages were estimated from the difference between the average ^{14}C ages of coeval atmospheric and planktic ^{14}C plateaus. Uncertainties in planktic reservoir ages (uncertainty in Figure 1; Table S1) were estimated by Gaussian error propagation and include the uncertainties of coeval atmospheric and marine ^{14}C plateaus (for 1.68σ, equivalent to a confidence interval of 90% for Gaussian distribution). Planktic ^{14}C reservoir ages were analyzed on various foraminifer species that represent different habitats and growth seasons (details in supporting information Text S3). Oceanographic implications are discussed below.

In total, the suites of ^{14}C plateau boundaries provide us with 7–18 age control points in each core, depending on the time span of the ^{14}C record reconstructed (Figure S1). These ages fully confirm the age estimates first deduced from $\delta^{18}O$ and XRF records (Figures S1 and S2). The cal. ages derived by visual and mathematical methods of plateau definition generally deviate by less than 50–100 years [*Sarnthein et al.*, 2015]. In summary, we regard the suite of plateau boundary ages in each core as a robust estimate, in particular, since the series of reservoir ages appear fairly stable over a complete suite of plateaus and internally consistent within any particular ^{14}C record. They reveal no abrupt rise that may result in an artificial plateau with boundaries that may mistakenly be picked as age tie points, except in Core GeoB 1711-4, where they jump from 420 to 880 years going from the top of plateau 2a to the base of plateau 1 (Figure S1a).

Given that changes in atmospheric ^{14}C are short-term reflected by those of ocean surface waters [*Sweeney et al.*, 2007], one may consider a simple test on this question: In case a ^{14}C age-depth plateau does not reflect any coeval atmospheric plateau defined at Lake Suigetsu but just reflects a temporary local rise in (upwelling and) reservoir age, we may necessarily expect that the ^{14}C plateau immediately subsequent will record the elevated level of reservoir age reached during the increase of reservoir age over the antecedent "pseudo"-

plateau under discussion. This test case does not apply to any of the ^{14}C records employed in this study (Figure S1). Moreover, the suites of ^{14}C plateaus employed each show a distinct atmospheric analogue.

3. Results

Previous studies claimed that planktic reservoir ages were largely constant at ~400 ^{14}C years in low-latitude surface waters [*Broecker et al*., 2004] (based on data of *Stuiver and Braziunas* [1993]). By contrast, our new data reveal distinct spatial and temporal variations reasonably linked to major features of ocean circulation (Table 1 and Figure 1). Widely stratified surface waters along the west Atlantic continental margin (GeoB 3910-1; KNR 159-5-36GGC) show low reservoir ages ranging from 150 to 350 ^{14}C years over Younger Dryas (YD)-to-late Heinrich Stadial 1 (HS-1) times, ages that rose up to 650–870 ^{14}C years over early HS-1 and the terminal Last Glacial Maximum (LGM). By contrast, glacial-to-deglacial reservoir ages in the subtropical upwelling zone off Southwest Africa (GeoB 1711-4) ranged from 650 to 1100 ^{14}C years, except for late HS-1, where reservoir ages shortly dropped to 420 ^{14}C years. Reservoir ages were far more variable in both the midlatitude Southern and Northern Atlantic. At 44°S (MD07-3076), they almost reached 2500 ^{14}C years at the end of the LGM as compared to 700–1200 ^{14}C years during HS-1-to-YD times. Near the Azores they reached ~1600 ^{14}C years during HS-1 as compared to ~500 ^{14}C years and less before and after (MD08-3180).

It is interesting to compare our new age control points in GeoB 1711, GeoB 3910-1, and KNR 159-5-36 (Figures 1 and S1a–S1c) to published age control points derived from both conventional ^{14}C dating and tuning of abrupt local changes in ocean climate to climate signals dated in Greenland or Antarctic ice core records. After all, the quality of our new plateau boundary-based ages appear superior to most age estimates that result from the widely used simple match of allegedly coeval oscillations in paleoclimate and paleoceanography, oscillations that actually do not need to be contemporaneous.

In Core GeoB 1711-4 *Vidal et al*. [1999] based their age model of glacial-to-deglacial climate events on four planktic ^{14}C ages, assuming that ^{14}C reservoir ages of 400 ^{14}C years were constant. Moreover, they used conversion standards into calendar ages that were based on a tuning of various benthic $\delta^{18}O$ oscillations in their core during MIS 1–3 to those of Core SU90-08 in the distant North Atlantic at 40°N. These oscillations were only coarsely dated by orbital tuning in the sense of *Prell et al*. [1986] and can hardly be coeval with those in GeoB 1711-4 on a millennial age scale because of transit times of deep waters that exceed many hundred years. Our new age interpolation between age-calibrated ^{14}C plateau boundaries (Tables S1 and S3 and Figure S1a) now results in calendar ages that exceed the former estimates as much as 1650 (late HS-1) to 2500 years (top LGM).

Core GeoB 3910-1 was retrieved at the site of GeoB 3910-2 (core depths correlated in supporting information Table S2). Its age model was based on 5–6 planktic ^{14}C ages, using a constant ^{14}C reservoir age of 400 ^{14}C years [*Jaeschke et al*., 2007]. Our new reservoir age estimates (Table S1) and age interpolation between age-calibrated ^{14}C plateau boundaries (Figure S1b) now lead to calendar ages that are much younger than the former age estimates, by up to 1000 years for the time span of early ^{14}C plateau 2a, 15.5–16 cal. ka. We tested our new age model by means of a salient Ti/Ca maximum during HS-1 (Figure S2), which documents enhanced humidity on land [*Jaeschke et al*., 2007]. When compared to U/Th-dated periods of speleothem growth in Northeast Brazil that likewise record this humid event [*Wang et al*., 2004], the new (interpolated) ages for the upper and lower boundaries of the Ti/Ca maximum indeed match those of the very onset and end of speleothem growth within the uncertainty range of age control.

^{14}C plateau tuning at Core KNR 159-5-36 leads to a hiatus at 20.5 to ~21.5 cal. ka, which was formerly overlooked in the ^{14}C-based age model of *Sortor and Lund* [2011]. Moreover, our new calendar ages are significantly different. Prior to ~16 cal. ka, the former age estimates exceed our new ages by 600–1300 years, from 16 to 15 cal. ka by 150–500 years. From 15 to 13 cal. ka, both estimates are about equal, and after 13 cal. ka, our new age numbers for the YD exceed the former estimates by 300–500 cal. years (Table S3 and Figure S1c).

Finally, we used the youngest section of the planktic ^{14}C record and age model of MD07-3076 [*Skinner et al*., 2010] for a test of ^{14}C plateau tuning (Figures 1 and S1d). It revealed a distinct plateau 1, as expected, precisely coeval with the first part of the Antarctic Cold Reversal, where sedimentation rates are sufficiently high. We could only identify fragments of plateaus 2 and 4, where sedimentation rates are 8 cm/cal. kyr and less.

Note the ^{14}C reservoir ages revealed by tuning plateau 1, and the fragments of plateaus 2 and 4 precisely match those derived by the approach of *Skinner et al*. [2010] (Figure 1).

In all cores we studied, planktic ^{14}C ages form coherent records of ^{14}C plateaus and jumps, except for two groups of ^{14}C age outliers in KNR 159-5-36, which spread over 40 cm core depth each (Figure S1). The aberrant age populations closely gather around ages of 11.9 and 13.8 ^{14}C ka that differ by 2000–3500 and 1500–2000 ^{14}C years each from the remainder of the ^{14}C record which strictly follows the temporal pattern of the Suigetsu atmospheric ^{14}C record [*Bronk Ramsey et al*., 2012]. In harmony with *Sortor and Lund* [2011] we assign the age outliers to two Zoophycos burrowing events that now are precisely dated at 11.9 (planktic) ^{14}C kyr = ~13.5 cal. ka and 13.8 (planktic) ^{14}C kyr = 16.05–15.27 cal. ka (here extending over ^{14}C plateau 2a).

At Site ODP 1002 our new estimates exceed a formerly assumed ^{14}C reservoir age of 420 years [*Hughen et al*., 2006] by 300 years during early LGM [*Sarnthein et al*., 2015]. However, our new values are up to 400 years lower during late LGM and HS-1 as discussed below (details of species-specific reservoir ages in supporting information Text S3).

The closely spaced age-calibrated ^{14}C plateau boundaries imply multiple centennial-scale changes in sedimentation rate, as well as, two millennial-scale stratigraphic gaps during late LGM, previously undetected (Figures 1 and S1; details on Core MD08-3180 in *Sarnthein et al*. [2015]). In all cores sedimentation rates increase significantly over the YD, the second half of HS-1 (^{14}C plateau 2a), and at terminal LGM (^{14}C plateaus 4–5); in part, they rise by a factor >2. These short-term changes modify the age control formerly derived by linear interpolation of long-term sedimentation rates and thus may lead to major reassessments of paleoceanographic conclusions previously published. Reevaluations are suggested in view of Dansgaard-Oeschger cycles as short as 1500 years, the 2800 years interval of HS-1, and the urgent need to trace centennial-to-millennial-scale leads and lags of climate signals starting in either the northern or southernmost high-latitude Atlantic.

4. Discussion

4.1. Modeled Versus Empiric Reservoir Ages of LGM Surface Waters—A Comparison

Models of *Franke et al*. [2008] and *Butzin et al*. [2012] both assume that past reservoir age changes of tropical and subtropical-to-subpolar surface waters mainly result from changes in both atmospheric ^{14}C concentration and reductions in AMOC. According to *Franke et al*. [2008], using only atmospheric ^{14}C concentrations and a 30% AMOC reduction, LGM reservoir ages did not differ from preindustrial (PD) values by more than 100 ^{14}C years, except for ~200 ^{14}C years simulated off Southern Brazil and in the Caribbean. By contrast, *Butzin et al*. [2012], using a more refined and realistic model, simulate LGM anomalies that reach 200–600 ^{14}C years in the low-latitude Atlantic and even 1400–1800 ^{14}C years near ~50°S (Figure 2 and Table 1). In the Caribbean early deglacial age anomalies briefly reach 500 ^{14}C years, though unspecified for the location precisely addressed by model simulation.

To compare the model data with our empiric monospecific records, we ignore interspecies offsets and different seasonal signals of various planktic species (for details see supporting information Text S3). Our empiric ^{14}C reservoir ages corroborate the main simulated patterns and trends of *Butzin et al*. [2012] (Table 1) but show discrepancies with model results of *Franke et al*. [2008], mainly in the extremes in low latitudes. In the Benguela upwelling belt, empiric LGM reservoir ages are significantly higher than those of *Franke et al*. [2008], in contrast to modestly high ages in the west Atlantic, off Southern Brazil. In the LGM Cariaco Basin (ODP 1002), which then formed a semienclosed lagoon due to low sea level, empiric reservoir ages fell to close to 0 at ~21–19 cal. ka. In this case the immediate exchange of atmospheric CO_2 dominated the LGM ^{14}C balance of Cariaco surface waters and replaced step-by-step antecedent incursions of old surface waters from outside dominant prior to 21.5 cal. ka.

At southern subpolar Site MD07-3076 LGM reservoir ages in part may present a subsurface signal because of meltwater stratification. These ages were reconstructed both by tuning SST signals to temperature signals of Antarctic ice cores [*Skinner et al*., 2010] and by our technique of ^{14}C plateau tuning (Figures 1 and S1d). Both lines of evidence produce reservoir ages that exceed the modeled age values of *Franke et al*. [2008] by 1000–2000 ^{14}C years but come fairly close to the estimates of *Butzin et al*. [2012] simulated for the major upwelling belt 4°–6° farther south. Similar and older reservoir ages were reported from the

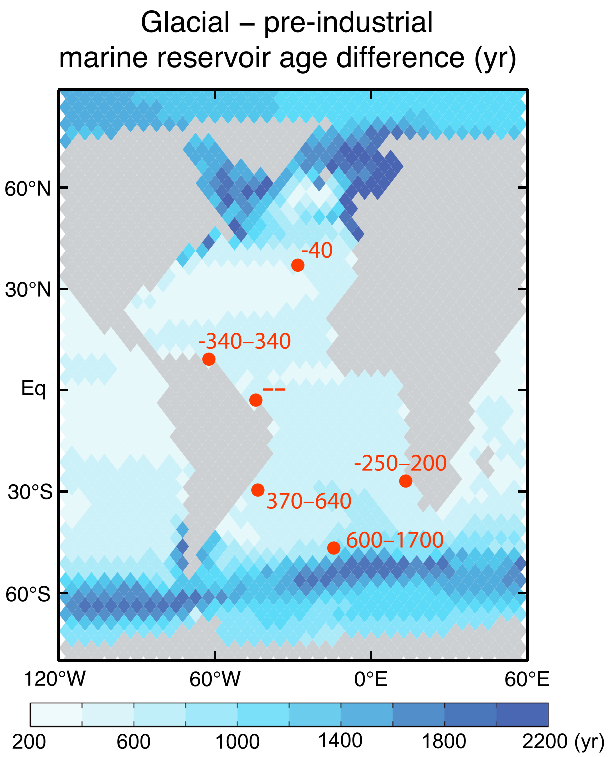

Figure 2. Simulated marine reservoir age difference between the glacial surface ocean (according to the spin-up with LGM climate forcing, i.e., MOC scenario GS, $\Delta^{14}C_{atm}$ = 520‰ and atmospheric CO_2 = 185 ppmv) and the preindustrial (PD) surface ocean (control integration with present-day climate forcing $\Delta^{14}C_{atm}$ = 0‰ and atmospheric CO_2 = 280 ppmv) [*Butzin et al.*, 2012, modified]. Red numbers are empiric LGM-to-B/A reservoir age anomalies regarded as in principle similar to those between the LGM and PD surface ocean.

glacial southwestern Pacific near to the Subtropical Front SE of New Zealand [*Sikes and Guilderson*, 2016; *Ronge et al.*, 2016]. However, a detailed intercomparison with short-term deglacial ^{14}C events in our records is precluded, since absolute age markers (two tephras at 14 and 18 ka and a third age back at 25.5 ka) are scarce and the ^{14}C sampling density is insufficient to define plateaus.

By contrast, empiric LGM reservoir ages at North Atlantic Site MD08-3180 match the age range predicted by both models (Table 1), as this site still belonged to the subtropics [*Pflaumann et al.*, 2003]. Off Iberia, LGM reservoir ages of 400–500 years modeled by *Franke et al.* [2008] likewise contrast with values modeled by *Butzin et al.* [2012] and empiric values of 1100–1700 years of *Skinner et al.* [2014] (mainly based on *G. bulloides* and *N. pachyderma* sinistral). The high local values probably resulted from LGM coastal upwelling [*Abrantes*, 1991].

In summary, the closer affinity of our empiric ^{14}C reservoir ages to the model ages of *Butzin et al.* [2012] versus those of *Franke et al.* [2008] may be linked to the more realistic model design of Butzin et al. (Table 2), which considered the LGM freshwater balance in the Southern Ocean and, in particular, the LGM SST and wind fields, as well as a more realistic gas transfer velocity for the exchange of ^{14}C of CO_2 of *Sweeney et al.* [2007]. Thus, paleoceanographers building ^{14}C-based age models will gain quality when using reservoir ages from detailed realistic models like that of *Butzin et al.* [2012] instead of assuming constant ^{14}C year values of 400 years. Precise age control is an indispensable condition to derive deepwater (apparent) ventilation ages and local leads and lags that reveal past circulation geometries and help quantify the role of the ocean in the global carbon cycle [*Sarnthein et al.*, 2013]. In particular, precise ventilation ages document the net ocean primary productivity and patterns of deep and intermediate-water oxygenation under different glacial and deglacial climate conditions.

4.2. High- Versus Low-Latitude Trends in Glacial-to-Deglacial Reservoir Age Records

Though Site MD08-3180 lies slightly south of the LGM subpolar front at 38°N, LGM-to-deglacial reservoir ages (Figure 1) show a trend basically similar to that reported by *Stern and Lisiecki* [2013] for the “average high-latitude North Atlantic.” Their results agree with ours in showing low reservoir ages of 300–600 years for the LGM. They also agree for HS-1, when both high values of up to 1300–1600 years and paired planktic $\delta^{18}O$ minima at MD08-3180 suggest major meltwater incursions (Balmer and Sarnthein, submitted manuscript). In our record, however, these events lasted from 18 to 14.5 cal. ka but from 19.5 to 16 cal. ka in that of *Stern and Lisiecki* [2013]. The different timing may either record different meltwater events affecting different parts of the North Atlantic or suggest problems with the age model. By comparison, the deglacial, possibly meltwater-induced reservoir ages at South Atlantic Site MD07-3076 culminated as early as 19.2–18.0 cal. ka.

Trade winds are a major forcing of surface currents in the subtropical South Atlantic. As LGM trade winds intensified along the eastern continental margin during austral winter [*Little et al.*, 1997], coastal upwelling of ^{14}C-depleted intermediate waters was enhanced off Benguela, which resulted in maximum reservoir ages of surface waters (Figures 1 and S1a), a feature promoted by the seaward shift of LGM coastlines. On the other hand, LGM reservoir ages and upwelling also increased at Site KNR 159-5-36 in the Southeast Brazil Bight, here probably controlled by enhanced winds during austral summer (in the sense of *Campos et al*. [2000]) and by lowered sea level.

Reservoir ages and upwelling dropped all over the subtropical South Atlantic over HS-1. In particular, reservoir ages dropped to 250–400 years at ^{14}C plateau boundary 2a–2b, 16.05 cal. ka. This marked drop immediately followed a distinct short-term rise in atmospheric pCO_2 and West Antarctic temperature at 16.3–16.05 cal. ka [*Marcott et al*., 2014], which probably induced a reduction of subtropical winds. The subsequent low in ^{14}C reservoir ages and Benguela upwelling already ended at the end of HS-1 (Figure 1). In turn, *Thornalley et al*. [2015] demonstrated a clear feedback of the 16.2 ka event on AMOC with a strong pulse of deepwater convection that necessarily paralleled a widespread rejuvenation of surface waters as postulated by models and shown by our empiric records.

5. Conclusions

Glacial-to-deglacial planktic ^{14}C records were analyzed in the low-latitude and midlatitude Atlantic by means of the ^{14}C plateau-tuning technique. The results suggest significant spatial and temporal changes in the ^{14}C reservoir age of surface waters (Figure 1) that imply a major step forward toward more accurate radiocarbon chronologies for the last deglaciation. In part, the changing reservoir ages are linked to changes in the habitat depth of planktic tracer species, taking into account differential monospecific ^{14}C records measured in parallel, and to changes in seasonal climate. These changes of climate affected the coastal upwelling belts off Southern Africa and Southern Brazil, where LGM reservoir ages reached 750–100 and almost 900 ^{14}C years, respectively, suggesting an enhanced upwelling intensity as result of strengthened long-shore winds and seaward shoreline shift. Both changing reservoir ages and the interpolation of calendar ages between age-calibrated ^{14}C plateau boundaries lead to new age assignments that precisely match correlated U/Th-dated events in speleothems but strongly differ from previous ^{14}C-based chronologies, thus implying the need of a reevaluation of paleoceanographic correlations.

In the tropics and subtropics our empiric ^{14}C reservoir ages are largely consistent with model-based estimates of *Butzin et al*. [2012] for the LGM, also with extremes found in southern midlatitudes, but disagree with model estimates of *Franke et al*. [2008] that underestimate our midlatitude values by up to ~2000 ^{14}C years. The differences of the two models imply that realistic boundary conditions of SST and wind fields, as well as the freshwater balance and past ^{14}C concentrations, are needed to obtain realistic ^{14}C reservoir ages. Thus, ^{14}C reservoir ages provide a highly sensitive and important tracer of past changes in ocean surface conditions and ocean circulation.

Our new estimates of ^{14}C reservoir ages provide a novel basis to improve centennial-to-millennial-scale chronologies of the last glacial and deglaciation. They facilitate a series of new insights into past changes of climate and the spatial details and leads and lags of ocean circulation over short time scales by highlighting the importance of using detailed realistic boundary conditions in modeling.

Acknowledgments
We acknowledge valuable discussions with Gerrit Lohmann and Birgit Schneider, as well as most constructive suggestions of reviewers on an earlier version of this manuscript. We thank the Kiel Leibniz Laboratory for AMS ^{14}C ages and John Southon, University of California Irvine, for measuring AMS ^{14}C ages on extremely small foraminifera samples, as well as various students for careful help in sample preparation. Samples from South Atlantic cores were kindly provided by Delia Oppo, Woods Hole, and MARUM, Bremen, that also gave access to an XRF facility. Our study was supported by DFG grant Sa207/48. Scientific data are stored at http://doi.pangaea.de/10.1594/PANGAEA.

References

Abrantes, F. (1991), Increased upwelling off Portugal during the last glaciation: Diatom evidence, *Mar. Micropaleontol.*, *17*, 285–310.

Bitz, C. M., M. M. Holland, A. J. Weaver, and M. Eby (2001), Simulating the ice-thickness distribution in a coupled climate model, *J. Geophys. Res.*, *206*, 2241–2464.

Broecker, W. S., and E. A. Olson (1961), Lamont radiocarbon measurements VIII, *Radiocarbon*, *3*, 176–204.

Broecker, W., S. Barker, E. Clark, I. Hajdas, G. Bonani, and L. Stott (2004), Ventilation of the glacial deep Pacific Ocean, *Science*, *306*, 1169–1172.

Bronk Ramsey, C., R. A. Staff, C. L. Bryant, F. Brock, H. Kitagawa, J. van der Plicht, G. Schlolaut, M. H. Marshall, A. Brauer, and H. F. Lamb (2012), A complete terrestrial radiocarbon record for 11.2 to 52.8 kyr BP, *Science*, *338*, 370–374.

Butzin, M., M. Prange, and G. Lohmann (2012), Readjustment of glacial radiocarbon chronologies by self-consistent three-dimensional ocean circulation modeling, *Earth Planet. Sci. Lett.*, *317*, 177–184.

Came, R. E., Oppo, D. W., and W. B. Curry (2003), Atlantic ocean circulation during the Younger Dryas: Insights from a new Cd/Ca record from the western subtropical South Atlantic, *Paleoceanography*, *18*(4), 1086, doi:10.1029/2003PA000888.

Campos, E. J., D. Velhote, and I. C. da Silveira (2000), Shelf break upwelling driven by Brazil Current cyclonic meanders, *Geophys. Res. Lett.*, *27*, 751–754, doi:10.1029/1999GL010502.

Castelao, R. M., E. J. D. Campos, and J. L. Miller (2004), A modelling study of coastal upwelling driven by wind and meanders of the Brazil Current, *J. Coastal Res.*, *20*(3), 662–671.

Darling, K. F., and C. M. Wade (2008), The genetic diversity of planktic foraminifera and the global distribution of ribosomal RNA genotypes, *Mar. Micropaleontol.*, *67*(3), 216–238.

Fanning, A. F., and A. J. Weaver (1996), An atmospheric energy-moisture balance model: Climatology, interpentadal climate change, and coupling to an ocean general circulation model, *J. Geophys. Res.*, *101*, 15,111–15,128, doi:10.1029/96JD01017.

Fraile, I., S. Mulitza, and M. Schulz (2009), Modeling planktonic foraminiferal seasonality: Implications for sea-surface temperature reconstructions, *Mar. Micropaleontol.*, *72*(1), 1–9.

Franke, J., A. Paul, and M. Schulz (2008), Modeling variations of marine reservoir ages during the last 45 000 years, *Clim. Past*, *4*, 125–136.

Freeman, E., L. Skinner, A. Tisserand, T. Dokken, A. Timmermann, L. Menviel, and T. Friedrich (2015), An Atlantic–Pacific ventilation seesaw across the last deglaciation, *Earth Planet. Sci. Lett.*, *424*, 237–244.

Ganssen, G., and M. Sarnthein (1983), Stable-isotope composition of foraminifers: The surface and bottom water record of coastal upwelling, in *Coastal Upwelling Its Sediment Record*, pp. 99–121, Springer, New York.

Gasser, T., and H.-G. Müller (1979), Kernel estimation of regression functions, in *Smoothing Techniques for Curve Estimation*, edited by T. Gasser and M. Rosenblatt, pp. 23–68, Springer, Berlin.

Gasser, T., and H.-G. Müller (1984), Estimating regression functions and their derivatives by the kernel method, *Scand. J. Stat.*, *11*(3), 171–185.

Groeneveld, J., and C. M. Chiessi (2011), Mg/Ca of *Globorotalia inflata* as a recorder of permanent thermocline temperatures in the South Atlantic, *Paleoceanography*, *26*, PA2203, doi:10.1029/2010PA001940.

Grootes, P. M. (2015), Radiocarbon: Clock and tracer, in *Encyclopedia of Marine Geosciences*, edited by J. Harff et al., pp. 1–7, Springer, Netherlands.

Hemleben, C., M. Spindler, and O. Erson (1989), *Modern Planktonic Foraminifera*, pp. 363, Springer, Berlin.

Huang, E., L. C. Skinner, S. Mulitza, A. Paul, and M. Schulz (2015), Radiocarbon distribution and radiocarbon-based circulation age of the Atlantic Ocean during Last Glacial Maximum, in *Nova Acta Leopoldina NF Nr. 121*, vol. 408, pp. 101–106, Deutsche Akademie der Naturforscher Leopoldina - Nationale Akademie der Wissenschaften, Halle (Saale).

Hughen, K. A., J. Southon, S. Lehman, C. Bertrand, and J. Turnbull (2006), Marine-derived ^{14}C calibration and activity record for the past 50,000 years updated from the Cariaco Basin, *Quat. Sci. Rev.*, *25*, 3216–3227.

Jaeschke, A., C. Rühlemann, H. Arz, G. Heil, and G. Lohmann (2007), Coupling of millennial-scale changes in sea surface temperature and precipitation off northeastern Brazil with high-latitude climate shifts during the last glacial period, *Paleoceanography*, *22*, PA4206, doi:10.1029/2006PA001391.

Key, R. M., A. Kozyr, C. L. Sabine, K. Lee, R. Wanninkhof, J. L. Bullister, R. A. Feely, F. J. Millero, C. Mordy, and T.-H. Peng (2004), A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP), *Global Biogeochem. Cycles*, *18*, GB4031, doi:10.1029/2004GB002247.

Lemieux-Dudon, B., E. Blayo, J.-R. Petit, C. Waelbroeck, A. Svensson, C. Ritz, J.-M. Barnola, B. M. Narcisi, and F. Parrenin (2010), Consistent dating for Antarctic and Greenland ice cores, *Quat. Sci. Rev.*, *29*, 8–20.

Little, M., R. Schneider, D. Kroon, B. Price, T. Bickert, and G. Wefer (1997), Rapid palaeoceanographic changes in the Benguela Upwelling System for the last 160,000 years as indicated by abundances of planktonic foraminifera, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *130*, 135–161.

Lütjeharms, J. E. R., and J. M. Meeuwis (1987), The extent and variability of south-east Atlantic upwelling, in *The Benguela and Comparable Ecosystems*, edited by A. L. L. Payne, J. A. Gulland, and K. H. Brink, *S. Afr. J. Mar. Sci.*, *5*, 51–62.

Marcott, S. A., T. K. Bauska, C. Buizert, E. J. Steig, J. L. Rosen, K. M. Cuffey, T. Fudge, J. P. Severinghaus, J. Ahn, and M. L. Kalk (2014), Centennial-scale changes in the global carbon cycle during the last deglaciation, *Nature*, *514*, 616–619.

Mudelsee, M. (2014), *Climate Time Series Analysis: Classical Statistical and Bootstrap Methods*, 2nd ed., pp. 454, Springer, Cham, Switzerland.

Mulitza, S., T. Wolff, J. R. Pätzold, W. Hale, and G. Wefer (1998), Temperature sensitivity of planktic foraminifera and its influence on the oxygen isotope record, *Mar. Micropaleontol.*, *33*(3), 223–240.

Nadeau, M. J., P. M. Grootes, M. Schleicher, P. Hasselberg, A. Rieck, and M. Bitterling (1998), Sample throughput and data quality at the Leibniz-Labor AMS facility, *Radiocarbon*, *40*(1), 239–245.

Nydal, R., K. Lovseth, and F. H. Skogseth (1980), Transfer of bomb ^{14}C in the surface ocean, *Radiocarbon*, *22*(3), 626–635.

Pflaumann, U., et al. (2003), Glacial North Atlantic: Sea-surface conditions reconstructed by GLAMAP 2000, *Paleoceanography*, *18*(3), 1065, doi:10.1029/2002PA000774.

Prell, W. L., J. Imbire, D. G. Martinson, J. J. Morley, N. G. Pistas, N. J. Shackleton, and H. F. Streeter (1986), Graphic correlation of oxygen isotope stratigraphy application to the late Quaternary, *Paleoceanography*, *1*, 137–162, doi:10.1029/PA001i002p00137.

Reimer, P. J., et al. (2013), INTCAL13 and MARINE13 radiocarbon age calibration curves 0–50,000 years cal BP, *Radiocarbon*, *55*(4), 1869–1887.

Ronge, T., R. Tiedemann, F. Lamy, P. Köhler, B. V. Alloway, R. De Pol-Holz, K. Pahnke, J. Southon, and L. Wacker (2016), Radiocarbon constraints on the extent and evolution of the South Pacific glacial carbon pool, *Nat. Commun.*, *7*, 11487, doi:10.1038/ncomms11487.

Sarnthein, M., P. M. Grootes, J. P. Kennett, and M. Nadeau (2007), *^{14}C Reservoir Ages Show Deglacial Changes in Ocean Currents and Carbon Cycle*, *Geophys. Monogr.*, vol. 173, pp. 175–196, AGU, Washington, D. C.

Sarnthein, M., B. Schneider, and P. M. Grootes (2013), Peak glacial ^{14}C ventilation ages suggest major draw-down of carbon into the abyssal ocean, *Clim. Past*, *9*, 2595–2614.

Sarnthein, M., S. Balmer, P. M. Grootes, and M. Mudelsee (2015), Planktic and benthic ^{14}C reservoir ages for three ocean basins, calibrated by a suite of ^{14}C plateaus in the glacial-to-deglacial Suigetsu atmospheric ^{14}C record, *Radiocarbon*, *57*, 129–151.

Sautter, L. R., and C. Sancetta (1992), Seasonal associations of phytoplankton and planktic foraminifera in an upwelling region and their contribution to the seafloor, *Mar. Micropaleontol.*, *18*, 263–278.

Schlitzer, R. (2015), Ocean data view. [Available at http://odv.awi.de].

Schwab, C., H. Kinkel, M. Weinelt, and J. Repschläger (2012), Coccolithophore paleoproductivity and ecology response to deglacial and Holocene changes in the Azores Current System, *Paleoceanography*, *27*, PA3210, doi:10.1029/2012PA002281.

Shannon, L. V., and G. Nelson (1996), The Benguela: Large-scale features and processes and system variability, in *The South Atlantic: Present and Past Circulation*, edited by G. Wefer et al., pp. 163–210, Springer, Berlin.

Sikes, E. L., and T. P. Guilderson (2016), Southwest Pacific Ocean surface reservoir ages since the last glaciation: Circulation insights from multiple-core studies, *Paleoceanography*, *31*, 298–310, doi:10.1002/2015PA002855.

Simstich, J., M. Sarnthein, and H. Erlenkeuser (2003), Paired δ^{18}O signals of *Neogloboquadrina pachyderma* (s) and *Turborotalita quinqueloba* show thermal stratification structure in Nordic Seas, *Mar. Micropaleontol.*, *48*(1), 107–125.

Skinner, L. C., S. Fallon, C. Waelbroeck, E. Michel, and S. Barker (2010), Ventilation of the deep Southern Ocean and deglacial CO_2 rise, *Science*, *328*, 1147–1151.

Skinner, L. C., C. Waelbroeck, A. E. Scrivner, and S. J. Fallon (2014), Radiocarbon evidence for alternating northern and southern sources of ventilation of the deep Atlantic carbon pool during the last deglaciation, *Proc. Natl. Acad. Sci. U.S.A.*, *111*, 5480–5484.

Sortor, R. N., and D. C. Lund (2011), No evidence for a deglacial intermediate water $\Delta^{14}C$ anomaly in the SW Atlantic, *Earth Planet. Sci. Lett.*, *310*, 65–72.

Stern, J. V., and L. E. Lisiecki (2013), North Atlantic circulation and reservoir age changes over the past 41,000 years, *Geophys. Res. Lett.*, *40*, 3693–3697, doi:10.1002/grl.50679.

Stuiver, M., and H. A. Polach (1977), Discussion: Reporting of C-14 data, *Radiocarbon*, *19*(3), 355–363.

Stuiver, M., and P. J. Reimer (1993), Extended ^{14}C database and revised CALIB radiocarbon calibration program, *Radiocarbon*, *35*, 215–230.

Stuiver, M., and T. F. Braziunas (1993), Modeling atmospheric ^{14}C influences and ^{14}C ages of marine samples to 10,000 BC, *Radiocarbon*, *35*, 137–189.

Stuiver, M., G. W. Pearson, and T. Braziunas (1986), Radiocarbon age calibration of marine samples back to 9000 cal yr BP, *Radiocarbon*, *38*(2B), 980–1021.

Sweeney, C., E. Gloor, A. R. Jacobsen, R. M. Key, G. McKinley, J. l. Sarmiento, and R. Wanninkof (2007), Constraining global air-sea gas exchange for CO_2 with recent bomb ^{14}C measurements, *Global Biochem. Cycles*, *21*, GB2015, doi:10.1029/2006GB002784.

Thornalley, D. J. R., H. A. Bauch, G. Gebbie, W. Gua, M. Ziegler, S. M. Bernasconi, S. Barker, L. C. Skinner, and J. Wu (2015), A warm and poorly ventilated deep Arctic Mediterranean during the last glacial period, *Science*, *649*, 706–710.

Vidal, L., R. R. Schneider, O. Marchal, T. Bickert, T. Stocker, and G. Wefer (1999), Link between the North and South Atlantic during the Heinrich events of the last glacial period, *Clim. Dyn.*, *15*, 909–919.

Vogel, J. S., J. R. Southon, D. Nelson, and T. A. Brown (1984), Performance of catalytically condensed carbon for use in accelerator mass spectrometry, *Nucl. Instrum. Methods Phys. Res. B*, *5*(2), 289–293, doi:10.1016/0168-583x(84)90529-9.

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