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Climate of the Past

Ventilation changes in the western North Pacific since the last glacial period

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Abstract. We reconstructed the ventilation record of deep water at 2100 m depth in the mid-latitude western North Pacific over the past 25 kyr from radiocarbon measurements of coexisting planktic and benthic foraminiferal shells in sediment with a high sedimentation rate. The ^{14}C data on fragile and robust planktic foraminiferal shells were concordant with each other, ensuring high quality of the reconstructed ventilation record. The radiocarbon activity changes were consistent with the atmospheric record, suggesting that no massive mixing of old carbon from the abyssal reservoir occurred throughout the glacial to deglacial periods.

1 Introduction

The atmospheric CO_2 content during glacial periods was about 80 ppm lower than the pre-industrial level (Monnin et al., 2001). During the early phase of the deglacial period between 17.5 and 15 kyr BP, the ratio of the radionuclides ^{231}Pa and ^{230}Th in northern Atlantic sediments suggests a slowdown of the Atlantic Meridional Overturning Circulation (AMOC), triggered by the massive discharge of fresh water to the North Atlantic known as Heinrich Event 1 (H1) (McManus et al., 2004). Because of a 190 ‰ drop in the ^{14}C/^{12}C ratio in the atmosphere and an atmospheric CO_2 rise of 40 ppm during H1, renewal of the isolated carbon reservoir in deep water is thought to be linked to reorganizations in AMOC (Denton et al., 2006; Broecker and Barker, 2007).

Recently, Okazaki et al. (2010) examined a compilation of radiocarbon records and modelling simulations and suggested that deep water was formed in the North Pacific extending to a depth of ~2500 m during H1. The main simulated pathway of deepwater spreading is along the western margin of the North Pacific, in a deep western boundary current analogous to the present one in the North Atlantic. However, our knowledge of paleo-ventilation, particularly in water deeper than 2000 m in the western North Pacific, is limited because of poor preservation of foraminiferal shells in sediment. Here we present a detailed account of ventilation changes in the mid-latitude western North Pacific based on radiocarbon records from coexisting planktic and benthic foraminifera in sediment with high sedimentation rates. Because our ventilation reconstruction is based on radiocarbon data from multiple planktic species in the mid to high-latitude western North Pacific, our record provides robust evidence for the ventilation history in the region.

2 Materials and methods

2.1 Sediment samples

Giant piston core MD01-2420 was obtained from the western North Pacific off Japan (36°04′ N, 141°49′ E; water depth 2101 m; Fig. 1; Table 1) during the International Marine Past Global Change Study (IMAGES, http://www.images-pages.org/), Western Pacific Margin (WEPAMA) 2001 Cruise of the R/V *Marion Defresne*. Stormy conditions led to limited core recovery of 8.99 m. Sediments in the core are composed mainly of dark olive-grey homogeneous silty clay, and no sediment disturbance is apparent. In order to evaluate the core quality, Sagawa et al. (2006) confirmed the high quality of the core by comparing the sediment colour and planktic foraminiferal δ^{18}O between this core and MD01-2421, another IMAGES piston core adjacent to the MD01-2420 site with well-established age control (Oba and Murayama, 2004; Oba et al., 2006).

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Table 1. Location of sediment cores and their ΔR in the North Pacific used in this study.

Core ID	Latitude	Longitude	Water depth (m)	ΔR (yr)	Error ($\pm 1\sigma$)	Reference
MD01-2420	36.07° m	141.82° E	2101	100	200	This study
CH84-14	41.73° N	142.55° E	978	500	300	Duplessy et al. (1989)
GH02-1030	42.23° N	144.21° E	1212	500	300	Sagawa and Ikehara (2008)
MR01K03-PC4/5	41.12° N	142.40° E	1366	500	300	Ahagon et al. (2003)
KR02-15-PC6	40.40° N	143.50° E	2215	500	300	Minoshima et al. (2007)
KT89-18-P4	32.15° m	133.90° E	2700	100	200	Murayama et al. (1992)
MD97-2138	1.25° S	146.23° E	1900	160	150	Broecker et al. (2004b)
MD98-2181	6.3° N	125.82° E	2114	160	150	Broecker et al. (2004b)
MD01-2386	1.13° N	129.79° E	2816	160	150	Broecker et al. (2008)
ODP 887	54.37° N	148.45° W	3647	500	300	Galbraith et al. (2007)
W8709A-13PC	42.1° N	125.8° W	2710	500	300	Lund et al. (2011)

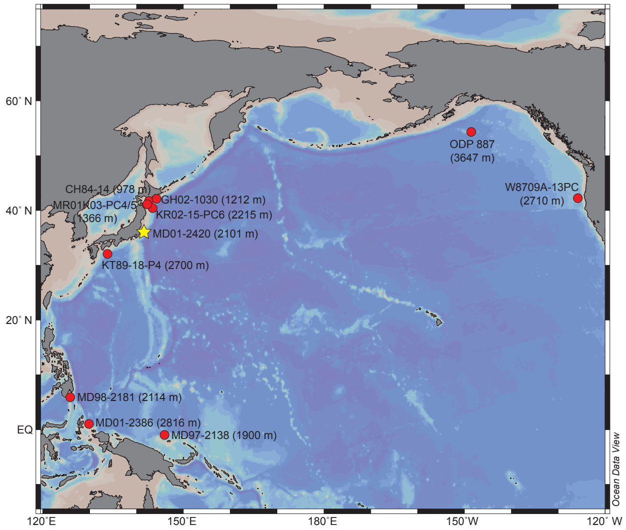

Fig. 1. Map showing the locations of core MD01-2420 (yellow star) and cores used in previous ventilation studies (red circles) in the western North Pacific. The map was drawn using Ocean Data View (http://odv.avi.de/).

2.2 Radiocarbon measurements

We extracted sediment samples 2 cm thick at 15 horizons from the upper 6 m of core MD01-2420. Samples were washed on a 63 µm mesh sieve and dried in an oven at 60 °C. Coexisting planktic foraminifera (*Globigerina bulloides* and *Globorotalia inflata*) and benthic foraminifera (*Uvigerina* spp. and mixed species) were used for radiocarbon dating. We picked foraminiferal shells from the >250 µm fraction of each sample under a stereomicroscope. When the numbers were insufficient, we also picked shells from 125–250 µm fractions. If the amount of shells was still insufficient, we picked additional shells from adjoining sediment samples.

The foraminiferal shells were cleaned by soaking them in 99.5 % methyl alcohol, followed by ultrasonication until all chambers were open. After confirming that all dirt had been removed, we washed the shells in Milli-Q water and dried them in an oven at 40 °C. ^{14}C ages were measured by accelerator mass spectrometry (AMS) at the National Ocean Sciences AMS facility (NOSAMS) at Woods Hole Oceanographic Institution (Table 2). Three ^{14}C ages of *G. inflata* were measured at the Center for Chronological Research, Nagoya University, Japan (Table 2; Sagawa et al., 2006).

We converted radiocarbon ages of the planktic foraminifera samples to calendar ages by using the Calib 6.0 program with the Marine09 calibration dataset (Reimer et al., 2009). The regional marine reservoir age (ΔR) is defined as the deviation of the local radiocarbon age from the globally averaged reservoir age (~400 yr). For core MD01-2420, we chose $\Delta R = 100 \pm 200$ yr based on Shishikura et al. (2007) and Yoneda et al. (2007) (Table 1).

Radiocarbon activity (Δ^{14}C) in bottom water, where benthic foraminifera dwell, was calculated by

$$\Delta^{14}\mathrm{C} = \left(\frac{e^{-^{14}\mathrm{C\ age\ of\ benthic}/8033}}{e^{-\mathrm{cal\ age}/8266}} - 1 \right) \times 1000 \qquad (1)$$

where 8033 and 8266 are the Libby and true radiocarbon mean-life in years, respectively (Adkins and Boyle, 1997).

3 Results and discussion

3.1 Evaluation of radiocarbon data

Bioturbation creates major biases when we try to reconstruct past ocean ventilation based on radiocarbon age differences between co-existing planktic and benthic foraminiferal shells (Broecker et al., 1984). Hence, samples from sediments of high sedimentation rate are required. Because such sediments are found near the continental slopes, we must rule out the presence of reworked materials (Broecker et al., 2004a).

Table 2. Radiocarbon ages of planktic and benthic foraminifera in core MD01-2420. Errors are $\pm 1\sigma$.

Depth top (cm)	Depth bottom (cm)	Species	Conventional age (^{14}C yr BP)	Error (yr)	Lab code*
70.1	72.5	*G. inflata*	3010	25	NUTA2-7849
233.4	238.2	*G. inflata*	7880	40	OS-78784
298.8	300.2	*G. inflata*	9530	40	NUTA2-7850
339.2	344.1	*G. inflata*	10 700	55	OS-78785
353.8	358.6	*G. bulloides*	11 150	55	OS-85356
370.7	375.6	*G. bulloides*	11 750	45	OS-85348
370.7	375.6	*G. inflata*	11 600	85	OS-85355
382.9	385.3	*G. inflata*	12 150	50	OS-78787
390.1	392.6	*G. bulloides*	13 000	55	OS-78802
390.1	392.6	*G. inflata*	12 400	45	OS-78803
404.7	407.1	*G. bulloides*	13 350	60	OS-85351
404.7	407.1	*G. inflata*	13 150	65	OS-78805
419.2	421.6	*G. bulloides*	13 550	50	OS-78807
419.2	421.6	*G. inflata*	13 350	100	OS-78822
431.3	433.7	*G. bulloides*	13 900	80	OS-85388
431.3	433.7	*G. inflata*	13 900	65	OS-85386
451.6	454.1	*G. bulloides*	14 650	55	OS-85384
451.6	454.1	*G. inflata*	14 750	60	OS-85353
489.2	494.2	*G. bulloides*	16 550	65	OS-85349
489.2	494.2	*G. inflata*	16 350	70	OS-85324
504.1	506.6	*G. bulloides*	17 050	80	OS-78827
504.1	506.6	*G. inflata*	17 000	65	OS-78809
600.2	602.1	*G. inflata*	19 555	60	NUTA2-7851
70.1	72.5	Mixed benthic	4560	35	OS-78783
233.4	238.2	Mixed benthic	9020	50	OS-78823
298.8	302.6	Mixed benthic	10 800	65	OS-78828
341.6	344.1	Mixed benthic	12 100	50	OS-78786
353.8	358.6	*Uvigerina* spp.	12 400	65	OS-85343
370.7	375.6	Mixed benthic	13 050	60	OS-85340
382.9	385.3	Mixed benthic	13 450	65	OS-78788
390.1	392.6	Mixed benthic	13 750	55	OS-78804
404.7	407.1	Mixed benthic	14 600	60	OS-78806
419.2	421.6	Mixed benthic	14 750	55	OS-78808
431.3	433.7	*Uvigerina* spp.	15 250	60	OS-85339
451.6	454.1	*Uvigerina* spp.	15 850	65	OS-85323
489.2	491.7	Mixed benthic	18 000	75	OS-85325
504.1	506.6	Mixed benthic	18 350	70	OS-78810
600.2	602.1	Mixed benthic	21 100	100	OS-78811

* NUTA2, Center for Chronological Research, Nagoya University, Japan; OS, National Ocean Sciences AMS facility, Woods Hole Oceanographic Institution

To test these biases, radiocarbon measurements on multiple planktic foraminiferal species employing fragile and robust species are effective (Broecker et al., 2004a, 2006). In core MD01-2420, we used two planktic species: *Globigerina bulloides* with relatively fragile shells and *Globorotalia inflata* with robust shells from eight intervals (Table 2). The planktic species yielded closely matching ^{14}C ages (except in the 390.1 cm interval) and the sedimentation rate was high (~30 cm kyr^{-1}) without age reversal, suggesting that core MD01-2420 was appropriate for reconstruction of past ventilation (Tables 2 and 3; Fig. 2). In the sample from the 390.1 cm interval, the ^{14}C age of *G. bulloides* was 600 yr older than that of *G. inflata*, implying considerable contamination by reworking. We selected the ^{14}C age of *G. inflata* for the 390.1 cm interval because the younger radiocarbon age was closest to the true age of the sediment (Broecker et al., 2004a).

3.2 Ventilation changes in core MD01-2420

Radiocarbon age differences between co-existing planktic and benthic foraminiferal shells (B-P age) indicate apparent

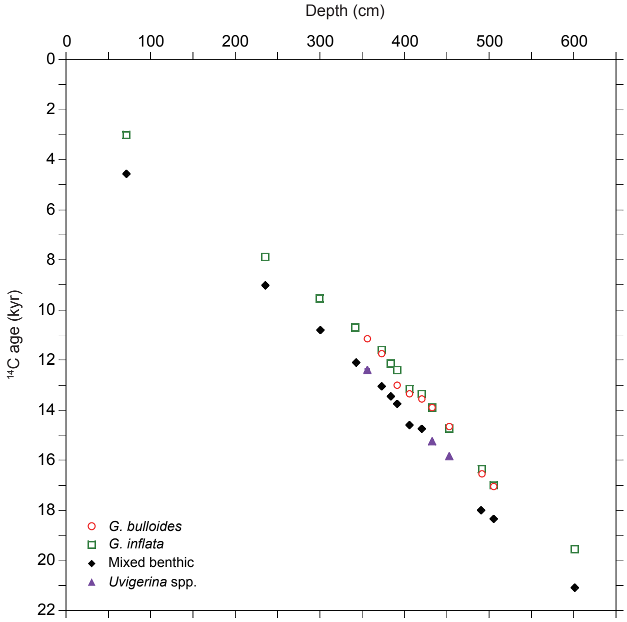

Fig. 2. Age-depth plot for core MD01-2420 showing radiocarbon ages from planktic foraminiferal species *Globigerina bulloides* and *Globorotalia inflata* and benthic foraminiferal *Uvigerina* spp. and mixed benthic foraminiferal species.

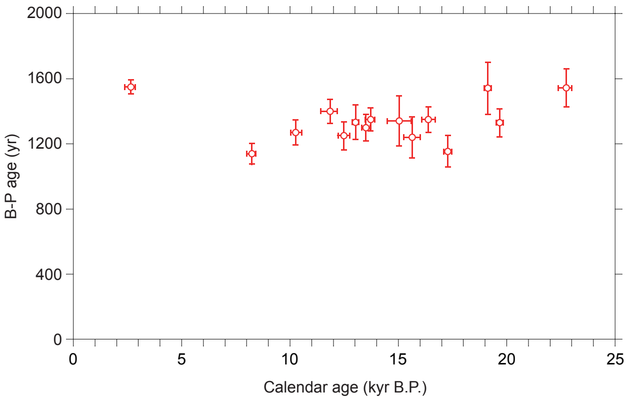

Fig. 3. Changes in ^{14}C age offset between coexisting planktic and benthic foraminiferal shells (B-P age) in core MD01-2420 during the last 25 kyr. Errors are $\pm 1\sigma$.

ventilation ages in the past. B-P ages in core MD01-2420 ranged from 1150 to 1550 yr during the last 25 kyr (Fig. 3). Because the weighted average variance was 1360 ± 140 yr, the apparent ventilation ages in core MD01-2420 showed no significant changes within the measurement uncertainties. Thus, there is no sign of intrusions of anomalously old water masses at the MD01-2420 site throughout the last 25 kyr, which is consistent with previous studies (Broecker et al., 2004b, 2008).

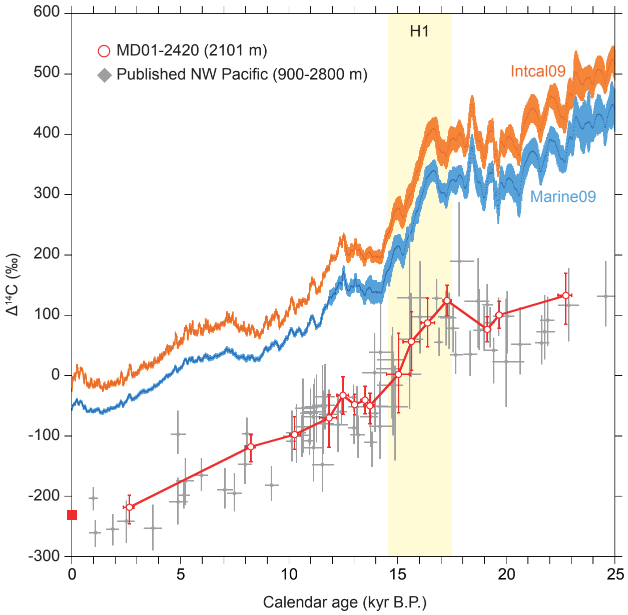

Fig. 4. Δ^{14}C change during the last 25 kyr in core MD01-2420 (red symbols) and in the western North Pacific between 900 and 2800 m water depths (grey symbols; Duplessy et al., 1989; Murayama et al., 1992; Ahagon et al., 2003; Broecker et al., 2004b; Minoshima et al., 2007; Broecker et al., 2008; Sagawa and Ikehara, 2008). Orange and blue curves are atmospheric (Intcal09) and surface ocean (Marine09) Δ^{14}C records (Reimer et al., 2009), respectively. Red square is present Δ^{14}C value at MD01-2420 site (Key et al., 2004). Yellow band represents the Heinrich Event 1 between 14.6 and 17.5 kyr BP.

Because we had to take into account large atmospheric Δ^{14}C changes, including a 190 ‰ drop between 14.5 and 17.5 kyr BP (Broecker and Barker, 2007), we calculated Δ^{14}C of benthic foraminiferal shells in core MD01-2420 using Eq. (1) (Table 4; Fig. 4). Our Δ^{14}C record changed in concert with previously published atmospheric (Intcal09) and tropical surface ocean (Marine09) curves (Reimer et al., 2009) throughout the last 25 kyr. We compiled western North Pacific Δ^{14}C records calculated by using published radiocarbon ages from eight cores ranging in water depth from 900 to 2800 m (Table 1; Fig. 1; Duplessy et al., 1989; Murayama et al., 1992; Ahagon et al., 2003; Broecker et al., 2004b, 2008; Minoshima et al., 2007; Sagawa and Ikehara, 2008). These records were consistent with the Δ^{14}C record in MD01-2420 (Fig. 4). The western North Pacific Δ^{14}C records co-varied with atmospheric Δ^{14}C changes during the last glacial to deglacial periods, which is in clear contrast with data from the eastern Pacific showing that very old intermediate water masses observed at two sites off Baja California (Marchitto et al., 2007) and near the Galapagos Islands (Stott et al., 2009) during the last deglacial period.

Table 3. Radiocarbon ages of planktic foraminiferal species *Globigerina bulloides* and *Globorotalia inflata* in core MD01-2420.

Depth top (cm)	Depth bottom (cm)	*G. bulloides* (^{14}C yr BP)	Error (yr)	*G. inflata* (^{14}C yr BP)	Error (yr)	Δinfla-bull age (yr)	Error (yr)	Planktic age* (^{14}C yr BP)	Error** (yr)
70.1	72.5			3010	25			3010	25
233.4	238.2			7880	40			7880	40
298.8	300.2			9530	40			9530	40
339.2	344.1			10 700	55			10 700	55
353.8	358.6	11 150	55					11 150	55
370.7	375.6	11 750	45	11 600	85	−150	96	11 717	88
382.9	385.3			12 150	50			12 150	50
390.1	392.6	13 000	55	12 400	45	−600	71	12 400	45
404.7	407.1	13 350	60	13 150	65	−200	88	13 258	141
419.2	421.6	13 550	50	13 350	100	−200	112	13 510	113
431.3	433.7	13 900	80	13 900	65	0	103	13 900	50
451.6	454.1	14 650	55	14 750	60	100	81	14 696	70
489.2	494.2	16 550	65	16 350	70	−200	96	16 457	141
504.1	506.6	17 050	80	17 000	65	−50	103	17 020	50
600.2	602.1			19 555	60			19 555	60

* Planktic ages are weighted mean of radiocarbon ages of two planktic foraminiferal species. Planktic age for sample of 390.1-392.6 cm is from *G. inflata* only (see text).
**Error in planktic age was estimated by weighed average variance (Bevington and Robinson, 2003).

Table 4. Radiocarbon measurements on paired planktic and benthic foraminifera, reconstructed ventilation ages and bottom-water Δ^{14}C values in core MD01-2420. Errors are $\pm 1\sigma$.

Depth top (cm)	Depth bottom (cm)	Planktic age (^{14}C yr BP)	Error (yr)	Benthic age (^{14}C yr BP)	Error (yr)	Calendar age (yr BP)	Lower limit (yr BP, -1σ)	Upper limit (yr BP, $+1\sigma$)	B-P offset (yr)	Error (yr)	Δ^{14}C (‰)	Lower limit (‰, -1σ)	Upper limit (‰, $+1\sigma$)
70.1	72.5	3010	25	4560	35	2656	2366	2870	1550	43	−218	−245	−198
233.4	238.2	7880	40	9020	50	8246	8008	8430	1140	64	−118	−143	−98
298.8	302.6	9530	40	10 800	65	10 262	10 035	10 535	1270	76	−98	−122	−68
339.2	344.1	10 700	55	12 100	50	11 852	11 406	12 186	1400	74	−70	−119	−32
353.8	358.6	11 150	55	12 400	65	12 484	12 215	12 741	1250	85	−33	−64	−2
370.7	375.6	11717	88	13 050	60	13 023	12 877	13 169	1333	106	−48	−65	−31
382.9	385.3	12 150	50	13 450	65	13 497	13 302	13 694	1300	82	−41	−63	−18
390.1	392.6	12 400	45	13 750	55	13 725	13 461	13 909	1350	71	−50	−80	−29
404.7	407.1	13 258	141	14 600	60	15 040	14 497	15 583	1342	153	2	−62	70
419.2	421.6	13 510	113	14 750	55	15 632	15 251	16 013	1240	126	57	9	106
431.3	433.7	13 900	50	15 250	60	16 386	16 079	16 693	1350	78	88	48	129
451.6	454.1	14 696	70	15 850	65	17 281	17 096	17 466	1154	96	125	100	150
489.2	494.2	16 457	141	18 000	75	19 132	18 973	19 290	1543	160	77	56	97
504.1	506.6	17 020	50	18 350	70	19 675	19 507	19 843	1330	86	101	78	123
600.2	602.1	19 555	60	21 100	100	22 745	22 389	23 009	1545	117	133	85	170

3.3 Ventilation history and water mass structure change in the North Pacific

Figure 5 shows a comparison of glacial-deglacial changes in Δ^{14}C records at 2101 m at core MD01-2420, at 3647 m water depth in the Gulf of Alaska at ODP Site 887 (Galbraith et al., 2007), and at 2710 m water depth in the eastern North Pacific off the Oregon coast at W8709A-13PC (Mix et al., 1999; Lund et al., 2011). During the last glacial maximum between 18 and 21 kyr BP, the difference in Δ^{14}C between MD01-2420 and ODP 887 was 76 ± 34 ‰ (weighed average). During early H1 between 17 and 17.5 kyr BP, the difference increased to 142 ± 47 ‰. Note, however, that the comparison is based on a single data point in core ODP 887. After the Bølling interstadial (∼14.5 kyr BP), there was no significant Δ^{14}C difference between ODP 887 and MD01-2420, which was comparable to the present Δ^{14}C distribution in the North Pacific (Key et al., 2004). Δ^{14}C in core W8709A-13PC were lower than that in core MD01-2420 throughout the glacial-deglacial period (Fig. 5). This feature is consistent with the present Δ^{14}C distribution in the North Pacific (Key et al., 2004). During the glacial to early H1 interval, the Δ^{14}C in core W8709A-13PC changed consistently with that in core ODP 887. On the other hand, Δ^{14}C in core W8709A-13PC appears to be lower than that of core ODP 887 during the Bølling-Allerød (∼13.0–14.5 kyr BP). These Δ^{14}C

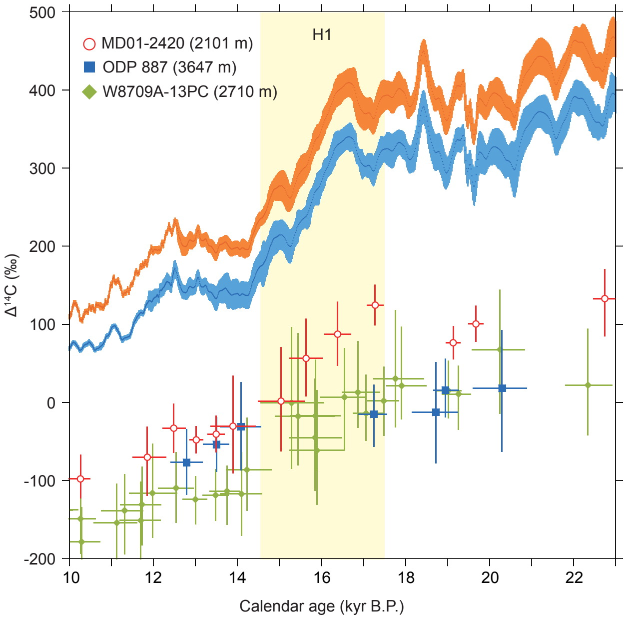

Fig. 5. Δ^{14}C change in core MD01-2420 (this study), core ODP 887 in the Gulf of Alaska (3647 m, Galbraith et al., 2007) and core W8709A-13PC in the eastern North Pacific (2710 m, Mix et al., 1999; Lund et al., 2011) between 10 and 23 kyr BP along with Intcal09 and Marine09 curves (Reimer et al., 2009).

variations suggest a reorganization of water-mass structure in the North Pacific during the deglacial period from a stratified glacial mode to an upwelling interglacial mode. The glacial Pacific Ocean had two water masses: well-ventilated and nutrient-depleted glacial North Pacific Intermediate Water (GNPIW) above ∼2000 m and less-ventilated and nutrient-enriched deep water below ∼2000 m (Keigwin, 1998; Matsumoto et al., 2002). GNPIW is a thicker and more deeply penetrating water mass than today's North Pacific Intermediate Water (NPIW). Although a water mass extending to 2000 m should not be called an intermediate-water in the sense of physical oceanography (Matsumoto et al., 2002), we use the term "GNPIW" to refer to the well-ventilated water mass following Matsumoto et al. (2002). The source of GNPIW was possibly in the Bering Sea, given microfossil (Ohkushi et al., 2003) and neodymium isotope evidence (Horikawa et al., 2010). During H1 in the early deglacial period, deep water extending to a depth of ∼2500 m formed in the North Pacific, regarded as an intensified NPIW (Ohkouchi et al., 1994; Okazaki et al., 2010). This deep water may have yielded the large Δ^{14}C differences during H1 between MD01-2420 (2101 m) and ODP 887 (3647 m) by enhancing ventilation in the intensified GNPIW during the early H1 between 17 and 17.5 kyr BP (Fig. 5). Since the Bølling-Allerød period, ocean circulation in the North Pacific has been in an interglacial mode, essentially the same as the present one. The present abyssal circulation from the south flows into the North Pacific, and upwells to mid-depth and returns south as the Pacific Deep Water (PDW) (Schmitz, 1996). Above the PDW, the NPIW with a salinity minimum lies at depths of 300 to 800 m (Talley, 1993). The main pathway of deep-water is along the western margin of the ocean basins, as a deep western boundary current. In the North Pacific, the western boundary flow is a principal factor in establishing the east-west gradient of deep-Pacific ventilation, which is found in sedimentary Δ^{14}C records in cores MD01-2420 and W8709A-13PC. However, this gradient is still too weak to explain the very old intermediate water in the eastern Pacific during the last deglacial period (Marchitto et al., 2007; Stott et al., 2009). Obviously, more sedimentary ventilation records are required to reconstruct the spatial and temporal ventilation change in the North Pacific. In particular, the following three regions are potential candidates to be tackled: (1) the Bering Sea, as a possible ventilation source during glacial-deglacial periods; (2) the western subarctic Pacific off the Kamchatka Peninsula, principal pathway of deep water flow; and (3) mid-depth of the eastern North Pacific to fill the gap between 1000 and 2700 m water depths.

3.4 Implications for the release of old carbon from the deep sea during the last glacial termination

During the H1 period, old carbon must have been released from the abyssal reservoir (Broecker and Barker, 2007), probably from the Southern Ocean (Skinner et al., 2010). At the same time, very old intermediate water masses existed in the eastern Pacific (Marchitto et al., 2007; Stott et al., 2009). However, there is no sign of an old carbon release in the Antarctic Intermediate Water pathway (De Pol-Holz et al., 2010; Rose et al., 2010). Recently, Hain et al. (2011) pointed out that the Δ^{14}C anomalies in the intermediate water are not basin-scale but local phenomena. In the western North Pacific, there is no Δ^{14}C anomaly between 900 and 2800 m relative to the atmospheric Δ^{14}C change. During the early H1, Okazaki et al. (2010) suggested that well ventilated deepwater extending to ∼2500 m, originated from the North Pacific, flowed southward along the western margin of the North Pacific. We suggest that the deepwater from the North Pacific may have helped produce the local mid-depth Δ^{14}C anomalies in the eastern equatorial Pacific by flushing a part of old deep Pacific water. From the abyssal North Pacific, old carbon release was suggested at the beginning of the Bølling-Allerød (Galbraith et al., 2007). Relatively low Δ^{14}C at core W8709A-13PC during the Bølling-Allerød might be caused by an influence of the aged abyssal water.

Major reorganization of ocean circulation in the North Pacific during the glacial-deglacial period affected productivity through upwelling. During the last glacial maximum, primary productivity in the subarctic Pacific was low because of stratification (Narita et al., 2002; Jaccard et al., 2005; 2009; Galbraith et al., 2007; Brunelle et al., 2010). Thick GNPIW with low nutrient concentrations down to ∼2000 m suppressed biological productivity in the euphotic layer. This stratification temporarily intensified during H1 because of the expansion of the nutrient-depleted water mass down to ∼2500 m in the North Pacific (Okazaki et al., 2010). At the beginning of the Bølling, productivity in the subarctic Pacific rose rapidly (Crusius et al., 2004; Galbraith et al., 2007; Jaccard et al., 2009; Brunelle et al., 2010; Davies et al., 2011) in association with enhanced upwelling by breakdown of the glacial stratification.

4 Conclusions

We measured radiocarbon ages of multiple planktic and benthic foraminiferal species in sediment core MD01-2420 obtained at 2100 m from an area with a high sedimentation rate in the western North Pacific. The reconstructed ventilation history of the western North Pacific demonstrates changes consistent with the radiocarbon activity of the atmosphere, suggesting no sign of massive mixing of old carbon from the abyssal reservoir throughout the glacial to deglacial period. Comparison of Δ^{14}C records between cores MD01-2420, ODP 887 (Gulf of Alaska, 3647 m, Galbraith et al., 2007) and W8709A-13PC (eastern North Pacific, 2710 m, Mix et al., 1999; Lund et al., 2011) suggests a reorganization of water-mass structure in the North Pacific during the deglacial period from a stratified glacial mode, with two water masses bounded at 2000 m, to an upwelling interglacial mode to an upwelling interglacial mode during the last deglacial period. The western boundary flow appears to be a principal factor for the east-west gradient of the North Pacific ventilation, yielding horizontal Δ^{14}C anomalies during the deglacial reorganization.

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