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Near constancy of the Pacific Ocean surface to mid-depth radiocarbon-age difference over the last 20 kyr

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ABSTRACT

Although ^{13}C to ^{12}C and cadmium to calcium ratios provide information regarding the distribution of deep water masses during late glacial time and during the period of deglaciation, our knowledge of the rate at which these water masses were ventilated comes mainly from the difference in radiocarbon-age between coexisting bottom- and surface-dwelling foraminifera. Paired benthic/planktonic foraminiferal radiocarbon-age differences covering last 20 kyr in a high-deposition-rate western equatorial Pacific core, MD01-2386, from a water depth of 2.8 km show no significant climate-related variations over this period. This result is surprising for we would have expected a change in this age difference between the last glacial maximum (LGM) and the Holocene and also during the Mystery Interval (17.5–14.5 kyr ago) when the waters in a radiocarbon-depleted abyssal reservoir were presumably being mixed back into the remainder of the ocean.
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1. Introduction

There are many reasons to suspect that the rate of ventilation of the deep Pacific Ocean changed over the last 20 kyr, a period extending from the Last Glacial Maximum (LGM) through the interval of deglaciation into the Holocene. During the LGM sea level stood 120 m lower than it does today eliminating the shallow waters responsible for most of today's tidal friction. The presence of the large Laurentide ice sheet certainly distorted the wind field and hence the friction it exerts on the sea. Extended sea ice cover in the northern Atlantic and around Antarctica impacted the production of deep waters; and also the magnitude of the transport of water vapor from Atlantic to the Pacific likely differed. As a consequence, the mode of circulation in the Atlantic Ocean was quite different from today's. During the LGM the deep Atlantic was divided into two quite different water masses. Below about 2.5 km it was ventilated by high nutrient-content water originating in the Southern Ocean. Above this depth it was ventilated by low nutrient-content water originating in the northern Atlantic. The difference in nutrient-content is documented by carbon 13 to carbon 12 and cadmium to calcium ratio measurements on the shells of benthic foraminifera (Boyle and Keigwin, 1982; Oppo and Fairbanks, 1987). A corresponding difference in ventilation rate is documented by paired ^{14}C measurements made on paired benthic and planktonic shells (Broecker et al., 1990; Keigwin and Schlegel, 2002). By contrast, during the Holocene water descending in the northern Atlantic dominated its deep water column.

During the 10 kyr period of deglaciation, 50 million cubic kilometers of fresh water was delivered to the world ocean as a result of the melting of the excess continental ice. Further, the extent of the excess sea ice fluctuated and then disappeared. Changes in the Atlantic's deep circulation occurred in concert with these changes. Measurements of the ^{231}Pa to ^{230}Th ratio in northern Atlantic sediments suggest that during the early phase of deglaciation (i.e., the Mystery Interval which extended from 17.5 to 14.5 ka; Denton et al., 2006), deep circulation was largely shut down (McManus et al., 2004). This phase came to an abrupt close when the Atlantic's conveyor circulation popped back into action at the onset of the Northern Hemisphere's Bølling-Allerød warm interval. Then, in parallel with the Younger Dryas cold event, a reduction in deep water production in the northern Atlantic occurred. This reduction is recorded by an increase in the ratio of ^{231}Pa to ^{230}Th (McManus et al., 2004) and was likely responsible for an increase in the ^{14}C to C ratio in the atmosphere and surface-ocean (Hughen et al., 2004a,b).

Although evidence for corresponding changes in the ventilation of the deep Pacific Ocean would certainly be expected, surprisingly none stand out in the sedimentary record. As is the case today, neither the $^{13}C/^{12}C$ nor the Cd/Ca measurements of LGM Pacific benthic foraminifera

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Table 1
Radiocarbon-ages of, and differences between, *P. obliquiloculata* and *G. sacculifer* and between *N. dutertrei* and *G. sacculifer* in 16 samples from western equatorial Pacific core 2386

Depth in core (cm)	Age *G. sac* (^{14}C yr)	Age *P. obl* (^{14}C yr)	Age *N. dut* (^{14}C yr)	Δ *obl.–sac.* age (yr)	Δ *dut.–sac.* age (yr)
0–5	1470±25	1680±25	1640±25	+210±40	+170±40
98–103	5080±40	5130±50	4920±45	+50±70	−160±70
198–203	9520±50	9480±50	9420±50	−40±80	−100±80
223–228	10,150±55	10250±50	10,100±45	+100±80	−50±70
248–252	11,050±40	11,050±75	11,150±80	+75±60	+100±60
273–278	11,750±80	11,750±45	11,500±45	0±100	−250±100
298–302	12,490±105	12,750±85	12,640±120	+260±140	+150±250
323–327	12,800±80	–	12,720±90	–	−80±140
348–352	13,470±95	–	13,490±95	–	+20±140
373–377	14,250±70	–	14,250±70	–	0±105
398–401	14,550±75	14,560±100	13,920±110	+10±140	−620±140
423–427	15,050±65	–	14,950±75	–	−100±100
448–452	14,900±55	–	15,300±60	–	+400±90
473–477	15,350±250	–	15,900±80	–	+550±80
498–502	16,100±65	16,430±120	16,590±130	+230±150	+490±130
523–527	17,150±60	16,340±150	16,840±160	−810±160	−310±170

show significant gradients with water depth (Boyle, 1992; Matsumoto and Lynch-Stieglitz, 1999; Broecker et al., 2007). Further, published radiocarbon differences for LGM and deglacial age benthic–planktonic pairs from the tropical and North Pacific Ocean are not greatly different from today's (Keigwin and Schlegel, 2002; Broecker et al., 2004; Ohkushi et al., 2004). However, as these measurements cover only the upper portion of the deep water column. Perhaps as is the case in the Atlantic, the situation for waters below 2 km was quite different. Radiocarbon measurements by Marchitto et al. (2007) on samples from a thermocline depth core from the margin of the eastern North Pacific and by Galbraith et al. (2007) from abyssal depth cores in the northern Pacific certainly point to existence of such changes during the deglacial time interval. Indeed, quite a strong case can be made that, in order to explain the elevated ^{14}C to C ratio atmospheric and surface-ocean carbon during the last glacial period, it is necessary to call on a large abyssal reservoir isolated from radiocarbon renewal for many thousands of years (Adkins et al., 2002; Adkins and Schrag, 2003; Broecker and Barker, 2007).

To this end, we undertook to obtain a detailed record of the radiocarbon-age difference between benthic and planktonic foraminifera in a core from 2.8 km water depth in the western equatorial Pacific. As outlined in the sections which follow, much to our surprise, disappointment and dismay, the results in 16 samples covering the last 20 kyr showed that the age difference remained within the measurement uncertainty of today's difference.

2. Today's radiocarbon distribution

Before discussing the radiocarbon results, some background regarding the distribution of this isotope in today's ocean is called for. By convention, radiocarbon to carbon ratios are expressed as ^{13}C-normalized per mil differences from that in pre-industrial atmospheric CO_2. On this scale, warm surface waters have values averaging −40‰. Deep water formed in the northern Atlantic have values close to −70‰ and deep water formed in the Southern Ocean values close to −140‰. As the deep waters in today's Pacific currently consist of a roughly 50–50 mixture of water descending in the northern Atlantic and water descending in the Southern Ocean (Peacock et al., 1999), the preformed value for the mix is close to −105‰. Expressed as an apparent age relative to warm surface water, the 65 (105–40) per mil preformed deep water to warm surface water difference corresponds to a radiocarbon-age of 580 yr. Deep water in the equatorial Pacific currently has a $\Delta^{14}C$ value close to −210‰. Thus its radiocarbon-age difference relative to warm surface waters is about 1600 yr and that relative to the 50–50 new deep water mix is about 1000 yr.

3. Radiocarbon in the glacial deep Pacific

By measuring the ^{14}C to C ratios in coexisting planktonic and benthic foraminifera, the apparent age difference between warm surface water and deep water at times past can be reconstructed. But, as discussed above, this age contains the preformed component as well as the component related to the actual ventilation age, it must be kept in mind that either or both may have changed. Notwithstanding, the ability to reconstruct in-situ deep water $\Delta^{14}C$ in the past allows us to construct a picture of global radiocarbon distribution through the last 20 kyr or so. Combined with records of atmospheric $\Delta^{14}C$ this provides a diagnostic as to likely changes in deep ocean ventilation that occurred during deglaciation.

4. Radiocarbon and stable isotope measurements

Thanks to Eva Moreno (Muséum National d'Histoire Naturelle, Paris, France), we were able to obtain sufficiently large samples from a Marion Dufresne giant piston core (MD01-2386) from 2.8 km depth in the westernmost Pacific Ocean (1°N, 130°E) to provide the material

Table 2
Benthic–planktonic offsets

Core depth (cm)	Planktonic ^{14}C age[a] (yr)	Error (yr)	Benthic ^{14}C age (yr)	Error (yr)	B–P offset (yr)	Error (yr)	Calendar age[b] (yr)	Lower limit (1 sigma)	Upper limit (1 sigma)
0–5	1597	88	2790	35	1193	95	990	810	1167
98–103	5043	90	6800	60	1757	108	5174	4962	5411
198–203	9473	91	10,750	110	1277	143	10,112	9887	10,368
223–228	10,166	91	11,550	70	1384	115	10,938	10,727	11,160
248–253	11,120	72	12,550	55	1430	91	12,477	12,310	12,795
273–278	11,662	93	12,900	70	1238	116	13,031	12,885	13,144
298–203	12,644	94	14,100	210	1456	230	13,967	13,736	14,155
323–328	12,761	122	14,200	75	1439	143	14,152	13,805	14,429
348–353	13,480	126	15,100	85	1620	152	15,260	14,973	15,562
373–378	14,250	117	15,350	250	1100	276	16,285	15,979	16,593
398–403	14,362	102	16,000	95	1638	139	16,432	16,134	16,723
423–428	15,001	117	16,450	90	1449	148	17,370	17,016	17,743
448–453	15,098	114	16,900	80	1802	139	17,516	17,174	17,894
473–478	15,760	147	17,550	90	1790	172	18,485	18,455	18,773
498–503	16,338	105	17,850	60	1512	121	19,008	18,842	19,153
523–528	16,849	111	18,550	65	1701	129	19,442	19,222	19,575

[a] Ages are pooled means of all planktonic dates (see Table 1).
[b] Calculated from the pooled mean planktonic ^{14}C ages using Calib v.5.0.1 (Stuiver and Reimer, 1993; Stuiver et al., 2005) with the Marine04 calibration curve (Hughen et al., 2004a, b) and ΔR = 160±150 yr (Broecker et al., 2004) for all samples.

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