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

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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 CO₂ 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.

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 atmospheric equilibration. 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 Northwest Atlantic, is currently bathed in northward recirculating North- east 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 δ¹³C 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 CO₂ 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 CO₂ 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.

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in near-perfect agreement with the North Greenland Ice Core Project (NGRIP) ice-core chronology (Fig. 1C), 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 possible specific pleistocene 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. 1A). These results demonstrate a degree of coherence between regional ocean–atmosphere radiocarbon disequilibrium (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 CO₂ exchange efficiency across the uppermost surface ocean under glacial climate conditions. This, in turn, has implications for our interpretation of the atmospheric radiocarbon (Δ¹⁴C 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.

![Diagram](https://example.com/diagram.png)

**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 δ¹⁸O 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 δ¹⁸O 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)).
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. 2B) 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. New planktonic δ13C measurements from core MD07-3076 in the Southern Ocean (Supporting Information and Fig. 3B) 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 the Bølling–Allerød interstadial.

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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 δ18O 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.
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 CO₂ 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 CO₂ 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 CO₂ 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...
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Supporting Information

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SI Materials and Methods

Core Locations. The locations of cores MD99-2334K and MD07-3076 are shown in Fig. S1. The site of MD99-2334K (37°48′N; 10°10′W; 3,146 m), on the Iberian Margin in the Northeast Atlantic, is currently bathed in northward recirculating Northeast Atlantic Deep Water, a modified form of North Atlantic Deep Water that includes ~47% Lower Deep Water (derived from Antarctic Bottom Water) (1). The site of MD07-3076 (44°4.46′S; 14°12.47′W; 3,770 m), on the eastern flank of the mid-Atlantic Ridge in the sub-Antarctic South Atlantic, is currently bathed in a predominantly southward-flowing mixture of modified North Atlantic Deep Water and Lower Circumpolar Deep Water, which feeds into the core of eastward flowing Circumpolar Deep Water. Fig. S1 illustrates the locations of these cores within the field of modern (prebomb) seawater radiocarbon concentrations, as well as the estimated proportion of water that is currently derived from the surface North Atlantic (~40°N) versus the surface Southern Ocean (~40°S), based on the methods of ref. 2.

Planktonic Stable Carbon Isotopes. Planktonic stable carbon isotopes were measured on samples of Globigerina bulloides, using ~30 individuals handpicked from the 250–300-μm size-fraction of core MD07-3076. Stable isotope analyses were carried out using a VG SIRA mass spectrometer at the Godwin Laboratory, Cambridge, United Kingdom, reacted sequentially using an ISOCARB preparation system. Measurements of δ13C were determined relative to the Vienna Peedee Belemnite standard; analytical precision is better than 0.06‰.

Radiocarbon Dates and Chronology. Radiocarbon dates from core MD99-2334K are listed in Datasets S1 and S2. Here we have supplemented radiocarbon dates previously reported in ref. 3. Where planktonic dates are not available from precisely the same depth interval as the benthic dates, interpolated planktonic dates have been used to calculate benthic–planktonic (B-P) offsets. To obtain a record of surface- and deep-water reservoir age variability (i.e., the evolving offset between marine and atmosphere radiocarbon concentrations), radiocarbon dates from core MD99-2334K must first be placed on an independent calendar age-scale. It has been shown that past changes in Greenland temperatures, as recorded by ice-core precipitation isotope records, have been closely tracked by surface temperature changes on the Iberian Margin, as recorded by planktonic δ18O (4, 5) and Mg/Ca (6), as well as pollen transported from the Iberian Peninsula (7). This close coupling (which is also conceptually supported) provides a basis for aligning marine records from the Iberian Margin to the Greenland ice-core event stratigraphy.

A similar alignment may also be performed with the event stratigraphy of the east Asian speleothem records (8–11). The advantage of this alignment is that it permits the transference of the relatively precise and accurate radiometric speleothem age-scale (12, 13). In the context of this study, a further advantage of adopting the speleothem chronostratigraphy is that it directly incorporates atmospheric radiocarbon measurements that have been performed in the Hulu speleothem H82 (11).

If the Greenland and Asian speleothem event stratigraphies are indeed coupled, and if the independent chronologies associated with each of these stratigraphies are indeed correct, then an alignment of marine records to each of these event stratigraphies should be equivalent and should be consistent with further independent calendar age constraints [including uranium-series dated atmospheric radiocarbon estimates from corals, for example, (13)]. Despite small discrepancies between Asian speleothem ages and the most recent Greenland NGRIP-GICC05 ice-core chronology (14), it does appear that the two chronologies are very close indeed (15).

The Greenland/Asian speleothem link is robust for the clearly identifiable Greenland Isotope Stages 1–4, for example, but it appears to break down in the interval comprising Heinrich Stadial 1 (HS1) and the Last Glacial Maximum (LGM), where the Greenland event stratigraphy itself becomes ambiguous, and the latter approach ignores additional information on the structure of radiocarbon dates versus atmospheric ages from the Hulu H82 radiocarbon calibration curve (15) (0,670 y BP) and the Hulu H82 speleothem (11) (10,674–26,850 y BP).

For surface reservoir ages, we take the most conservative approach of only inferring reservoir ages at tie-points (using interpolated planktonic radiocarbon dates where necessary). These reservoir-age constraints are used to correct down-core planktonic radiocarbon dates (interpolating where necessary), which are then used to derive a Behron (17) age-depth model that is consistent with both the structure in the down-core radiocarbon dates and the calendar age constraints from the two alternative speleothem chronostratigraphies. Deep-water reservoir ages [i.e., benthic versus atmosphere radiocarbon age offsets, or benthic–atmosphere (B-Atm)] are determined as the sum of the known down-core B-P offsets and interpolated surface reservoir ages, consistent with the best guess and bounding Behron chronologies.

It is important to stress that this approach is preferable to simply placing the sediment core on two alternative stratigraphic age-models, based on linear interpolation between very sparse depth-age constraints, and then deriving offsets between planktonic and benthic radiocarbon dates versus atmospheric ages from the Hulu H82 speleothem (the resultant B-Atm ventilation age records are illustrated in Fig. S3 for comparison). The reason for this is that the latter approach ignores additional information on the structure of the age–depth relationship in MD99-2334K (i.e., from the succession of planktonic radiocarbon dates) in the intervals where there is no information on the likely age–depth relationship from chronostratigraphic tie-points (e.g., when tie-points in the HS1/LGM interval are ignored for the minimum age-model, as discussed earlier). Our approach essentially follows the premise that it is more reasonable to assume smooth/minimal changes in surface reservoir ages between exceedingly sparse chronostratigraphic constraints than to assume completely invariant sedimentation rates.
between exceedingly sparse chronostratigraphic constraints. Accordingly, the difference between the two approaches is maximized when the number of available chronostratigraphic tie-points is minimized.

Finally, by plotting optimum reservoir age estimates within a possible range, we underline the proposition that the likelihood distribution of possible reservoir/ventilation ages within the maximum/minimum range is probably not uniform. This proposition will be correct to the extent that the “best guess” speleothem chronology is also closest to being correct. It is notable that the radiocarbon age versus depth relationship in MD99-2334K has a similar shape to the calendar age versus depth relationship defined by the best guess chronology (Fig. S3). This is not the case for the age scale that would derive from a linear interpolation that ignores the possible age constraints in the LGM/HS1 interval. This would suggest that the best guess chronology is indeed more likely to be correct than one that ignores age constraints during the HS1/LGM interval.

Revised Ventilation Ages in MD07-3076. For consistency, it is important the two radiocarbon records we compare are both referenced to the same atmospheric radiocarbon dataset. For MD99-2334K, placed on the “speleothem age scale,” we adopt the Intcal09 and Hulu Cave radiocarbon records (11, 16), whereas the reservoir ages, chronology, and radiocarbon ventilation estimates from core MD07-3076 were originally derived using a splice of the Intcal04 (18) (0–26,000 y BP) and Cariaco Basin (>26,045 y BP) (12) datasets. Using the same calendar age constraints on core MD07-3076 as originally published, we have reassessed the reservoir ages, the calibrated radiocarbon-age Bchron chronology, and the inferred B-Atm ventilation ages for MD07-3076, using the same Intcal09/Hulu atmospheric radiocarbon splice as used here for MD99-2334K. As shown in Fig. S4, this results in almost no change at all, except before ~20,000 y BP, where the revised ventilation ages in MD07-3076 are slightly older, yet still within the originally estimated uncertainty range (19).


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Fig. S1. Location of cores discussed in the text; MD99-2334K (37°48′N, 10°10′W; 3,146 m) and MD07-3076 (44° 4.46′S; 14°12.47′W, 3,770 m) are indicated by solid and open circles, respectively. Color shading indicates modern Global Data Analysis Project prebomb radiocarbon concentrations (20), and dashed contours indicate the proportion of water that last made contact with the surface Southern Ocean >40°S, based on the methods in ref. 2, courtesy of Primeau.

Fig. S2. Alignment of planktonic δ18O measured in core MD99-2334K (6), with the Asian speleothem event stratigraphy (10, 11, 15). The Greenland (NGRIP) event stratigraphy on the GICC05 age scale is essentially identical (14), although it is difficult to identify the same tie-points as in the speleothem records within the HS1-LGM interval (crosses with dashed vertical drop-lines). Two bounding age scales are therefore considered in this study, one using all tie-points to the speleothem event stratigraphy (red line in top plot) and one that avoids using tie-points within the HS1-LGM interval (gray line in top plot).
Fig. S3. (A) Best guess, maximum, and minimum likely surface reservoir ages in core MD99-2334K. (B) Deep ventilation ages (solid dark gray line indicates B-P offsets; solid black squares and line with 1σ radiocarbon dating uncertainties indicate best guess B-Atm offsets with maximum/minimum shaded range; dashed gray lines indicate alternative inferior ventilation histories as described in the text). (C) Benthic radiocarbon dates (black symbols) and planktonic radiocarbon dates (red symbols) compared with a range of Bchron calendar age–depth models (solid black line indicates the best guess or 50% cumulative probability age, and the shaded area indicates maximum/minimum or 2.5–97.5% cumulative probability age range), as well as the speleothem-based calendar age constraints on which these Bchron age-models are based (colored crosses). The maximum Bchron age-scale in C is derived from the minimum surface reservoir ages in A, which ignore the calendar age constraints within the HS1-LGM interval (red crosses in C). All error bars represent 1σ.

Fig. S4. Comparison of previously published ventilation age estimates from core MD07-3076 (19) [red circles and dotted line; referenced to the Intcal04 and Cariaco Basin radiocarbon records (12, 18)], with the revised estimates presented in Fig. 2 [black crossed circles and solid line; referenced to the Intcal09 and Hulu speleothem atmospheric radiocarbon records instead (11, 16)]. The Hulu speleothem record only extends to 25,850 yr BP.

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Other Supporting Information Files

Dataset S1 (TXT)
Dataset S2 (TXT)