Deglacial changes in ocean circulation from an extended radiocarbon calibration

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Temporal variations in the atmospheric concentration of radiocarbon sometimes result in radiocarbon-based age-estimates of biogenic material that do not agree with true calendar age. This problem is particularly severe beyond the limit of the high-resolution radiocarbon calibration based on tree-ring data, which stretches back only to[1,2] about 11.8 kyr before present (BP), near the termination of the Younger Dryas cold period. If a wide range of palaeoclimate records are to be exploited for better understanding the rates and patterns of environmental change during the last deglaciation, extending the well-calibrated radiocarbon timescale back further in time is crucial. Several studies attempting such an extension, using uranium/thorium-dated corals[3–5] and laminae counts in varved sediments[6–9], show conflicting results. Here we use radiocarbon data from varved sediments in the Cariaco basin, in the southern Caribbean Sea, to construct an accurate and continuous radiocarbon calibration for the period 9 to 14.5 kyr BP, nearly 3,000 years beyond the tree-ring-based calibration. A simple model compared to the calculated atmospheric radiocarbon concentration and palaeoclimate data from the same sediment core suggests that North Atlantic Deep Water formation shut down during the Younger Dryas period, but was gradually replaced by an alternative mode of convection, possibly via the formation of North Atlantic Intermediate Water.

The annually laminated sediments of the Cariaco basin are composed of light (plankton-rich) and dark (mineral-rich) layers that result from strong seasonal fluctuations in trade-wind-induced upwelling and regional precipitation[10,11]. Previous work has shown that relative reflectance (grey scale) and light-laminae thickness from the Cariaco basin are proxies for North Atlantic trade-wind intensity[12], which responds rapidly to changes in the temperature gradient between the high-latitude and tropical North Atlantic[12–14]. It has been demonstrated previously that Cariaco basin light-laminae thickness and $\delta^{18}O$ from the GRIP Greenland ice core[15] show similar event durations and patterns of change at the decade scale during the last deglaciation. This indicates that both responded to the same forcing (high-latitude North Atlantic sea surface temperature (SST)) and recorded synchronous events[12]. In the present study, we investigated a sediment interval between 12.6 and 8.0 ^{14}C kyr BP from core PL07-56PC containing thick, distinct laminations, and constructed a 5,500-year-long floating varve chronology by counting laminae pairs. From the ~8,000 ^{14}C yr level to the sediment surface, laminae become thinner and less distinct. Monospecific samples (51) of the planktonic foraminifer *Globigerina bulloides* were taken for accelerator mass spectrometry (AMS) ^{14}C dating, and an average measured reservoir age[10] of 420 yr was subtracted from each date. Cariaco basin geometry dictates that only surface waters (<146 m) well-equilibrated with the atmosphere, and possessing a reservoir age of ~400 yr, can enter the basin, thus maintaining the basin reservoir age near open-ocean values. Despite a varying upwelling regime, ^{14}C dating of multiple surface samples of known age indicates that the reservoir age of these samples agrees with present-day, open Atlantic values. Taken together, these lines of evidence suggest that the Cariaco basin reservoir age is not greatly influenced by local upwelling.

The 5,500-year-long floating varve chronology was anchored to an absolute calendar timescale by wiggle-matching[16] radiocarbon versus calendar age variations to those generated from tree-ring

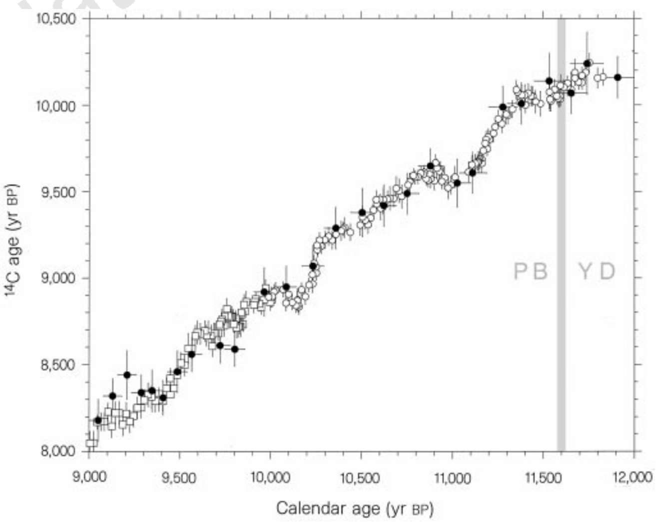

Figure 1 Variations in radiocarbon versus varve age for the Cariaco basin compared to those from tree-rings[1,2]. Solid circles are data from Cariaco basin core PL07-56PC, open circles are from German pines and open squares are from German oaks. The relationship between German oak and pine-tree-ring data sets has been revised recently from that of Kromer and Becker[1] and Björck *et al.*[2], with the result that the pine chronology has now been securely anchored to the oak chronology (B. Kromer, personal communication). A 5,500-year floating chronology for the Cariaco basin was constructed by varve-counting between 12.6 and 8.0 ^{14}C kyr BP. Approximately 3% of the varve-counted sediments contained short sections (1–2 cm thick) disturbed by microbioturbation that could not be bridged by switching to alternative cores. We interpolated through these sections using average varve thickness values from the immediately adjacent 10 cm of sediment above and below the disturbed sections. Maximum and minimum average varve thicknesses over 2-cm increments within the 10-cm sections were used to generate a cumulative uncertainty due to disturbance of 1.7% in 5,500 varve years. The match between the Cariaco basin and tree-ring data sets was carried out using a procedure that objectively minimizes the squared distance between independent time series[16]. The resulting correlation ($r = 0.993$) was used to anchor the floating Cariaco basin varve chronology to an absolute timescale at 9.051 yr BP. Inherent uncertainties in the Cariaco basin radiocarbon and varve ages introduce an estimated additional ±50 yr uncertainty to the anchoring of the absolute varve chronology. Shaded line indicates the Younger Dryas (YD) to Preboreal (PB) transition as determined by Cariaco basin grey scale. ^{14}C errors are shown at 2σ.

data[1] (Fig. 1). The correlation between the varve and tree-ring ^{14}C variations is excellent ($r = 0.993$), and is used to anchor the varve chronology ending at 9051 calendar years before present (cal. yr BP). The data (Fig. 1) also show that the present-day reservoir age of 420 yr did not change during the interval 11.5–9.0 cal. kyr BP. In particular, the brief overlap of Cariaco basin and tree-ring ^{14}C ages at the end of the Younger Dryas shows that the reservoir age remains unchanged even during times of greatly increased upwelling.

To assess the accuracy of the anchored varve chronology, we compared palaeoclimate records from the Cariaco basin and the GISP2 Greenland ice core. Cariaco basin grey scale and GISP2 accumulation[17,18] are plotted against their independently derived annual timescales, from 15 to 9.0 cal. kyr BP (Fig. 2a). Based on an objective method that minimizes the square of the distance between the two time-series[16] (correlation $r = 0.667$), we transferred the GISP2 chronology to the Cariaco basin record and then directly compared the two annual chronologies (Fig. 2b). The two time-scales agree closely, well within the estimated errors, supporting the interpretation of similar palaeoclimate events in the two records as synchronous, as well as the accuracy of the Cariaco basin varve chronology.

The anchored Cariaco basin varve chronology was used to calibrate radiocarbon dates from 13 to 8.0 ^{14}C kyr BP (15 to 9.0 cal. kyr BP; Supplementary Information; Fig. 3a, b). There are radiocarbon age plateaux centred at 11.7, 11.4 and 9.6 ^{14}C kyr BP, in addition to a long, sloping 'plateau' from 10.6 to 10.0 ^{14}C kyr BP,

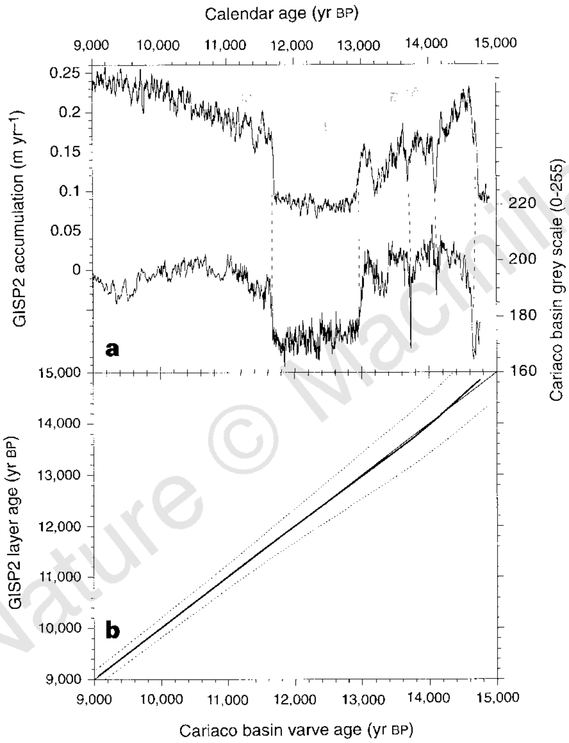

Figure 2 Independent assessment of Cariaco basin varve chronology using comparison to GISP2 palaeoclimate record. **a**, Cariaco basin grey scale[12] (lower curve) compared to accumulation data from the GISP2 ice core[17,18] (upper curve) from 9.0 to 15 cal. kyr BP. Both data sets are plotted against their independent annual timescales. GISP2 accumulation is used here as a proxy for sub-polar North Atlantic SST based on the thermodynamic dependence of precipitation on temperature as well as its dynamic dependence on the location of storm tracks, which are controlled by North Atlantic SST gradient[18]. Large-scale, abrupt climate transitions and events that are identified as the same in Cariaco basin and GISP2 records, and used as tie points for correlation by a least-squares procedure[16], are indicated by dashed lines. The correlation ($r = 0.669$) was used to assign GISP2 layer ages to the Cariaco basin grey scale record in order to compare the two chronologies (described in text). Letters indicate Preboreal (PB), Younger Dryas (YD), and Bølling/Allerød (B/A) climate periods. **b**, Cariaco basin varve age plotted versus GISP2 layer age (thick line). A one-to-one correlation is shown by the thin straight line and combined errors in the chronologies are indicated by the dotted lines. In places, the independent ages are nearly identical, and in all cases they agree well within estimated errors.

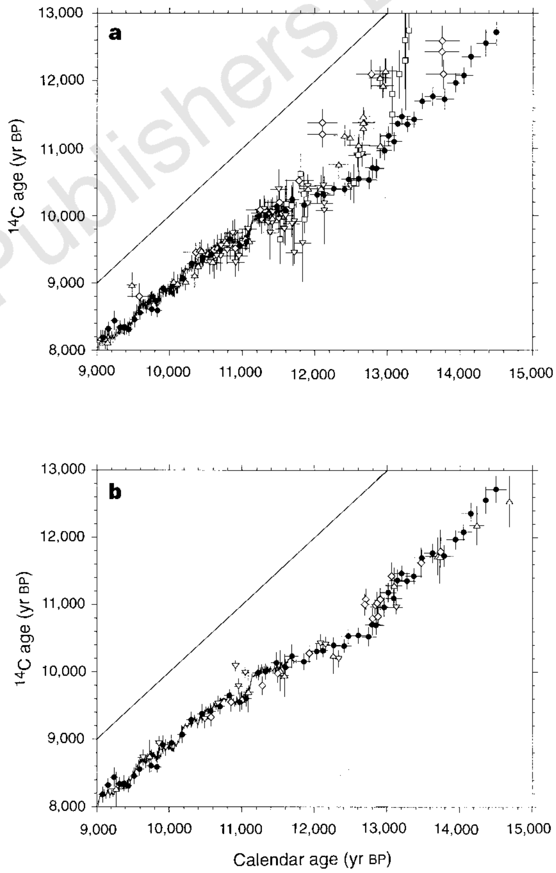

Figure 3 Radiocarbon ages versus calendar ages derived from new and published sources. **a**, Results from the Cariaco basin compared to those from European varved lake sediments and the Swedish varve chronology. Solid circles are Cariaco basin varves; solid line is German pine and German oak data[1]; upside-down triangles (▽) are varves from Lake Gosciaz, Poland[7]; upright triangles (△) are varves from Lake Soppensee, Switzerland[6]; diamonds are varves from Lake Holzmaar, Germany[8]; open squares are Swedish varves[9]. **b**, Results from the Cariaco basin compared to those from coral U/Th dates from the Atlantic and Pacific oceans. Solid circles are Cariaco basin varves; solid line is German pine and German oak data[1]; upside-down triangles are coral U/Th from Papua New Guinea[4]; upright triangles are coral U/Th from Barbados[3]; diamonds are coral U/Th from Tahiti[5]. Ten additional ^{14}C dates from Cariaco basin core PL07-39PC (not shown for clarity) were correlated to PL07-56PC on the basis of distinct, millimetre-scale marker laminae. For each of the ten duplicate samples, the ages agree closely or are nearly identical, demonstrating the reproducibility of Cariaco basin ^{14}C dates. Shaded lines indicate the beginning and end of the Younger Dryas based on Cariaco basin grey scale; line thickness indicates the length of these transitions in Cariaco basin varve years. All radiocarbon dates are presented with 2σ errors.

during which radiocarbon ages decrease only 600 yr in 1,600 varve years. The beginning of this sloping 'plateau' coincides with the onset of the climatic Younger Dryas, but continues for an additional 400 varve years after the Younger Dryas termination (Fig. 3a, b). Before 12 cal. kyr BP, our results generally agree with U/Th-^{14}C data from Atlantic and Pacific corals[3–5] (Fig. 3b), but disagree with calibration results from lakes Soppensee[6] and Holzmaar[8], and the Swedish varve chronology[9] (Fig. 3a). As reported by Wohlfarth[9], the Swedish chronology may contain some erroneous connections between varve segments. In addition, it appears that the Soppensee and Holzmaar varve chronologies are missing varve years, possibly owing to the sediments being intermittently laminated during the Younger Dryas. This discrepancy cannot be attributed to a general land–sea difference due to a variable ocean reservoir age because the ocean radiocarbon dates, in this case, are younger than their implied calendar-age equivalents on land.

Calibrated radiocarbon ages were used to calculate radiocarbon activity (Δ^{14}C) for the period 14.5–9.0 cal. kyr BP (Fig. 4). Although surface waters can be expected to smooth out year- to decade-long fluctuations in atmospheric Δ^{14}C, comparisons of atmospheric and

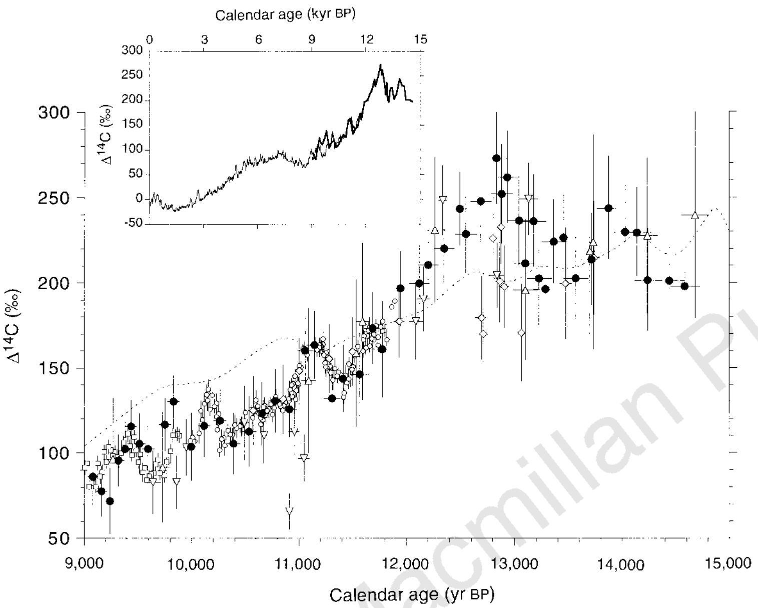

Figure 4 Atmospheric radiocarbon concentration (Δ^{14}C), expressed as the difference in ^{14}C activity (measured in per mil) between the sample and a standard, after corrections for fractionation and sample age[29], calculated from various sources. Symbols are the same as in Fig. 3. $\Delta^{14}C_{geo}$, calculated from ^{14}C production rates resulting from changes in geomagnetic field intensity, is shown by dotted line. To ensure the intercomparability of results, the $\Delta^{14}C_{geo}$ values shown are from Goslar *et al.*[7] using the calculations of Lal[29], and modelled using an initial Δ^{14}C of 230‰ at 15 ^{14}C kyr BP and field intensity data from Tric *et al.*[30]. Inset shows Δ^{14}C data from the Cariaco basin with the continuous record from tree rings[1]. Note increased amplitude of high-frequency fluctuations before ~10 cal. kyr BP.

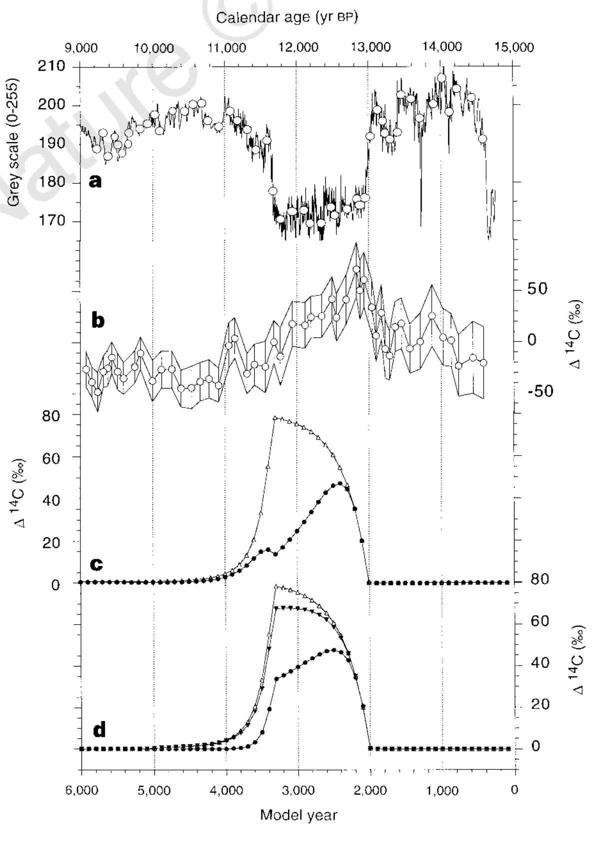

Figure 5 Observed palaeoclimate and Δ^{14}C from the Cariaco basin used to constrain box-model simulations of varying ocean circulation. **a**, Grey scale plotted versus calendar age for Cariaco basin core PL07-56PC. Open circles show locations of samples taken for AMS ^{14}C dating. **b**, Cariaco basin $\Delta^{14}C_{res}$ from core PL07-56PC corrected for geomagnetic production rate changes. Open circles are calculated values, upper and lower limits show 2σ errors. **c**, Simulated atmospheric Δ^{14}C from a geochemical box model as a function of different configurations of oceanic circulation. In the first experiment, NADW was switched abruptly from 20 sverdrups (1 Sv = 10^6 m^3 s^{-1}) to 0 Sv at model year 2000, and then abruptly from 0 to 20 Sv at model year 3330 (open triangles). In a second experiment (solid circles), NADW was specified as above, with the addition of NAIW formation and export increasing linearly from 0 to 20 Sv during the period from model year 2200 to 3330, then abruptly switching back to 0 Sv at 3330 (timing of peak ^{14}C activity depends on arbitrary lag in NAIW initiation). Model circulation regimes were prescribed as changes from the control run of ref. 24. NAIW is formed in the boreal Atlantic surface box and exported according to the following scheme: 25% is recirculated within the North Atlantic; 75% is incorporated into an 'intermediate conveyor' and advected into Pacific and Indian Ocean intermediate boxes. **d**, Same as **c**, with the first experiment simulating a shutdown of NADW (open triangles). In the second experiment, instead of NAIW formation and export, convection in the Southern Ocean was increased gradually by 0 to 20 Sv during the Younger Dryas (solid triangles). For the third experiment (solid circles), in addition to increased convection, gas exchange rates for the surface Southern Ocean were increased by 2× throughout the run, and the mass exchange rates between the deep Southern Ocean and surrounding deep ocean boxes were increased during the Younger Dryas by 40 Sv each (4× total exchange).

oceanic time series of bomb ^{14}C activity suggest that surface waters faithfully record past changes in atmospheric $\Delta^{14}C$ lasting just a few decades[19]. In Fig. 4 calculated $\Delta^{14}C$ is compared to results from tree rings[1,2] and corals[3–5], as well as estimated $\Delta^{14}C$ arising from changes in ^{14}C production due to shifts in Earth's geomagnetic field strength ($\Delta^{14}C_{geo}$), as previously modelled by Goslar *et al.*[7]. To isolate the changes in atmospheric $\Delta^{14}C$ arising from exchange between carbon reservoirs (the additional possibility of forcing from solar variability is rejected because proxy data show no large fluctuations in solar activity at that time; B. Finkel, personal communication), we subtracted $\Delta^{14}C_{geo}$ from observed $\Delta^{14}C$ to obtain a residual ($\Delta^{14}C_{res}$). Comparing this to a grey-scale record from the same Cariaco basin core (Fig. 5a, b) allows a direct correlation of North Atlantic palaeoclimate and atmospheric $\Delta^{14}C$ proxy records. Our data reveal a large asymmetrical increase in $\Delta^{14}C_{res}$ during the Younger Dryas, with a rise of 50–80‰ occurring in ~200 years, followed by a gradual decline of the same amplitude occurring over 1,100 years. The rapid rise in $\Delta^{14}C_{res}$ is synchronous, within errors, with the onset of the climatic Younger Dryas, suggesting that changes in both $\Delta^{14}C_{res}$ and climate were caused by the same forcing mechanism.

It has been suggested previously that shifts in North Atlantic thermohaline circulation were a possible cause of rapid changes in $\Delta^{14}C$ in addition to climate during the Younger Dryas[20–23]. To test this, we used a geochemical box model of the oceans and atmosphere[24] to simulate atmospheric $\Delta^{14}C$ as a function of changes in oceanic circulation. In the first experiment, North Atlantic Deep Water (NADW) formation was switched abruptly 'off', kept 'off' for the duration of the Younger Dryas, and was returned abruptly 'on' at the Younger Dryas termination. As seen in some earlier studies[2,7], the simulated $\Delta^{14}C$ increase (80‰) is relatively gradual, followed by an abrupt decrease at the Younger Dryas termination (Fig. 5c, d), whereas the observed time series of $\Delta^{14}C_{res}$ peaks early and declines gradually throughout the Younger Dryas (Fig. 5b). A simple shutdown of NADW seems to explain the increase but not the subsequent drawdown of $\Delta^{14}C_{res}$ during the Younger Dryas, implying the presence of an additional mechanism which lowers atmospheric $\Delta^{14}C$ during the interval of reduced deep-water formation.

Several published general circulation model (GCM) experiments involving freshwater perturbations to the North Atlantic that interrupted or stopped deep-water production also show a spontaneous oceanic response in the form of either increased North Atlantic Intermediate Water (NAIW) formation or increased convection in the Southern Ocean[25,26]. Box-model experiments reveal that NAIW formation and export to other ocean basins (in the manner of NADW today) provides an effective sink for atmospheric ^{14}C. Using the same schedule of NADW formation as in the first experiment, we can reproduce observed $\Delta^{14}C_{res}$ by gradually increasing NAIW formation and export during the period in which NADW has been shut down (Fig. 5b, c). Similar experiments show that simply increasing convection in the Southern Ocean during the period in which NADW is shut down has very little effect on modelled $\Delta^{14}C$ (Fig. 5d), primarily due to incomplete isotopic equilibration of surface waters, and inadequate export of deep Southern Ocean water to other deep basins. Doubling the gas exchange rate and quadrupling the overall exchange with adjoining deep-water reservoirs results in a ^{14}C drawdown during the Younger Dryas (Fig. 5d), but it is smaller than that seen either in observations (Fig. 5b) or in model experiments with NAIW formation and export (Fig. 5c).

Ocean GCMs indicate that NAIW formation is much less effective at bringing heat north than NADW[26], although we find it can be an effective sink for atmospheric ^{14}C. It is thus possible that a shutdown of NADW produced dramatic cooling of the North Atlantic region and increased atmospheric $\Delta^{14}C$ during the Young Dryas, while its gradual replacement by NAIW acted to draw down $\Delta^{14}C$ even as cooling was maintained. This model is compatible with observational constraints ($\Delta^{14}C$ and palaeoclimate) from the Cariaco basin, and is also in agreement with previous studies suggesting some form of continued North Atlantic sub-surface ventilation during the Younger Dryas[27], which may have occurred specifically through the formation of NAIW[21,28]. In addition to a detailed ^{14}C calibration for the entire interval between 14.5 and 11.5 cal. kyr BP, our data provide a clear picture of how atmospheric $\Delta^{14}C$ changed during the last deglaciation, and place needed constraints on the origin of atmospheric ^{14}C changes and possible modes of ocean circulation during the Younger Dryas. □

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Supplementary Information is available on *Nature*'s World-Wide Web site (http://www.nature.com) and as paper copy from Mary Sheehan at the London editorial office of *Nature* and also at the World Data Center-A for Paleoclimatology (http://www.ngdc.noaa.gov).

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