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An Atlantic–Pacific ventilation seesaw across the last deglaciation

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ABSTRACT

It has been proposed that the rapid rise of atmospheric CO_2 across the last deglaciation was driven by the release of carbon from an extremely radiocarbon-depleted abyssal ocean reservoir that was 'vented' to the atmosphere primarily via the deep- and intermediate overturning loops in the Southern Ocean. While some radiocarbon observations from the intermediate ocean appear to confirm this hypothesis, others appear to refute it. Here we use radiocarbon measurements in paired benthic- and planktonic foraminifera to reconstruct the benthic–planktonic ^{14}C age offset (i.e. 'ventilation age') of intermediate waters in the western equatorial Atlantic. Our results show clear increases in local radiocarbon-based ventilation ages during Heinrich-Stadial 1 (HS1) and the Younger Dryas (YD). These are found to coincide with opposite changes of similar magnitude observed in the Pacific, demonstrating a 'seesaw' in the ventilation of the intermediate Atlantic and Pacific Oceans that numerical model simulations of North Atlantic overturning collapse indicate was primarily driven by North Pacific overturning. We propose that this Atlantic–Pacific ventilation seesaw would have combined with a previously identified North Atlantic–Southern Ocean ventilation seesaw to enhance ocean–atmosphere CO_2 exchange during a 'collapse' of the North Atlantic deep overturning limb. Whereas previous work has emphasized a more passive role for intermediate waters in deglacial climate change (merely conveying changes originating in the Southern Ocean) we suggest instead that the intermediate water seesaw played a more active role via relatively subtle but globally coordinated changes in ocean dynamics that may have further influenced ocean–atmosphere carbon exchange.

1. Introduction

The two-step increase in atmospheric CO_2 at the end of the last glacial maximum (LGM) is well documented (e.g. Marcott et al., 2014), yet the source of CO_2 and its mechanism of release remain elusive. Synchronous drops in the radiocarbon (^{14}C) activity of atmospheric CO_2 are observed in numerous records (e.g. Beck et al., 2001; Hughen et al., 2004; Fairbanks et al., 2005; Southon et al., 2012) leading to the proposal that CO_2 was released from a radiocarbon depleted oceanic abyssal reservoir that had previously been isolated from the atmosphere (e.g. Marchitto et al., 2007; Broecker and Clark, 2010). Upon release, the radiocarbon-depleted carbon would mix with the atmospheric carbon pool, increasing CO_2 whilst reducing its $^{14}C/^{12}C$ ratio. It is possible that the observed deglacial changes in atmospheric radiocarbon activity could primarily reflect perturbations to the Atlantic overturning that had only a minor impact on atmospheric CO_2, which would have responded much more sensitively to relatively small changes in the ventilation of the ocean interior via the deep Southern Ocean and the Pacific (e.g. Hain et al., 2014). One way of testing these hypotheses is to assess the existence of a significant volume of radiocarbon-depleted water in the ocean interior prior to deglaciation, as well as the occurrence of changes in marine radiocarbon 'ventilation' (i.e. ocean–atmosphere ^{14}C equilibration) that would be consistent with renewed ocean–atmosphere carbon exchange across the last deglaciation, specifically in the Southern Ocean and/or Pacific.

A plethora of recent studies at numerous locations, investigating changes in the distribution of radiocarbon in intermediate

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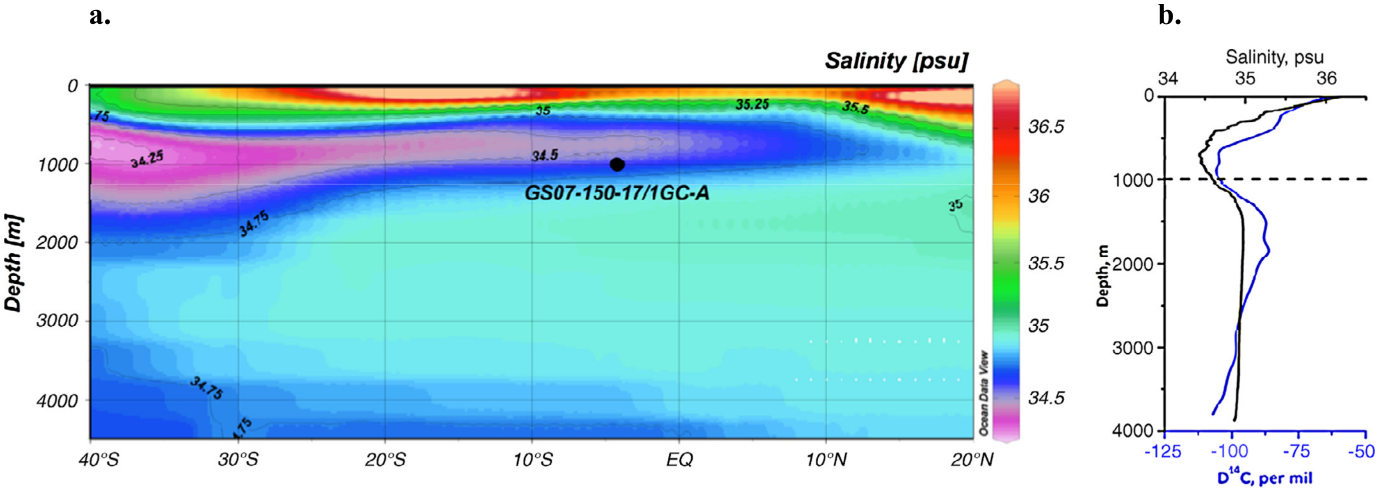

Fig. 1. Hydrography of site GS07-150-17/1GC-A (04°12.98′S, 37°04.52′W, 1000 m): a) Western Atlantic salinity section showing the core location. b) Brazil Margin water profile. (Blue) Modern background ^{14}C distribution (GEOSECS; Stuiver and Ostlund, 1980). (Black) Salinity (Cruise No. GS07-150, R/V G.O. SARS, RETRO Project). Dashed line indicates the water depth of core site 17/1GC-A. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and deep waters since the LGM, has yielded contradictory conclusions. Many of these studies may have been hampered by a lack of radiocarbon-independent calendar age control, and therefore the exclusive use of benthic–planktonic age offsets, which can be relatively insensitive to changes in ocean–atmosphere radiocarbon age offsets, particularly during periods of rapid change in atmospheric radiocarbon activity (Adkins and Boyle, 1997). Nevertheless, extremely large radiocarbon depletions (relative to the atmosphere), observed at some shallow/intermediate water locations (Marchitto et al., 2007; Stott et al., 2009; Bryan et al., 2010; Mangini et al., 2010), have been interpreted as indicating that poorly ventilated waters exited through the Southern Ocean and were transported via Antarctic Intermediate Water (AAIW) into the Atlantic and Pacific Oceans. However radiocarbon data from several other locations that are also believed to have been influenced by AAIW across the last deglaciation have been interpreted as showing no large change in the ventilation age of this water mass since the last glacial period (De Pol-Holz et al., 2010; Cleroux et al., 2011). If the general pattern of ocean circulation seen today is also assumed for the last glacial period, it is hard to see how AAIW could have carried radiocarbon depleted water to the sites where it is reported without leaving any sign at those where it seems not to have been detected. A coherent framework for the evolution of intermediate water (500–2000 m) ventilation across the last deglaciation therefore has yet to be proposed. We seek to address this question using new and existing radiocarbon data, in combination with intermediate complexity numerical model simulations.

2. Materials and methods

2.1. Study site

Here we present a record of intermediate water radiocarbon-based ventilation change across the last deglaciation, in the equatorial Atlantic off the coast of Brazil. Radiocarbon measurements were conducted on benthic and planktonic foraminifera from core GS07-150-17/1GC-A (04°12.98′S, 37°04.52′W, 1000 m). This site is currently bathed predominantly in AAIW, with a minor influence of North Atlantic deep water, NADW, which lies immediately below (Fig. 1). AAIW is predominantly formed in two locations north of the Subantarctic Front, in the southeast Pacific and southwest Atlantic where surface waters are subducted to intermediate depths during austral winter and early spring (Sloyan et al., 2010). The two main formation sites lead to two types of AAIW, one in the South Pacific, and one in the Atlantic that is colder and fresher (Piola and Georgi, 1982). In the North Pacific, modified southern-sourced intermediate waters compete for space with North Pacific intermediate water (NPIW), a low-salinity cold water mass which today forms in the Sea of Okhotsk (Yasuda, 1997).

2.2. Radiocarbon measurements

Foraminifera were picked from the >212 μm size fraction and where necessary from the 150–212 μm fraction. 28 monospecific samples of *Globigerinoides ruber* and 15 samples of mixed benthic foraminifera were picked and graphitized in the Godwin Laboratory at the University of Cambridge using a standard hydrogen/iron catalyst reduction method (Vogel et al., 1984). For some samples it was necessary to combine benthic foraminifera from two adjacent samples in order to have enough material to date accurately. AMS-^{14}C dates were obtained at the ^{14}Chrono Centre, Queens University Belfast (Table S1). All dates are reported as conventional radiocarbon ages following Stuiver and Polach (1977).

2.3. Age model

The age model for this core was constructed based on the radiocarbon ages of 28 planktonic samples. The AMS-^{14}C ages were converted to calendar ages using BChron and the calibration curve IntCal13 with a surface ocean–atmosphere ^{14}C age offset (i.e. ‘reservoir age’) of 458 ^{14}C-years (based on the modern average value in this region), (GEOSECS; Stuiver and Ostlund, 1980). Since knowledge of changes in the shallow sub-surface reservoir age over the deglaciation is lacking in this context, we assume a constant modern reservoir age. However, this represents a severe limitation and should be seen as a working hypothesis only; reservoir ages must have varied to some extent during deglaciation if only due to changes in the partial pressure of atmospheric CO_2 (Stocker and Wright, 1996; Butzin et al., 2012), resulting in reservoir ages perhaps ~200–300 yrs higher than present during the last glacial period, depending on the state of the overturning circulation (Butzin et al., 2012).

2.4. Ventilation ages

The radiocarbon-based ventilation age of the bottom waters (expressed in ^{14}C years), was determined using the difference be-

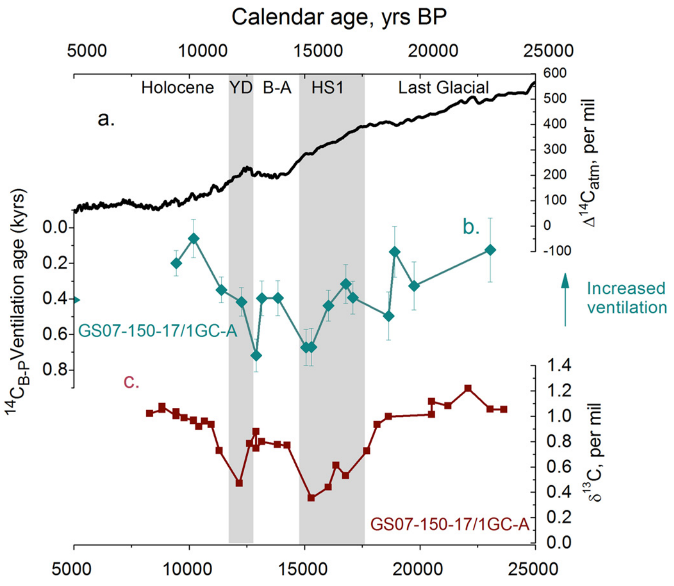

Fig. 2. Deglacial ventilation of Brazil Margin intermediate-water: a) Atmospheric $\Delta^{14}C$ record, IntCal13 (Reimer et al., 2013). b) Radiocarbon-based ventilation ages of GS07-150-17/1GC-A. Radiocarbon ages of mixed benthic foraminifera are compared to that of the contemporaneous planktonic foraminifera. The modern ventilation age is indicated by a triangle on the y-axis. c) Deglacial benthic stable carbon isotope record measured on *C. wuellerstorfi*.

tween paired benthic and planktonic radiocarbon dates (B–P), giving the ^{14}C age offset between the bottom of the water column and the top of the water column. Although arguably it is preferable to use radiocarbon age offsets between bottom-water and the atmosphere (B-Atm), our age-model is based on the assumption of a constant surface ocean–atmosphere ^{14}C age offset (i.e. 'reservoir age') of 458 ^{14}C-years, which means that B-Atm will exhibit the same patterns of variability as B–P, albeit with a constant offset of 458 ^{14}C-years. For simplicity we therefore only refer to B–P offsets in this study (Table S2).

3. Results and discussion

During the LGM our site was well ventilated, with a benthic–planktonic ventilation age similar to that of the early Holocene, 226 yrs and 199 yrs respectively (Fig. 2b). Over the deglaciation however, clear yet subtle changes in the ventilation age occurred. There are two periods, one during Heinrich-Stadial 1, HS1, and the other at the start of the Younger Dryas, YD, where the ventilation age increases by 200–500 yrs. These are transient events lasting around 2200 yrs and 900 yrs in HS1 and the YD respectively. These periods are both associated with cooling in the Northern Hemisphere and a 'thermal bipolar seesaw' response in the Southern high latitudes (Schmittner et al., 2003; Barker et al., 2009). During these times, the benthic stable carbon isotopic signature, $\delta^{13}C$, also decreased by up to 0.8‰ (Fig. 2c).

Our site is currently at the boundary between AAIW (above) and NADW (below), and therefore would in principle be sensitive to changes in the ventilation state and the relative contribution of both water masses. Nutrient proxies from the North Atlantic provide conflicting evidence for changes in AAIW presence at intermediate-depth during the cold stadials (Came et al., 2008; Rickaby and Elderfield, 2005). A recent neodymium (Nd) isotope study (Huang et al., 2014), indicates reduced influence of AAIW between 671 m and 1100 m water depth on the Demerara Rise (North Brazil) during both HS1 and the YD (Fig. 3). Whilst a definitive conclusion regarding changes in AAIW (which may depend sensitively on location) does not emerge from these studies, what is clear is that NADW formation and export were certainly reduced at these times (e.g. McManus et al., 2004; Robinson et al., 2005; Liu et al., 2009; Menviel et al., 2011). Therefore, whilst changes in the contribution of AAIW at our site over the deglaciation remain ambiguous, a decrease in ventilation at times of reduced NADW export is evident. This ventilation decrease could be due to a slower overturning rate of NADW (allowing a greater amount of radiocarbon decay to occur before reaching our site), a change in the initial radiocarbon disequilibrium of newly formed NADW, or due to a greater influence of southern-sourced waters at our site as a result of NADW shoaling, or indeed due to a combination of these. One alternative scenario, whereby the radiocarbon-based ventilation age and nutrient content of AAIW increased during HS1 and the YD with no change in the relative contribution of northern versus southern-sourced water at our site, can be ruled out given the evidence for reduced NADW export (McManus et al., 2004), as well as observations of low sub-surface reservoir ages in the Southern Ocean by the end of HS1 and the during the YD (Burke and Robinson, 2012; Skinner et al., 2014, 2015) (Fig. 3f). Changes in NADW rather than AAIW must therefore be the primary cause of the high ventilation ages at our site during stadials.

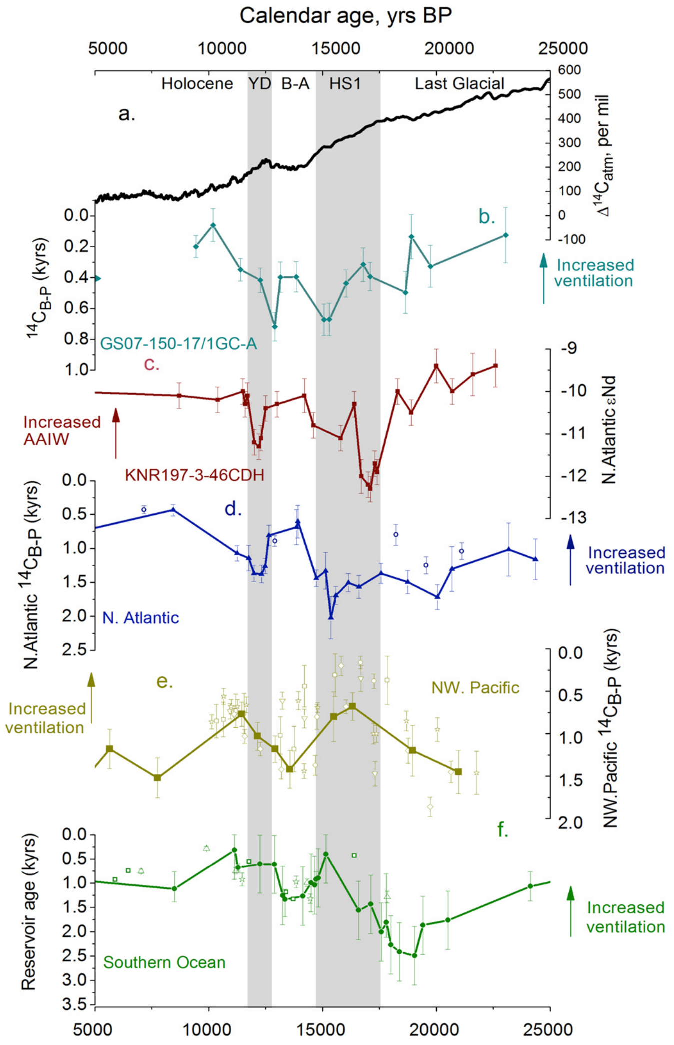

Fig. 3. a) Atmospheric $\Delta^{14}C$ record, IntCal13 (Reimer et al., 2013). b) Radiocarbon-based ventilation ages of GS07-150-17/1GC-A. c) εNd data from the North Atlantic (Huang et al., 2014). d) Radiocarbon-based ventilation ages in the North Atlantic (open circles: Keigwin and Schlegel, 2002; solid triangles: Skinner et al., 2014). e) Radiocarbon-based ventilation ages in the northwest Pacific (solid squares: Ahagon et al., 2003; open symbols: Okazaki et al., 2010, Max et al., 2014). f) Surface and intermediate ventilation ages in the Southern Ocean (solid circles: Skinner et al., 2010; open stars: Siani et al., 2013; open triangles: Skinner et al., 2014; open squares: Burke and Robinson, 2012).

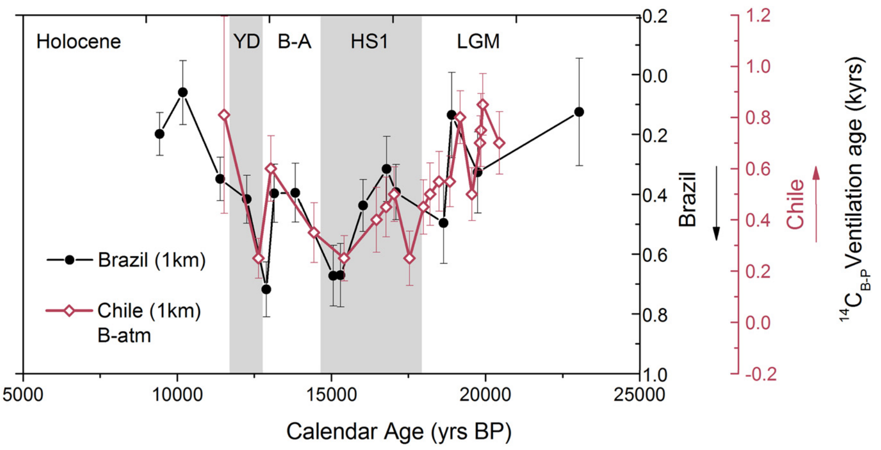

Fig. 4. Comparison of deglacial ventilation ages of intermediate-water on the Brazil Margin (this study) to those of intermediate-water off Chile, SO161-SL22 (De Pol-Holz et al., 2010). The two cores have been plotted on separate *y*-axis with one inverted to highlight the seesaw relationship of the ventilation ages at these sites.

Radiocarbon-based LGM ventilation ages at our intermediate-depth site (1000 m) are much lower than those in the deep North Atlantic (~3000 m) (Keigwin and Schlegel, 2002; Skinner et al., 2014), confirming the existence of well-ventilated (possibly vigorous) Glacial North Atlantic Intermediate Water, GNAIW (Fig. 3). This water mass was most likely reduced during HS1 and the YD leading to a greater proportion of southern sourced waters at our site. During the Bølling–Allerød, B–A, both the intermediate and the deep Atlantic are as well ventilated as in the modern ocean, suggesting that a ‘modern-like’ NADW circulation cell was established at that time. Ventilation ages in the early Holocene are around 300 yrs lower than in the modern ocean potentially due to enhanced NADW at the end of the deglaciation or due to changes in the influence of AAIW at our site.

Radiocarbon-based ventilation age changes measured in a marine sediment core located on the Chilean Margin (De Pol-Holz et al., 2010), display striking similarities, albeit of opposite sign, to our radiocarbon based ventilation age changes in the intermediate Atlantic (Fig. 4). Radiocarbon data from this southeast Pacific AAIW location, initially interpreted as showing no change in ventilation over the deglaciation, in fact shows slightly reduced ventilation ages during both HS1 and the YD. The clear anti-phasing of ventilation ages between these two cores reveals an Atlantic–Pacific seesaw in intermediate water ventilation over the last deglaciation.

Numerical modeling experiments performed with Earth System models of intermediate complexity, LOVECLIM and the UVic ESCM (e.g. Menviel et al., 2014; Huiskamp and Meissner, 2012; see supplementary info) also show a Pacific–Atlantic seesaw, although this is most strongly expressed in the Northern Hemisphere. In these idealized model experiments, the North Atlantic is perturbed with freshwater, resulting in a cessation of NADW formation and decreased $\Delta^{14}C$ over most of the North Atlantic (including our study site) and below 2000 m in the South Atlantic (Fig. 5).

These simulations report a coincident decrease in ventilation ages in the intermediate depth Pacific (this study; e.g. Mikolajewicz et al., 1997; Okazaki et al., 2010; Chikamoto et al., 2012; Huiskamp and Meissner, 2012) (Fig. 6). More specifically, these simulations show increased formation of North Pacific intermediate and/or deep waters and spreading of these waters at depths of 500–1500 m throughout the entire Pacific. In both the UVic ESCM and LOVECLIM simulations, lower ventilation ages at intermediate depths in the Pacific are mainly due to the vigorous formation of North Pacific Intermediate and Deep Water, which leads to the southward advection of younger waters to the South Pacific, South Indian Ocean and through the Agulhas leakage.

Ventilation age reconstructions from the North Pacific further support the model results, indicating a clear seesaw in the ventilation age of NW Pacific intermediate/deep waters (700–1400 m) versus deep waters in the North Atlantic (Okazaki et al., 2010) (Fig. 3d–e). Although a transient pulse of increased ventilation in the North Pacific has also been observed at a depth >3600 m during HS1, the extent of this ventilation anomaly has yet to be confirmed (Rae et al., 2014). It is also notable that two records from intermediate depths in the low-latitude Pacific conflict with the inference of widespread decreased ventilation ages in the intermediate Pacific during North Atlantic stadials. These show large increases in radiocarbon-based ventilation age during HS1 and the YD (Marchitto et al., 2007; Stott et al., 2009). However data from one of these cores suggests that intermediate water oxygenation improved during Heinrich events, as expected if ventilation improved (Cartapanis et al., 2011). These contrasting observations could be reconciled if the observed changes in oxygenation were sufficient to rapidly oxidize buried ‘fossil’ organic carbon at these locations of high export productivity and high sediment accumulation, thus contributing to very high radiocarbon ages in benthic foraminifera. However, this scenario can only work if a very large amount of very old organic carbon is oxidized in this way. The availability of such a large amount of old sedimentary carbon might not be entirely plausible, and its oxidation would likely have caused under-saturation of pore-waters with respect to carbonate, contrary to evidence for enhanced carbonate preservation (Ortiz et al., 2004). An alternative explanation for the very high radiocarbon-based ventilation ages is the input of radiocarbon dead carbon from clathrates as the ocean warms (Stott and Timmermann, 2011), however this also remains controversial (Adkins, 2013).

It is notable that the Atlantic–Pacific seesaw described above would have operated in unison with a previously identified alternation between North Atlantic and Southern Ocean sources of ventilation of the deep Atlantic (e.g. Skinner et al., 2014). While this other ventilation seesaw has been proposed to primarily affect the deep Atlantic, it is possible that intermediate waters in the Pacific and therefore on the Chilean Margin, were affected by changes originating both in the North Pacific and the Southern Ocean. Indeed, Fig. 3 shows that shallow sub-surface and intermediate depth reservoir/ventilation ages in the Southern Ocean show a similar deglacial pattern to that of the NW Pacific, supporting the proposition of a two-pronged ventilation pulse from the North Pacific and Southern Ocean. This is supported by radiocarbon-based ventilation ages from a core in the South Atlantic (Sortor and Lund, 2011), which show an anti-phase relationship to our core from the equatorial Atlantic. Decreases in radiocarbon ventilation ages are thus seen in the intermediate South Atlantic (1.3 km) during late HS1 and the YD, synchronous with increases at our site.

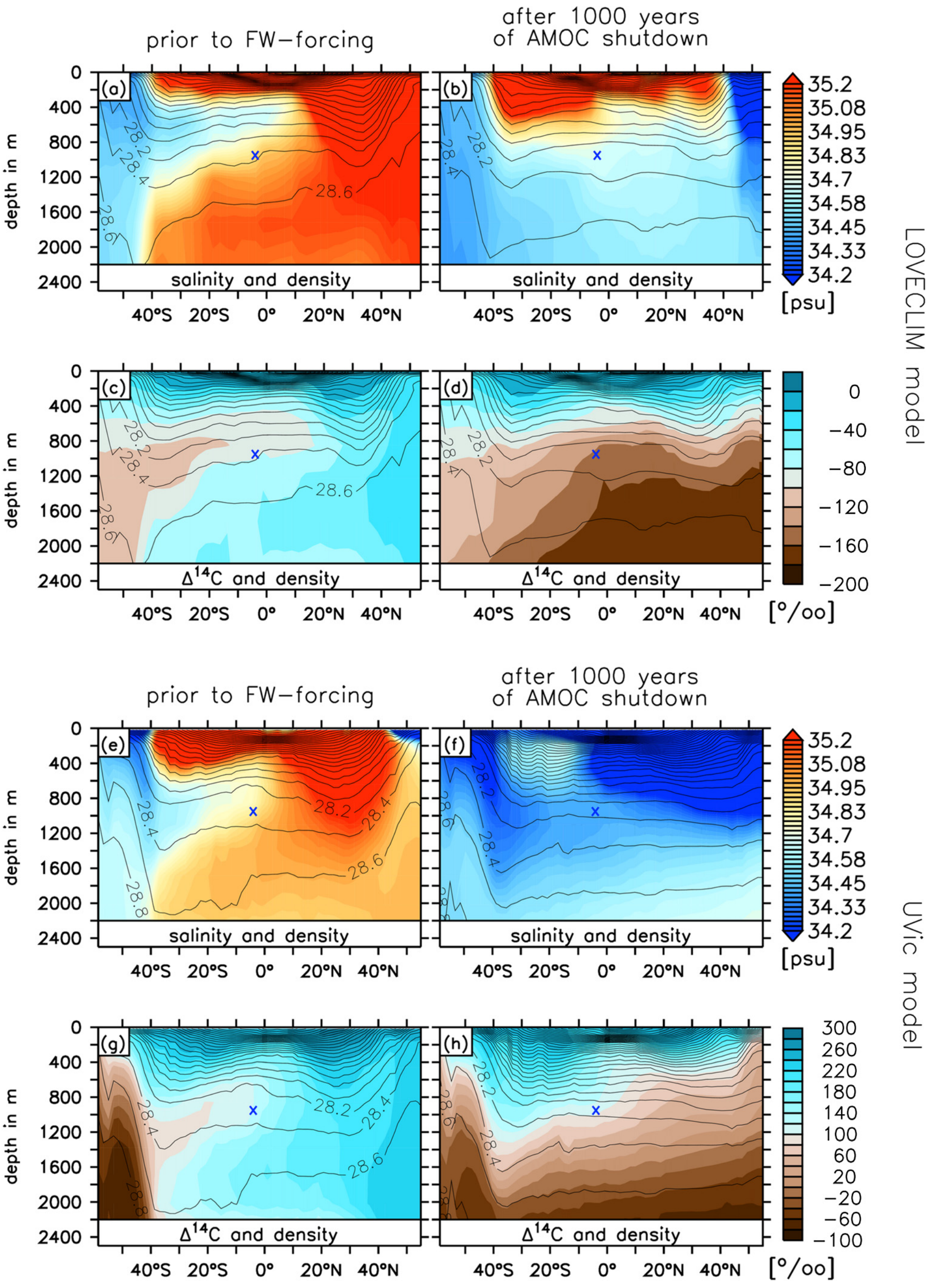

Fig. 5. Simulated salinity and density and Δ^{14}C (permil) distribution in LOVECLIM (a–d), and in the UVic ESCM (e–h) prior (left) and during (right) AMOC shutdown, zonally averaged over the Atlantic basin.

Whilst the magnitude of radiocarbon-based ventilation changes observed at low- and southern latitude intermediate depths off Brazil (this study), in the South Atlantic (Sortor and Lund, 2011) and off Chile (De Pol-Holz et al., 2010) is larger than seen in the model simulations, the general patterns of change are in good agreement and are further reinforced by ventilation reconstructions from the NW Pacific, North Atlantic, and Southern Ocean (Keigwin and Schlegel, 2002; Ahagon et al., 2003; Okazaki et al., 2010 [and references within]; Skinner et al., 2010, 2014; Burke and Robinson, 2012; Siani et al., 2013; Max et al., 2014) (Fig. 3). Model and proxy data display a similar pattern of response, but models underestimate the ventilation changes occurring at intermediate depth and do not reproduce the changes in Southern Ocean overturning and ventilation that are suggested by various deglacial records (e.g. Anderson et al., 2009; Burke and Robinson, 2012; Skinner et al., 2014). This indicates that not all processes contributing to enhanced ocean interior ventilation are captured by the highly idealized models (Menviel et al., 2014). Nevertheless, taken together, the existing data and numerical model simulations provide strong *prima facie* support for the operation of two 'ventilation seesaws', whereby a weakening of NADW formation triggers an increase in North Pacific and Southern Ocean overturning, and therefore opposing changes in ventilation at intermediate depths in the Atlantic and Pacific basins. We therefore propose that when the North Atlantic is not ventilating the ocean interior, the North Pacific and Southern Ocean are.

Despite the consistent support provided by data and model simulations for the proposed Atlantic–Pacific ventilation seesaw,

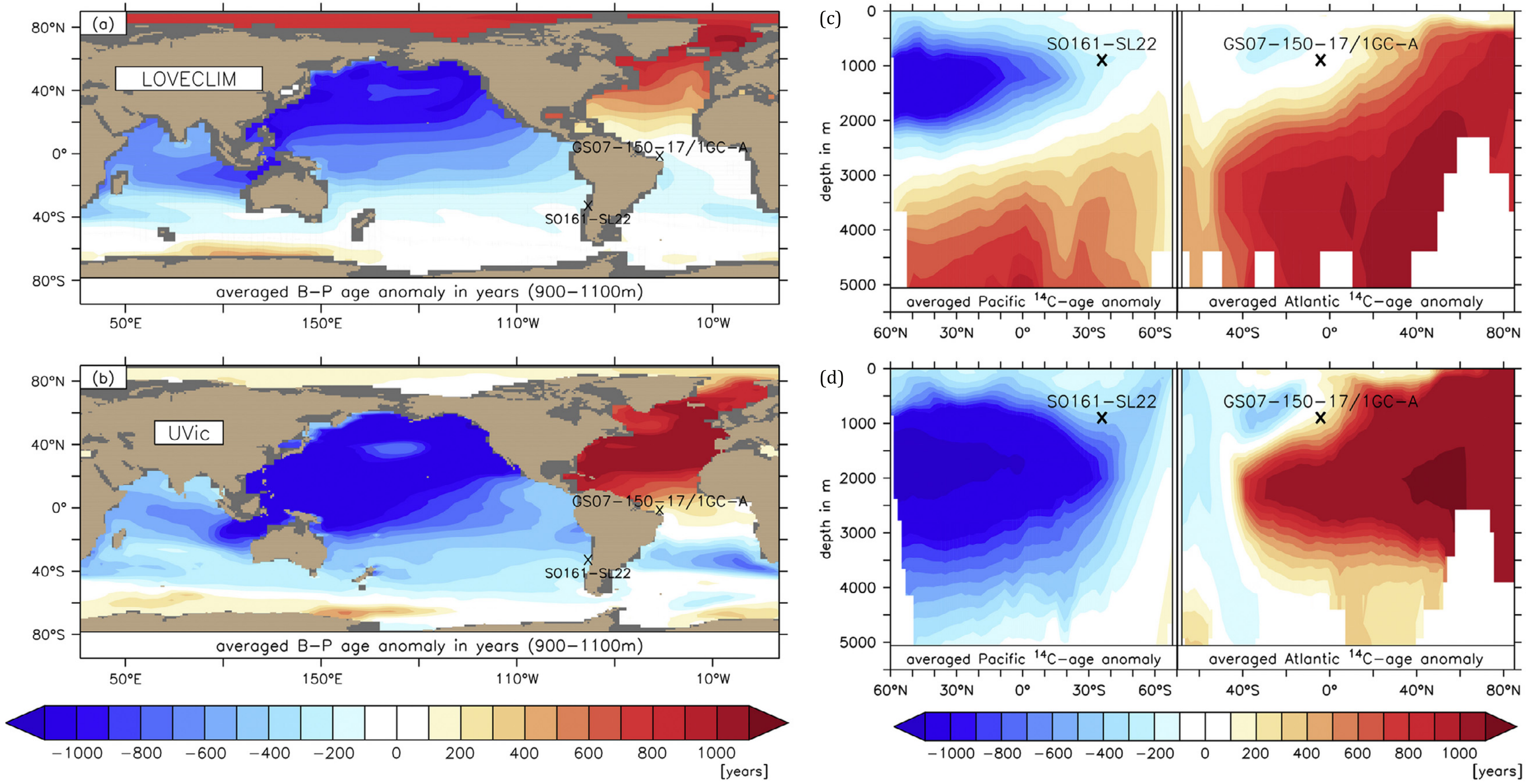

Fig. 6. Simulated radiocarbon ventilation age anomalies (years) obtained in idealized meltwater experiments conducted with LOVECLIM (a and c) and the UVic ESCM (b and d) 1000 years after an input of freshwater into the North Atlantic. Left (a and b): Averaged age anomalies between 900 and 1100 m water depth. Right (c and d): Zonal mean depth profiles of Pacific Ocean (left) and Atlantic Ocean (right) age anomalies.

many more well-resolved radiocarbon time-series will be needed to completely document the character of intermediate-water circulation changes across the last deglaciation. This is underlined by the fact that not only the magnitude of change but also the direction of change in radiocarbon-based ventilation age will depend sensitively on the location and in particular on the depth of the monitoring/study location. Depth transects at the key time periods will therefore be vital for confirming the details of intermediate depth circulation changes and water mass distributions over the last deglaciation.

4. Conclusions

Intermediate-water radiocarbon-based ventilation ages from the Brazil margin show clear yet relatively low amplitude changes over the last deglaciation. These changes are of the same magnitude as, but anti-correlated with, those reported from the Chilean Margin, (De Pol-Holz et al., 2010). This Atlantic–Pacific "seesaw" behavior is also reported in numerical modeling studies, which see a switch to active NPDW during NADW shutdown (Saenko et al., 2004). If NPDW was initiated at HS1 and the YD, the resulting exchange of CO_2 between the ocean and the atmosphere is likely to have contributed to the deglacial increase in atmospheric CO_2 (Menviel et al., 2014) and the simultaneous fall in atmospheric radiocarbon activity (Ramsey et al., 2012). This mechanism would have bolstered a similar effect that appears to have operated via the Southern Ocean at the same time, via a North–South 'Atlantic ventilation seesaw' (Skinner et al., 2014). More ventilation age reconstructions are needed to determine how much of the Pacific was affected during HS1 and the YD before the amount of CO_2 released to the atmosphere through this mechanism can be quantified. Our findings do not support the existence of an extremely radiocarbon-depleted signature conveyed via AAIW during the YD and HS1. Instead they underline the potential importance of relatively subtle yet globally coordinated changes in ocean dynamics and ventilation for the global carbon cycle, and ultimately the deglacial process.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2015.05.032.

References

Adkins, J.F., Boyle, E.A., 1997. Changing atmospheric $\Delta^{14}C$ and the record of deep water paleoventilation ages. Paleoceanography 12 (3), 337–344.
Adkins, Jess F., 2013. The role of deep ocean circulation in setting glacial climates. Paleoceanography 28 (3), 539–561.
Ahagon, N., Ohkushi, K., Uchida, M., Mishima, T., 2003. Mid-depth circulation in the northwest Pacific during the last deglaciation: evidence from foraminiferal radiocarbon ages. Geophys. Res. Lett. 30 (21), 2097.
Anderson, R.F., Ali, S., Bradtmiller, L.I., Nielsen, S.H.H., Fleisher, M.Q., Anderson, B.E., Burckle, L.H., 2009. Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO_2. Science 323 (5920), 1443–1448.
Barker, Stephen, Diz, Paula, Vautravers, Maryline J., Pike, Jennifer, Knorr, Gregor, Hall, Ian R., Broecker, Wallace S., 2009. Interhemispheric Atlantic seesaw response during the last deglaciation. Nature 457 (7233), 1097–1102.
Beck, J.W., Jull, A.J.T., Biddulph, D., Richards, D.A., Edwards, R.L., Silverman, B.W., Smart, P.L., Donahue, D.J., Hererra-Osterheld, S., Burr, G.S., Calsoyas, L., 2001. Extremely large variations of atmospheric ^{14}C concentration during the last glacial period. Science 292 (5526), 2453–2458.
Broecker, W., Clark, E., 2010. Search for a glacial-age c-14-depleted ocean reservoir. Geophysical research letters 37.
Bryan, Sean P., Marchitto, Thomas M., Lehman, Scott J., 2010. The release of ^{14}C-depleted carbon from the deep ocean during the last deglaciation: evidence from the Arabian Sea. Earth Planet. Sci. Lett. 298 (1–2), 244.
Burke, Andrea, Robinson, Laura F., 2012. The Southern Ocean's role in carbon exchange during the last deglaciation. Science 335 (6068), 557–561.
Butzin, Martin, Prange, Matthias, Lohmann, Gerrit, 2012. Readjustment of glacial radiocarbon chronologies by self-consistent three-dimensional ocean circulation modeling. Earth Planet. Sci. Lett. 317–318, 177–184.
Came, Rosemarie E., Oppo, Delia W., Curry, William B., Lynch-Stieglitz, Jean, 2008. Deglacial variability in the surface return flow of the Atlantic meridional overturning circulation. Paleoceanography 23 (1), PA1217.
Cartapanis, Olivier, Tachikawa, Kazuyo, Bard, Edouard, 2011. Northeastern Pacific oxygen minimum zone variability over the past 70 kyr: impact of biological production and oceanic ventilation. Paleoceanography 26 (4).
Chikamoto, Megumi O., Menviel, Laurie, Abe-Ouchi, Ayako, Ohgaito, Rumi, Timmermann, Axel, Okazaki, Yusuke, Harada, Naomi, Oka, Akira, Mouchet, Anne, 2012. Variability in North Pacific intermediate and deep water ventilation during Heinrich events in two coupled climate models. Deep-Sea Res., Part II 61–64, 114–126.
Cleroux, C., Demenocal, P., Guilderson, T., 2011. Deglacial radiocarbon history of tropical Atlantic thermocline waters: absence of CO_2 reservoir purging signal. Quat. Sci. Rev. 30 (15–16), 1875–1882.
De Pol-Holz, R., Keigwin, L., Southon, J., Hebbeln, D., Mohtadi, M., 2010. No signature of abyssal carbon in intermediate waters off Chile during deglaciation. Nat. Geosci. 3 (3), 192–195.
Fairbanks, Todd W., Fairbanks, Richard G., Nadeau, Marie-Josee, Mortlock, Richard A., Chiu, Tzu-Chien, Cao, Li, Kaplan, Alexey, Guilderson, Thomas P., Bloom, Arthur L., Grootes, Pieter M., 2005. Radiocarbon calibration curve spanning 0 to 50,000 years bp based on paired $^{230}Th/^{234}U/^{238}U$ and ^{14}C dates on pristine corals. Quat. Sci. Rev. 24 (16), 1781–1796.
Hain, M.P., Sigman, D.M., Haug, G.H., 2014. Distinct roles of the Southern Ocean and North Atlantic in the deglacial atmospheric radiocarbon decline. Earth Planet. Sci. Lett. 394, 198–208.
Huang, K.F., Oppo, D.W., Curry, W.B., 2014. Decreased influence of Antarctic intermediate water in the tropical Atlantic during North Atlantic cold events. Earth Planet. Sci. Lett. 389, 200–208.
Hughen, K., Lehman, S., Southon, J., Overpeck, J., Marchal, O., Herring, C., Turnbull, J., 2004. ^{14}C activity and global carbon cycle changes over the past 50,000 years. Science 303 (5655), 202–207.
Huiskamp, W.N., Meissner, K.J., 2012. Oceanic carbon and water masses during the mystery interval: a model-data comparison study. Paleoceanography 27 (4).
Keigwin, L.D., Schlegel, M.A., 2002. Ocean ventilation and sedimentation since the glacial maximum at 3 km in the western North Atlantic. Geochem. Geophys. Geosyst. 3 (6), 1034.
Liu, Z., Brook, E., Erickson, D., Jacob, R., Kutzbach, J., Cheng, J., Otto-Bliesner, B.L., He, F., Brady, E.C., Tomas, R., Clark, P.U., Carlson, A.E., Lynch-Stieglitz, J., Curry, W., 2009. Transient simulation of last deglaciation with a new mechanism for Bolling–Allerod warming. Science 325 (5938), 310–314.
Mangini, A., Godoy, J.M., Godoy, M.L., Kowsmann, R., Santos, G.M., Ruckelshausen, M., Schroeder-Ritzrau, A., Wacker, L., 2010. Deep-sea corals off Brazil verify a poorly ventilated southern Pacific ocean during H2, H1 and the Younger Dryas. Earth Planet. Sci. Lett. 293 (3–4), 269–276.
Marchitto, Thomas M., Lehman, Scott J., Ortiz, Joseph D., Flückiger, Jacqueline, van Geen, Alexander, 2007. Marine radiocarbon evidence for the mechanism of deglacial atmospheric CO_2 rise. Science 316 (5830), 1456–1459.
Marcott, Shaun A., Kalk, Michael L., McConnell, Joseph R., Sowers, Todd, Taylor, Kendrick C., White, James W.C., Brook, Edward J., Bauska, Thomas K., Buizert, Christo, Steig, Eric J., Rosen, Julia L., Cuffey, Kurt M., Fudge, T.J., Severinghaus, Jeffery P., Ahn, Jinho, 2014. Centennial-scale changes in the global carbon cycle during the last deglaciation. Nature 514 (7524), 616–619.
Max, L., Lembke-Jene, L., Riethdorf, J.-R., Tiedemann, R., Nuernberg, D., Kuehn, H., Mackensen, A., 2014. Pulses of enhanced North Pacific intermediate water ventilation from the Okhotsk Sea and Bering Sea during the last deglaciation. Clim. Past 10 (2), 591–605.
McManus, J.F., Francois, R., Gherardi, J.-M., Keigwin, L.D., Brown-Leger, S., 2004. Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. Nature 428 (6985), 834–837.
Menviel, L., Timmermann, A., Timm, O.E., Mouchet, A., 2011. Deconstructing the last glacial termination: the role of millennial and orbital-scale forcings. Quat. Sci. Rev. 30 (9), 1155–1172.
Menviel, L., England, M.H., Meissner, K.J., Mouchet, A., Yu, J., 2014. Atlantic–Pacific seesaw and its role in outgassing CO_2 during Heinrich events. Paleoceanography 29 (1), 58–70.

Mikolajewicz, U., Crowley, T.J., Schiller, A., Voss, R., 1997. Modelling teleconnections between the North Atlantic and North Pacific during the Younger Dryas. Nature 387 (6631), 384–387.

Okazaki, Y., Timmermann, A., Menviel, L., Harada, N., Abe-Ouchi, A., Chikamoto, M.O., Mouchet, A., Asahi, H., 2010. Deepwater formation in the North Pacific during the last glacial termination. Science 329 (5988), 200–204.

Ortiz, J.D., O'Connell, S.B., DelViscio, J., Dean, W., Carriquiry, J.D., Marchitto, T., Zheng, Y., van Geen, A., 2004. Enhanced marine productivity off western North America during warm climate intervals of the past 52 ky. Geology 32 (6), 521–524.

Piola, Alberto R., Georgi, Daniel T., 1982. Circumpolar properties of Antarctic intermediate water and subantarctic mode water. Deep-Sea Res., Part I: Oceanogr. Res. Pap. 29 (6), 687–711.

Rae, James W.B., Sarnthein, Michael, Foster, Gavin L., Ridgwell, Andy, Grootes, Pieter M., Elliott, Tim, 2014. Deep water formation in the North Pacific and deglacial CO_2 rise. Paleoceanography 29 (6), 645–667.

Ramsey, Christopher, Staff, Richard A., Bryant, Charlotte L., Brock, Fiona, Kitagawa, Hiroyuki, van der Plicht, Johannes, Schlolaut, Gordon, Marshall, Michael H., Brauer, Achim, Lamb, Henry F., Payne, Rebecca L., Tarasov, Pavel E., Haraguchi, Tsuyoshi, Gotanda, Katsuya, Yonenobu, Hitoshi, Yokoyama, Yusuke, Tada, Ryuji, Nakagawa, Takeshi, 2012. A complete terrestrial radiocarbon record for 11.2 to 52.8 kyr b.p. Science 338 (6105), 370–374.

Reimer, Paula, Bard, Edouard, Bayliss, Alex, Beck, J., Blackwell, Paul, Ramsey, Christopher Bronk, Buck, Caitlin, Cheng, Hai, Edwards, R. Lawrence, Friedrich, Michael, Grootes, Pieter, Guilderson, Thomas, Haflidason, Haflidi, Hajdas, Irka, Hatte, Christine, Heaton, Timothy, Hoffmann, Dirk, Hogg, Alan, Hughen, Konrad, Kaiser, K., Kromer, Bernd, Manning, Sturt, Niu, Mu, Reimer, Ron, Richards, David, Scott, E., Southon, John, Staff, Richard, Turney, Christian, van der Plicht, Johannes, 2013. Intcal13 and marine13 radiocarbon age calibration curves 0–50,000 years cal bp. Radiocarbon 55 (4).

Rickaby, R.E.M., Elderfield, H., 2005. Evidence from the high-latitude North Atlantic for variations in Antarctic intermediate water flow during the last deglaciation. Geochem. Geophys. Geosyst. 6 (5), Q05001.

Robinson, Laura F., Adkins, Jess F., Keigwin, Lloyd D., Southon, John, Fernandez Diego, P., Scheirer, Daniel S., 2005. Radiocarbon variability in the western North Atlantic during the last deglaciation. Science 310 (5753), 1469–1473.

Saenko, O.A., Schmittner, A., Weaver, A.J., 2004. The Atlantic–Pacific seesaw. J. Climate 17 (11), 2033–2038.

Schmittner, A., Saenko, O.A., Weaver, A.J., 2003. Coupling of the hemispheres in observations and simulations of glacial climate change. Quat. Sci. Rev. 22 (5), 659–671.

Siani, Giuseppe, Michel, Elisabeth, De Pol-Holz, Ricardo, Devries, Tim, Lamy, Frank, Carel, Mclanie, Isguder, Gulay, Dewilde, Fabien, Lourantou, Anna, 2013. Carbon isotope records reveal precise timing of enhanced Southern Ocean upwelling during the last deglaciation. Nat. Commun. 4, 2758.

Skinner, L.C., Fallon, S., Waelbroeck, C., Michel, E., Barker, S., 2010. Ventilation of the deep Southern Ocean and deglacial CO_2 rise. Science 328 (5982), 1147–1151.

Skinner, Luke C., Waelbroeck, Claire, Scrivner, Adam E., Fallon, Stewart J., 2014. Radiocarbon evidence for alternating northern and southern sources of ventilation of the deep Atlantic carbon pool during the last deglaciation. Proc. Natl. Acad. Sci. USA 111 (15), 5480.

Skinner, L., McCave, I.N., Carter, L., Fallon, S., Scrivner, A.E., Primeau, F., 2015. Reduced ventilation and enhanced magnitude of the deep Pacific carbon pool during the last glacial period. Earth Planet. Sci. Lett. 411, 45–52.

Sloyan, B.M., Talley, L.D., Chereskin, T.K., Fine, R., Holte, J., 2010. Antarctic intermediate water and subantarctic mode water formation in the southeast Pacific: the role of turbulent mixing. J. Phys. Oceanogr. 40 (7), 1558–1574.

Sortor, Rachel N., Lund, David C., 2011. No evidence for a deglacial intermediate water $D^{14}C$ anomaly in the SW Atlantic. Earth Planet. Sci. Lett. 310 (1–2), 65.

Southon, John, Noronha, Alexandra L., Cheng, Hai, Edwards, R.L., Wang, Yongjin, 2012. A high-resolution record of atmospheric ^{14}C based on Hulu cave speleothem H82. Quat. Sci. Rev. 33, 32.

Stocker, T.F., Wright, D.G., 1996. Rapid changes in ocean circulation and atmospheric radiocarbon. Paleoceanography 11 (6), 773–795.

Stott, L., Southon, J., Timmermann, A., Koutavas, A., 2009. Radiocarbon age anomaly at intermediate water depth in the Pacific Ocean during the last deglaciation. Paleoceanography 24 (2223).

Stott, L., Timmermann, A., 2011. Hypothesized link between glacial/interglacial atmospheric CO_2 cycles and storage/release of CO_2-rich fluids from deep-sea sediments. In: Abrupt Climate Change: Mechanisms, Patterns, and Impacts. In: Geophysical Monograph Series, vol. 193, pp. 123–138.

Stuiver, M., Polach, H., 1977. Reporting of ^{14}C data. Radiocarbon 19 (3), 355–363.

Stuiver, Minze, Ostlund, H.G., 1980. GEOSECS Atlantic radiocarbon. Radiocarbon 22 (1), 1–24.

Vogel, J.S., Southon, J.R., Nelson, D.E., Brown, T.A., 1984. Performance of catalytically condensed carbon for use in accelerator mass spectrometry. Nucl. Instrum. Methods Phys. Res. B 5 (2), 289–293.

Yasuda, I., 1997. The origin of the North Pacific intermediate water. J. Geophys. Res., Oceans 102 (C1), 893–909.