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North Atlantic circulation and reservoir age changes over the past 41,000 years

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[1] Constraints on the timing of Atlantic meridional overturning circulation (AMOC) changes during the last deglaciation are fundamental to understanding the climate's rapid response to insolation forcing. However, uncertainty about high-latitude North Atlantic (HLNA) radiocarbon reservoir ages has previously precluded robust age model development for this critical region. HLNA reservoir ages also serve as a proxy for AMOC strength. We present regionally averaged HLNA reservoir ages for 0 to 41 thousand years before the present (kyr BP) based on over 500 radiocarbon dates from 33 North Atlantic cores. An early deglacial increase to >1000 ^{14}C yr reservoir ages between 18.5 and 16.5 kyr BP suggests reduced AMOC before peak Heinrich Stadial 1 (HS1) ice-rafted debris (IRD). A rapid decrease in reservoir ages coincident with the IRD maximum at 16 kyr BP indicates strong stratification of the upper water column caused by massive freshwater release.
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1. Introduction

[2] Robust chronologies for high-latitude North Atlantic (HLNA) sediment cores are critical to understanding glacial and deglacial abrupt climate changes because climate responses in this region have global impacts, especially through the effects of Atlantic meridional overturning circulation (AMOC) change. However, while coral-based sea level estimates [e.g., *Peltier and Fairbanks*, 2006], precipitation proxies from cave speleothems [e.g., *Wang et al*., 2001], Antarctic [e.g., *EPICA Community Members*, 2006] and Greenland [e.g., *North Greenland Ice Core Project Members*, 2004] ice core records, and low-latitude marine sediment cores [e.g., *Waelbroeck et al*., 2011] all have age uncertainties less than a couple hundred years during the most recent deglaciation, the uncertainties for HLNA age models are up to 2000 years [*Waelbroeck et al*., 2001; *Thornalley et al*., 2011]. The primary challenge to improving HLNA age models is the lack of constraints on past radiocarbon reservoir ages.

[3] Marine radiocarbon age models require the use of reservoir ages, which are a measure of the offset between the radiocarbon content of the surface ocean and the contemporaneous atmosphere in units of radiocarbon years (^{14}C yr). Reservoir ages are set by the balance between surface-ocean mixing with the atmosphere, where ^{14}C is produced, and the deep ocean, where ^{14}C decays. Modern (prebomb) reservoir ages of 400–500 ^{14}C yr in the HLNA reflect a vigorous AMOC as deepwater formation in the North Atlantic drives a compensatory northward flow of recently equilibrated tropical surface waters. A significant increase in regional-scale HLNA reservoir ages requires the combined effects of a southward shift in the Northern Hemisphere polar front and reduced AMOC, both of which increase the influence of old, polar waters relative to young, tropical surface waters in the region (see supporting information). Thus, in addition to being a valuable age model constraint, HLNA reservoir ages are also a proxy for AMOC strength.

[4] The assumption of constant reservoir age is commonly used in HLNA radiocarbon age models [*Meland et al*., 2008; *Marcott et al*., 2011], but previous studies have reconstructed HLNA reservoir ages of 600–1000 ^{14}C yr during the Younger Dryas (YD; 12.8 to 11.6 kyr BP) and up to 2000 ^{14}C yr during late HS1 [*Bard et al*., 1994; *Waelbroeck et al*., 2001; *Bondevik et al*., 2006; *Thornalley et al*., 2011]. However, some of these extreme HS1 reservoir ages have been questioned [*Broecker et al*., 2009], and the individual sites used in these studies are not necessarily characteristic of regional-scale changes [*Thornalley et al*., 2011]. Reservoir age estimates older than late HS1 are even less well constrained. Additionally, some previous studies [e.g., *Peck et al*., 2007] have erroneously reported reservoir ages in calendar years rather than ^{14}C yr and thus do not provide true reservoir ages. Finally, earlier reservoir age reconstructions were not time continuous, making their practical application difficult.

2. Methods

[5] We compiled previously published data from 33 deep (>2000 m) North Atlantic cores (Figure 1; Figure S1 and Table S1 in the supporting information) with benthic δ^{18}O records and planktonic ^{14}C dates. We assume that deep North Atlantic benthic δ^{18}O changes are synchronous and that differences between aligned high- and low-latitude radiocarbon ages derive from changes in high-latitude (>40 °N) reservoir age (supplemental discussion in supporting information). Initial radiocarbon age models for the individual cores were developed using each core's ^{14}C dates, the Bayesian age modeling program Bchron [*Parnell et al*., 2008], the Marine09 calibration [*Reimer et al*., 2009], and constant 405 ^{14}C yr reservoir ages. We also aligned all of the cores using benthic δ^{18}O and, where available, ice-rafted debris (IRD) and relative geomagnetic paleointensity data (Figures S2–S4). A preliminary low-latitude ^{14}C age model was

Additional supporting information may be found in the online version of this article.

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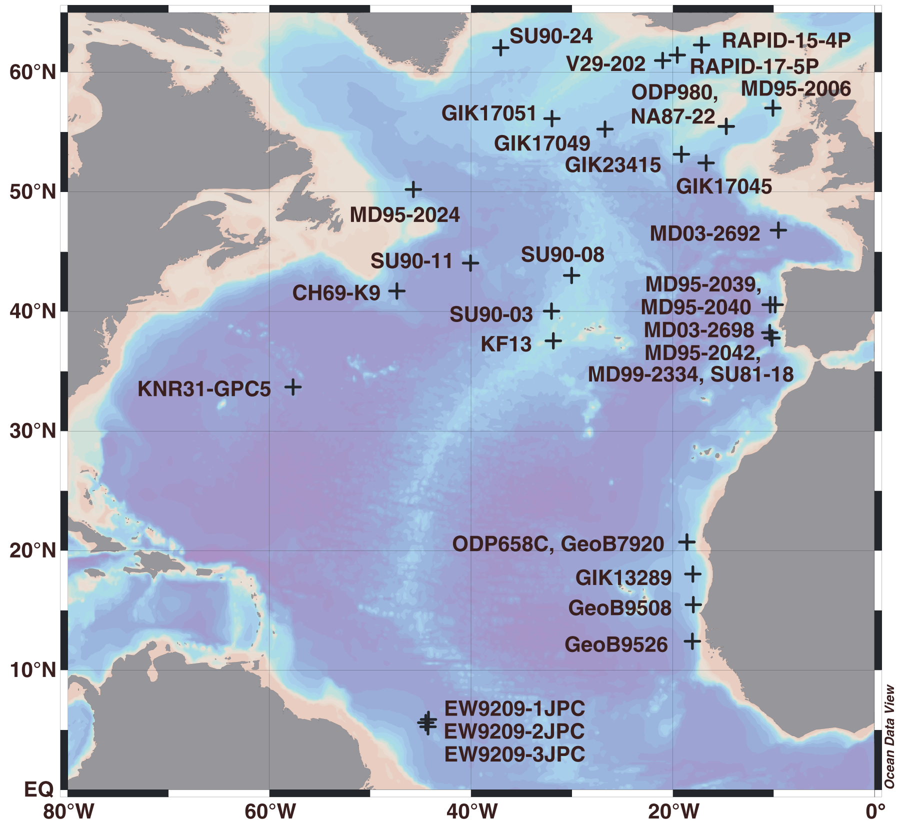

Figure 1. Locations of cores used in this study. Complete data references are available in Table S1 in the supporting information.

developed using our alignments and the average radiocarbon age estimates for all low-latitude (0-40 °N) cores. Then, we made separate high- and low-latitude ^{14}C age models by averaging Bchron age estimates for all aligned cores at evenly spaced 500 year intervals on the preliminary low-latitude age model (Figure S5). A direct comparison of the two age models would not provide true reservoir ages because the units are still in calendar years. Therefore, we "uncalibrated" the radiocarbon ages of both the high- and low-latitude age models at each time step and compared these uncalibrated surface ocean ^{14}C ages to the contemporaneous atmospheric ^{14}C ages provided by IntCal09 [*Reimer et al.*, 2009]. Our final HLNA reservoir ages were calculated as the difference between uncalibrated high- and low-latitude reservoir ages plus 405 ^{14}C yr.

[6] An IRD stack was created from 15 records and has a 500 year resolution on the low-latitude ^{14}C age model (Figure S3). IRD records were scaled to have a maximum of one before stacking, so the IRD stack is presented in arbitrary units. Each stacked value represents the average of all available scaled IRD values within ±250 years. The IRD stack averages records over a broad region and therefore does not capture differences in the timing of IRD inputs from individual ice sheets (Figure S6). Further methods details are available in the supporting information.

3. Reservoir Age Results

[7] Figure 2 shows these HLNA reservoir ages and IRD stack on our low-latitude ^{14}C age model. The ages of the main HS1–4 IRD peaks are in good agreement with maxima in the U-Th dated Hulu speleothem δ^{18}O record [*Wang et al.*, 2001] and the timing of Greenland stadials according to the layer-counted GICC05 age model [*North Greenland Ice Core Project Members*, 2004; *Svensson et al.*, 2008] (Figure 2).

[8] We find similar to modern 400 ^{14}C yr reservoir ages for most of the Holocene from 0 to 10 kyr BP, in agreement with previous estimates [*Ascough et al.*, 2009] and consistent with proxy evidence that no major AMOC changes occurred over this time [*McManus et al.*, 2004]. Our YD reservoir ages of 900–1000 ^{14}C yr also agree with previous work [*Bard et al.*, 1994; *Waelbroeck et al.*, 2001; *Bondevik et al.*, 2006; *Thornalley et al.*, 2011], supporting the notion of brief freshwater-induced AMOC reduction during the YD [*McManus et al.*, 2004; *Carlson and Clark*, 2012]. HLNA reservoir ages of 500–800 ^{14}C yr during the Bølling-Allerød (BA; 14.7 to 12.8 kyr BP) are within the range of previous estimates [*Bondevik et al.*, 2006] and are consistent with alternating periods of reinvigorated AMOC [*Björck et al.*, 1996; *McManus et al.*, 2004; *Bondevik et al.*, 2006] and ice sheet melting [*Obbink et al.*, 2010; *Thornalley et al.*, 2010; *Carlson and Clark*, 2012].

[9] Our reconstruction suggests that the AMOC was vigorous enough to maintain HLNA reservoir ages within error of modern (~400 ^{14}C yr) for the entire interval from 20 to 41 kyr BP, including during HS2–4 (Figure 2). However, glacial overturning was likely shallower than modern [*Curry and Oppo*, 2005], and the 95% confidence range for this time interval allows for reservoir age shifts of up to 1500 ^{14}C yr. Previously, almost all the HLNA reservoir age estimates for this period (Figure S12) came from three sites located near the British-Irish Ice Sheet [*Knutz et al.*, 2007; *Peck et al.*, 2007; *Hall et al.*, 2011], a region that may not be representative of average North Atlantic conditions.

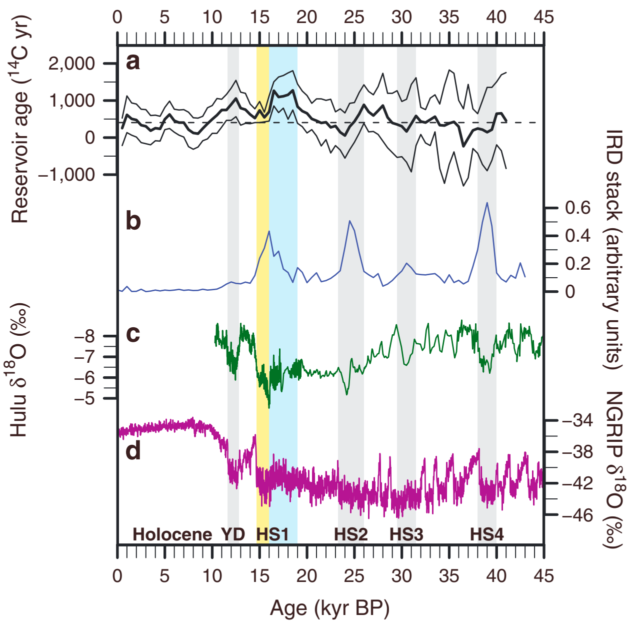

Figure 2. High-latitude North Atlantic (HLNA) reservoir ages and the timing of Heinrich stadials. (a) Regionally averaged HLNA reservoir ages (thick line) with 95% confidence intervals (thin lines) on a low-latitude ^{14}C age model (this study). The dashed line is at the modern globally averaged reservoir age of 405 ^{14}C yr. (b) A stack of 15 ice-rafted debris (IRD) records on the same low-latitude ^{14}C age model as (a) (this study). (c) Hulu Cave speleothem $\delta^{18}O$, a proxy for East Asian monsoon strength, on its U-Th age model [*Wang et al.*, 2001]. (d) NGRIP ice $\delta^{18}O$, a Greenland temperature proxy, on the GICC05 age model [*North Greenland Ice Core Project Members*, 2004; *Svensson et al.*, 2008]. Gray vertical bars indicate the timing of the Younger Dryas (YD) and Heinrich stadials (HS) 2–4. The light blue and yellow vertical bars indicate early and late HS1, respectively.

[10] HLNA reservoir ages suggest distinct AMOC responses for early HS1 (19 to 16.5 kyr BP) compared to late HS1 (16 to 14.7 kyr BP) (Figure 3). Large reservoir ages of 1000–1300 ^{14}C yr between 18.5 and 16.5 kyr BP are significantly above modern at the 95% level and agree with estimates of 1400 ^{14}C yr around 18 kyr BP [*Thornalley et al.*, 2011]. The timing of the transition into large reservoir ages is difficult to identify precisely, but likely corresponds with the 19 kyr BP meltwater pulse [*Carlson and Clark*, 2012] and clearly precedes peak HS1 iceberg discharge (Figure 3). We do not find a significant change in HLNA reservoir age at 17.5 kyr BP, although some climate records [*Bard et al.*, 2000; *Waelbroeck et al.*, 2011] display large shifts at this time. At 16 kyr BP, we observe a steep drop to smaller reservoir ages of 500–700 ^{14}C yr, considerably smaller than most previous estimates for late HS1 [*Waelbroeck et al.*, 2001; *Thornalley et al.*, 2011]. We attribute these differences to the use of oceanographically unique site locations (for *Thornalley et al.*, [2011]), outdated Greenland ice core age models and radiocarbon calibration curves (for *Waelbroeck et al.* [2001]), and large uncertainties in the age models of individual cores (see supporting information for further discussion).

4. AMOC Changes During HS1

[11] We propose that increased early HS1 reservoir ages were caused by reduced AMOC and a southward shift of the Northern Hemisphere polar front in response to meltwater events, as proposed for other intervals of increased

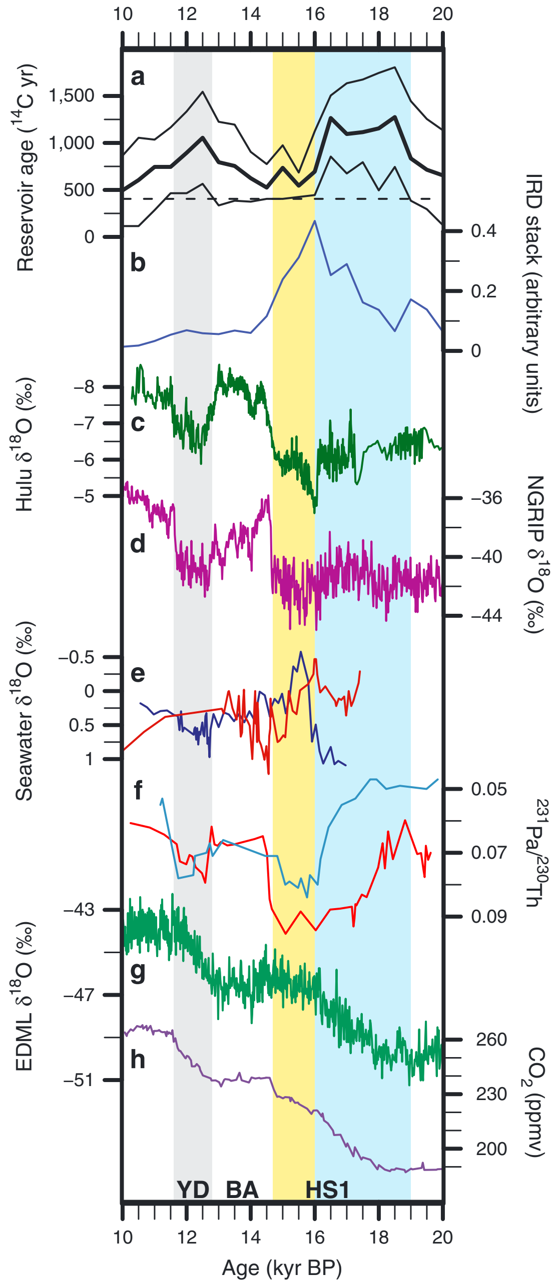

Figure 3. Deglacial climate records. (a–d) Same as in Figure 2. (e) North Atlantic seawater $\delta^{18}O$, an indicator of surface freshening, from cores RAPID-10-1P (dark blue) [*Thornalley et al.*, 2010] and OCE326-GGC14 (brown) [*Obbink et al.*, 2010]. (f) North Atlantic Pa/Th, a proxy for Atlantic meridional overturning strength, from cores OCE326-GGC5 (red) [*McManus et al.*, 2004] and SU81-18 (blue) [*Gherardi et al.*, 2005]. (g) EDML $\delta^{18}O$, a proxy for Atlantic-sector Antarctic temperature [*EPICA Community Members*, 2006; *Lemieux-Dudon et al.*, 2010]. (h) EPICA Dome C atmospheric CO_2 [*Parrenin et al.*, 2013]. Vertical bars as indicated for Figure 2. BA = Bølling-Allerød.

reservoir ages [*Bard et al.*, 1994; *Waelbroeck et al.*, 2001; *Bondevik et al.*, 2006]. Several other studies have reported reduced AMOC and southward shifting frontal systems during early HS1 [*Wang et al.*, 2001; *Peck et al.*, 2007; *Marcott et al.*, 2011]. Other proposed mechanisms for reservoir age increases are unlikely to explain the large regional changes we observe (see supporting information).

[12] When compared to earlier Heinrich events, the uniquely large reservoir ages of early HS1 suggest that insolation-induced melting played an important role in suppressing the AMOC during H1 [e.g., *He et al.*, 2013]. The insolation-driven 19 kyr BP meltwater pulse [*Carlson and Clark*, 2012; *Shakun et al.*, 2012] likely served as the initial trigger for AMOC weakening. Melting equivalent to approximately 5–10 m of sea level rise over a few hundred years occurred around 19 kyr BP, mostly from Northern Hemisphere ice sheets [*Carlson and Clark*, 2012]. The specific location of freshwater delivery can also affect AMOC sensitivity [*Roche et al.*, 2010].

[13] Increased HLNA reservoir ages during early HS1 also support the hypothesis that freshwater-induced AMOC reduction triggered the Laurentide-sourced ice-rafting event, possibly through subsurface ocean warming [*Álvarez-Solas et al.*, 2011; *Marcott et al.*, 2011]. We observe that HLNA reservoir ages clearly increase before the HS1 IRD peak in our stack, which begins at 18 kyr BP and reaches a minor peak at 17 kyr BP, consistent with the timing of European precursory IRD and peak Laurentide-sourced IRD, respectively [*Bard et al.*, 2000; *Peck et al.*, 2007; *Broecker et al.*, 2009]. Thus, AMOC reduction may play an important role in amplifying ice sheet responses to the initial deglacial increase in Northern Hemisphere summer insolation, particularly with respect to global deglacial warming beginning at 19 kyr BP [*Shakun et al.*, 2012] and CO_2 release beginning at 18 kyr BP [*Parrenin et al.*, 2013].

[14] Additionally, we propose that the rapid transition to smaller reservoir ages between 16.5 and 16.0 kyr BP was a response to freshwater-induced vertical stratification that allowed surface waters to equilibrate with the atmosphere. The timing of this reservoir age decrease coincides with the main HS1 IRD peak in our stack (Figure 3) and agrees with the established age of a major European-sourced IRD peak [*Bard et al.*, 2000; *Peck et al.*, 2007; *Broecker et al.*, 2009]. At the same time, a basin-wide rapid decrease in seawater δ^{18}O indicates significant surface freshening [*Obbink et al.*, 2010; *Thornalley et al.*, 2010] (Figure 3), and divergence between δ^{18}O of different planktonic species indicates upper ocean stratification [*Peck et al.*, 2007]. Furthermore, modeling experiments have demonstrated that freshwater-induced stratification can lead to a decrease in HLNA reservoir ages [*Ritz et al.*, 2008]. Thus, we conclude that AMOC strength reached a minimum around 16 kyr BP, consistent with the timing of maximum North Atlantic Pa/Th [*McManus et al.*, 2004; *Gherardi et al.*, 2005] (Figure 3). A minor AMOC reinvigoration after 16 kyr BP but before the start of the BA (14.7 kyr BP) [*Carlson et al.*, 2008] may have allowed relatively small reservoir ages to persist through late HS1.

[15] Extreme climate changes associated with the transition between early and late HS1 at 16 kyr BP are just beginning to be recognized and understood. These include a decrease in NGRIP ice δ^{18}O [*North Greenland Ice Core Project Members*, 2004], decelerations in both the atmospheric CO_2 rise and Atlantic-sector Antarctic warming [*EPICA Community Members*, 2006; *Broecker et al.*, 2009; *Stenni et al.*, 2011], a minimum in East Asian monsoon strength [*Wang et al.*, 2001] (Figure 3), plateaus in atmospheric methane [*Broecker et al.*, 2009; *Parrenin et al.*, 2013] and δ^{13}C [*Schmitt et al.*, 2012], drought in the Sahel region, and increased precipitation in northeast Brazil [*Bouimetarhan et al.*, 2012]. We propose that strong North Atlantic stratification at 16 kyr BP was the trigger for coeval circulation changes in the Southern Ocean [*Anderson et al.*, 2009], North Pacific [*Okazaki et al.*, 2010], and atmosphere [*Broecker et al.*, 2009; *Bouimetarhan et al.*, 2012], which together caused these large, rapid climate shifts.

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