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A high-resolution record of Southern Ocean intermediate water radiocarbon over the past 30,000 years

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ABSTRACT

The circulation of intermediate waters plays an important role in global heat and carbon transport in the ocean and changes in their distribution are closely tied to glacial–interglacial climate change. Coupled radiocarbon and U/Th measurements on deep-sea *Desmophyllum dianthus* corals allow for the reconstruction of past intermediate water ventilation. We present a high-resolution time series of Antarctic Intermediate Water radiocarbon from 44 corals spanning 30 ka through the start of the Holocene, encompassing the transition into the Last Glacial Maximum (LGM) and the last deglaciation. Corals were collected south of Tasmania from water depths between 1430 and 1950 m with 80% of them between 1500 and 1700 m, giving us a continuous record from a narrow depth range. The record shows three distinct periods of circulation: the MIS 3–2 transition, the LGM/Heinrich Stadial 1 (extending from ∼22 to 16 kyr BP), and the Antarctic Cold Reversal (ACR). The MIS 3–2 transition and the ACR are characterized by abrupt changes in intermediate water radiocarbon while the LGM time period generally follows the atmosphere at a constant offset, in support of the idea that the LGM ocean was at steady state for its ^{14}C distribution. Closer inspection of the LGM time period reveals a 40‰ jump at ∼19 ka from an atmospheric offset of roughly 230‰ to 190‰, coincident with an observed 10–15 m rise in sea level and a southward shift of the Subantarctic and Polar Fronts, an abrupt change not seen in deeper records. During the ACR time period intermediate water radiocarbon is on average less offset from the atmosphere (∼110‰) and much more variable. This variability has been captured within the lifetimes of three individual corals with changes of up to 35‰ over ∼40 yr, likely caused by the movement of Southern Ocean fronts. This surprising result of relatively young and variable intermediate water radiocarbon during the ACR seems to go against the canonical idea of reduced circulation and ventilation in the south during this time period. However comparisons with other records from the Southern Ocean highlight zonal asymmetries, which can explain the deviation of our Tasmanian record from those in Drake Passage and the eastern Pacific. These signals seen in Tasmanian intermediate water $\Delta^{14}C$ can also be found in Greenland ice core $\delta^{18}O$ and East Asian monsoon strength. Throughout the LGM and the deglaciation, our Tasmanian intermediate water record is sensitive to times when the upper and lower cells of the meridional overturning circulation are more or less interconnected, which has important implications for the global climate system on glacial–interglacial time scales.

1. Introduction

The ocean is an important driver of global climate on a variety of timescales. Water has a large heat capacity, which allows the oceans to transport significant amounts of sensible heat from the tropics to the poles. Relative to its volume transport, intermediate water carries a large amount of heat due to the large temperature difference between its formation and upwelling regions (Talley, 2013, 2003). In addition to the ocean's direct effect on climate through heat transport, the deep ocean stores 60 times more carbon than the atmosphere, so changes in ocean circulation can have dramatic impacts on the global carbon cycle. Carbon is stored in the deep ocean via the biological, solubility, and alkalinity pumps, and deeply regenerated CO_2 returns to the atmosphere when deep water upwells to the surface as part of the meridional overturning circulation (Hain et al., 2014; Sigman et al., 2010).

One important tracer that is useful both for reconstructing mean and local ocean circulation is radiocarbon. Radiocarbon (^{14}C)

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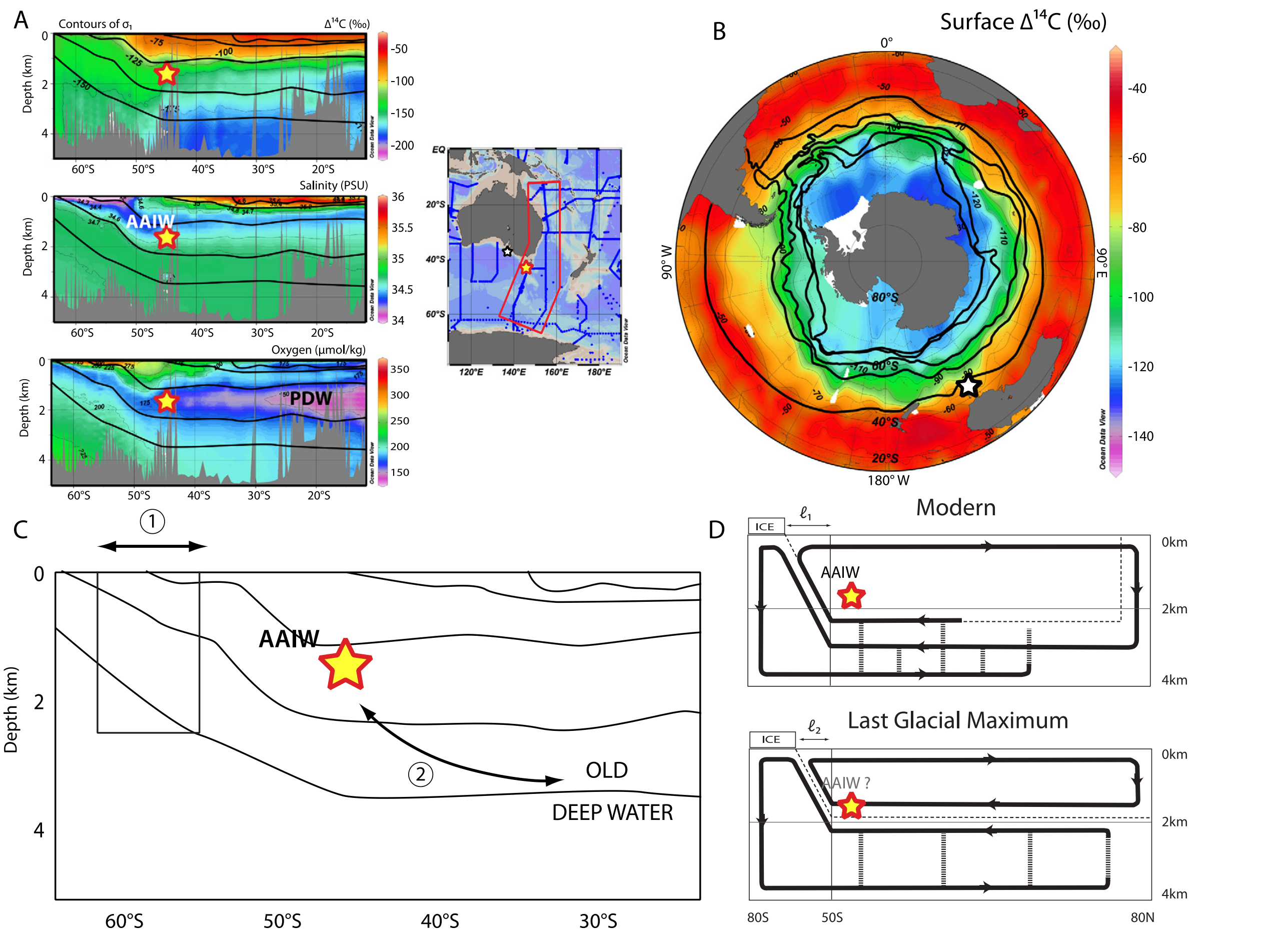

Fig. 1. Hydrography for the broader region around our sample location. A) Sections of bomb-corrected $\Delta^{14}C$ (top), salinity (middle), and oxygen (bottom) from ~65°S to 10°S for the region marked on the inset map (Key et al., 2004). Sample location marked with a yellow star. Thick black contour lines are isopycnals (σ_1). In this region, tracers largely move along density surfaces. Map to the right shows the location of the sections, the Tasmanian coral location (yellow star) and the location of core MD-03-2611 (black star). B) Surface map of bomb-corrected $\Delta^{14}C$ for the whole Southern Ocean. Thick black lines mark the positions of the major Southern Ocean fronts (from furthest north to furthest south: Subtropical Front (STF), Subantarctic Front (SAF), Polar Front (PF), Southern ACC Front (SACCF), and the Southern Boundary (SB)). C) Schematic Southern Ocean section with contours of density (taken from panel A). Coral location is marked with yellow star, and arrows show the two main ways to change radiocarbon values. D) Schematic of modern and glacial meridional overturning circulation with coral location marked with yellow star (adapted from Ferrari et al., 2014). In the modern, upper and lower cells are intertwined whereas in the glacial, cells are separated. This is due to increased sea ice extent (note: ℓ_1 in the upper panel is greater than ℓ_2 in the lower panel). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

is cosmogenically produced in the atmosphere where it is quickly converted to $^{14}CO_2$. Its 5730-yr half-life makes ^{14}C well suited as a tracer for deep ocean circulation, which occurs on time scales of ~1000 yr. The rate of change of radiocarbon in the atmosphere is a balance between ^{14}C production (which is variable in time), exchange with the ocean, and self-decay, which makes the radiocarbon value of the atmosphere a very sensitive recorder of globally integrated ocean overturning. Reconstructions of ^{14}C production through time (Hain et al., 2014; Laj et al., 2002; Muscheler et al., 2004) are helpful for disentangling these competing processes that imprint themselves on atmospheric $\Delta^{14}C$. However, production rate records are difficult to generate. Although mean ocean circulation changes can help explain global shifts in climate, the specific regions involved and the timing of regional changes is also crucial for understanding the mechanisms at work. Measurements of radiocarbon in the ocean are therefore important because they provide local information that can be combined with the atmospheric record to generate a global understanding of how the ocean behaves over millennial timescales.

We provide an intermediate water $\Delta^{14}C$ reconstruction from south of Tasmania in the Indo-Pacific region of the Southern Ocean (Fig. 1). In the modern ocean, Antarctic Intermediate Water (AAIW) ventilates this region between ~500 and 1500 m. Intermediate waters are defined by extrema in salinity, and AAIW can be easily seen in the middle panel of Fig. 1A as the tongue of low-salinity water extending from the surface of the Southern Ocean to between ~500–1500 m. At the sample location this water has a bomb-corrected $\Delta^{14}C$ value of around −150‰ (Fig. 1A, top panel), and underlying Circumpolar Deep Water (CDW) and Antarctic Bottom Water (AABW) are more depleted in radiocarbon. The core of Pacific Deep Water is marked by an oxygen minimum (Talley, 2013), and its return flow to the Southern Ocean intersects with our sample location (Fig. 1A, bottom panel). As Talley points out, the modern meridional overturning circulation (MOC) does not consist of two separate cells stacked on top of one another; instead both cells are intertwined (Fig. 1D, top panel).

Through the application of simple box models, it has been shown that increasing the meridional overturning strength and reducing the efficiency of the biological pump together are able to accomplish the full glacial to interglacial CO_2 change (Knox and McElroy, 1984; Sarmiento and Toggweiler, 1984; Siegenthaler and Wenk, 1984). The configuration of the ocean during the Last Glacial Maximum (LGM) was distinct from the modern (Curry and Oppo, 2005), and it is thought that the ocean circulation was near steady state during this time. Benthic carbon and oxygen isotope measurements show a shoaling of the boundary between the northern