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Reduced ventilation and enhanced magnitude of the deep Pacific carbon pool during the last glacial period

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ABSTRACT

It has been proposed that the ventilation of the deep Pacific carbon pool was not significantly reduced during the last glacial period, posing a problem for canonical theories of glacial–interglacial CO_2 change. However, using radiocarbon dates of marine tephra deposited off New Zealand, we show that deep- (>2000 m) and shallow sub-surface ocean–atmosphere ^{14}C age offsets (i.e. 'reservoir-' or 'ventilation' ages) in the southwest Pacific increased by ∼1089 and 337 yrs respectively, reaching ∼2689 and ∼1037 yrs during the late glacial. A comparison with other radiocarbon data from the southern high-latitudes suggests that broadly similar changes were experienced right across the Southern Ocean. If, like today, the Southern Ocean was the main source of water to the glacial ocean interior, these observations would imply a significant change in the global radiocarbon inventory during the last glacial period, possibly equivalent to an increase in the average radiocarbon age >2 km of ∼700 yrs. Simple mass balance arguments and numerical model sensitivity tests suggest that such a change in the ocean's mean radiocarbon age would have had a major impact on the marine carbon inventory and atmospheric CO_2, possibly accounting for nearly half of the glacial–interglacial CO_2 change. If confirmed, these findings would underline the special role of high latitude shallow sub-surface mixing and air–sea gas exchange in regulating atmospheric CO_2 during the late Pleistocene.

1. Introduction

Radiocarbon can provide unique insights into the ocean's large-scale overturning circulation, in particular its impact on the average timescale of carbon exchange between the atmospheric and marine carbon pools. The latter, set against the rate of biogenic-carbon and carbonate export to the deep ocean, determines the ocean's capacity to sequester CO_2 from the atmosphere. Indeed, it has been proposed that the ∼90 ppmv increase in atmospheric CO_2 that accompanied the last deglaciation (Monnin et al., 2001) was associated with a significant increase in the rate at which CO_2 was exchanged between the deep ocean and the atmosphere, in particular via the Southern Ocean (Anderson et al., 2009; Burke and Robinson, 2012; Skinner et al., 2010, 2013). While atmospheric radiocarbon (Hughen et al., 2006; Muscheler et al., 2004) and stable carbon isotope ($\delta^{13}CO_2$) (Lourantou et al., 2010) records spanning the last deglaciation are consistent with this proposition (Lourantou et al., 2010; Skinner et al., 2010), it continues to be challenged as inadequately verified, refuted or even physically impossible (Broecker et al., 2008; Cleroux et al., 2011; De Pol-Holz et al., 2010; Hain et al., 2011). Marine radiocarbon evidence is crucial in this regard: if the average time-scale of ocean–atmosphere CO_2 exchange was greatly increased during the last glacial period, then a significant reduction of the marine radiocarbon inventory should be observed relative to the contemporary atmosphere. Despite existing and apparently conflicting marine radiocarbon evidence (e.g. Broecker et al., 2008; Burke and Robinson, 2012; De Pol-Holz et al., 2010; Galbraith et al., 2007; Marchitto et al., 2007; Robinson et al., 2005; Sarnthein et al., 2007, 2013; Sikes et al., 2000; Skinner et al., 2010; Skinner and Shackleton, 2004; Thornalley et al., 2011), the true magnitude of the glacial marine radiocarbon inventory, let alone its temporal evolution across the last deglaciation, has yet to be established. Pinning down the radiocarbon inventory of the glacial Pacific is particularly important in this regard, as this basin accounts for ∼50% of the global ocean volume (Menard and Smith, 1966).

It has previously been proposed that the deep Pacific Ocean was not significantly more radiocarbon-depleted during the last

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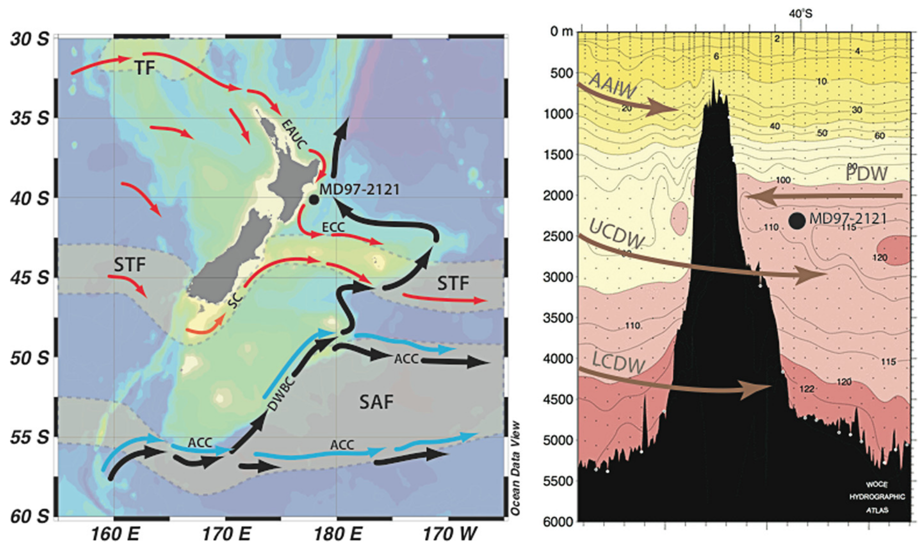

Fig. 1. Location of core MD97-2121, after Carter et al. (2008), relative to the modern regional hydrography, including the sub-tropical front (STF), sub-Antarctic front (SAF), Deep Western Boundary Current (DWBC), Antarctic Circumpolar Current (ACC), Tasman Front (TF), East Auckland Current (EAUC), East Cape Current (ECC), Southland Current (SC). The right hand panel shows modern contoured silicate concentrations (μmol/kg) from WOCE section P15, illustrating the influence of Antarctic Intermediate Water (AAIW), Upper Circumpolar Deep Water (UCDW), Pacific Deep Water (PDW), and Lower Circumpolar Deep Water (LCDW).

glacial period, *versus* today (Broecker et al., 2004a, 2004b, 2007, 2008). Despite the identification of transient ventilation anomalies of varying magnitude and sign across the last deglaciation, primarily in the intermediate/shallow Pacific (<2000 m) (Ahagon et al., 2003; De Pol-Holz et al., 2010; Marchitto et al., 2007; Siani et al., 2013; Stott et al., 2009), the majority of these studies appear to confirm the absence of a large change in the radiocarbon ventilation age during the last glacial period, prior to the onset of deglaciation. Studies of the deep Pacific (>2000 m) are more equivocal, with conflicting evidence from the deep northwest Pacific (Galbraith et al., 2007; Lund et al., 2011), conflicting evidence in the eastern- and western equatorial Pacific (Broecker et al., 2008; Shackleton et al., 1988), and widespread and at times conflicting evidence (based on a novel ventilation age reconstruction method) for greatly increased ventilation ages in the western- and northern Pacific (Sarnthein et al., 2013). The null hypothesis that the glacial deep Pacific ventilation age was similar to modern also conflicts with reconstructions from the deep- and intermediate Southern Ocean (Burke and Robinson, 2012; Sikes et al., 2000; Skinner et al., 2010). The latter is particularly surprising, as the Southern Ocean is currently the source of ∼56% of the ocean interior water mass budget (i.e. below the surface mixed layer) (DeVries and Primeau, 2011). If the Southern Ocean was also the main origin of deep water during the last glacial, or indeed an even greater contributor (Curry and Oppo, 2005; Skinner, 2009), then we should expect some similarity between radiocarbon ventilation changes in the deep Pacific and the deep Southern Ocean.

A principal challenge in advancing data that might resolve this apparent conflict lies in the assessment of the true 'calendar' age of marine radiocarbon dates. This, along with an accurate record of changing atmospheric radiocarbon concentrations, is required to determine the extent of radiocarbon-depletion in a given water mass relative to its contemporary atmosphere (i.e. its 'apparent ventilation age', or 'B-Atm' age offset). Here, in order to overcome this challenge, we make use of volcanic tephra, synchronously deposited on land and at sea, as marker horizons that link marine radiocarbon dates with correlative atmospheric radiocarbon ages obtained in terrestrial sequences (e.g. Siani et al., 2001; Sikes et al., 2000). We apply this approach to a marine sediment core off the east coast of New Zealand to demonstrate that both surface- and deep-water (>2000 m) radiocarbon reservoir ages in the southwest Pacific increased significantly during the last glacial period. This contradicts the null hypothesis of an invariant radiocarbon inventory in the deep Pacific across the last deglaciation, with implications for the ocean's role in glacial–interglacial CO_2 change.

2. Methods

Core MD97-2121 was recovered off the coast of New Zealand by the *R.V. Marion Dufresne* at 40°22.935′S; 177°59.68′E in a water depth of 2314 m (Fig. 1). The core site is currently just north of the Subtropical Front that separates subtropical surface water (STSW) in the north from southern sub-Antarctic surface water (SASW), with Antarctic Intermediate Water (AAIW) dominating the subsurface from ∼600 to 1400 m depth, and a mixture of Upper Circumpolar Deep Water (UCDW) and Pacific Deep Water (PDW) dominating the remainder of the water column (Carter et al., 2008; McCave et al., 2008; Talley et al., 2011). The modern circulation is complex, with the upper ∼800 m of the ocean dominated by a southward current overprinted with southward migrating mesoscale eddies (Chiswell, 2005; Roemmich and Sutton, 1998), and the deeper flow predominantly northward in concert with the Pacific deep western boundary current that underlies a deep reaching southwest Pacific sub-tropical gyre (Talley et al., 2011). MD97-2121 is characterised by high sedimentation rates (∼30 cm/kyr; though these may be affected by 'stretching', Skinner and McCave, 2003) and frequent deposition of volcanic tephra time-markers, as described previously by Carter et al. (2008). For this study, mixed benthic foraminifera (excluding agglutinated and broken shells) and monospecific samples of the planktonic foraminifer *Globigerina inflata* were picked from within or immediately below tephra-bearing horizons. Samples were cleaned by hand on a glass plate and rinsed in deionised water and methanol prior to drying and sealing in evacuated double-wadded 3.5 ml septum vials for hydrolysis in 0.5 ml of dry phosphoric acid at 60 °C. Carbon dioxide evolved from the samples was graphitised at the University of Cambridge using a standard hydrogen/iron-catalyst protocol (Vogel et al., 1984). Samples were graphitised in parallel with size-matched Iceland Spar calcite backgrounds, as well as primary and secondary standards for normalisation and quality control (Santos et al., 2007). Pressed graphite