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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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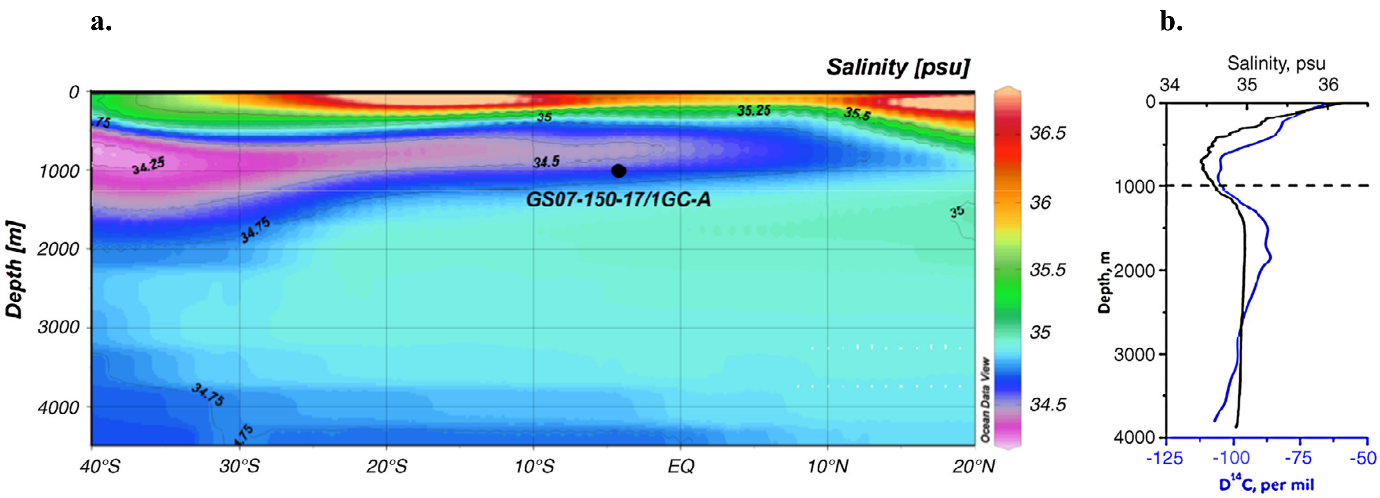

Fig. 1. Hydrography of site GS07-150-17/1GC-A (04°12.98′S, 37°04.52′W, 1000 m): a) Western Atlantic salinity section showing the core location. b) Brazil Margin water profile. (Blue) Modern background ^{14}C distribution (GEOSECS; Stuiver and Ostlund, 1980). (Black) Salinity (Cruise No. GS07-150, R/V 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-