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Deep Pacific ventilation ages during the last deglaciation: Evaluating the influence of diffusive mixing and source region reservoir age

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ABSTRACT

Enhanced ventilation of the deep ocean during the last deglaciation may have caused the rise in atmospheric carbon dioxide that drove Earth's climate from a glacial to interglacial state. Recent results based on the projection age method, however, suggest the ventilation rate of the deep Pacific slowed during the deglaciation, opposite the expected pattern (Lund et al., 2011). Because the projection age method does not account for tracer diffusion (Adkins and Boyle, 1997) it can yield spurious results and therefore requires validation with alternative techniques. Here ventilation ages are determined using the transit-time equilibration-time distribution (TTD–ETD) method which explicitly accounts for diffusive mixing in the ocean interior (DeVries and Primeau, 2010). The overall time history of deep Pacific TTD–ETD and projection ages is very similar; both show a 1000-yr increase in ventilation age during Heinrich Stadial 1 (HS1; 14.5–17.5 kyr BP) and a 500-yr increase during the Younger Dryas (YD). The similarity is due in part to the use of projection age error estimates that take into account uncertainty in both calendar age and benthic ^{14}C age. Centennial-scale offsets between the TTD–ETD and projection ages are due primarily to the different approaches used to estimate surface ocean radiocarbon content. Both the TTD–ETD and projection age results imply that the ventilation rate of the deep Pacific decreased during the deglaciation, opposite the pattern expected if Southern Ocean upwelling and enhanced meridional overturning drove outgassing of CO_2 from the abyss. Variations in surface water reservoir age could cause an apparent shift in deep Pacific ventilation age but existing proxy records from the Southern Ocean appear to be inconsistent with such a driver.

1. Introduction

The transition from the Last Glacial Maximum (LGM; ∼20 kyr BP) to the early Holocene (∼10 kyr BP) is characterized by the disappearance of large continental ice sheets in North America and Eurasia (Clark et al., 2009), an apparent reorganization of the oceanic circulation (Curry and Oppo, 2005; Lynch-Stieglitz et al., 2007; Herguera et al., 2010; Hoffman and Lund, 2012), increasing atmospheric carbon dioxide levels (Monnin et al., 2001), and a rise in global average temperatures (Shakun et al., 2012). The reduction in planetary albedo due to melting of continental ice and the enhanced greenhouse effect due to elevated CO_2 levels are thought to be the primary amplifiers that forced the Earth's climate system from a glacial to interglacial state (Shakun et al., 2012).

Given the central role of atmospheric CO_2 in glacial–interglacial cycles, unraveling the processes that regulate CO_2 is one of the central goals of paleoclimate research. Because greater than 90% of oceanic, terrestrial, and atmospheric carbon resides in the deep ocean, the degree of carbon exchange between the deep ocean and atmosphere is thought to play a primary role in glacial–interglacial CO_2 variability (Sigman and Boyle, 2000). Release of carbon from the deep sea occurs primarily in the Southern Ocean where carbon-rich waters upwell to the surface (Lovenduski et al., 2007; Marshall and Speer, 2012). Reduced outgassing of CO_2 from the Southern Ocean may have caused lower atmospheric CO_2 levels during the LGM (Sigman et al., 2010) while enhanced upwelling and outgassing may have been the primary driver of rising atmospheric CO_2 during the last deglaciation (Anderson et al., 2009).

An increase in the ventilation rate of the deep ocean during the last deglaciation would cause its ventilation age (i.e., the time elapsed since water was last in contact with the atmosphere) to decrease. Because the deep Pacific represents ∼50% of global ocean carbon inventory, constraining the ventilation age of this reservoir is key to understanding ocean–atmosphere carbon exchange. Using a 3-D carbon cycle model, Tschumi et al. (2011) found that an 80% increase in Southern Ocean wind stress causes atmospheric CO_2 to rise about 20 ppmv and the δ^{13}C of atmospheric CO_2 to decrease by ∼0.2‰, similar to the changes observed early in the deglaciation (Monnin et al., 2001; Schmitt et al., 2012). The simulated global average deep water age below 2000 m decreased 250 yr,

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Table 1

Deep water source	Fraction[1]	Mean surface water reservoir age (yr)[2]	1σ	SE	n
Southern Ocean, <60°S	0.47	1130	190	48	16
Southern Ocean, 45°S–60°S	0.19	720	30	–	–
North Atlantic, 50°N–70°N	0.28	400	100	8	148
Surface Pacific, 40°S–40°N	0.04	430	180	8	415
North Pacific, >40°N	0.02	690	150	18	70

[1] Fraction for the deep Northeast Pacific (42°N, 126°W, 2700 m) from Gebbie and Huybers (2012).

[2] Calculated using data from the CALIB Marine Reservoir Database (http://calib.qub.ac.uk/marine/). Due to a lack of data in the sub-Antarctic, the reservoir age estimate for 45°S–60°S is based on the surface water ^{14}C age for this region in Gebbie and Huybers (2012) (860 ± 30 yr) minus the average atmospheric ^{14}C age for all of the data in the CALIB database (140 ± 10 yr) (Reservoir Age = Marine ^{14}C Age – Atmospheric ^{14}C Age).

with a reduction of about 100 yr in the deep Pacific. In contrast, a compilation of projection ages from the deep Pacific suggests the ventilation age increased by more than 500 yr during the deglaciation (Lund et al. 2011). Thus, there appears to be a fundamental disagreement between model predictions of ventilation age and observational constraints from the paleoceanographic record.

The primary aim of this paper is to evaluate whether confounding factors associated the projection age method may yield spurious ventilation ages. Projection ages do not explicitly account for either (1) mixing in the ocean interior, or (2) changes in source region reservoir age. To address the first point, ventilation ages are determined using the transit-time distribution, equilibration-time distribution (TTD–ETD) method developed by DeVries and Primeau (2010) (hereafter DP10). The second point is evaluated by inverting deep Pacific Δ^{14}C to determine the changes in Southern Ocean reservoir age required to produce the deep Δ^{14}C data and then comparing the resulting time series to published records from the Southern Ocean.

2. Methods

2.1. Revised projection ages

The projection age method developed by Adkins and Boyle (1997) marked an important advancement in the study of the paleo-ventilation ages because it was the first to explicitly account for the history of atmospheric Δ^{14}C. Prior to the projection age method, the most common approach for determining ventilation ages involved subtracting the planktonic foraminiferal ^{14}C age from the benthic foraminiferal ^{14}C age in the same sample (a.k.a. benthic–planktonic or B–P age). Although the method is appealing in its simplicity, Adkins and Boyle (1997) clearly demonstrated that B–P ages yield biased results if atmospheric Δ^{14}C varies through time. Given that most of the last 50,000 yr is characterized by substantial variations in atmospheric Δ^{14}C (Reimer et al., 2009), B-P ages are generally unreliable for estimating ventilation age.

The original projection age method takes the atmospheric radiocarbon history into account by projecting a given deep ocean Δ^{14}C estimate along its decay trajectory until it intersects the atmospheric Δ^{14}C curve (Adkins and Boyle, 1997). The difference in calendar age of the Δ^{14}C estimate and the intersection point with the atmospheric Δ^{14}C curve is known as the projection age relative to the atmosphere. To obtain a true ventilation age (that is, one that reflects the time elapsed since water was last in contact with the atmosphere), the surface water reservoir age in the deep water formation region is subtracted from the projection age relative to the atmosphere.

Lund et al. (2011) used the projection age method to create a high resolution record of ventilation ages for the deep Northeast Pacific from 20 to 8 kyr BP. Each benthic Δ^{14}C estimate was projected back to the atmospheric Δ^{14}C curve. Because the Southern Ocean is the primary source of deep water in the Pacific (Gebbie and Huybers, 2010), the surface water reservoir age for the Southern Ocean was then subtracted to determine the projection age. Lund et al. (2011) used a surface water reservoir age of 1100 ± 200 yr (1σ) estimated using the data from south of 60°S in the CALIB Marine Database (http://calib.qub.ac.uk/marine/).

Here a revised projection age method is used that projects benthic Δ^{14}C values back to a surface ocean Δ^{14}C curve because it better represents the actual decay trajectory a given water parcel would take as it moves from the surface ocean into the abyss. As in Lund et al. (2011), errors in calendar age and benthic ^{14}C age are fully propagated using a Monte Carlo approach to create 1000 estimates of Δ^{14}C for each benthic sample.

Each of the Δ^{14}C estimates is then projected back to the surface ocean Δ^{14}C curve to create a distribution of possible projection ages. This approach prevents spurious projection age estimates that can result from abrupt peaks in the surface ocean Δ^{14}C history. The revised method was followed to determine projection ages for published data from the Northeast Pacific (Galbraith et al., 2007; Gebhardt et al., 2008; Lund et al. 2011) and the western equatorial Pacific (Broecker et al., 2008).

The surface ocean Δ^{14}C curve was constructed assuming a constant surface water reservoir age for waters that enter the deep Pacific. Unlike in Lund et al. (2011), a weighted approach was used to take into account the proportion of water at 2700 m in the North Pacific originating from different locations (Table 1). Each proportion was multiplied by its corresponding mean surface water reservoir age and the resulting values were summed to yield a net reservoir age of 810 ± 460 yr (1σ). Using the standard errors in Table 1, which reflect uncertainty in the mean reservoir age for each region, the propagated uncertainty for the net reservoir age is ±70 yr. An 810-yr reservoir age better represents the ‘preformed’ age of the source waters for the deep Pacific than the 1100-yr value used in Lund et al. (2011) and is consistent with estimates of 800–900 yr based on modern observations (Gebbie and Huybers, 2012; Khatiwala et al., 2012). Increasing (decreasing) the reservoir age shifts the projection ages to lower (higher) values but has little influence on the relative change through time.

2.2. TTD–ETD ages

One of the shortcomings of the projection age method is that it does not account for mixing in the ocean interior. In reality, the radiocarbon content of a water parcel in the deep ocean reflects both radiocarbon decay from its point of origin but also mixing with other water parcels that are both older and younger. In this sense, the radiocarbon age of the deep Pacific represents a range of advective pathways from the surface ocean into the abyss. To account for this more complex picture, DP10 argued that paleo-ventilation ages should instead be determined using the TTD method.

The TTD approach is based on the premise that the range of transit times from the surface ocean into the ocean interior can be parameterized and used to capture the effects of advection and diffusion on ^{14}C ages. Similar to the projection age approach, it assumes that most of the water in the deep Pacific originates from