Synchronous Radiocarbon and Climate Shifts During the Last Deglaciation
Konrad A. Hughen, et al.
Science 290, 1951 (2000);
DOI: 10.1126/science.290.5498.1951

The following resources related to this article are available online at www.sciencemag.org (this information is current as of January 4, 2007):

Updated information and services, including high-resolution figures, can be found in the online version of this article at:
http://www.sciencemag.org/cgi/content/full/290/5498/1951

Supporting Online Material can be found at:
http://www.sciencemag.org/cgi/content/full/290/5498/1951/DC1

A list of selected additional articles on the Science Web sites related to this article can be found at:
http://www.sciencemag.org/cgi/content/full/290/5498/1951#related-content

This article cites 15 articles, 3 of which can be accessed for free:
http://www.sciencemag.org/cgi/content/full/290/5498/1951#otherarticles

This article has been cited by 118 article(s) on the ISI Web of Science.

This article has been cited by 21 articles hosted by HighWire Press; see:
http://www.sciencemag.org/cgi/content/full/290/5498/1951#otherarticles

This article appears in the following subject collections:
Atmospheric Science
http://www.sciencemag.org/cgi/collection/atmos

Information about obtaining reprints of this article or about obtaining permission to reproduce this article in whole or in part can be found at:
http://www.sciencemag.org/help/about/permissions.dtl


Synchronous Radiocarbon and Climate Shifts During the Last Deglaciation

Konrad A. Hughen,1* John R. Southon,2 Scott J. Lehman,3 Jonathan T. Overpeck4

Radiocarbon data from the Cariaco Basin provide calibration of the carbon-14 time scale across the period of deglaciation (15,000 to 10,000 years ago) with resolution available previously only from Holocene tree rings. Reconstructed changes in atmospheric carbon-14 are larger than previously thought, with the largest change occurring simultaneously with the sudden climatic cooling of the Younger Dryas event. Carbon-14 and published beryllium-10 data together suggest that concurrent climate and carbon-14 changes were predominantly the result of abrupt shifts in deep ocean ventilation.

Efforts to calibrate the radiocarbon time scale and to quantify the record of changes in past atmospheric 14C concentration [Δ14C, reported as per mil (%)] deviations from the preindustrial value] rely primarily on 14C measurements on tree-ring dated wood (1, 2). However, these dendrochronological records extend back only to ∼11,900 calendar years before present (1.9 cal kyr B.P.) and do not provide calibration during most of the large, abrupt climate changes of the last deglaciation, including the Younger Dryas cold reversal. Paired U/Th-14C dates from corals have abrupt climate changes of the last deglaciation provide calibration during most of the large, before present (11.9 cal kyr B.P.) and do not tend back only to ever, these dendrochronological records extended as per mil (‰) deviations from the preindustrial.

1Department of Marine Chemistry and Geochemistry, Lawrence Livermore National Laboratory, Livermore, CA 94551, USA. 2Institute of Arctic and Alpine Research and Department of Geological Sciences, University of Colorado, Boulder, CO 80309, USA. 3Institute for the Study of Planet Earth and Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA.

*To whom correspondence should be addressed. E-mail: khughen@whoi.edu

in both 14C and climate (7–11). However, those data are not of high enough resolution to conclusively determine the timing of the Δ14C shift relative to the Younger Dryas onset, leading to speculation that the Δ14C changes were caused by another mechanism (e.g., solar variability) (12). Here we present 14C data from Cariaco Basin core PL07-58PC (hereafter 58PC), providing 10- to 15-year resolution through most of deglaciation. The new calibration data demonstrate conclusively that Δ14C changes were synchronous with climate shifts during the Younger Dryas. Calculated Δ14C is strongly correlated to climate proxy data throughout early deglaciation (r = 0.81). Comparing Δ14C and 10Be records leads us to conclude that ocean circulation changes, not solar variability, must be the primary mechanism for both 14C and climate changes during the Younger Dryas.

Cariaco Basin core 58PC (10°40.60′N, 64°57.70′W; 820 m depth) has an average sedimentation rate (70 cm/kyr) more than 25% higher than core 56PC (10°41.22′N, 64°58.07′W; 810 m depth) (13, 14), and shares similar hydrographic conditions. Restricted deep circulation and high surface productivity in the Cariaco Basin off the coast of Venezuela create an anoxic water column below 300 m. The climatic cycle of a dry, windy season with coastal upwelling, followed by a nonwindy, rainy season, results in distinctly laminated sediment couplets of light-colored, organic-rich plankton tests and dark-colored mineral grains from local river runoff (13). It has been demonstrated previously that the laminae couplets are annually deposited varves and that light laminae thickness, sediment reflectance (gray scale), and abundance of the foraminifer Globigerina bulloides are all sensitive proxies for surface productivity, upwelling, and trade wind strength (14, 15). Nearly identical patterns, timing, and duration of abrupt changes in Cariaco Basin upwelling compared with surface temperatures in the high-latitude North Atlantic region at 1- to 10-year resolution during the last 110 years and the last deglaciation (7, 14, 15) provide evidence that rapid climate shifts in the two regions were synchronous. A likely mechanism for this linkage is the response of North Atlantic trade winds to the equator-pole temperature gradient forced by changes in high-latitude North Atlantic temperature (16).

The hydrography of the Cariaco Basin provides excellent conditions for 14C dating (17). The shallow sills (146 m depth) constrain water entering the basin to the surface layer, well equilibrated with atmospheric CO2. Despite anoxic conditions, the deep waters of the Cariaco Basin have a brief residence time, as little as 100 years (17). Two radiocarbon dates on G. bulloides of known recent calendar age gave the same surface water-atmospheric 14C difference (reservoir age) as the open Atlantic Ocean (7). Good agreement during the early Holocene and Younger Dryas between Cariaco Basin and terrestrial 14C dates, including German pines and plant macrofossils from lake sediments (1, 9, 11, 18) (Fig. 1), suggests that Cariaco Basin reservoir age does not change measurably as a response to increased local upwelling (i.e., during the Younger Dryas) (19). Planktonic foraminiferal abundance permits continuous sampling at 1.5-cm increments, providing 10- to 15-calendar-year resolution throughout most of deglaciation.

For this work, the varve chronology is largely the same as that used for core 56PC (7). Varves have been re-counted during periods of particular importance, such as the overlap with tree rings and the onset of the Younger Dryas, as well as the deepest, oldest laminations that are less distinct. The floating Cariaco Basin varve chronology was anchored to the German pine dendrochronology by wiggle-matching 14C variations in both curves (Fig. 1). The correla-
tion between the two time series is excellent, $r = 0.989$ (Fig. 1, inset), anchoring the Cariaco Basin floating chronology to an absolute calendar time scale (20). Independent confirmation for this age match is provided by the close agreement for the timing of the Younger Dryas termination recorded by tree rings (11,570 cal yr B.P.) and Cariaco Basin gray scale (11,565 cal yr B.P., ±10 years relative to tree rings) (20).

The anchored Cariaco Basin varve chronology provides radiocarbon calibration at high resolution from ~14.8 to 10.5 cal kyr B.P. (Fig. 2) (21). The abrupt beginning and end of the large drop in $^{14}$C age during the Younger Dryas onset are shown to be sharp changes in slope rather than gradual transitions. A $^{14}$C plateau can be discerned at 11.7 to 11.8 $^{14}$C kyr B.P., lasting about 250 calendar years. The oldest part of the record is characterized by another plateau at 12.5 $^{14}$C kyr B.P., extending beyond (18) the Glacial/Bølling boundary where the Cariaco Basin laminations begin. A decrease in $^{14}$C age at the Younger Dryas onset of the same amplitude as core 58PC is also seen in coral and Lake Suigetsu data (Fig. 2). In addition, some of the same fine structure during the Younger Dryas in core 58PC is also reported in corals from Vanuatu (6), although there is a slight offset in the steep $^{14}$C decline around 12.4 cal kyr B.P. (Fig. 2). The similar trends suggest this offset may result from reservoir age differences between the Atlantic and Pacific Oceans.

Atmospheric $^{14}$C concentrations calculated from 58PC calibration data reveal large variations throughout the deglaciation period (Fig. 3). The most distinct features are the sharp rise and increased $^{14}$C during the early Younger Dryas, between 13 and 11.5 cal kyr B.P. Elevated $^{14}$C during the Younger Dryas has been reported previously (4, 7, 9, 12), but the pattern and timing of change is revealed here in greater detail. In only 200 calendar years, $^{14}$C rose 70 ± 10‰ (22), with abrupt transitions at the beginning and end of the increase. The record also shows century-scale oscillations of 20 to 30‰ occurring between 15 and 13 cal kyr B.P. A rapid rise in $^{14}$C (25% in 15 years) occurs at 14.1 cal kyr B.P., followed by a brief period of elevated $^{14}$C that lasted ~40 years before declining. More gradual $^{14}$C increases of ~30% can be seen at 13.5 and 13.3 cal kyr B.P. (Fig. 3).

To facilitate comparison to other climatic and cosmogenic production records, we subtracted a linear trend from $^{14}$C (Fig. 3). The trend is intended to represent the decline in atmospheric $^{14}$C arising from gradually increasing geomagnetic field intensity over the interval of deglaciation (23). This treatment intentionally overlooks possible additional short-term (millennial-centennial) structure in some geomagnetic field strength data, which are typically within data uncertainties. The use of a simple linear model instead of a geomagnetically forced $^{14}$C production model also avoids errors introduced by parameterization of uncertain long-term changes in the carbon cycle (e.g., changes in size of biosphere C reservoir). Detrended $^{14}$C and climate proxy data from the same sediments (Fig. 4) show a significant anticorrelation ($r = -0.81$) from 15 to 12.5 cal kyr B.P. and allow precise determination of the relative timing of abrupt changes in $^{14}$C versus climate. The timing of the $^{14}$C rise at 13.0 cal kyr B.P. can be identified within the resolution of the sampling (~10 years) as precisely synchronous with climatic changes during the onset of the Younger Dryas. Immediately after the Younger Dryas onset, $^{14}$C decreases and continues to decline.
throughout the Younger Dryas period. At the Younger Dryas termination, $\Delta^{14}C$ shows an abrupt 25 to 30% drop with a distinctly different slope than the overall decline within the Younger Dryas (Fig. 4). In addition to large changes during the Younger Dryas, there is evidence for $\Delta^{14}C$ shifts concurrent with century-scale climate events as well. The sharp 25% $\Delta^{14}C$ increase at 14.1 cal kyr B.P. occurs precisely at the beginning of the Older Dryas cold event. In addition, a 20 to 25% $\Delta^{14}C$ rise is discernable at the beginning of the cold event around 13.7 cal kyr B.P. A 20% $\Delta^{14}C$ increase also occurs at the onset of the Inter-Allerød Cold Period around 13.3 cal kyr B.P., but this rise is more gradual and cannot be distinguished within errors from a general increase beginning earlier.

The correspondence of $\Delta^{14}C$ and climate variations suggests that both have been influenced by a common forcing mechanism (24). The two most plausible candidate forcings are large-scale changes in ocean circulation and variations in solar irradiance. Changes in the large-scale overturning circulation of the ocean and in the rate of formation of North Atlantic Deep Water (NADW) in particular influence the rate of formation of North Atlantic Deep water (NADW) in particular influence the irradiance. Changes in the large-scale overturning circulation of the ocean and in the rate of formation of North Atlantic Deep Water (NADW) in particular influence the global distribution of heat and moisture as well as the sequestration of $^{14}C$ into the ocean interior. Different modes of thermohaline circulation have been invoked previously as a potential explanation for rapid changes in climate (8, 25–27) as well as atmospheric $\Delta^{14}C$ (4, 7–11). Direct evidence for ocean circulation change, including Cd/Ca and stable isotopes ($^{613}C$ and $^{618}O$) in benthic foraminifera from the North Atlantic Ocean, indicates that NADW formation was reduced or absent during the Younger Dryas (25–27). Calculations using a geochemical box-model show that the magnitude of atmospheric $\Delta^{14}C$ increase after a complete NADW shutdown may reach 80‰ (7). Simulations of reduced NADW formation with the use of more complex numerical and general circulation models (GCMs) result in smaller magnitude $\Delta^{14}C$ responses of 15 to 30‰, although including the effects of sea ice may roughly double the atmospheric $\Delta^{14}C$ response (10, 11, 28).

Changes in solar irradiance may also have a direct effect on climate, and associated heliomagnetic changes modulate the production of cosmogenic isotopes. Comparisons of global and Northern Hemisphere average temperature and solar irradiance trends over the past 500 years suggest that much of the preindustrial natural temperature variability may have been caused by the sun (29). In addition, evidence for a solar influence on $\Delta^{14}C$ is well documented by records showing $\Delta^{14}C$ increases during known periods of reduced solar activity such as the Maunder Minimum (30), during which irradiance is estimated to have been 0.25% lower than present (29). However, the largest Holocene $\Delta^{14}C$ anomalies attributed to solar forcing are only ~25 to 30‰, much smaller than the 70‰ Younger Dryas event. Also, it is unlikely that solar forcing alone produced the largest of the observed deglacial climate changes, as much as 20°C in the northern North Atlantic region. For example, GCM simulations specifying a 0.25% reduction in solar irradiance only produced...

Fig. 3. Atmospheric radiocarbon concentration ($\Delta^{14}C$) calculated from Cariaco Basin and tree ring data sets. Solid circles and thin black line, Cariaco Basin core PL07-58PC data; thick gray line, German pine data (1) spliced to the end of the INTCAL98 data set (2). Dashed line is a linear model approximating geomagnetic field intensity used to detrend the raw Cariaco Basin $\Delta^{14}C$ data for comparison to other cosmogenic and paleoclimatic data sets. Error bars are 1σ uncertainties calculated by taking into account $^{14}C$ uncertainties only. The wide gray swaths shows total $\Delta^{14}C$ uncertainty, including the uncertainty contributed by calendar age error (22).

Fig. 4. Observed paleoclimatic and detrended $\Delta^{14}C$ from the Cariaco Basin and tree rings compared with paleoclimatic and cosmogenic isotopes from the GISP2 ice core. Each set of records during deglaciation was measured on the same core and is shown plotted on its own independent time scale, ice-core chronology for GISP2, and anchored varve chronology for the Cariaco Basin. (A) Thin line (upper curve) is GISP2 ice accumulation data ($^{10}Be$). Line with solid circles (lower curve) is atmospheric $^{10}Be$ concentration ($^{10}Be_{atm}$) calculated from ice $^{10}Be$ concentrations and snow accumulation measured in the GISP2 ice core (33–35). Gray bars indicate climate transitions based on shifts in accumulation rate. (B) Gray line, detrended atmospheric $\Delta^{14}C$ data from German pines (1) spliced together with INTCAL98 data (2); black line with solid circles, detrended $\Delta^{14}C$ measured in Cariaco Basin core PL07-58PC (upper curves). Black line (lower curve) is Cariaco Basin gray scale. Gray bars indicate climate transitions based on shifts in gray scale and light laminar thickness. Previous work (7, 14) suggests that abrupt climate shifts in both regions were synchronous. The age differences for the events shown here (gray bars) are well within the combined errors of the Cariaco Basin and GISP2 chronologies. Dashed lines indicate century-scale anomalies common to both cosmogenic $^{10}Be$ and $^{14}C$, seen throughout the Holocene and attributed to solar variability (33).
0.5° to 1.0°C surface temperature change in the same region (31). Thus, solar changes would have to have been at least an order of magnitude larger than those during the Maunder Minimum in order to account for observed deglacial climate changes. Although there are suggestions of possible indirect links (and amplifying mechanisms) between solar variability and climate (32), these remain unproven.

Direct evaluation of solar change during the Younger Dryas can be sought by comparing cosmogenic isotope records. Estimates of 14C and atmospheric 10Be concentration (10Be\textsubscript{atm}), derived from measurements in ice cores, covary during much of the Holocene (33, 34). However, the Younger Dryas Δ14C anomaly, which is by far the largest of the last 15,000 years, is not matched in amplitude by corresponding atmospheric 10Be concentration estimates (Fig. 4). Thus, available 10Be data do not support the interpretation of the Younger Dryas Δ14C anomaly as solely or mostly due to increased production. However, it must be pointed out that the calculation of 10Be\textsubscript{atm} from ice core concentrations depends heavily on knowledge of the mode of 10Be deposition, which itself may vary with changing climate (34, 35). Thus, the GISP2 10Be\textsubscript{atm} reconstruction is especially suspect before about 11.5 cal kyr B.P. and does not conclusively represent solar variability.

We conclude that the largest of the concurrent changes in climate and atmospheric Δ14C during deglaciation were predominantly of ocean origin, although we cannot eliminate the possibility that some of these events were triggered by the sun. New data here allow for little or no time lag between the initial rise in Δ14C and the associated Younger Dryas climate reversal. Thus, if solar changes triggered the event, the data require extremely tight coupling between solar cooling and the amplifying ocean circulation change that accounts for much or most of the observed Δ14C and climate change. Lastly, accurate conversion of 14C ages to calendrical time is essential to attempts to evaluate the behavior of the climate system from geologic data. Results presented here provide a 14C calibration that spans the climatically unstable deglacial interval with resolution comparable to that previously available only from tree rings.

References and Notes

19. The rapid shift from intense to reduced upwelling in the Cariaco Basin at the Younger Dryas–Preboreal transition is an ideal test for changes in reservoir age from local upwelling. The 14C data sets show close agreement immediately before and after the rapid shift in Cariaco Basin upwelling at the Younger Dryas termination (Fig. 1). The lack of a step-wise decrease in Cariaco 14C age across this boundary relates to tree-ring analysis that suggests that the Cariaco Basin reservoir age has a likely remained unchanged despite variable upwelling within the basin.
20. The floating German pine chronology was itself anchored to the absolute oak dendrochronology primarily through wiggle-matching 14C variations, but also through matching ring-width patterns. Uncertainty in the absolute pine age is reported conservatively at 20 years to account for the relatively short period of overlap (<400 years), unequal spacing of 14C dates, and potential missing rings (1). The Cariaco-pine overlap is 1370 years, and the high resolution of the two records provides a unique time lag of maximum correlation, rather than a range of lags with equally high correlation values. Due to the 10-year sampling resolution of both chronologies, we estimate an uncertainty of ±10 years in the wiggle match for a total Cariaco Basin uncertainty in the anchoring of ±30 years.
21. This marine calibration data set assumes a constant reservoir age through time. Although Cariaco reservoir age is likely unaffected by local upwelling changes in surface Atlantic water sources before the overlap with tree rings may have introduced gradual shifts in Cariaco Basin reservoir age. Close agreement between (constant reservoir-corrected Cariaco Basin 14C data) and Lake Sulgetu, however (fig. 2), suggest that any potential shifts in reservoir age were not likely to have exceeded ±100 years. Greater certainty requires a higher-resolution terrestrial 14C calibration record for the deglacial period.
22. Error bars for Δ14C in Fig. 3 do not include calendar age uncertainty. Although there is uncertainty in Cariaco Basin calendar age based on uncertainty in the wiggle match to tree rings, this will affect the floating Cariaco Basin calendar age as a whole. Similarly, cumulative errors in counting the varve chronology in surface (arctic) reservoir ages before the overlap with tree rings may have introduced gradual shifts in Cariaco Basin reservoir age. Close agreement between (constant reservoir-corrected Cariaco Basin 14C data) and Lake Sulgetu, however (fig. 2), suggest that any potential shifts in reservoir age were not likely to have exceeded ±100 years. Greater certainty requires a higher-resolution terrestrial 14C calibration record for the deglacial period.
23. Error bars for Δ14C in Fig. 3 do not include calendar age uncertainty. Although there is uncertainty in Cariaco Basin calendar age based on uncertainty in the wiggle match to tree rings, this will affect the floating Cariaco Basin calendar age as a whole. Similarly, cumulative errors in counting the varve chronology in surface (arctic) reservoir ages before the overlap with tree rings may have introduced gradual shifts in Cariaco Basin reservoir age. Close agreement between (constant reservoir-corrected Cariaco Basin 14C data) and Lake Sulgetu, however (fig. 2), suggest that any potential shifts in reservoir age were not likely to have exceeded ±100 years. Greater certainty requires a higher-resolution terrestrial 14C calibration record for the deglacial period.