

Rapid transient changes in northeast Atlantic deep water ventilation age across Termination I

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[1] A sequence of accelerator mass spectrometry (AMS) ^{14}C dates performed on benthic and planktonic foraminifera from a northeast Atlantic deep-sea core (MD99-2334K; $37^{\circ}48'\text{N}$, $10^{\circ}10'\text{W}$; 3146 m) permit the reconstruction of deep water “ ^{14}C ventilation ages” across the last deglaciation. The records from MD99-2334K have been placed on the GISP2 timescale via the synchrony of temperature changes recorded in the Greenland ice cores and in North Atlantic planktonic $\delta^{18}\text{O}_{\text{cc}}$ (calcite $\delta^{18}\text{O}$). On the basis of a range of estimates for past source water $\Delta^{14}\text{C}$, this permits the estimation of ^{14}C projection ventilation ages for comparison with benthic-planktonic ^{14}C age differences. Although the accurate estimation of past ventilation ages is precluded by unknown deep water $\Delta^{14}\text{C}$ source signatures, and by uncertainty regarding the extent of deep water mixing, it is clear that deep water ventilation in the northeast Atlantic was significantly reduced during the last glaciation, increased abruptly coincident with the Bølling-Allerød warming, and rapidly became reduced again during the Younger Dryas cold reversal. The character of these changes is consistent with a varying dominance of North Atlantic Deep Water (NADW) versus Antarctic Bottom Water (AABW). Parallel benthic $\delta^{13}\text{C}$, deep water temperature (T_{dw}), and deep water $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{\text{dw}}$) estimates support this inference. The fact that deglacial changes in the deep water radiocarbon content of the northeast Atlantic run parallel to opposite changes in atmospheric radiocarbon content, and in parallel with Greenland temperature fluctuations, unequivocally implicates changes in ocean circulation in deglacial climate evolution and illustrates the capacity for the deep ocean to respond and contribute to abrupt climate change. *INDEX TERMS:* 0330 Atmospheric Composition and Structure: Geochemical cycles; 1035 Geochemistry: Geochronology; 1620 Global Change: Climate dynamics (3309); 4504 Oceanography: Physical: Air/sea interactions (0312); *KEYWORDS:* Termination I, ventilation age, thermohaline circulation

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1. Introduction

[2] Changes in the ventilation rate of the deep sea are directly linked to climate via their dependence on the meridional overturning, which is capable of redistributing vast quantities of heat over the globe and responsible for the efficient mixing of surface waters (variously equilibrated with the atmosphere) deep into the ocean's interior. The radiocarbon content of the deep sea provides a direct estimate of deep water ventilation, provided the calendar age of the deep water, the extent of mixing of different initial source waters and the initial $^{14}\text{C}/\text{C}$ ratio (expressed as permil $\Delta^{14}\text{C}$) of each of these sources can be ascertained. Estimates of past deep water ventilation are most commonly made on the basis of parallel ^{14}C dates for planktonic and benthic foraminifer shells [Broecker *et al.*, 1984], though well-calibrated ^{14}C ages for benthic samples, in combination with estimates of past source-water $\Delta^{14}\text{C}$, provide an alternative and more elegant method [Adkins and Boyle, 1997]. In all paleoventilation reconstructions, defining calendar ages, the initial $\Delta^{14}\text{C}$ of source waters and the extent of source mixing for past deep water $\Delta^{14}\text{C}$ estimates is

often, if not generally, impossible, particularly given the lack of well-tested reconstructions of past atmospheric $\Delta^{14}\text{C}$ variations beyond ~ 15 kyr BP. In the Atlantic Ocean, unambiguously determining the degree of northern versus southern source water mass mixing represents a further persistent difficulty; a difficulty that is compounded by the potentially variable character of water mass signatures on glacial-interglacial timescales and the convoluted and variable controls on proxies often used as source indicators, such as benthic $\delta^{13}\text{C}$ [Curry *et al.*, 1988]. In addition, great care must be taken in the interpretation of radiocarbon ratios, which generally cannot be interpreted simply in terms of water mass flow rates and will only rarely reveal indications of true “circulation times” [Wunsch, 2003].

[3] If accurate knowledge of past atmospheric $\Delta^{14}\text{C}$ is essential to the reconstruction of deep sea $\Delta^{14}\text{C}$ changes, deep sea $\Delta^{14}\text{C}$ reconstructions are in turn necessary for a full understanding (hence explanation) of past atmospheric $\Delta^{14}\text{C}$ perturbations. It is estimated that the deep equatorial Atlantic and Pacific were both less ventilated during the last glaciation, with deep waters ~ 325 years ($\sim 190\%$) older on average in the Atlantic and ~ 600 years ($\sim 140\%$) older in the Pacific [Shackleton *et al.*, 1988; Broecker *et al.*, 1990; Adkins and Boyle, 1997]. These estimates imply a reduced flow of North Atlantic Deep Water (NADW) into the deep

glacial ocean, corroborating benthic $\delta^{13}\text{C}$ and Cd/Ca evidence to the same effect [Boyle and Keigwin, 1987; Curry *et al.*, 1988; Duplessy *et al.*, 1988], though they do not necessarily imply an overall reduced glacial overturning [Wunsch, 2003]. Indeed, in many cases, evidence of a reduced southward export of NADW may be equivalent to evidence of increased northward export of AABW [Curry *et al.*, 1988; Duplessy *et al.*, 1988; Broecker, 1998; Skinner *et al.*, 2003], and may also be consistent with an overall increased meridional over-turning vigor, depending on atmospheric boundary conditions for example [Wunsch, 2003].

[4] It has been suggested that NADW flow was strongly curtailed during millennial scale ice-rafting and stadial events that punctuated the glaciation and the glacial termination, including Heinrich event 1 and the Younger Dryas [Broecker, 1998; Boyle, 2000; Clark *et al.*, 2002b]. Although there is radiocarbon evidence for ventilation changes at intermediate water depths in the Atlantic and Pacific oceans across the Bølling-Allerød, Younger Dryas, Holocene transition [Schroder-Ritzrau *et al.*, 2003], the data remains too sparse to adequately resolve ventilation transients [Adkins and Boyle, 1997; Adkins *et al.*, 1998] and is lacking from deep sea settings (>2000 m) where the deglacial evolution of NADW flow will have been directly recorded. Despite the relative paucity of geological evidence for deep-sea $\Delta^{14}\text{C}$ fluctuations, numerous modeling studies [Stocker and Wright, 1996, 1998; Muscheler *et al.*, 2000b; Delaygue *et al.*, 2003] have yielded important insights into the possible mechanisms that have been responsible for past radiocarbon budget variations that are expressed in the geological record [Bard *et al.*, 1998; Stuiver *et al.*, 1998; Hughen *et al.*, 2000; Kitagawa and van der Plicht, 2000; Beck *et al.*, 2001; Hughen *et al.*, 2004]. These modeling studies have indicated in particular the significance of freshwater forced thermohaline circulation collapse (and atmospheric circulation) in effecting large and rapid changes in the atmospheric ^{14}C budget [e.g., Delaygue *et al.*, 2003], thus providing a useful conceptual basis for the interpretation of geological $\Delta^{14}\text{C}$ reconstructions, which in turn provide important criteria for the evaluation of the modeling premises.

[5] Here parallel benthic and planktonic ^{14}C dates obtained from a high sedimentation rate core raised from the deep northeast Atlantic (MD99-2334K; $37^{\circ}48'\text{N}$, $10^{\circ}10'\text{W}$; 3146 m) permit the reconstruction of deep-sea ventilation changes across the last deglaciation. By placing core MD99-2334K on the GISP2 calendar chronology, local surface water reservoir ages and projection ages may be estimated in addition to benthic-planktonic ^{14}C age differences. These in turn may be interpreted in terms of deep water mass exchange by drawing on parallel benthic $\delta^{13}\text{C}$ measurements and estimates of deep water temperature (T_{dw}) and $\delta^{18}\text{O}_{\text{dw}}$ also from MD99-2334K.

2. Material and Methods

[6] Core MD99-2334K was raised from a water depth of 3146 m on the Iberian Margin ($37^{\circ}48'\text{N}$, $10^{\circ}10'\text{W}$). Sixteen monospecific samples of *Globigerina bulloides* and/or *Neogloboquadrina pachyderma* (*sinistral*) and 6 samples of benthic foraminifera were taken from local abundance maxima for each foraminifer type in order to minimize the effects of bioturbation [Bard *et al.*, 1987a]. Sample sizes were ~ 11 mg on average. For benthic samples it was necessary to combine specimens from 2–3 cm intervals in order to obtain sufficient material for reliable dating. Depths for benthic samples are thus quoted as averages weighted according to the ratio of carbonate taken from each 1 cm interval. All AMS ^{14}C dates were performed at the LSCE (Gif-sur-Yvette, France). Benthic $\delta^{13}\text{C}$ measurements were performed on samples of *Planulina wuellerstorfi* (>212 μm), and were carried out at the Godwin Laboratory (Cambridge University) on a Micromass Multicarb Sample Preparation System attached to a PRISM mass spectrometer. Measurements of $\delta^{13}\text{C}$ were determined relative to the Vienna Pee Dee belemnite (VPDB) standard, and the analytical precision was better than 0.06‰.

globoquadrina pachyderma (*sinistral*) and 6 samples of benthic foraminifera were taken from local abundance maxima for each foraminifer type in order to minimize the effects of bioturbation [Bard *et al.*, 1987a]. Sample sizes were ~ 11 mg on average. For benthic samples it was necessary to combine specimens from 2–3 cm intervals in order to obtain sufficient material for reliable dating. Depths for benthic samples are thus quoted as averages weighted according to the ratio of carbonate taken from each 1 cm interval. All AMS ^{14}C dates were performed at the LSCE (Gif-sur-Yvette, France). Benthic $\delta^{13}\text{C}$ measurements were performed on samples of *Planulina wuellerstorfi* (>212 μm), and were carried out at the Godwin Laboratory (Cambridge University) on a Micromass Multicarb Sample Preparation System attached to a PRISM mass spectrometer. Measurements of $\delta^{13}\text{C}$ were determined relative to the Vienna Pee Dee belemnite (VPDB) standard, and the analytical precision was better than 0.06‰.

3. Results and Discussion

3.1. AMS ^{14}C Dates

[7] The planktonic and benthic ^{14}C dates obtained for core MD99-2334K are summarized in Table 1. Three pairs of *G. bulloides* and *N. pachyderma* samples yield ^{14}C dates that differ by less than their 2- σ uncertainty level, supporting the absence of significant bioturbation and/or dissolution effects on these samples [Broecker *et al.*, 1984, 1990]. A comparable diagenetic integrity is expected for all of the samples from MD99-2334K, in which the average sedimentation rate is ~ 20.5 cm kyr $^{-1}$. Because of the requirement of larger (2–3 cm) sample intervals for benthic analyses, the planktonic and benthic samples could not be taken from precisely matching core depths; hence corresponding planktonic dates must be interpolated from bounding planktonic ^{14}C age measurements. The depth offsets between benthic and planktonic samples are small enough (<6 cm) to preclude significant errors in the interpolated planktonic ^{14}C dates, as such errors would require unrealistic nonlinear variations in sedimentation rate over centimeter scales. Indeed interpolated planktonic ^{14}C ages never differ from their nearest measured planktonic ^{14}C date by more than the 2- σ uncertainty inherent in the original ^{14}C age measurements. Additional planktonic ^{14}C dates have been transferred from the nearby core SU81-18 [Bard *et al.*, 1987b] by correlation of the planktic $\delta^{18}\text{O}_{\text{cc}}$ (calcite $\delta^{18}\text{O}$) records from SU81-18 and MD99-2334K. This provides the interpolated planktonic ^{14}C date that corresponds to the youngest of the benthic ^{14}C dates obtained in MD99-2334K.

3.2. Benthic-Planktonic and Projection Ventilation Ages

[8] The comparison of contemporaneous benthic and planktonic ^{14}C ages is one method of inferring past deep-sea ventilation rates [Broecker *et al.*, 1990]. Another strategy involves the calculation of “projection ages”: the age difference between deep water and its assumed source at the time of sequestration (rather than the surface water above it) [Adkins and Boyle, 1997]. This method requires calendar ages for benthic ^{14}C dated samples and a record of source-water $\Delta^{14}\text{C}$. Both of these approaches suffer drawbacks: the

Table 1. Planktonic and Benthic ^{14}C Dates, and Correlative Calendar Ages, for Core MD99-2334K

MD99-2334K Corrected Depth, cm	Species	^{14}C Age, ^a years	^{14}C Error, 1σ years	GISP2 Correlative Age, years	GISP2 Error, ^b 1σ years	$\Delta^{14}\text{C}$, ‰	$\Delta^{14}\text{C}$ Error, 1σ ‰
<i>Planktonic Dates</i>							
154	G. bull	12,960	110	14,438	289	142.58	24.01
172	G. bull	13,890	130	15,293	306	128.67	23.26
186	G. bull	13,920	110	15,956	319	218.28	29.98
186	N. pac-s	14,050	120	15,956	319	198.72	28.04
226	N. pac-s	15,050	140	17,848	357	330.74	33.84
246	G. bull	16,180	120	18,795	376	296.35	38.99
278	G. bull	17,780	140	20,309	406	275.75	39.82
314	G. bull	19,170	150	22,276	446	361.38	47.12
346	G. bull	21,160	190	24,165	483	335.43	45.69
346	N. pac-s	21,070	180	24,165	483	350.47	47.83
370	G. bull	22,700	220	26,141	523	400.24	49.33
390	G. bull	24,480	220	27,788	556	369.31	53.49
414	G. bull	26,310	200	29,767	595	385.27	63.77
414	N. pac-s	26,710	200	29,767	595	317.98	60.67
422	G. bull	27,110	310	30,428	609	358.32	46.76
450	G. bull	29,640	360	32,741	655	311.40	44.35
<i>Benthic Dates</i>							
115	Mixed	11,800	150	12,064	241	-9.40	48.57
149	Mixed	13,230	150	14,148	283	66.74	57.95
150	Mixed	13,290	130	14,244	285	71.25	55.65
173	Mixed	15,220	140	15,293	306	-43.55	53.50
186	Mixed	15,940	150	15,909	318	-57.99	55.42
313	Mixed	20,370	180	22,161	443	156.28	91.34

^aUncorrected for reservoir age.^bFrom Meese *et al.* [1997].

former due to the false assumption of unchanging source-water $\Delta^{14}\text{C}$ and the difficulty of obtaining precisely coupled planktonic and benthic ^{14}C ages; and the latter due to the difficulty of constraining calendar ages and source-water $\Delta^{14}\text{C}$ changes. In the context of the deep North Atlantic, where past variations in source-water $\Delta^{14}\text{C}$ are likely to have been very large [Bard, 1988], any accuracy gained by the projection method is likely to be solely methodological. Consequently, both methods are employed and compared here, with the basic premise that each method may yield information that the other cannot.

[9] MD99-2334K has been placed on the GISP2 calendar age scale [Meese *et al.*, 1997] based on the synchronicity of temperature changes recorded in Greenland $\delta^{18}\text{O}_{\text{ice}}$ and North Atlantic planktonic $\delta^{18}\text{O}_{\text{oc}}$ records [Shackleton *et al.*, 2000]. The resulting chronology, illustrated in Figure 1, is supported by its consistency with available calibrations of the planktonic ^{14}C dates from MD99-2334K, and by the consequent timing of Heinrich events 1–3 identified in the core [Skinner *et al.*, 2003]. The agreement of the GISP2 correlation with these two independent criteria is significant, since although all three of the chronological constraints are of limited certainty, and of some circularity (i.e., the assumption of constant reservoir ages for the purposes of ^{14}C age calibration), their convergence must either indicate a degree of mutual verification or require the rather unlikely positive correlation of any postulated errors in all three of the chronological constraints.

[10] As underlined above, the greatest difficulty in determining benthic projection ages lies in estimating the initial $\Delta^{14}\text{C}$ of the deep water source, as this requires knowledge of the atmospheric $\Delta^{14}\text{C}$ it equilibrated with, its reservoir age and the extent of mixing of different sources (poten-

tially, if not probably, with different ventilation ages at the time of mixing). Currently, the atmospheric $\Delta^{14}\text{C}$ record is very well resolved as far back as ~ 15 calendar (cal) years BP, based on tree ring data [Stuiver *et al.*, 1998] and the ^{14}C dated varve chronology from the Cariaco Basin [Hughen *et al.*, 1998a]. Beyond 15 cal years BP, the atmospheric $\Delta^{14}\text{C}$ record is best constrained back to ~ 50 cal years BP by AMS ^{14}C dating of Cariaco Basin sediments that have been correlated to the GISP2 ice core record [Hughen *et al.*, 2004], with further constraints provided (back to ~ 23 cal years BP, albeit at relatively low resolution) by coupled $^{230}\text{Th}/^{234}\text{U}$ and ^{14}C dates performed on corals [Bard *et al.*, 1998]. For each of these latter data sets, the surface water reservoir age is assumed to have remained essentially constant at ~ 420 and 400 years respectively [Bard *et al.*, 1990; Hughen *et al.*, 2004].

[11] Additional constraints on surface water $\Delta^{14}\text{C}$ in the Icelandic Sea and North Atlantic come from planktonic foraminifer ^{14}C dates placed, as in this study, on the GISP2 ice core age scale [Joris and Weninger, 1998; Voelker *et al.*, 2000]. These studies yield important information regarding the extent of past surface water reservoir age variability in the northern North Atlantic. Similarly, the planktonic ^{14}C dates from MD99-2334K (this study), placed on the GISP2 chronology, provide a record of changing surface water $\Delta^{14}\text{C}$ on the Iberian Margin (which may include a variable local reservoir effect).

[12] The various records of atmospheric and marine $\Delta^{14}\text{C}$ are illustrated in Figure 2, including the $\Delta^{14}\text{C}$ of deep water indicated by the benthic ^{14}C dates from MD99-2334K (red stars). Projection lines for each benthic ^{14}C date trace the ^{14}C decay path taken by the deep water through time [Adkins and Boyle, 1997], disregarding the potential con-

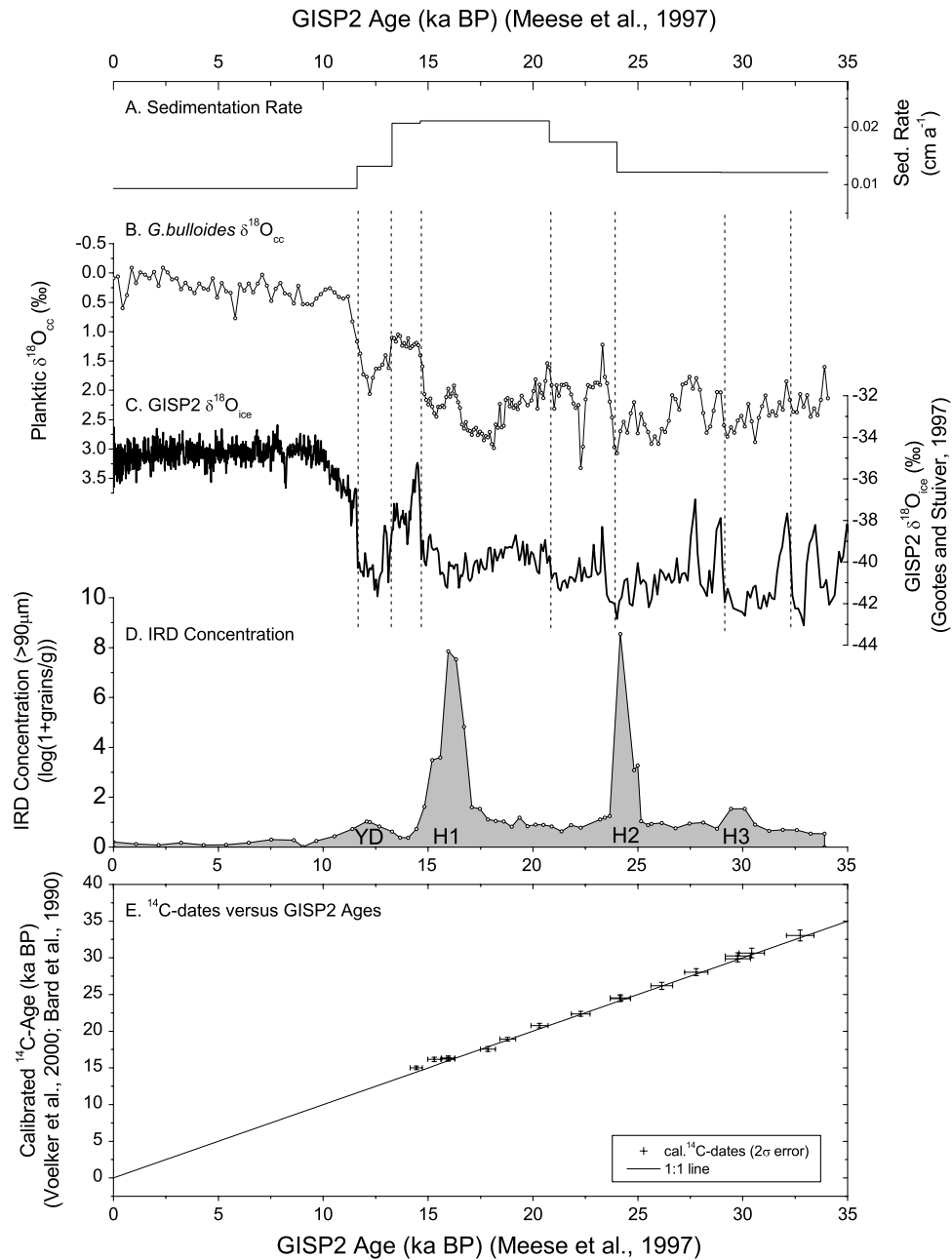


Figure 1. Age model for core MD99-2334K, reproduced from *Skinner et al.* [2003], based on synchrony of temperature changes recorded in planktonic $\delta^{18}\text{O}_{\text{oc}}$ and GISP2 $\delta^{18}\text{O}_{\text{ice}}$, and corroborated by ^{14}C dating. (a) Changes in sedimentation rate defined by age tie points. (b) Planktonic $\delta^{18}\text{O}_{\text{oc}}$ measured in *G. bulloides* (250–300 μm) from MD99-2334K. (c) GISP2 $\delta^{18}\text{O}_{\text{ice}}$ record [*Grootes and Stuiver, 1997*] used for correlation with planktonic $\delta^{18}\text{O}_{\text{oc}}$ record, yielding age model on GISP2 age scale [*Meese et al., 1997*]. (d) Concentration of terrigenous clastics counted in $>90 \mu\text{m}$ fraction, taken as indication of local IRD deposition. IRD peaks correspond to peak Greenland stadials that accompany Heinrich events 3, 2, 1, and the Younger Dryas. (e) Comparison of calibrated ^{14}C ages with correlative GISP2 ages derived from correlation. Calibration of ^{14}C ages ($\sim 12\text{--}35$ ^{14}C kyr BP) is based on second-order polynomial fit to data from *Bard et al.* [1990] and *Voelker et al.* [2000], giving preference to coral dates prior to ~ 20 ^{14}C kyr BP. For ^{14}C ages $\sim 12\text{--}35$ kyr BP, using a constant reservoir age of 400 years, calendar age = $-2.12108 + 1.48538(^{14}\text{C}_{\text{age}}) - 0.00967(^{14}\text{C}_{\text{age}})^2$; $R^2 = 0.994$. The paired dates describe a linear relationship that is indistinguishable from 1:1 at the 95% confidence level.

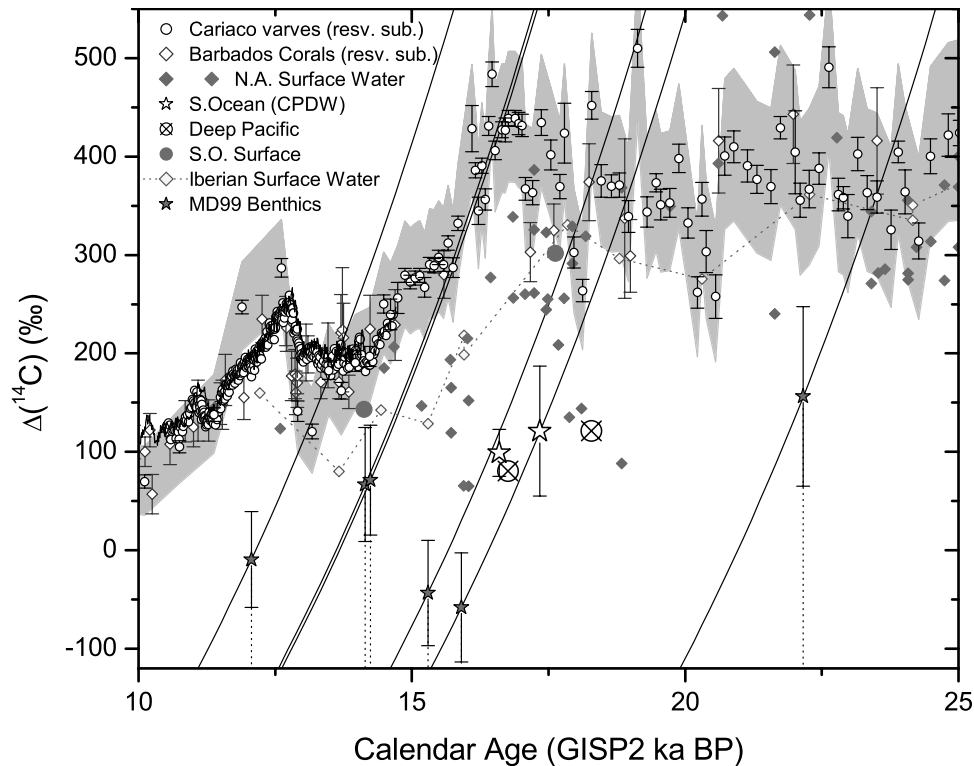


Figure 2. Estimates of past $\Delta^{14}\text{C}$ for various reservoirs that provide possible intersection ages (for projection ventilation age determination) for the benthic ^{14}C data from MD99-2334K (red stars). The past $\Delta^{14}\text{C}$ of surface water on the Iberian Margin, estimated from planktonic ^{14}C dates in MD99-2334K, is shown by yellow diamonds (with connecting dotted line). Analogous $\Delta^{14}\text{C}$ estimates for the northern North Atlantic are shown by green [Joris and Weninger, 1998] and red [Voelker et al., 2000] diamonds. Data from coral [Bard et al., 1998] and varve [Hughen et al., 1998b; Hughen et al., 2004] chronologies (shown by blue diamonds and open circles, respectively) have been corrected for constant 400- and 420-year reservoir ages respectively (“resv. sub.” in legend) and thus indicate the estimated trend in atmospheric $\Delta^{14}\text{C}$. The gray envelope indicates the possible error in the Cariaco Basin data of Hughen et al. [2004] owing to correlative calendar age uncertainties. Tree ring data (black jagged line) provide an accurate record of atmospheric $\Delta^{14}\text{C}$ back to ~ 15 cal years BP [Stuiver et al., 1998]. Open stars indicate two estimates for Southern Ocean $\Delta^{14}\text{C}$ at 1125 m water depth [Goldstein et al., 2001]. Open circles with crosses indicate two estimates for $\Delta^{14}\text{C}$ in the deep equatorial Pacific [Shackleton et al., 1988; Adkins and Boyle, 1997]. Projection ventilation ages for the benthic ^{14}C dates from MD99-2334K are estimated as the difference between the calendar age of the benthic ^{14}C date and the calendar age of the intersection point of the ^{14}C decay projection curves (black curved lines running through the benthic data) with the assumed source $\Delta^{14}\text{C}$ record. The intersection with a 400-year old reservoir (i.e., tropical surface water) is assumed here for clarity, given the difficulty in justifying the assumption of any other reservoir(s) from such a wide range of possibility. See color version of this figure at back of this issue.

tributions of distinct deep water sources (and indeed the complexities of transient changes in advection and diffusion [Wunsch, 2003]). The intersection ages of the projection lines and the surface environment $\Delta^{14}\text{C}$ records thus indicate possible initial ages for the deep water. The tree ring, varve, and coral $\Delta^{14}\text{C}$ records in Figure 2 have been corrected for their respective reservoir ages to provide intersection ages for a theoretical surface water source that was completely equilibrated with the atmosphere (i.e., zero reservoir age). It has been shown that the assumption of tropical ocean or even constant reservoir ages at middle to high latitudes (where the most significant deep water production generally occurs) is not realistic, particularly

across the last Termination in the North Atlantic [Bard et al., 1994; Sikes et al., 2000; Siani et al., 2001; Waelbroeck et al., 2001; Bjorck et al., 2003]. The $\Delta^{14}\text{C}$ records from MD99-2334K and from the northern North Atlantic already include local reservoir effects, and thus provide possible intersection ages for middle and high-latitude North Atlantic surface water sources. The planktonic ^{14}C dates from MD99-2334K exhibit reservoir ages of ~ 580 years on average, possibly as a result of seasonal upwelling in this region [Monge Soares, 1993]. However, past changes in upwelling on the Iberian Margin will have made a limited contribution to changing benthic-planktonic age differences recorded in MD99-2334K because local surface reservoir

Table 2. Benthic-Planktonic and Projection Ventilation Age Estimates for Core MD99-2334K^a

MD99-2334K Corrected Depth, cm	GISP2 Correlative Age, years	GISP2 Error, 1 σ years	Benthic-Planktonic Age Difference, years	B-P Error, 1 σ years	Projection Intersection Age ("Tropical" Source), years	Projection Ventilation Age, years	Projection Age Error, 1 σ years
115	12,064	241	1566	186	13,155	1091	73
149	14,148	283	489	186	14,700	552	15
150	14,244	285	505	170	14,780	536	27
173	15,293	306	1326	191	17,566	2272	264
186	15,909	318	1955	198	18,490	2582	478
313	22,161	443	1239	234	23,510	1349	57

^aProjection ages are expressed relative to a "tropical source" with a 400-year reservoir age. Benthic-planktonic age differences include the surface reservoir age, and are therefore expressed relative to northeast Atlantic surface water (reservoir age \sim 580 years on average).

ages deviate from their mean value by only \sim 300 years on average, and will have no effect on ventilation ages estimated by the projection age method.

[13] There is a relative paucity of calendar-dated radiocarbon data for potential southern surface water sources, however estimates of reservoir ages for the last glaciation based on ^{14}C dated foraminifera reveal very large changes at subpolar and subtropical southern latitudes, with deep water ventilation ages as high as \sim 5000 years prior to \sim 25 cal years BP [Sikes *et al.*, 2000]. Unfortunately these estimates from the Southern Ocean do not cover the time interval of interest here, though Pacific and Southern Ocean deep water ventilation ages during the late glacial (black stars and crossed circles in Figure 2) [Shackleton *et al.*, 1988; Adkins and Boyle, 1997; Goldstein *et al.*, 2001] attest to offsets between deep water and atmospheric $\Delta^{14}\text{C}$ that are greater than today and closer to that of modern Circumpolar Deep Water (\sim 1200 years old) [Stuiver and Ostlund, 1980; Broecker and Peng, 1982].

[14] The wide range of possible projection ages obtainable by considering a range of deep water sources and source-water reservoir ages (see Figure 2) illustrates the uncertainty inherent in defining projection ages, and indeed the error in assuming constant source-water $\Delta^{14}\text{C}$ when simply calculating benthic-planktonic ^{14}C age differences (particularly for a North Atlantic setting). Projection ventilation ages for the benthic ^{14}C dates in MD99-2334K are therefore reported in Table 2 relative to tropical surface water (with a constant 400 year reservoir age) in order to provide a "normalized" estimate of the total ^{14}C age of the deep water that does not include unwarranted assumptions regarding source-water reservoir ages and deep water source mixing. The resulting ventilation age estimates are bracketed by a 1- σ range of uncertainty that is determined based on the scatter of various possible source-water candidates, including northern North Atlantic, midlatitude North Atlantic and tropical surface water. Parallel benthic-planktonic ^{14}C age differences are also reported in Table 2, and the temporal evolution of deep-sea ventilation ages across the deglaciation is illustrated in Figure 3.

3.3. Deep Water Ventilation Changes

[15] Qualitatively, there is no difference between the two methods of ventilation age estimation: both indicate a significantly reduced deep northeast Atlantic ventilation during the last glaciation (\sim 22 cal years BP), followed by a rapid initiation of modern ventilation rates coincident with

the Bølling-Allerød transition (between \sim 16 and 14 cal years BP), and subsequently an abrupt reversal in deep water ventilation during the Younger Dryas (\sim 12 cal years BP) (see Figure 3). The reconstructed ventilation ages suggest conditions approaching modern for the northeast Atlantic (i.e., dominated by northeast Atlantic Deep Water, NEADW) at the height of the Bølling-Allerød warm period, while ventilation ages during the Younger Dryas, at the end of Heinrich event 1, and prior to the Last Glacial Maximum (LGM) are consistent with a much "older" water mass, possibly akin to modern Antarctic Bottom Water (AABW) [Stuiver and Ostlund, 1980; Broecker and Peng, 1982]. Quantitatively, the ventilation ages obtained in MD99-2334K are broadly in agreement with the results of modeling studies, which have suggested that North Atlantic deep water ^{14}C age may increase from \sim 400 to \sim 1600 years due a freshwater forced "collapse" of North Atlantic Deep Water (NADW) export [Stocker and Wright, 1996, 1998; Delaygue *et al.*, 2003].

[16] It is important to avoid the implicit suggestion of changes in deep ocean circulation vigor when discussing reconstructed changes in ^{14}C ventilation age. Ventilation ages are interpreted here as indications of the net $^{14}\text{C}/\text{C}$ ratio recorded by benthic foraminifera at a given point in time, and therefore reflect a combination of changes in deep water character, deep water source and source ^{14}C age, in addition to changes in circulation vigor. Indeed large changes in deep water $\Delta^{14}\text{C}$ are more efficiently obtained by changes in deep water mass source contribution (e.g., AABW versus NADW) than by changes in the rapidity of water mass circulation [Adkins *et al.*, 1998; Wunsch, 2003], though it is likely that deep water source dominance and circulation vigor must nevertheless remain coupled to some degree [Stocker *et al.*, 1992]. Currently, AABW exhibits relatively old ventilation ages primarily due to the fact that it is largely derived from upwelled intermediate waters that are already poorly ventilated and that only partially re-equilibrate with the atmosphere (thus only partially "resetting their radiocarbon clocks") [Broecker and Peng, 1982], irrespective of its rate of transport with respect to NADW.

[17] Just prior to the Bølling-Allerød transition, at the end of Heinrich event 1 (H1), two benthic projection ages in MD99-2334K suggest that deep water was twice as old as modern AABW (i.e., \sim 2400 years), while the benthic-planktonic ^{14}C age differences indicate similar ventilation ages for the Younger Dryas, H1 and prior to the LGM (all \sim 1500 years). Differences between the projection and

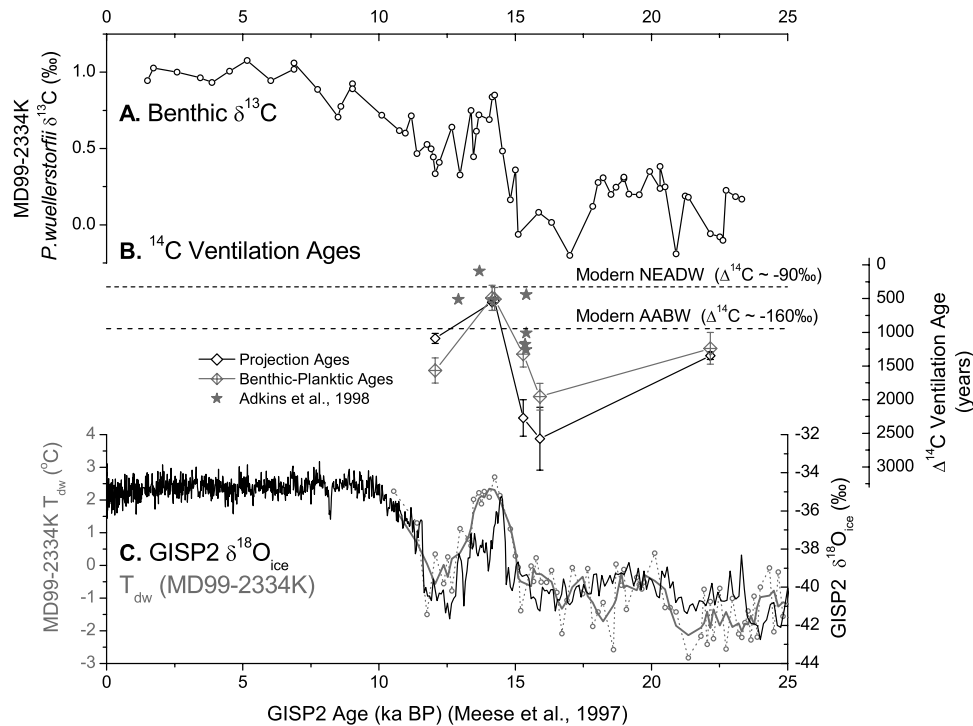


Figure 3. The evolution of deep water nutrients, ventilation age, and temperature across the last deglaciation, as recorded in MD99-2334K. The records are placed on the GISP2 age scale [Meese et al., 1997] by correlation of GISP2 $\delta^{18}O_{ice}$ with surface water temperature variations (planktonic $\delta^{18}O_{cc}$) recorded in MD99-2334K. (a) *P. wuellerstorffii* $\delta^{13}C$ in MD99-2334K, as an indication of changing deep water nutrient levels across the deglaciation. (b) Deep water ventilation age estimates from MD99-2334K based on benthic-planktonic ^{14}C age differences (crossed diamonds) and benthic ^{14}C projection ages (open diamonds). Projection ventilation ages for North Atlantic corals from 1800 m water depth (stars) [Adkins et al., 1998] are shown for comparison. Dashed horizontal lines indicate $\Delta^{14}C$ for deep water in the modern northeast and southern Atlantic [Stuiver and Ostlund, 1980; Broecker and Peng, 1982]. (c) The GISP2 $\delta^{18}O_{ice}$ record [Grootes and Stuiver, 1997] in black with deep water temperature (T_{dw}) estimates from MD99-2334K superposed in gray (open circles indicate original data; thick gray line is 3-point running average). T_{dw} estimates are based on Mg/Ca measurements in benthic foraminifera [Skinner et al., 2003].

benthic-planktonic ventilation ages will relate to the rate of change of atmospheric $\Delta^{14}C$ ($\Delta^{14}C_{atm}$) while the deep water was aging, and to the difference between the reservoir age of the surface water at the time of the benthic ^{14}C date and the reservoir age of the deep water's source at the time of sequestration. Hence for example, a projection ventilation age will be reduced relative to a benthic-planktonic ventilation age if the deep water was aging (its $\Delta^{14}C$ decreasing) during a period of increasing $\Delta^{14}C_{atm}$, unless the reservoir age of the surface water contemporaneous with the benthic sample was sufficiently greater than the reservoir age of the deep water source. Such a scenario could explain the lower projection ventilation age versus benthic-planktonic ^{14}C age difference obtained for the Younger Dryas in MD99-2334K.

[18] Similarly, the late glacial (including H1) represents a time of variable $\Delta^{14}C_{atm}$, which increased from ~ 20 –16 cal years BP and then rapidly decreased from ~ 16 –14 cal years BP [Hughen et al., 2004]. It has been shown by Hughen et al. [2004] that the earlier rise in $\Delta^{14}C_{atm}$ essentially runs in opposition to the estimated trend in global ^{14}C production

(as derived from reconstructions of Earth's magnetic field intensity [Laj et al., 2002]), while the subsequent period of decreasing $\Delta^{14}C_{atm}$ that followed H1 ran in parallel with the global ^{14}C production trend. These observations suggest that a large reduction in the ventilation of the deep sea dominated over the global ^{14}C production trend leading up to H1, and that subsequently the $\Delta^{14}C_{atm}$ record became dominated by a major reduction in the global production trend, possibly in parallel with a gradual resumption of deep-sea ventilation from ~ 16 cal years BP. Although they do not constrain the trend in $\Delta^{14}C$ leading up to the culmination of H1, the two elevated benthic ^{14}C dates presented here for late-H1 support these suggestions, indicating a gradual increase in deep water $\Delta^{14}C$ and hence deep-sea ventilation (in opposition to the $\Delta^{14}C_{atm}$ trend), beginning ~ 16 cal years BP at least (see Figures 2 and 3).

[19] The fact that the two benthic ^{14}C dates from late-H1 in MD99-2334K are positioned within a period of decreasing $\Delta^{14}C_{atm}$ (see Figure 2) renders projection age estimates for these dates particularly sensitive to relatively small changes

in the assumed reservoir/ventilation age of the initial deep water source. A less ventilated intermediate-depth source or a southern deep water source (rather than the tropical source used here for simplicity) would greatly reduce the two projection age estimates for H1 (and thus bring them more into line with their respective benthic-planktonic age differences). Interestingly, the projection curves for the late-H1 benthic ^{14}C dates in MD99-2334K intersect the $\Delta^{14}\text{C}$ values from Southern Ocean deep-sea corals (1125 m water depth) that lived ~ 1400 years before and that are estimated to exhibit a ventilation age of ~ 1000 years [Goldstein *et al.*, 2001] (see Figure 2). A similar age offset is exhibited with respect to deep Pacific benthic foraminifer ^{14}C dates with an estimated ventilation age of ~ 1200 years [Shackleton *et al.*, 1988; Adkins and Boyle, 1997]. Hence late in Heinrich 1, a northern North Atlantic deep water source that was very poorly equilibrated with atmospheric CO_2 (i.e., with a reservoir age ~ 1000 years, as in the modern Southern Ocean) is equivalent to a southern deep water source (of initial ventilation age ~ 1000 – 1200 years), in terms of the final ^{14}C ages of deep water in the northeast Atlantic recorded in MD99-2334K. Furthermore, both of these possible deep water sources imply an equally, and implausibly, long ventilation time of over 2000 years if benthic “ventilation ages” are interpreted simplistically in terms of circulation rates. This demonstrates that the circulation of deep water in the Atlantic was indeed “reorganized” during the last glaciation (i.e., not just “slowed down”) [Curry *et al.*, 1988; Duplessy *et al.*, 1988; Stocker *et al.*, 1992], and also that it was rather more sequestered from the atmosphere.

[20] It is impossible to determine from the benthic $\Delta^{14}\text{C}$ estimates alone exactly how much of the reconstructed ventilation ages in MD99-2334K should be attributed to source-water age residuals as opposed to changes in deep water source and/or changes in overturning rates. However, based on the evidence available it appears that deep water source that supplied the deep northeast Atlantic at the end of Heinrich 1 was very poorly ventilated indeed; certainly much less than most modern high latitude surface waters, in line with estimates derived by Waelbroeck *et al.* [2001] for the North Atlantic and Sikes *et al.* [2000] for the Southern Ocean.

3.4. Ventilation and Deep Water Source Variations

[21] In order to help constrain deep water source mixing and/or exchange as potential controls on the ventilation age variations exhibited in MD99-2334K, reference may be made to benthic $\delta^{13}\text{C}$ measurements and parallel estimates of past deep water temperature (T_{dw}) [Skinner *et al.*, 2003]. As shown in Figure 3, the reduced ventilation age prior to the LGM, the rapid initiation of modern ventilation at the onset of the Bølling-Allerød, and the subsequent collapse of ventilation during the Younger Dryas, are all associated with concomitant variations in benthic $\delta^{13}\text{C}$ and deep water temperature (T_{dw}). In the modern Atlantic ocean, trends in deep water geochemistry are largely controlled by the mixing of northern and southern sourced deep water, which bear contrasting signatures primarily due to their different conditions and modes of formation [Broecker and Peng, 1982]. Thus modern deep water $\Delta^{14}\text{C}$ consistently covaries with temperature and deep water $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{\text{dw}}$), and is

inversely related to nutrient levels [Stuiver and Ostlund, 1980; Broecker and Peng, 1982]. In MD99-2334K, coupled T_{dw} and $\delta^{18}\text{O}_{\text{dw}}$ changes reconstructed for the last glaciation and glacial termination based on benthic Mg/Ca and $\delta^{18}\text{O}_{\text{cc}}$ measurements have been suggested to exhibit deep water mass source signatures which closely resemble those of the modern Atlantic, suggesting the alternating dominance of NADW versus AABW in the deep Atlantic at millennial timescales [Skinner *et al.*, 2003].

[22] A comparison of parallel $\Delta^{14}\text{C}_{\text{dw}} - \Delta^{14}\text{C}_{\text{trop}}$ (the difference between the local deep water and contemporary tropical surface water ^{14}C activity), $\delta^{13}\text{C}$, T_{dw} and $\delta^{18}\text{O}_{\text{dw}}$ conditions reconstructed in MD99-2334K is shown in Figure 4, indicating qualitatively similar trends to those of the modern deep Atlantic, though with significantly greater maximum ventilation ages (obtained during late-H1 in particular) than are observed in the modern ocean [Stuiver and Ostlund, 1980; Broecker and Peng, 1982]. As suggested above, such extreme $\Delta^{14}\text{C}_{\text{dw}} - \Delta^{14}\text{C}_{\text{trop}}$ values are likely to reflect the poor constraints available for past deep water source ages (which may have been considerably larger than at present), though they may also represent conditions without modern analogues. Despite such uncertainties, the trends in Figures 3 and 4 remain consistent with changes in deep hydrography that are expressed primarily in terms of northern and southern sourced deep water mass exchange rather than simply in terms of changes in circulation rate. Indeed deep water mass exchange may even be the only way to obtain such large and relatively rapid changes in ventilation [Wunsch, 2003]. These findings thus lend further support to previous benthic $\delta^{13}\text{C}$ and Cd/Ca reconstructions in suggesting the occurrence of changes in deep water source dominance in the North Atlantic in association with abrupt climate change [e.g., Boyle and Keigwin, 1987; Charles *et al.*, 1996; Boyle, 2000].

4. Conclusions: Paleoceanographic Implications

[23] The data from MD99-2334K illustrate a number of important aspects of deep circulation and its relation to climate change across the last deglaciation. Consistent with previous findings [Broecker *et al.*, 1990], three benthic foram ^{14}C dates in MD99-2334K indicate that deep water in the North Atlantic was much less ventilated during the last glaciation than today. The reduction in the ventilation of glacial North Atlantic deep waters is interpreted here purely in terms of ^{14}C distribution within the carbon cycle, without reference to the rate of carbon redistribution. In the same sense, modern AABW is understood to be less ventilated than NADW (due to poor equilibration of AABW source waters with the atmosphere), though this does not require a more sluggish export of AABW. Indeed it is in fact exported at a greater rate [Ganachaud and Wunsch, 2000].

[24] The transition from glacial to essentially modern deep water ventilation in the deep northeast Atlantic was effected once at the onset of the Bølling-Allerød warm period, and then again sometime after the Younger Dryas cold reversal, during which deep water ventilation once again reverted to glacial levels. The fact that the changes in deep water $\Delta^{14}\text{C}$ recorded in MD99-2334K across the

Bølling-Allerød and Younger Dryas events occur in parallel with opposite trends in atmospheric $\Delta^{14}\text{C}$ unequivocally implicates changes in the deep ocean's ^{14}C reservoir (and hence changes in the deep ocean's exchange with the atmosphere), rather than changes in the global ^{14}C inven-

tory, as the reason for the observed benthic ^{14}C age variations. Indeed it may therefore be argued that at least part of the millennial variations in the atmospheric $\Delta^{14}\text{C}$ record represent internal changes in the global carbon cycle that have been mediated by changes in the deep ocean's ventilation.

[25] The most efficient mode of transport of ^{14}C into the deep ocean is currently via the formation of NADW in the North Atlantic [Broecker and Peng, 1982; Bard, 1988]. Benthic $\delta^{13}\text{C}$ measurements and estimates of deep water T_{dw} and $\delta^{18}\text{O}_{\text{dw}}$ performed in parallel with the benthic and planktonic ^{14}C dates in MD99-2334K strongly support the hypothesis that the rapid increase and subsequent collapse of ventilation across the Bølling-Allerød and Younger Dryas events represents primarily the effect of changing NADW versus AABW dominance in the deep North Atlantic. These results provide direct support for the conclusions of Hughen *et al.* [2000], based on their combined geological and modeling evidence, and the modeling results of Muscheler *et al.* [2000a], which indicate that reconstructions of past $\Delta^{14}\text{C}_{\text{atm}}$ and ^{14}C production are most easily reconciled by invoking a reduced NADW export during the Younger Dryas. However, much remains to be learned regarding the role of the high southern latitudes, and hence southern sourced deep water, in contributing to changes in the ventilation of the deep sea, and hence in controlling the exchange of ^{14}C (and CO_2) between the ocean and the atmosphere. Our understanding of the global carbon cycle might therefore benefit from further investigations into the relationships that exist between the various marine reservoirs (e.g., northern versus southern deep water), in addition to the relationships that control the exchange of carbon between the marine and the atmospheric reservoirs.

[26] The fact that the major initiation of NADW flux to the deep North Atlantic occurred coincident with the onset of the Bølling-Allerød, marking the end of H1 and in time with peak rates of sea level rise (MWP-1A) [Hanebuth *et al.*, 2000; Kienast *et al.*, 2003], suggests that NADW formation was unimpeded by the intensification of meltwater flux to the ocean at that time. This is consistent with the suggestion of an Antarctic source for MWP-1A [Clark *et al.*, 2002a], and is also consistent with the modeled stabilization of NADW in response to Southern Ocean deglacial warming and sea-ice retreat [Knorr and Lohmann, 2003] or a forced collapse in AABW stability [Weaver *et al.*, 2003]. Whatever the trigger for NADW resumption at the last deglaciation, the parallel increase of melting rates, Greenland temperature, deep water temperature and deep water

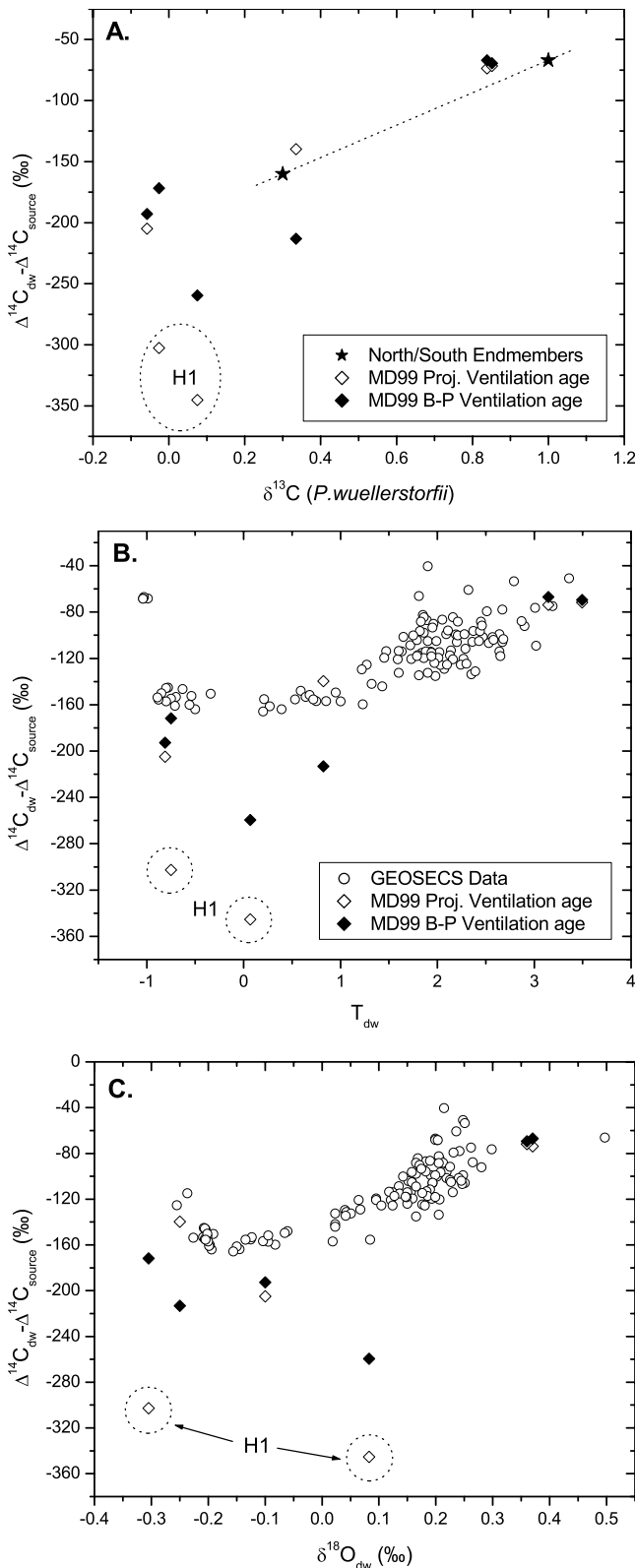


Figure 4. (a) The inferred offset between tropical surface water and North Atlantic deep water $\Delta^{14}\text{C}$ compared with parallel benthic $\delta^{13}\text{C}$ measurements and (b) estimates of past T_{dw} and (c) $\delta^{18}\text{O}_{\text{dw}}$ from MD99-2334K. In all three plots, deep water $\Delta^{14}\text{C}$ estimates based on benthic-planktonic age ^{14}C differences are shown by filled diamonds, while those based on projection ages are shown by open diamonds. In Figure 4c, symbols are as for Figure 4b. The projection method yields extremely large $\Delta^{14}\text{C}$ offsets for two benthic ^{14}C dates from Heinrich 1 (H1), enclosed by dotted circles.

ventilation at ~15 cal years BP clearly implicates the reorganization of deep water circulation in the deglacial process.

[27] The inferred presence of AABW in the deep North Atlantic during the Younger Dryas is important in at least two respects. As discussed above, it demonstrates the capacity of the deep ocean's hydrography to respond and contribute to climate change in a rapid and nonlinear fashion. However, it also raises the issue of how best to interpret deep ocean circulation changes when a reduction in the local influence of NADW is equivalent to an increase in the local influence of AABW (and vice versa). Thus the most obvious and pressing question of what

caused NADW to rapidly become stabilized at ~15 cal years BP might be usefully posed in terms of the relative stability of NADW with respect to AABW [Knorr and Lohmann, 2003; Weaver *et al.*, 2003], rather than simply in terms of the relationship between freshwater forcing and surface water stratification in the high northern latitudes.

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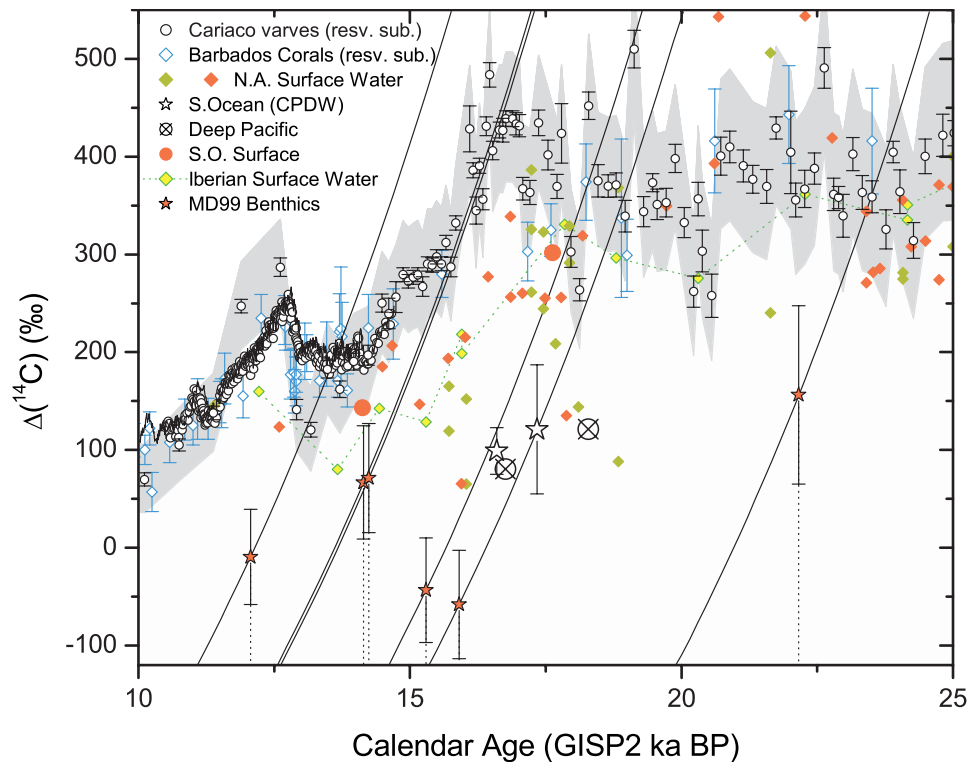


Figure 2. Estimates of past $\Delta^{14}\text{C}$ for various reservoirs that provide possible intersection ages (for projection ventilation age determination) for the benthic ^{14}C data from MD99-2334K (red stars). The past $\Delta^{14}\text{C}$ of surface water on the Iberian Margin, estimated from planktonic ^{14}C dates in MD99-2334K, is shown by yellow diamonds (with connecting dotted line). Analogous $\Delta^{14}\text{C}$ estimates for the northern North Atlantic are shown by green [Joris and Weninger, 1998] and red [Voelker et al., 2000] diamonds. Data from coral [Bard et al., 1998] and varve [Hughen et al., 1998b; Hughen et al., 2004] chronologies (shown by blue diamonds and open circles, respectively) have been corrected for constant 400- and 420-year reservoir ages respectively (“resv. sub.” in legend) and thus indicate the estimated trend in atmospheric $\Delta^{14}\text{C}$. The gray envelope indicates the possible error in the Cariaco Basin data of Hughen et al. [2004] owing to correlative calendar age uncertainties. Tree ring data (black jagged line) provide an accurate record of atmospheric $\Delta^{14}\text{C}$ back to ~ 15 cal years BP [Stuiver et al., 1998]. Open stars indicate two estimates for Southern Ocean $\Delta^{14}\text{C}$ at 1125 m water depth [Goldstein et al., 2001]. Open circles with crosses indicate two estimates for $\Delta^{14}\text{C}$ in the deep equatorial Pacific [Shackleton et al., 1988; Adkins and Boyle, 1997]. Projection ventilation ages for the benthic ^{14}C dates from MD99-2334K are estimated as the difference between the calendar age of the benthic ^{14}C date and the calendar age of the intersection point of the ^{14}C decay projection curves (black curved lines running through the benthic data) with the assumed source $\Delta^{14}\text{C}$ record. The intersection with a 400-year old reservoir (i.e., tropical surface water) is assumed here for clarity, given the difficulty in justifying the assumption of any other reservoir(s) from such a wide range of possibility.