Title: Synchronous Centennial Abrupt Events in the Ocean and Atmosphere during the Last Deglaciation

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Abstract: Antarctic ice-core data reveal that the atmosphere experienced abrupt centennial increases in CO_2 concentration during the last deglaciation (~18-11 thousand years, ka). Establishing the role of ocean circulation in these changes requires high-resolution, accurately-dated marine records. Here we report radiocarbon data from uranium-thorium dated deep-sea corals in the Equatorial Atlantic and Drake Passage over the last 25 ka. Two major deglacial radiocarbon increases occurred in phase with centennial atmospheric CO_2 rises at 14.8 ka and 11.7 ka. We interpret these radiocarbon-enriched signals to represent two short-lived (<500 years) 'overshoot' events with Atlantic meridional overturning stronger than modern. These results provide compelling evidence for a close coupling of ocean circulation and centennial climate events during the last deglaciation.

One Sentence Summary: High resolution ^{14}C data of independently dated deep-sea corals indicate ocean circulation is closely coupled with centennial climate events during the last deglaciation.

Paleo-records have shown that warming during the transition from the Last Glacial Maximum (LGM; ~22-18 ka) to the Holocene occurred in several abrupt events, which were not synchronous between hemispheres, e.g., (*1*). The warming in the Southern Hemisphere was accompanied by millennial-scale atmospheric CO_2 concentration increases during the Younger Dryas (YD: 12.9-11.5 ka) and Heinrich Stadial 1 (HS1: ~18-14.6 ka) (*2*). Together the timing of interhemispheric temperature and CO_2 changes at millennial scales point to a critical role for Atlantic Meridional Overturning Circulation (AMOC) through its ‘seesaw’ behavior (*3, 4*). Reduced AMOC strength decreased heat transport from the South to the North during the YD and HS1 (*5*). At the same time, increased Southern Ocean upwelling likely enhanced the release of CO_2 (*6, 7*). Recently, a new, high-resolution Antarctic ice-core record (*8*) has revealed three abrupt centennial-scale atmospheric CO_2 increases superimposed on the millennial-scale deglacial CO_2 rise, each of 10 to 15 ppmV, contributing a significant portion of the total 90 ppmV deglacial CO_2 increase. Within the constraints of the ice-age and gas-age offsets, the timings of the latter two of these centennial changes are coincident with abrupt Northern Hemisphere warming at the end of YD and HS1. These two abrupt centennial CO_2 rises have been interpreted as being driven from the north by reinvigoration of AMOC (*8*).

In order to establish direct links between the atmosphere and ocean at centennial time scales, it is necessary to have well-dated, high-resolution marine records which are comparable with ice-core records. Deep-sea fossil corals have the particular advantage that they can be precisely dated by U-series disequilibrium methods (*9*). The aragonite skeletons of scleractinian corals also record the radiocarbon (^{14}C) content of dissolved inorganic carbon (DIC) at the time of growth, such that coupled $^{14}C/^{12}C$ analysis and U-series dating of deep-sea corals provides the reconstruction of past deep-ocean $^{14}C/^{12}C$ ratios. Radiocarbon is produced in the upper atmosphere by cosmic ray-induced nuclear reaction and has a decay half-life of 5730 years. Once introduced into the deep sea from the surface ocean, it is isolated from the atmosphere and decays away. Variability of ^{14}C in the deep ocean thus provides a proxy that is related to the isolation and geometry of deep-water masses and the rate of deep circulation both in the modern and the geological past. In this study, we have generated a detailed deglacial radiocarbon history in the Equatorial Atlantic mainly at depths from 750 m to 2100 m (Intermediate / Deep waters (EAI/DW)) and at locations within modern day Southern Ocean Upper Circumpolar Deep Water (UCDW, 700-1800 m) from the Drake Passage on an absolute time scale based on deep-sea corals. We use these data to put new constraints on the millennial to centennial mechanisms connecting the Atlantic, the Southern Ocean, and the atmosphere.

Methods and Results. The Equatorial Atlantic coral samples (5-15 °N) were recovered from depths of 750-2800 m from the Sierra Leone Rise, the Mid-Atlantic Ridge and Researchers Ridge (*10*). The modern hydrography is mainly composed of North Atlantic Deep Water (NADW), Antarctic Intermediate Water (AAIW, core depth 700-800 m) and a lesser contribution from subtropical surface waters (Fig. S1) (*10*). Samples of interest with ages less than 25 ka were selected and dated precisely by isotope-dilution methods (*9*). Radiocarbon analyses were made on samples with U-Th ages that passed our screening criteria (*10*). We have calculated $\Delta^{14}C$, $\Delta\Delta^{14}C$, and B-Atmosphere age (*11*) for each sample based on IntCal13 (*12*). The deglacial ^{14}C evolution of UCDW has been reported before but with lower sampling resolution (*13*). In this study we have filled important gaps in the earlier record and increased the number of samples from 31 to 55 allowing a comparison of ^{14}C ventilation between the Southern Ocean and EAI/DW at sub-millennial time scales (Fig. 1B and D).

Holocene $\Delta^{14}C$ values of EAI/DW corals agree well with $\Delta^{14}C$ of the modern-day seawater DIC (Fig. S2). Strong advection of ^{14}C-enriched NADW and relatively ^{14}C-depleted AAIW in the modern Atlantic results in increasing $\Delta^{14}C$ with depth between 1000-2000 m (*14*), which is reflected in coral ^{14}C reconstruction (Fig. S2). The deepest sample, recovered from 2800 m water depth, has a calendar age of 10.4 ka and has almost the same $\Delta^{14}C$ as other early Holocene samples in the EAI/DW (Fig. 1C, star).

The $\Delta^{14}C$ values of the shallow EAI/DW layers (750-1162 m) (Fig. 1A) decreased from ~365‰ during the early LGM to ~-110‰ in the late Holocene, with a slightly larger offset from the contemporary atmosphere ($\Delta\Delta^{14}C$) in the glacial period (~ -140‰ to -200‰ around 25 to 18 ka) than the Holocene (~ -100‰). At the end of HS1 and YD, the ^{14}C gradient between deep and shallow depths was eroded (Fig. 1C). One glacial coral has a $\Delta^{14}C$ similar to the contemporary atmosphere (Fig. S3, Table S2). However, without more data to confirm the ^{14}C-enriched signature, we do not interpret this ^{14}C result as a signature of ventilation in the EAI/DW.

New ^{14}C data from the Drake Passage (Fig. 1B and D) support previous findings (*13*) and further constrain the timing of ^{14}C evolution towards a smaller $\Delta\Delta^{14}C$ during late HS1. A rapid return to a relatively ^{14}C-depleted condition during the early B-A (Bølling-Allerød, 14.6-12.9 ka) was followed by a second abrupt $\Delta\Delta^{14}C$ increase during the YD to Holocene transition (Fig. 1D) (*13*).

LGM ^{14}C ventilation of EAI/DW and the transition to a deglacial climate. Observations from nutrient proxies indicate that a strong chemical gradient existed between 2000 and 2500 m depth in the Atlantic during the LGM, e.g., (*15*). Glacial reconstructions also show ^{14}C-depleted signatures in the deep Atlantic, thus supporting a more isolated deep-ocean (*16-18*). However data in the intermediate ocean are more challenging to interpret. For example, geostrophic reconstructions from the Florida Straits point to a reduced Gulf Stream (*19*), whereas evidence from sedimentary Pa/Th ratios suggests that glacial Atlantic upper ocean circulation (<2000 m) was at least as strong as the modern deep overturning (*20*). Our ^{14}C data (Fig. 2C, S4) from intermediate depths (750-1492 m) as well as a published record from thermocline waters (*21*) (500-600 m) indicate that the upper Equatorial Atlantic during the glacial period was filled with ^{14}C-enriched water similar to the modern, supporting relatively strong circulation in the upper ocean. However, the ^{14}C age differences between UCDW and the shallow layer (750-1162 m) of EAI/DW were much larger during LGM (~800 to 1000 years) than the present (~ 500 years) (Fig. 2C). Mechanisms that could maintain these large glacial ^{14}C gradients might be related to water mass mixing and advection rates, as well as more extreme ^{14}C endmember compositions during the glacial period (*10*).

In the early HS1 (18.0-16.0 ka), deep sedimentary Pa/Th ratios indicate a substantial reduction in AMOC rates (*5*) which coincided with the initiation of the deglacial atmospheric CO_2 rise (*8*) as well as the decrease in atmospheric Δ^{14}C (*12*) (Fig. 2A, B, and E). During this time period, the mid-depth North Atlantic and Brazil Margin (1500-2000 m) both saw a major decrease in benthic δ^{13}C (*22, 23*) with a coincident decrease in North Atlantic [CO_3^{2-}] concentration (~1800 m) (*24*). These changes in the carbon chemistry of the mid-depth Atlantic may have been due to the weakened AMOC and its associated effects (such as respired carbon accumulation in mid-depth waters) rather than upwelling in the deep South Atlantic (>2500 m) (*22*, *23*, *25*). Under this scenario, an additional, well-ventilated North Atlantic water mass at shallower depths (e.g., <1200 m) is required to explain the early HS1 Atlantic benthic δ^{13}C- δ^{18}O data (*23*). In support of this hypothesis, our ^{14}C data from 972 m to 1162 m do not show any substantial decrease during the initial transition from glacial to the early HS1 (18-17.0 ka, Fig. S4). This result can be best explained by a persistent North Atlantic shallow overturning (*26*) fed by relatively ^{14}C-enriched waters from the North as observed during the LGM. There is also no evidence in the Equatorial Atlantic for the extremely ^{14}C-depleted signals during HS1 that have been observed at other locations in intermediate waters of the Pacific, Atlantic, and Indian Oceans (*27-29*). Given that extremely depleted ^{14}C waters do not seem to pass through the intermediate depths of the Southern Ocean or Equatorial Atlantic (*13, 21, 30*), those ^{14}C depletions are likely to be regional or localized features.

In the deeper waters of the Equatorial Atlantic (1827-2100 m), the early part of HS1 is characterized by a decreasing Δ^{14}C trend from 17.4 to 16.2 ka (Fig. 1A). The B-atmosphere age at 17.4 ka was more than 400 ^{14}C years older than the intermediate waters (972-1162 m), which is in marked contrast with the Holocene (Fig. 2C) and is consistent with a reduced presence of ^{14}C-rich NADW. From the LGM to the early HS1 (Fig. 1D), the $\Delta\Delta^{14}$C of UCDW in the Drake Passage increased by about 90‰. However, by 16.6 ka this trend was reversed with $\Delta\Delta^{14}$C decreasing by about 80‰, consistent with increased mixing of ^{14}C depleted waters from below (*13*) and potentially associated with a reduction in AMOC. At the same time, between 18-16 ka, Greenland remained cold (*31*), whereas Antarctic δ^{18}O indicates continuous warming under a background of increasing CO_2 forcing (Fig. 2F). These changes in the early HS1 suggest a reduced/shoaled AMOC (Fig. 2E) and a comparatively low efficiency of heat transport from SH to NH.

Throughout HS1 the water column of the equatorial Atlantic was characterized by low-Δ^{14}C deep waters underlying shallower, more ^{14}C-enriched waters. Whilst we find no evidence for enhanced ^{14}C ventilation in the 1827-2100 m layer, our records show that the Drake Passage records and Equatorial Atlantic mid-depth (1296-1612 m) waters started to shift towards a higher Δ^{14}C values compared to the early HS1 (Fig. 2C). Therefore it is unlikely that this shift was caused by upwelling of ^{14}C enriched waters from below, but rather from increased lateral advection of a relatively well-ventilated intermediate water mass. We cannot distinguish the exact source of ventilation (e.g., Northern Component Water (NCW) from the North Atlantic, Southern Component Water (SCW) from the Southern Ocean, or both) here, but the better ventilation of mid-depth waters in late HS1 is a distinct feature of our records. Foraminifera Nd isotopes from the tropical Atlantic have previously highlighted a two-phase HS1 water-mass provenance shift at intermediate water depths (~1000 m) (*33*). In contrast, Pa/Th ratios and Nd isotopes from the deep subtropical North Atlantic (*5, 34*) did not show a mid HS1 shift, consistent with our observation that the deeper Equatorial Atlantic remained in a poorly ^{14}C-ventilated condition throughout HS1. Together, these results suggest that increased ^{14}C ventilation and the possibly accompanied AMOC strengthening in the late HS1 might have been restricted to the upper ocean (e.g., <2500 m), while the abyssal Atlantic remained less affected (*5, 22*). This mid-HS1 shift in ^{14}C ventilation was accompanied by major reorganization of the atmosphere and the North Atlantic climate system (*10, 31, 32, 35*). At around the same time, a reversal in the early HS1 temperature decline at Northern Greenland (NGRIP) initiates NH deglacial warming (Fig. 3B).

Sub-millennial AMOC 'flushing' events and abrupt atmospheric CO_2 rises. Deglacial warming in the Northern Hemisphere is characterized by two abrupt warming events of ~10

°C at Northern Greenland, occurring at the HS1 to B-A transition and YD to Holocene transition (*31*), which were synchronous with the rapid intensification of Asian monsoon (Fig. 2D) *(35)*. During both events, CO_2 increased by ~12 ppmV (*8*) (Fig. 2B, 3), and two coincident abrupt resumptions of deep AMOC are indicated by sedimentary Pa/Th ratios (Fig. 3E) (*5*).

The two distinct centennial-scale events towards a ^{14}C-enriched water column in both EAI/DW and the Southern Ocean (14.8-14.6 ka, 11.7-11.5 ka, Fig. 3) provide strong support for an AMOC-related mechanism driving the abrupt increases in atmosphere CO_2 concentration (*8*) and NH warming (*31*). The atmospheric CO_2 concentration increased at the same time as the ^{14}C gradient was eroding, suggesting that CO_2 was released into the atmosphere when excess respired carbon in the deep ocean was being flushed out by newly-formed, high-$\Delta^{14}C$ NCW. At the same time changes in the solubility of CO_2 may have played a role in modulating atmospheric CO_2 as deep waters became warmer (less soluble) and fresher (more soluble). In contrast, the first centennial CO_2 increase at ~16.3 ka occurred during a period of reduced AMOC and with no notable changes in North Greenland temperature (Fig. 3C). Therefore, mechanisms other than sudden AMOC changes are likely to dominate this first centennial CO_2 increase, such as a rapid shift in ocean fronts driving the degassing of CO_2 from mid-depth waters of the Southern Ocean (*36*).

At the beginning of the B-A and Holocene, the Drake Passage records were even more ^{14}C-enriched than the modern day, by some 400-500 ^{14}C years at ~14.3 ka and ~11.3 ka, respectively (Fig. 2C, S4). Each of the two high-^{14}C peaks in the Drake Passage are well constrained by coral samples from similar depths and locations (*13*), adding confidence that these ^{14}C shifts reflected changes in deep-ocean circulation. We propose that rapid and deepened advection of well-ventilated NCW homogenized the ^{14}C composition of the water column during these two pronounced 'flushing' events. The presence of NCW at abyssal depths during the B-A and Holocene is also supported by the distinctive unradiogenic Nd isotopic shift and enriched ^{14}C signatures in the deep North Atlantic (*17, 34*).

A subsequent rapid return to a modern-like ^{14}C water column after both flushing events, highlighted by the rapid decrease in Drake Passage $\Delta^{14}C$ (Fig. 1B), adds weight to the idea of an 'AMOC overshoot', i.e., a transient stronger AMOC than the modern ocean. This 'AMOC overshoot' during B-A has been previously proposed in (*16*) based on benthic ^{14}C data, where it was described as a transient expansion of the NADW cell and a better ventilated deep ocean compared to the modern ocean, e.g., (*16, 18*). In contrast to, but not necessarily at odds with those studies which suggest an overshoot throughout B-A (*10*), our data indicate that the return to poorer ventilation of the Southern Ocean occurred within ~400-500 years after the start of B-A (14.6 ka) and Holocene (11.5 ka) (Fig. 3, A and B). The rapid return thus suggests that the timing of decline in peak AMOC strength occurred within <500 years which is more consistent with AMOC predictions from modelling studies (*16, 37*). These results therefore provide evidence for the existence of short-lived deep ocean flushing events during the last deglaciation.

After the AMOC 'overshoot' in the early B-A, the water-column structure of the EAI/DW was similar to the Holocene (Fig. 2C) (*16, 17*), providing support for the modern-like advection in the Atlantic. At the start of YD, the EAI/DW water column is characterized by high B-Atmosphere ages in the deeper layer, and low B-Atmosphere ages in the shallow layer (Fig. 2c, S5). However, the ^{14}C gradient during the YD was not as large as the early HS1, probably because the ^{14}C-depleted water that built up over the glacial period had been largely flushed out by the start of the B-A. Although the data are not well resolved during the Holocene, we do not see any evidence for substantial change in the water column structures of the EAI/DW during this time.

Comparison between millennial and centennial atmosphere CO_2 rises. The millennial-scale atmosphere CO_2 increase during YD and HS1 has been suggested to be caused by southward shift of the westerlies with increased upwelling in the Southern Ocean (*4*, *6*). At the same time, reduction of AMOC would lead to a decreased efficiency of the ocean's biological pump since NCW has lower preformed nutrients than SCW e.g., (*25*). These oceanic processes would perturb the deep-ocean alkalinity balance and facilitate further CO_2 release on millennial scales (*24*). For the centennial-scale abrupt changes, the first event at 16.3 ka may have been related to a southward shift of ocean fronts in the Southern Ocean (*36*) with a mechanism similar to the millennial-scale CO_2 rise. The processes driving the latter two CO_2 rise events are likely to be very different: they were related to enhanced AMOC and increased ventilation of the deep ocean with newly formed waters, as supported by the data presented here. While the terrestrial carbon reservoir may have contributed to carbon release at the beginning of B-A (14.6 ka) (*38*), the in-phase relationship between EAI/DW ventilation and atmosphere CO_2 concentration supports the fundamental role of deep-ocean carbon release during the latter two events. Therefore, mechanisms that can counteract the effect of efficient nutrient utilization of NCW (e.g., in contrast with the millennial mechanism) and that are faster than the alkalinity feedback are likely to play a more important role for these events. One of those mechanisms, for example, could be an increase in the preformed nutrient content of NCW associated with a shoaled organic matter remineralization depth during abrupt warming (*39*), combined with a fast oceanic overturning that rapidly releases respired CO_2 into the atmosphere.

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Fig. 1. Corrected relative ^{14}C activity (Δ^{14}C) of the EAI/DW (**A**) and Drake Passage (**B**), as well as the Δ^{14}C offset ($\Delta\Delta^{14}$C) of sample from the contemporary atmosphere of the EAI/DW

(**C**) and Drake Passage (**D**) with 2σ error ellipses reconstructed from deep-sea corals (*11*). Part of the Drake Passage data have been reported in (*13*), and new data of this study are reported in Table S3 and S4. For convenience of discussion, the EAI/DW records have been divided into 5 different layers according to the sample depths. Black line in (**A**) represents the IntCal13 (*12*) atmosphere radiocarbon curve (± 2σ uncertainties, grey lines). Red star in (**C**) represents the sample of 2.8 km depth. One LGM data point from 1097 m depth is not shown on this Figure as it lies directly on the atmospheric curve, and has not been replicated (Fig. S3). EAI/DW: Equatorial Atlantic Intermediate / Deep waters.

Fig. 2. Radiocarbon age variability in the EAI/DW of the last 25 ka in comparison with other climate records with good age control. (**A**) $\Delta^{14}C$ of the atmosphere from the IntCal13 compilation (*12*). (**B**) New high-resolution CO_2 concentration record from the West Antarctic Ice Sheet Divide ice core (WDC) (*8*). (**C**) B-Atmosphere age reconstructed from ^{14}C data of EAI/DW and Drake Passage (700-1800 m) (*13*). For clarity the 2σ error ellipses of Drake Passage records are not shown. Green (gray) arrow illustrates the modern radiocarbon age difference between EAI/DW (UCDW) and the atmosphere (*14*). Red star represents the sample of 2.8 km depth. (**D**) $\delta^{18}O$ (an Asian monsoon index) record of Hulu speleothem (*35, 40*). (**E**) $^{231}Pa/^{230}Th$ ratios (an AMOC strength index) of a subtropical North Atlantic deep sediment core (OCE326-GGC5, water depth 4550 m) (*5*). The age model has been revised based on IntCal13 (*12*). (**F**) $\delta^{18}O$ (a temperature index) record of the Northern Greenland (NGRIP) (*41*) and WDC (*8*) Ice cores. Grey lines in (**F**) represent 5-point moving average. Light yellow bands indicate cold stadials while light blue bands indicate periods of sudden centennial atmosphere CO_2 increases. UCDW: Upper Circumpolar Deep Water.

Fig. 3. Detailed comparison during (**A**) 11.0-12.5 ka; (**B**) 13.8-15.8 ka; and (**C**) 15.8-17.8 ka between B-Atmosphere ages of EAI/DW and UCDW (colour and symbol as Fig. 2c with 2σ error ellipses), reconstructed temperature of North Greenland NGRIP (thin purple line) (*31*), and high resolution atmosphere CO_2 concentration from WDC (thin blue line) (*8*). Three key intervals around abrupt centennial CO_2 increases are highlighted by light blue bands. Dashed lines in (**A**) and (**B**) mark the return of UCDW to reduced ^{14}C ventilation condition. Double sided arrows indicate periods of Atlantic Meridional Overturning Circulation (AMOC) overshoot, see main text for definition.