Radiocarbon evidence for alternating northern and southern sources of ventilation of the deep Atlantic carbon pool during the last deglaciation

Luke C. Skinner[a,1], Claire Waelbroeck[b], Adam E. Scrivner[a], and Stewart J. Fallon[c]

[a]Godwin Laboratory for Palaeoclimate Research, Department of Earth Sciences, University of Cambridge, Cambridge CB2 3EQ, United Kingdom; [b]Laboratoire des Sciences du Climat et de l'Environment/Institut Pierre Simon Laplace, Laboratoire Centre National de la Recherche Scientifique–Commissariat à l'Energie Atomique–Université de Versailles Saint-Quentin, F-91198 Gif-sur-Yvette Cedex, France; and [c]Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

Edited by Mark H. Thiemens, University of California, San Diego, La Jolla, CA, and approved March 4, 2014 (received for review January 14, 2014)

Recent theories for glacial–interglacial climate transitions call on millennial climate perturbations that purged the deep sea of sequestered carbon dioxide via a "bipolar ventilation seesaw." However, the viability of this hypothesis has been contested, and robust evidence in its support is lacking. Here we present a record of North Atlantic deep-water radiocarbon ventilation, which we compare with similar data from the Southern Ocean. A striking coherence in ventilation changes is found, with extremely high ventilation ages prevailing across the deep Atlantic during the last glacial period. The data also reveal two reversals in the ventilation gradient between the deep North Atlantic and Southern Ocean during Heinrich Stadial 1 and the Younger Dryas. These coincided with periods of sustained atmospheric CO_2 rise and appear to have been driven by enhanced ocean–atmosphere exchange, primarily in the Southern Ocean. These results confirm the operation of a bipolar ventilation seesaw during deglaciation and underline the contribution of abrupt regional climate anomalies to longer-term global climate transitions.

ocean circulation | carbon cycle | abrupt change

The apparent ubiquity of abrupt millennial-scale climate anomalies on Pleistocene glacial–interglacial transitions (1) has prompted some to suggest these events may represent a necessary component of the deglacial process, primarily through their effect on atmospheric CO_2 (2–4). According to this hypothesis (hereafter referred to as the "millennial purge" hypothesis), incipient deglaciation triggers a transient collapse of the North Atlantic overturning circulation, as well as a warming around Antarctica via the "thermal bipolar seesaw" mechanism (5). This, in turn, is proposed to drive the release of previously sequestered "marine" CO_2 to the atmosphere via increased upwelling and/or air–sea exchange in the Southern Ocean, which would have resulted from changes in the density stratification (6), sea ice cover (4) or wind forcing (2) around Antarctica.

Despite the promise of this new theory for deglacial CO_2 release, and despite emerging data in its support (4, 7, 8), it rests on two key premises that have yet to be confirmed. The first premise is the existence before deglaciation of a deeply sequestered, and hence radiocarbon-depleted (9), marine carbon pool of significant extent. The existence of such a carbon pool continues to be questioned (e.g., ref. 10). The second premise is a necessary (or at least conditional) alternation between northern and southern Atlantic ventilation anomalies, broadly in line with the bipolar seesaw in deep ocean ventilation that was initially proposed by Broecker (11). Direct evidence for this is still lacking. At this time, the strongest support for the bipolar ventilation seesaw of ref. 11 comes from Southern Ocean opal productivity pulses that occur in time with the deglacial stadial events Heinrich Stadial 1 (HS1) and the Younger Dryas (YD) (2). However, even these data strictly remain mute on the anticorrelation or otherwise of southern versus northern (hemisphere) ventilation of the Atlantic interior. Indeed, most other available proxy reconstructions have been interpreted as showing that Southern Ocean ventilation (as inferred, often ambiguously, from radiocarbon, stable carbon isotopes, carbonate preservation, or water mass sourcing) was reduced during North Atlantic stadials when CO_2 was increasing (e.g., refs. 12–14), in apparent conflict with the millennial purge hypothesis.

Results

To assess possible links between North and South Atlantic ventilation, we generated a continuous record of deep-water radiocarbon ventilation from the Northeast Atlantic, which we compare with similar data from the Atlantic sector of the sub-Antarctic Southern Ocean (4). Deep-water radiocarbon ventilation records specifically constrain the extent of isotopic equilibration between the deep-ocean and atmospheric carbon pools and therefore bear directly on the role of the ocean circulation on ocean–atmosphere carbon exchange. Here, radiocarbon measurements have been performed on paired samples of rigorously cleaned (15) monospecific planktonic and mixed benthic foraminifera from core MD99-2334K (37°48′N, 10°10′W; 3,146 m). The site of MD99-2334K, on the Iberian Margin in the Northeast Atlantic, is currently bathed in northward recirculating Northeast Atlantic Deep Water, which includes ∼47% Lower Deep Water (derived from Antarctic Bottom Water) (Fig. S1). The chronology for core MD99-2334K is based on the alignment of local surface temperature trends [recorded in foraminiferal $\delta^{18}O$ and Mg/Ca measurements (16)] to the uranium-series dated speleothem records from Hulu Cave (17–19) (Fig. S2). This alignment is

Significance

This study sheds light on the mechanisms of deglacial atmospheric CO_2 rise and, more specifically, on the hypothesized role of a "bipolar seesaw" in deep Atlantic ventilation. Comparing new high-resolution radiocarbon reconstructions from the Northeast Atlantic with existing data from the Southern Ocean, we show that a bipolar ventilation seesaw did indeed operate during the last deglaciation. Whereas today the deep Atlantic's carbon pool is "flushed" from the north by North Atlantic Deep Water export, it was flushed instead from the south during Heinrich Stadial 1 and the Younger Dryas, in time with sustained atmospheric CO_2 rise.

Author contributions: L.C.S. designed research; L.C.S. performed research; A.E.S. performed sample preparations and analyses; S.J.F. performed accelerator mass spectrometry analyses; L.C.S. and C.W. analyzed data; and L.C.S., C.W., A.E.S., and S.J.F. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence should be addressed. E-mail: lcs32@cam.ac.uk.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1400668111/-/DCSupplemental.

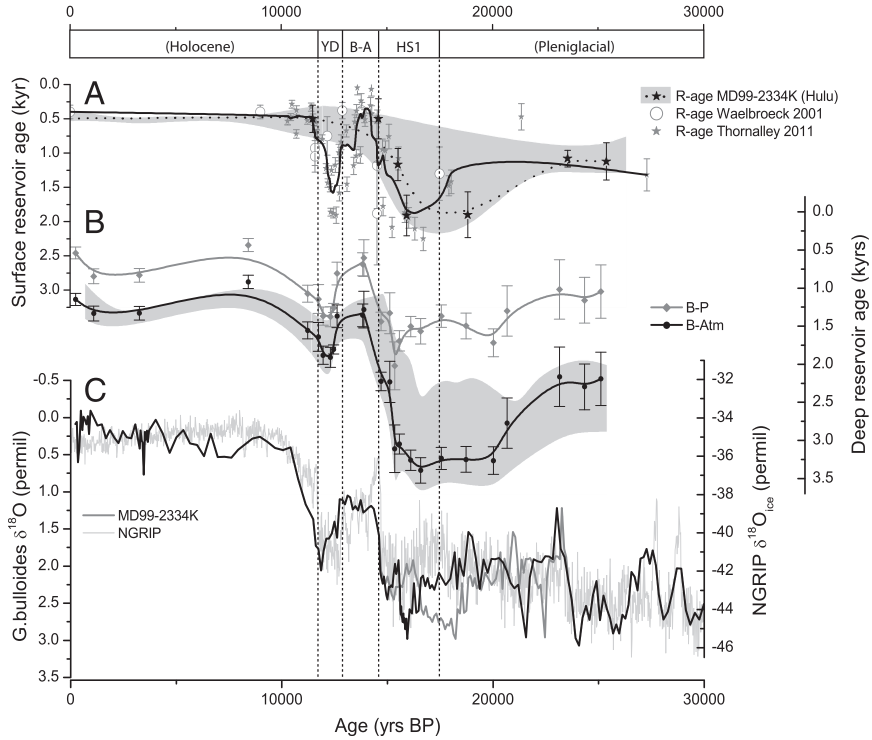

Fig. 1. (*A*) Surface reservoir ages in MD99-2334K (solid black stars with 1 sigma dating uncertainties and dashed b-spline, with shaded range of possible values implied by different viable calendar chronologies) compared with other Northeast Atlantic surface reservoir age estimates [open circles (21) and gray stars (22), with solid black 5-point smoothed b-spline]. (*B*) MD99-2334K benthic–planktonic age offsets (B-P, gray open diamonds and line) and deep-water reservoir ages (i.e., benthic–atmosphere age offsets, B-Atm) (solid black diamonds and line, with shaded max/min range). (*C*) Planktonic $\delta^{18}O$ in core MD99-2334K (solid black line), shown on two distinct calendar chronologies that encompass the range of reservoir ages in *A* and *B* (shaded range) compared with the NGRIP $\delta^{18}O$ record (fine gray line) (16, 35). All uncertainties are 1σ. Vertical lines show the timing of the YD, Bølling–Allerød, and HS1 [onset based on dust content in Greenland ice (36)].

in near-perfect agreement with the North Greenland Ice Core Project (NGRIP) ice-core chronology (Fig. 1*C*), although the timing of events between the LGM and HS1 is not obviously constrained by the NGRIP event stratigraphy. For this reason, we consider a range of possible calendar age constraints that permit the construction of a best guess and a maximum/minimum bounding range of sediment age-depth models (20) for core MD99-2334K (see *Supporting Information*). These age models are constructed to be consistent with the various possible speleothem calendar age-constraints while also taking into account the down-core radiocarbon dating constraints. Surface- and deep-water reservoir ages are then derived from the offset between down-core foraminifer radiocarbon ages in MD99-2334K (on the range of possible calendar age-scales) versus contemporary atmospheric radiocarbon ages recorded in the Hulu Cave deposits (19).

The resulting surface reservoir ages are in excellent agreement with previous estimates from the Northeast Atlantic (21, 22) (Fig. 1*A*). These results demonstrate a degree of coherence between regional ocean–atmosphere radiocarbon disequilibration (in the subsurface habitat of planktonic foraminifera) and the general climatic trends of the North Atlantic region, which may result from a combination of changes in the ventilation of the thermocline, the thickness of the mixed layer (e.g., the presence of a seasonal/perennial halocline), the presence of a radiocarbon-depleted subsurface water mass (e.g., from the Nordic Seas), and/or local upwelling effects. The significant variability of surface reservoir ages in this context (and others like it) has clear implications for marine radiocarbon-based chronologies (21); however, it also serves as a reminder that the a priori assumption of a constant surface reservoir age begs the question of air–sea CO_2 exchange efficiency across the uppermost surface ocean under glacial climate conditions. This, in turn, has implications for our interpretation of the atmospheric radiocarbon ($\Delta^{14}C_{atm}$) record (9) and for deep-water radiocarbon reconstructions (e.g., refs. 4, 22).

Whereas the benthic–planktonic (B-P) ventilation ages in MD99-2334K already suggest a significant increase (by ∼1,000 y) in the age of deep water filling the Northeast Atlantic during the last glacial period, benthic–atmosphere (B-Atm) ages indicate an increase, versus the atmosphere, that is up to 2.5 times larger. The radiocarbon reservoir age of the deep northeast Atlantic may thus have increased to between ∼2,250 and ∼3,400 y during the last glacial maximum. These results confirm the existence of a glacial marine carbon reservoir that was at least as radiocarbon-depleted as the oldest deep-water masses in the modern ocean, which extended from the deep North Atlantic (22) to the deep Southern Ocean (4, 7) and likely also contributed to a greater volume of the deep ocean "downstream" of these basins.

Recent estimates suggest that ∼25–30% of the modern ocean interior >1,500 m in depth is sourced from the North Atlantic (roughly >40°N) and that essentially the remainder (∼56–61%) is sourced from the Southern Ocean (roughly >40°S) (23, 24). If the surface reservoir age changes recorded at MD99-2334K and MD07-3076 (4) were broadly representative of their wider North Atlantic and Southern Ocean regions [which remains unproven but is not implausible, given the regional consistency of modern and paleo reservoir age estimates (4, 7, 21, 22)], a circulation geometry similar to today's would already require a significant change in the marine radiocarbon inventory during the late glacial period.

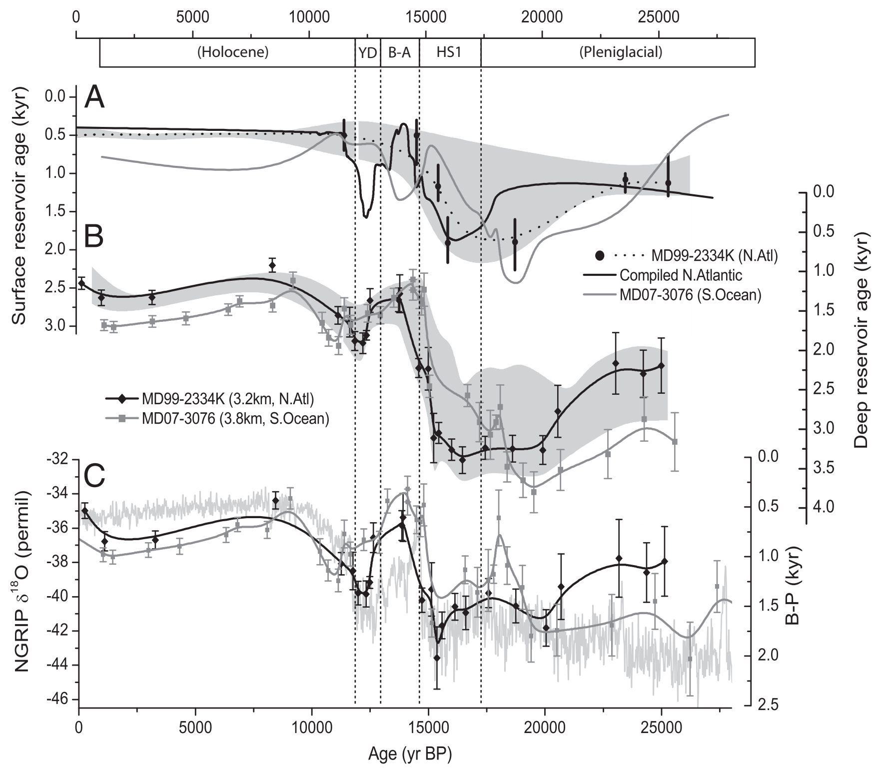

Fig. 2. Ventilation records from the North Atlantic (MD99-2334K) and Southern Ocean (MD07-3076). (*A*) Surface reservoir ages, as for Fig. 1. (*B*) Deep-water reservoir ages (i.e., benthic-atmosphere age offsets; B-Atm). (*C*) Benthic-planktonic age offsets (B-P) compared with the NGRIP $\delta^{18}O$ record (fine gray line) (35). Data from MD99-2334K are shown by black symbols and heavy lines; data from MD07-3076 are shown by gray symbols and heavy lines. B-A, Bølling–Allerød.

Fig. 2 compares the surface- and deep-water radiocarbon ventilation history of the northeast Atlantic (this study, MD99-2334K; 3,146 m) and the sub-Antarctic Atlantic (MD07-3076; 3,777 m) (4). For consistency, the sub-Antarctic records are shown here referenced to the same Hulu atmospheric radiocarbon values as used for MD99-2334K (see *Supporting Information*). The coherence between the surface and deep-water records in each hemisphere is striking, with similar patterns of variability and amplitudes of change exhibited at each location for all three measures of radiocarbon ventilation (surface reservoir ages, B-P age offsets, and deep-water reservoir ages; Fig. 2 *A*–*C*). However, important differences between the North Atlantic and Southern Ocean records emerge during HS1, and the YD in particular, when the radiocarbon ventilation gradient between the two sites collapsed. This is apparent in both surface- and deep-water reservoir ages and is expressed as a reversal of the north–south radiocarbon ventilation gradient on the "best guess" MD99-2334K calendar chronology. Benthic–planktonic offsets (Fig. 2*B*) also exhibit a clear reversal in the apparent ventilation gradient, although without a return to the "normal" north–south gradient seen in the B-Atm and surface reservoir age records during the Bølling–Allerød interstadial.

Discussion

These results confirm the operation of a bipolar "ventilation seesaw" across the last deglaciation, whereby the radiocarbon ventilation of the deep Southern Ocean increased during HS1 and the YD to a level commensurate with, or even above, that observed concurrently in the deep North Atlantic. This is further supported by the antiphase variability in shallow subsurface reservoir ages observed in each hemisphere (Fig. 2*A*). Fig. 3 shows how the reversal of the ventilation gradient between the North and South Atlantic corresponded with periods of sharply rising atmospheric CO_2 (25), as well as periods of inferred Atlantic meridional overturning circulation "collapse" (26). New planktonic $\delta^{13}C$ measurements from core MD07-3076 in the Southern Ocean (*Supporting Information* and Fig. 3*B*) further demonstrate a close correspondence between increased nutrient supply to the surface ocean and pulses in opal accumulation from across the Southern Ocean (2), as well as pulses in the ventilation age of the deep Southern Ocean (4), a strong indication that enhanced upwelling was indeed the driver of the observed export productivity pulses. This inference is further supported by silicon and nitrogen isotope evidence for enhanced nutrient supply to the surface ocean during HS1 and the YD (27). Together with the radiocarbon data from the North Atlantic, these findings provide strong evidence of enhanced ventilation specifically of the ocean interior's carbon pool, and specifically via the Southern Ocean in time with rapid atmospheric CO_2 rise during HS1 and the YD. Indeed, the sequence of events illustrated in Fig. 3 is essentially as required by the millennial purge hypothesis that has been advanced to explain the rapid and pulsed rise of atmospheric CO_2 across the last deglaciation (2, 3). According to the revised dating of the Antarctic ice cores (28), our data and chronologies indicate an overlap between the first indication of deep ocean hydrographic/circulation change in the Southern Ocean (at ~19.7 ± 0.6 ka) and the initiation of Antarctic temperature and CO_2 rise (at ~18.6 ± 1.9 ka; full absolute uncertainty). Given the chronological uncertainties, the apparent lag of ~1,000 y between the marine and atmospheric changes is not strictly significant, although superficially it might be seen as corroborating a proposed delay in the response of atmospheric CO_2 versus the onset of hydrographic change in the Southern Ocean (29). The suggested delay in the carbon cycle response would remain unexplained, and although our data cannot confirm or refute the speculation that it represents a threshold dependence of CO_2 rise on overturning circulation change (29), it is notable that a qualitatively similar threshold response does

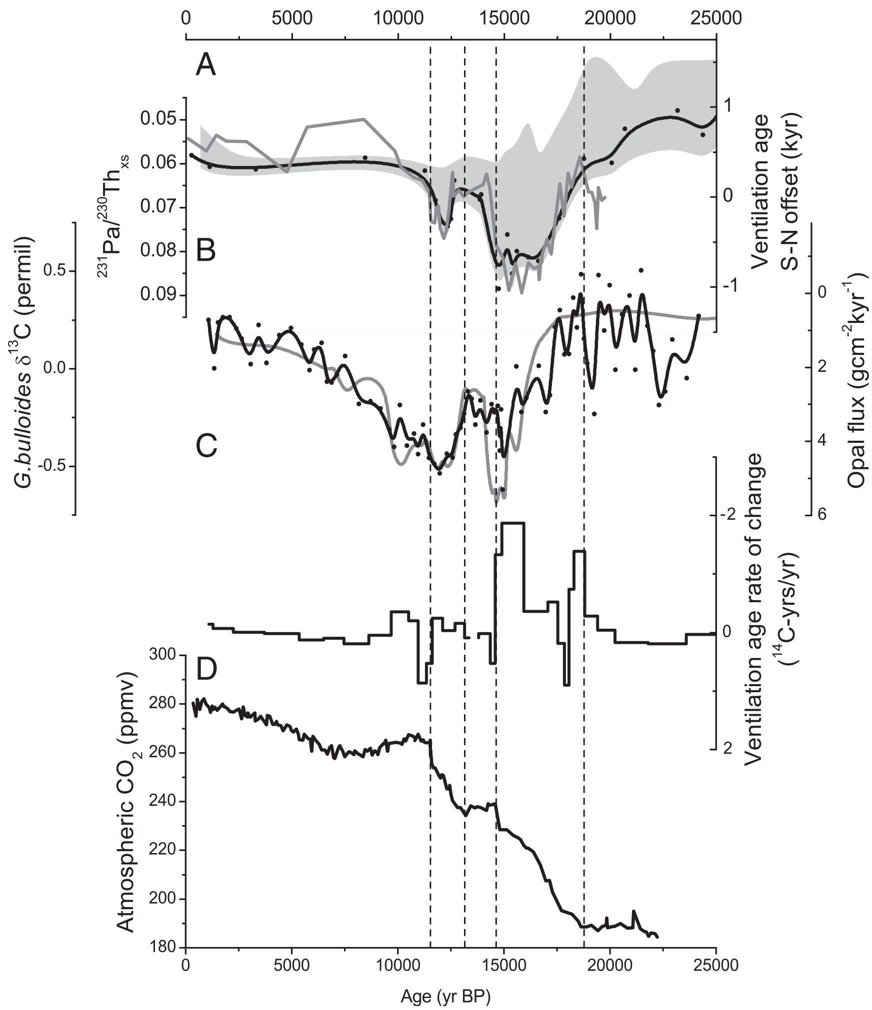

Fig. 3. (*A*) North–south offsets in deep-water reservoir ages (solid circles and heavy black line, with shaded range) compared with reconstructed North Atlantic overturning circulation strength derived from excess protactinium-231 to thorium-230 ratio ($^{231}Pa/^{230}Th_{xs}$) measurements [heavy gray line (26)]. (*B*) Southern Ocean upwelling, derived from planktonic $\delta^{13}C$ measured in core MD07-3076 (solid black circles and line), and opal flux measured in core TNO57-13PC4 (2) (solid gray line). (*C*) The rate of change of B-Atm ventilation ages in MD07-3076. (*D*) Atmospheric CO_2 concentrations from the European Project for Ice Coring in Antarctica ice-core, placed on the AICC2012 age-scale (28). Vertical lines indicate the timing of rapid CO_2 rise, broadly coinciding with HS1 and the YD.

appear in numerical model simulations (6). Determining the veracity of this lag and its implications for the triggering mechanisms of the bipolar ventilation seesaw and CO_2 release during HS1 will be an important future research goal.

It is important to note that if our observations confirm the operation of a ventilation seesaw in the deep Atlantic, they only do so in relation to "ventilation" as defined as a means of introducing radiocarbon (i.e., water with a dissolved inorganic carbon pool that has equilibrated with the atmosphere) into the ocean interior. This definition of ventilation is of particular relevance to ocean–atmosphere carbon exchange but is strictly not identical to definitions based on, for example, stable carbon isotope fractionation (14), carbonate preservation (12), or the direction/rate of mass transport (26) in the ocean interior. The suggestion of continued deep-water export from the North Atlantic to the Southern Ocean during late HS1, based on neodymium isotopes (13, 30), underlines this fact and may imply the existence of an "aged" (radiocarbon-depleted) water mass of North Atlantic origin.

The results presented here confirm two necessary and hitherto contested aspects of the millennial purge hypothesis for deglacial CO_2 rise; namely, the existence of a deeply sequestered carbon pool in the glacial ocean and the operation of a bipolar ventilation seesaw in the Atlantic. However, although these results indicate that the millennial purge hypothesis for deglacial CO_2 rise is indeed viable, they do not yet prove that this mechanism was necessary for late Pleistocene deglaciations (1, 3), in which global field insolation anomalies and albedo feedbacks will have played leading roles. Nevertheless, our findings indicate that via their carbon cycle effects, these potentially stochastic millennial events might have played a critical role in shaping the character and exact timing of Pleistocene deglaciations, the predictability of which would therefore be extremely limited on the millennial time frame.

Materials and Methods

Mixed benthic foraminifera (excluding agglutinated and broken shells) and monospecific samples of the planktonic foraminifer *Globigerina bulloides* or *Neogloboquadrina pachyderma* were picked from 1-cm slices of core MD99-2334K, supplementing previous radiocarbon dates reported by Skinner and Shackleton (31). Samples were cleaned according to the Mg/Ca cleaning method of ref. 15 before drying and sealing in evacuated septum "blood vials" for hydrolysis in 0.5 mL dry phosphoric acid at 60 °C. Carbon dioxide evolved from the samples was graphitized at the Research School of Earth Sciences (Australian National University), using a standard hydrogen/iron-catalyst protocol (32). Samples were graphitized in parallel with Iceland Spar calcite backgrounds, as well as primary and secondary standards for normalization and quality control. Pressed graphite targets were analyzed by single-stage accelerator mass spectrometry at the Australian National University (33). An additional suite of (similarly cleaned) samples were graphitized and analyzed by accelerator mass spectrometry at the Natural Environment Research Council/Scottish Universities Environmental Research Centre (SUERC) radiocarbon facility. Radiocarbon ages are reported according to the standard protocol of ref. 34.

ACKNOWLEDGMENTS. We are grateful to K. James at the Australian National University radiocarbon laboratory and S. Moreton at the SUERC/Natural Environment Research Council (NERC) radiocarbon laboratory for technical assistance. We are also grateful for the critical and constructive comments of two anonymous reviewers. This work was supported by the Royal Society United Kingdom through a University Research Fellowship (to L.C.S.), and by NERC radiocarbon Grant 1467.0410. C.W. is supported financially by the Centre National de la Recherche Scientifique, Institut National des Sciences d l'Univers. This is Laboratiore des Sciences du Climat et de l'Environment Contribution 5265.

1. Barker S, et al. (2011) 800,000 years of abrupt climate variability. *Science* 334(6054): 347–351.
2. Anderson RF, et al. (2009) Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO2. *Science* 323(5920):1443–1448.
3. Denton GH, et al. (2010) The last glacial termination. *Science* 328(5986):1652–1656.
4. Skinner LC, Fallon S, Waelbroeck C, Michel E, Barker S (2010) Ventilation of the deep Southern Ocean and deglacial CO2 rise. *Science* 328(5982):1147–1151.
5. Schmittner A, Saenko OA, Weaver AJ (2003) Coupling of the hemispheres in observations and simulations of glacial climate change. *Quat Sci Rev* 22:659–671.
6. Schmittner A, Galbraith ED (2008) Glacial greenhouse-gas fluctuations controlled by ocean circulation changes. *Nature* 456(7220):373–376.
7. Burke A, Robinson LF (2012) The Southern Ocean's role in carbon exchange during the last deglaciation. *Science* 335(6068):557–561.
8. Marchitto TM, Lehman SJ, Ortiz JD, Flückiger J, van Geen A (2007) Marine radiocarbon evidence for the mechanism of deglacial atmospheric CO2 rise. *Science* 316(5830): 1456–1459.
9. Broecker W, Barker S (2007) A 190 permil drop in atmospher's Delta-14C during the "Mystery Interval" (17.5 to 14.5 kyr). *Earth Planet Sci Lett* 256:90–99.
10. Hain MP, Sigman DM, Haug GH (February 17, 2011) Shortcomings of the isolated abyssal reservoir model for deglacial radiocarbon changes in the mid-depth Indo-Pacific Ocean. *Geophys Res Lett*, 10.1029/2010GL046158.
11. Broecker WS (1998) Palaeocean circulation during the last deglaciation: A bipolar seesaw? *Paleoceanography* 13:119–121.
12. Barker S, Knorr G, Vautravers M, Diz P, Skinner LC (2010) Extreme deepening of the Atlantic overturning circulation during deglaciation. *Nat Geosci* 3:567–571.
13. Piotrowski AM, Goldstein SL, Hemming SR, Fairbanks RG (2004) Intensification and variability of ocean thermohaline circulation through the last deglaciation. *Earth Planet Sci Lett* 225:205–220.
14. Waelbroeck C, et al. (2011) The timing of deglacial circulation changes in the Atlantic. *Paleoceanography* 26:PA3213.
15. Barker S, Greaves M, Elderfield H (2003) A study of cleaning procedures used for foraminiferal Mg/Ca paleothermometry. *Geochem Geophys Geosyst* 4(9):84078.
16. Skinner LC, Elderfield H (2005) Constraining ecological and biological bias in planktonic foraminiferal Mg/Ca and d18Occ: A multi-species approach to proxy calibration testing. *Paleoceanography* 20:1–15.
17. Wang YJ, et al. (2001) A high-resolution absolute-dated late Pleistocene Monsoon record from Hulu Cave, China. *Science* 294(5550):2345–2348.
18. Zhao K, Wang Y, Edwards L, Cheng H, Liu D (2010) High-resolution stalagmite d18O records of Asian monsoon changes in central and southern China spanning the MIS 3/2 transition. *Earth Planet Sci Lett* 298:191–198.
19. Southon J, Noronha AL, Cheng H, Edwards RL, Wang Y (2012) A high-resolution record of atmospheric C-14 based on Hulu Cave speleothem H82. *Quat Sci Rev* 33:32–41.
20. Parnell AC, Haslett J, Allen JRM, Buck CE, Huntley B (2008) A flexible approach to assessing synchroneity of past events using Bayesian reconstructions of sedimentation history. *Quat Sci Rev* 27:1872–1855.
21. Waelbroeck C, et al. (2001) The timing of the last deglaciation in North Atlantic climate records. *Nature* 412(6848):724–727.
22. Thornalley DJR, Barker S, Broecker WS, Elderfield H, McCave IN (2011) The deglacial evolution of North Atlantic deep convection. *Science* 331(6014):202–205.
23. Gebbie G, Huybers P (2010) Total matrix intercomparison: A method for determining the geometry of water-mass pathways. *J Phys Oceanogr* 40(8):1710–1728.
24. Khatiwala S, Primeau F, Holzer M (2012) Ventilation of the deep ocean constrained with tracer observations and implications for radiocarbon estimates of ideal mean age. *Earth Planet Sci Lett* 325-326:116–125.
25. Monnin E, et al. (2001) Atmospheric CO2 concentrations over the last glacial termination. *Science* 291(5501):112–114.
26. McManus JF, Francois R, Gherardi J-M, Keigwin LD, Brown-Leger S (2004) Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature* 428(6985):834–837.
27. Horn MG, Beucher CP, Robinson RS, Brzezinski MA (2011) Southern ocean nitrogen and silicon dynamics during the last deglaciation. *Earth Planet Sci Lett* 310(3-4): 334–339.
28. Veres D, et al. (2013) The Antarctic ice core chronology (AICC2012): An optimized multi-parameter and multi-site dating approach for the last 120 thousand years. *Clim. Past* 9(4):1733–1748.
29. Shakun JD, et al. (2012) Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation. *Nature* 484(7392):49–54.
30. Skinner L, et al. (April 29, 2013) North Atlantic versus Southern Ocean contributions to a deglacial surge in deep ocean ventilation. *Geology*, 10.1130/G34133.1.
31. Skinner LC, Shackleton NJ (2004) Rapid transient changes in Northeast Atlantic deepwater ventilation-age across Termination I. *Paleoceanography* 19:1–11.
32. Vogel JS, Southon JR, Nelson DE, Brown TA (1984) Performance of catalytically condensed carbon for use in accelerator mass spectrometry. *Nucl Instrum Methods Phys Res B* 5:289–293.
33. Fallon SJ, Fifield LK, Chappell JM (2010) The next chapter in radiocarbon dating at the Australian National University: Status report on the single stage AMS. (Translated from English). *Nucl Instrum Methods Phys Res B* 268(7-8):898–901.
34. Stuiver M, Polach HA (1977) Reporting of 14C data. *Radiocarbon* 19(3):355–363.
35. Svensson A, et al. (2008) A 60,000 year Greenland stratigraphic ice core chronology. *Clim. Past* 4:47–57.
36. Mayewski PA, et al. (1997) Major features and forcing of northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series. *J Geophys Res* 102(C12):26345–26366.