Clim. Past Discuss., 7, 2719–2739, 2011
www.clim-past-discuss.net/7/2719/2011/
doi:10.5194/cpd-7-2719-2011

Climate of the Past Discussions

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

Y. Okazaki[1], T. Sagawa[2], H. Asahi[3], K. Horikawa[4], and J. Onodera[1]

[1]Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokosuka, Japan
[2]Senior Research Fellow Center, Ehime University, Matsuyama, Japan
[3]Atmosphere and Ocean Research Institute, University of Tokyo, Kashiwa, Japan
[4]Graduate School of Science and Engineering, University of Toyama, Toyama, Japan

Received: 5 August 2011 – Accepted: 16 August 2011 – Published: 18 August 2011

Correspondence to: Y. Okazaki (okazakiy@jamstec.go.jp)

Published by Copernicus Publications on behalf of the European Geosciences Union.

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 shutdown 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

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

CPD

7, 2719–2739, 2011

Ventilation changes in the western North Pacific

Y. Okazaki et al.

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 $\delta^{18}O$ 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).

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

CPD
7, 2719–2739, 2011

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

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

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

CPD
7, 2719–2739, 2011

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). 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 ventilation ages in the past. B-P ages in core MD01-2420 ranged from 1150 to 1550 yr during the last 25 kyr. 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).

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 $\Delta^{14}C$ 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 $\Delta^{14}C$ record in MD01-2420 (Fig. 4). The western North Pacific $\Delta^{14}C$ records co-varied with atmospheric $\Delta^{14}C$ changes during the last glacial to deglacial periods which is in clear contrast with data from the eastern Pacific showing that very old water masses seeped into intermediate layers during the last deglacial period (Marchitto et al., 2007; Stott et al., 2009).

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

Figure 5 shows a comparison of our MD01-2420 $\Delta^{14}C$ data and glacial-deglacial changes in deep $\Delta^{14}C$ at 3647 m water depth in the Gulf of Alaska calculated using radiocarbon ages at ODP Site 887 (Galbraith et al., 2007). During the last glacial maximum between 18 and 21 kyr BP, the difference in $\Delta^{14}C$ between MD01-2420 and ODP 887 was 76 ± 34 ‰ (weighed average). During H1, in the early deglacial period between 17 and 17.5 kyr BP, the difference increased to 142 ± 47 ‰ because of a rise in $\Delta^{14}C$ at the site of MD01-2420. After the Bølling interstadial (~14.5 kyr BP), there was no significant $\Delta^{14}C$ difference between ODP 887 and MD01-2420, which was comparable to the present $\Delta^{14}C$ distribution in the North Pacific (Key et al., 2004).

These $\Delta^{14}C$ 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). The source of GNPIW was likely 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 to 3000 m formed in the North Pacific and flowed southward along the western margin of the North Pacific (Ohkouchi et al., 1994; Okazaki et al., 2010). This deep water yielded the large $\Delta^{14}C$ differences during H1 between MD01-2420 (2101 m) and ODP 887 (3647 m) by enhancing ventilation in the watermass above ~2500 to 3000 m (Fig. 5). Since the Bølling-Allerød period, ocean circulation in the North Pacific has been in an interglacial mode. The present abyssal circulation from the south flows into the North Pacific, 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).

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 mid-depth $\Delta^{14}C$ anomalies are not basin-scale but local phenomena. In the western North Pacific, there is no $\Delta^{14}C$ anomaly between 900 and 2800 m in harmony with atmospheric $\Delta^{14}C$ change because water mass above ~2500 m was well ventilated associated with a southward deepwater flow along the western margin of the North Pacific (Okazaki et al., 2010). We suggest that the deepwater from the North Pacific may have helped produce the local mid-depth $\Delta^{14}C$ anomalies in the eastern equatorial Pacific by flushing a part of old deep Pacific water. From the abyssal North Pacific, old carbon was released at the beginning of the Bølling Interstadial (Galbraith et al., 2007).

Major reorganization of ocean circulation in the North Pacific during the glacial-deglacial period affected productivity through upwelling. During the last glacial

CPD
7, 2719–2739, 2011
Ventilation changes in the western North Pacific
Y. Okazaki et al.

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). This stratification intensified during H1 because of 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 of nutrient-rich deepwater.

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 $\Delta^{14}C$ records between MD01-2420 and ODP 887 (Gulf of Alaska, 3647 m, Galbraith et al., 2007) suggests a major change of water mass structure in the North Pacific from a stratified glacial mode, with two water masses separated at ~2000 m, to an upwelling interglacial mode via temporal expansion of the well-ventilated upper water mass during H1.

Acknowledgements. We thank the captain, crew, and scientists of the IMAGES WEPAMA 2001 Cruise of the R/V Marion Defresne. We also thank Prof. Hodaka Kawahata for his management and financial support of the cruise. We are grateful to Professor Emeritus Tadamichi Oba for his leadership of the on-board work to collect the sediment cores. Ms. Asako Ino helped in the picking of foraminiferal shells. Radiocarbon measurements were performed at the NOSAMS, Woods Hole Oceanographic Institution. This work was partially funded by the MEXT (Ministry of Education, Culture, Sports, Science and Technology in Japan) Grants-in-Aid-for Scientific Research C Project No. 21510026.

CPD
7, 2719–2739, 2011

References

Adkins, J. F. and Boyle, E.A.: Changing atmospheric $\Delta^{14}C$ and the record of deep water paleoventilation ages, Paleoceanography, 12, 337–344, 1997.

Ahagon, N., Ohkushi, K., Uchida, M. and Mishima, T.: Mid-depth circulation in the northwest Pacific during the last deglaciation: Evidence from foraminiferal radiocarbon ages, Geophys. Res. Lett., 30, 2097, doi:10.1029/2003GL018287, 2003.

Bevington, P. R. and Robinson, K. D.: Data reduction and error analysis for the physical sciences, third edition, McGraw-Hill, New York, 2003.

Broecker, W. and Barker, S.: A 190 ‰ drop in atmosphere's $\Delta^{14}C$ during the "Mystery Interval" (17.5 to 14.5 kyr), Earth Planet. Sci. Lett., 256, 90–99, 2007.

Broecker, W., Mix, A., Andree, M., and Oeschger, H.: Radiocarbon measurements on coexisting benthic and planktic foraminifera shells: potential for reconstructing ocean ventilation times over the past 20000 years, Nucl. Instr. and Meth., B, 5, 331–339, 1984.

Broecker, W. S., Clark, E., Hajdas, I., and Bonani, G.: Glacial ventilation rates for the deep Pacific Ocean, Paleoceanography, 19, PA2002, doi:10.1029/2003PA000974, 2004a.

Broecker, W, Barker, S., Clark, E., Hajdas, I., Bonani, G., and Stott, L.: Ventilation of the glacial deep Pacific Ocean, Science, 306, 1169–1172, 2004b.

Broecker, W., Barker, S., Clark, E., Hajdas, I., and Bonani, G.: Anomalous radiocarbon ages for foraminifera shells, Paleoceanography, 21, PA2008, doi:10.1029/2005PA001212, 2006.

Broecker, W., Clark, E., and Barker, S.: Near constancy of the Pacific Ocean surface to mid-depth radiocarbon-age difference over the last 20 kyr, Earth Planet. Sci. Lett., 274, 322–326, 2008.

Brunelle, B. G., Sigman, D. M., Jaccard, S. L., Keigwin, L.D., Plessen, B., Schettler, G., Cook, M. S., and Haug, G. H.: Glacial/interglacial changes in nutrient supply and stratification in the western subarctic North Pacific since the penultimate glacial maximum, Quat. Sci. Rev., 29, 2579–2590, 2010.

Crusius, J., Pedersen, T. F., Keigwin, L., and Labeyrie, L.: Influence of northwest Pacific productivity on North Pacific Intermediate Water oxygen concentrations during the Bølling-Ållerød interval (14.7–12.9 ka), Geology, 32, 633–636, 2004.

Davies, M. H., Mix, A. C., Stoner, J. S., Addison, J. A., Jaeger, J., Finney, B., and Wiest, J.: The deglacial transition on the southeastern Alaska Margin: Meltwater input, sea level rise, marine productivity, and sedimentary anoxia, Paleoceanography, 26, PA2223,

doi:10.1029/2010PA002051, 2011.
Denton, G. H., Broecker, W. S., and Alley, R. B.: The mystery interval 17.5 to 14.5 kyrs ago, PAGES News, 14, 14–16, 2006.
De Pol-Holz, R., Keigwin, L., Southon, J., Hebbeln, D., and Mohtadi, M.: No signature of abyssal carbon in intermediate waters off Chile during deglaciation, Nat. Geosci., 3, 192–195, 2010.
Duplessy, J.-C., Arnold, M., Bard, E., Juillet-Leclerc, A., Kallel, N., and Labeyrie, L.: AMS ^{14}C study of transient events and of the ventilation rate of the Pacific intermediate water during the last deglaciation, Radiocarbon, 31, 493–502, 1989.
Galbraith, E. D., Jaccard, S. L., Pedersen, T. F., Sigman, D. M., Haug, G. H., Cook, M., Southon, J. R., and Francois, R.: Carbon dioxide release from the North Pacific abyss during the last deglaciation, Nature, 449, 890–894, 2007.
Hain, M. P., Sigman, D. M., and Haug, G. H.: Shortcomings of the isolated abyssal reservoir model for deglacial radiocarbon changes in the mid-depth Indo-Pacific Ocean, Geophys. Res. Lett., 38, L04604, doi:10.1029/2010GL046158, 2011.
Horikawa, K., Asahara, Y., Yamamoto, K., and Okazaki, Y.: Intermediate water formation in the Bering Sea during glacial periods: Evidence from neodymium isotope ratios, Geology, 38, 435–438, 2010.
Jaccard, S. L., Haug, G. H., Sigman, D. M., Pedersen, T. F., Thierstein, H. R. and Röhl, U.: Glacial/Interglacial changes in subarctic North Pacific stratification, Science, 308, 1003–1008, 2005.
Jaccard, S. L., Galbraith, E. D., Sigman, D. M., Haug, G. H., Francois, R., Pedersen, T. F., Dulski, P., and Thierstein, H. R.: Subarctic Pacific evidence for a glacial deepening of the oceanic respired carbon pool, Earth Planet. Sci. Lett., 277, 156–165, 2009.
Keigwin, L. D.: Glacial-age hydrography of the far northwest Pacific, Paleoceanography, 13, 323–339, 1998.
Key, R. M., Kozyr, A., Sabine, C. L., Lee, K., Wanninkhof, R., Bullister, J. L., Feely, R. A., Millero, F. J., Mordy, C., and Peng, T.-H.: A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP), Global Biogeochem. Cycles., 18, GB4031, doi:10.1029/2004GB002247, 2004.
Marchitto, T. M., Lehman, S. J., Ortiz, J. D., Flückiger, J., and van Geen, A.: Marine radiocarbon evidence for the mechanism of deglacial atmospheric CO_2 rise, Science, 316, 1456–1459, 2007.
Matsumoto, K., Oba, T., Lynch-Stieglitz, J., and Yamamoto, H.: Interior hydrography and circu-

lation of the glacial Pacific Ocean, Quat. Sci. Rev., 21, 1693–1704, 2002.
McManus, J. F., Francois, R., Gherardi, J.-M., Keigwin, L. D., and Brown-Leger, S.: Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes, Nature, 428, 834–837, 2004.
Minoshima, K., Kawahata, H., Irino, T., Ikehara, K., Aoki, K., Uchida, M., Yoneda, M., and Shibata, Y.: Deep water ventilation in the northwestern North Pacific during the last deglaciation and the early Holocene (15–5 cal. kyr BP) based on AMS ^{14}C dating, Nucl. Instr. and Meth., B, 259, 448–452, 2007.
Monnin, E., Indermühle, A., Dällenbach, A., Flückiger, J. Stauffer, B., Stocker, T. F., Raynaud, D., and Barnola, J.-M.: Atmospheric CO_2 concentrations over the last glacial termination, Science, 291, 112–114, 2001.
Murayama, M., Taira, A., Iwakura, H., Matsumoto, E., and Nakamura, T.: Northwest Pacific deep water ventilation rate during the past 35,000 years with the AMS ^{14}C foraminifera ages, Summaries of Researches Using AMS at Nagoya University (Nagoya University Center for Chronological Research, Nagoya, Japan), 3, 114–121, 1992 (In Japanese with English abstract).
Narita, H., Sato, M., Tsunogai, S., Murayama, M., Ikehara, M., Nakatsuka, T., Wakatsuchi, M., Harada, N., and Ujiie, Y.: Biogenic opal indicating less productive northwestern North Pacific during the glacial ages, Geophys. Res. Lett., 29, 1732, doi:10.1029/2001GL014320, 2002.
Oba, T. and Murayama, M.: Sea-surface temperature and salinity changes in the northwest Pacific since the Last Glacial Maximum, J. Quat. Sci., 19, 335–346, 2004.
Oba T., Irino, T., Yamamoto, M., Murayama, M., Takamura, A., and Aoki, K.: Paleoceanographic change off central Japan since the last 144,000 years based on high-resolution oxygen and carbon isotope records, Global Planet. Change, 53, 5–20, 2006.
Ohkouchi, N., Kawahata, H., Murayama, M., Okada, M., Nakamura, T., and Taira, A.: Was deep water formed in the North Pacific during the Late Quaternary? Cadmium evidence from the northwest Pacific, Earth Planet. Sci. Lett., 124, 185–194, 1994.
Ohkushi, K., Itaki, T., and Nemoto, N.: Last Glacial–Holocene change in intermediate-water ventilation in the Northwestern Pacific, Quat. Sci. Rev., 22, 1477–1484, 2003.
Okazaki, Y., Timmermann, A., Menviel, L., Harada, N., Abe-Ouchi, A., Chikamoto, M. O., Mouchet, A., and Asahi, H.: Deepwater formation in the North Pacific during the last glacial termination, Science, 329, 200–204, 2010.
Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey,

C., Buck, C. E., Burr, G. S., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Hajdas, I., Heaton, T. J., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., McCormac, F. G., Manning, S. W., Reimer, R. W., Richards, D. A., Southon, J. R., Talamo, S., Turney, C. S. M., van der Plicht, J., and Weyhenmeyer, C. E.: INTCAL09 and MARINE09 radiocarbon age calibration curves, 0-50,000 years cal BP, Radiocarbon, 51, 1111–1150, 2009.

Rose, K. A., Sikes, E. L., Guilderson, T. P., Shane, P., Hill, T. M., Zahn, R., and Spero, H. J.: Upper-ocean-to-atmosphere radiocarbon offsets imply fast deglacial carbon dioxide release, Nature, 466, 1093–1097, 2010.

Sagawa, T. and Ikehara, K.: Intermediate water ventilation change in the subarctic northwest Pacific during the last deglaciation, Geophys. Res. Lett., 35, L24702, doi:10.1029/2008GL035133, 2008.

Sagawa, T., Toyoda, K., and Oba, T.: Sea surface temperature record off central Japan since the Last Glacial Maximum using planktonic foraminiferal Mg/Ca thermometry, J. Quat. Sci., 21, 63–73, 2006.

Schmitz, W. J.: On the World Ocean Circulation: Volume II: The Pacific and Indian Oceans/A Global Update, Woods Hole Oceanographic Institution Technical Report, WHOI-96-0B, 237 pp., 1996.

Shishikura, M., Echigo, T., and Kaneda, H.: Marine reservoir correction for the Pacific coast of central Japan using ^{14}C ages of marine mollusks uplifted during historical earthquakes, Quat. Res., 67, 286–291, 2007.

Skinner, L. C., Fallon, S., Waelbroeck, C., Michel, E., and Barker, S.: Ventilation of the deep Southern Ocean and deglacial CO_2 rise, Science, 328, 1147–1151, 2010.

Stott, L., Southon, J., Timmermann, A., and Koutavas, A.: Radiocarbon age anomaly at intermediate water depth in the Pacific Ocean during the last deglaciation, Paleoceanography, 24, PA2223, doi:10.1029/2008PA001690, 2009.

Talley, L. D.: Distribution and Formation of North Pacific Intermediate Water, J. Phys. Oceanogr., 23, 517–537, 1993.

Yoneda, M., Uno, H., Shibata, Y., Suzuki, R., Kumamoto, Y., Yoshida, K., Sasaki, T., Suzuki, A., and Kawahata, H.: Radiocarbon marine reservoir ages in the western Pacific estimated by pre-bomb molluscan shells, Nucl. Instr. and Meth., B, 259, 432–437, 2007.

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

Core ID	Latitude	Longitude	Water depth (m)	ΔR (yr)	Error (±1σ)	Reference
MD01-2420	36.07° N	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° N	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)

CPD
7, 2719–2739, 2011

Table 2. Radiocarbon ages of planktic and benthic foraminifera in core MD01-2420. Errors are ±1σ.

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*	10700	55	OS-78785
353.8	358.6	*G. bulloides*	11150	55	OS-85356
370.7	375.6	*G. bulloides*	11750	45	OS-85348
370.7	375.6	*G. inflata*	11600	85	OS-85355
382.9	385.3	*G. inflata*	12150	50	OS-78787
390.1	392.6	*G. bulloides*	13000	55	OS-78802
390.1	392.6	*G. inflata*	12400	45	OS-78803
404.7	407.1	*G. bulloides*	13350	60	OS-85351
404.7	407.1	*G. inflata*	13150	65	OS-78805
419.2	421.6	*G. bulloides*	13550	50	OS-78807
419.2	421.6	*G. inflata*	13350	100	OS-78822
431.3	433.7	*G. bulloides*	13900	80	OS-85388
431.3	433.7	*G. inflata*	13900	65	OS-85386
451.6	454.1	*G. bulloides*	14650	55	OS-85384
451.6	454.1	*G. inflata*	14750	60	OS-85353
489.2	494.2	*G. bulloides*	16550	65	OS-85349
489.2	494.2	*G. inflata*	16350	70	OS-85324
504.1	506.6	*G. bulloides*	17050	80	OS-78827
504.1	506.6	*G. inflata*	17000	65	OS-78809
600.2	602.1	*G. inflata*	19555	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	10800	65	OS-78828
341.6	344.1	Mixed benthic	12100	50	OS-78786
353.8	358.6	*Uvigerina* spp.	12400	65	OS-85343
370.7	375.6	Mixed benthic	13050	60	OS-85340
382.9	385.3	Mixed benthic	13450	65	OS-78788
390.1	392.6	Mixed benthic	13750	55	OS-78804
404.7	407.1	Mixed benthic	14600	60	OS-78806
419.2	421.6	Mixed benthic	14750	55	OS-78808
431.3	433.7	*Uvigerina* spp.	15250	60	OS-85339
451.6	454.1	*Uvigerina* spp.	15850	65	OS-85323
489.2	491.7	Mixed benthic	18000	75	OS-85325
504.1	506.6	Mixed benthic	18350	70	OS-78810
600.2	602.1	Mixed benthic	21100	100	OS-78811

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

CPD
7, 2719–2739, 2011

CPD
7, 2719–2739, 2011

Ventilation changes in the western North Pacific

Y. Okazaki et al.

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			10700	55			10700	55
353.8	358.6	11150	55					11150	55
370.7	375.6	11750	45	11600	85	−150	96	11717	88
382.9	385.3			12150	50			12150	50
390.1	392.6	13000	55	12400	45	−600	71	12400	45
404.7	407.1	13350	60	13150	65	−200	88	13258	141
419.2	421.6	13550	50	13350	100	−200	112	13510	113
431.3	433.7	13900	80	13900	65	0	103	13900	50
451.6	454.1	14650	55	14750	60	100	81	14696	70
489.2	494.2	16550	65	16350	70	−200	96	16457	141
504.1	506.6	17050	80	17000	65	−50	103	17020	50
600.2	602.1			19555	60			19555	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).

CPD

7, 2719–2739, 2011

Ventilation changes in the western North Pacific

Y. Okazaki et al.

Table 4. Radiocarbon measurements on paired planktic and benthic foraminifera, reconstructed ventilation ages and bottom-water $\Delta^{14}C$ 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	10800	65	10262	10035	10535	1270	76	−98	−122	−68
339.2	344.1	10700	55	12100	50	11852	11406	12186	1400	74	−70	−119	−32
353.8	358.6	11150	55	12400	65	12484	12215	12741	1250	85	−33	−64	−2
370.7	375.6	11717	88	13050	60	13023	12877	13169	1333	106	−48	−65	−31
382.9	385.3	12150	50	13450	65	13497	13302	13694	1300	82	−41	−63	−18
390.1	392.6	12400	45	13750	55	13725	13461	13909	1350	71	−50	−80	−29
404.7	407.1	13258	141	14600	60	15040	14497	15583	1342	153	2	−62	70
419.2	421.6	13510	113	14750	55	15632	15251	16013	1240	126	57	9	106
431.3	433.7	13900	50	15250	60	16386	16079	16693	1350	78	88	48	129
451.6	454.1	14696	70	15850	65	17281	17096	17466	1154	96	125	100	150
489.2	494.2	16457	141	18000	75	19132	18973	19290	1543	160	77	56	97
504.1	506.6	17020	50	18350	70	19675	19507	19843	1330	86	101	78	123
600.2	602.1	19555	60	21100	100	22745	22389	23009	1545	117	133	85	170

CPD
7, 2719–2739, 2011

Ventilation changes in the western North Pacific

Y. Okazaki et al.

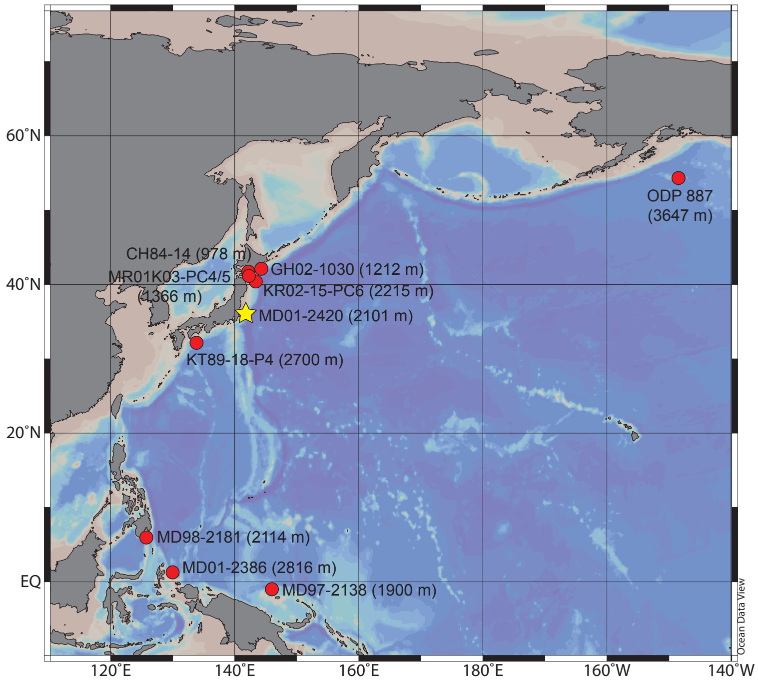

Fig. 1. Map showing the locations of core MD01-2420 (yellow star) and cores used in previous ventilation studies (red circles) in the western North Pacific. The map was drawn using Ocean Data View (http://odv.avi.de/).

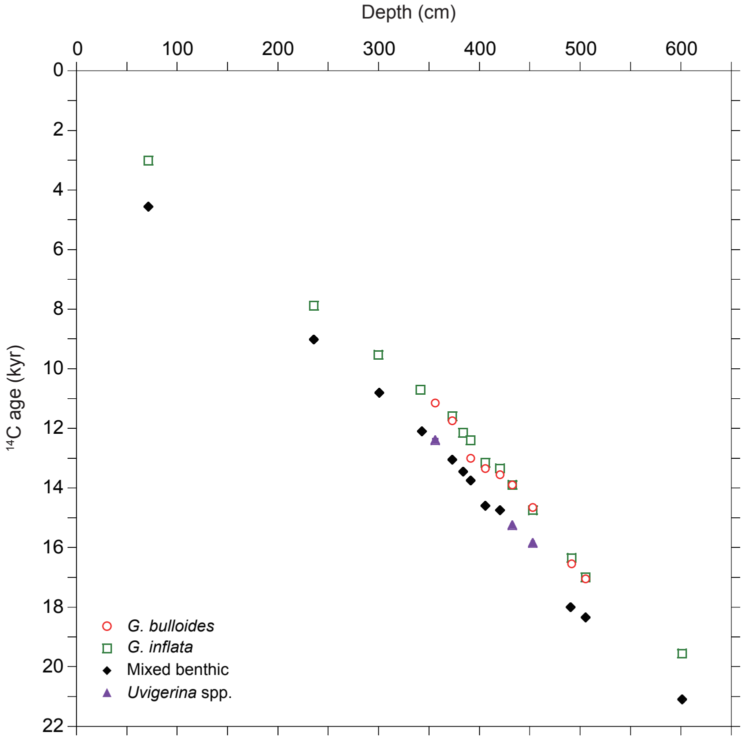

Fig. 2. Age-depth plot for core MD01-2420 showing radiocarbon ages from planktic foraminiferal species *Globigerina bulloides* and *Globorotalia inflata* and benthic foraminiferal *Uvigerina* spp. and mixed benthic foraminiferal species.

CPD
7, 2719–2739, 2011

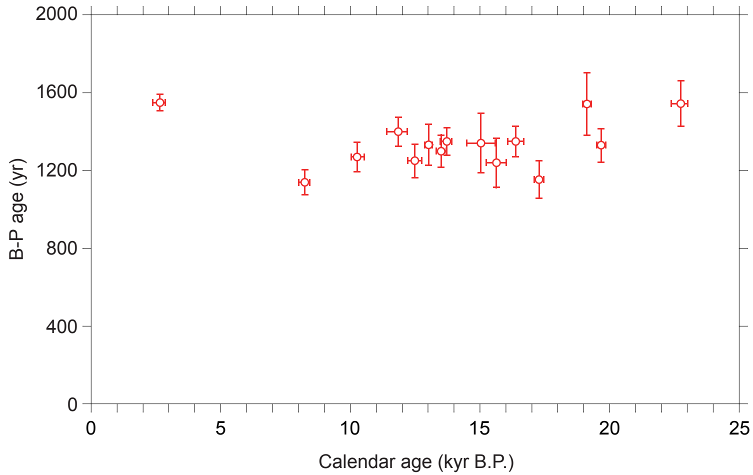

Fig. 3. Changes in ^{14}C age offset between coexisting planktic and benthic foraminiferal shells (B-P age) in core MD01-2420 during the last 25 kyr. Errors are $\pm 1\sigma$.

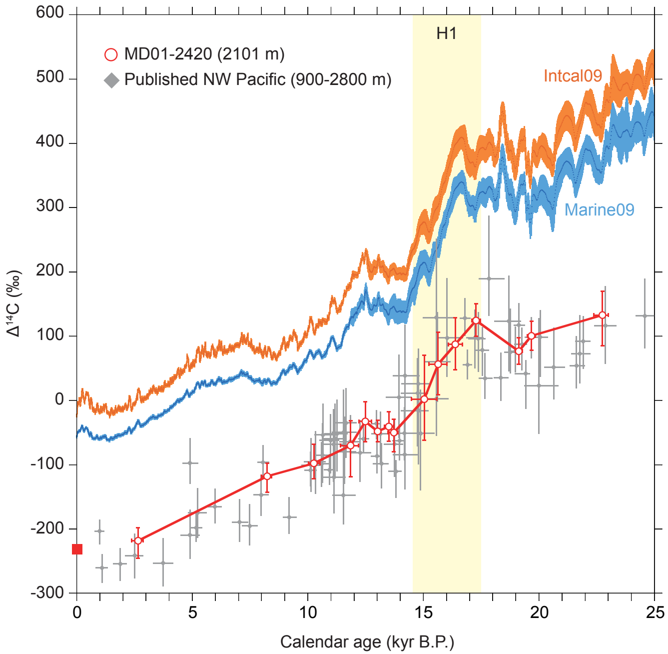

Fig. 4. $\Delta^{14}C$ change during the last 25 kyr in core MD01-2420 (red symbols) and in the western North Pacific between 900 and 2800 m water depths (grey symbols; Duplessy et al., 1989; Murayama et al., 1992; Ahagon et al., 2003; Broecker et al., 2004b; Minoshima et al., 2007; Broecker et al.,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

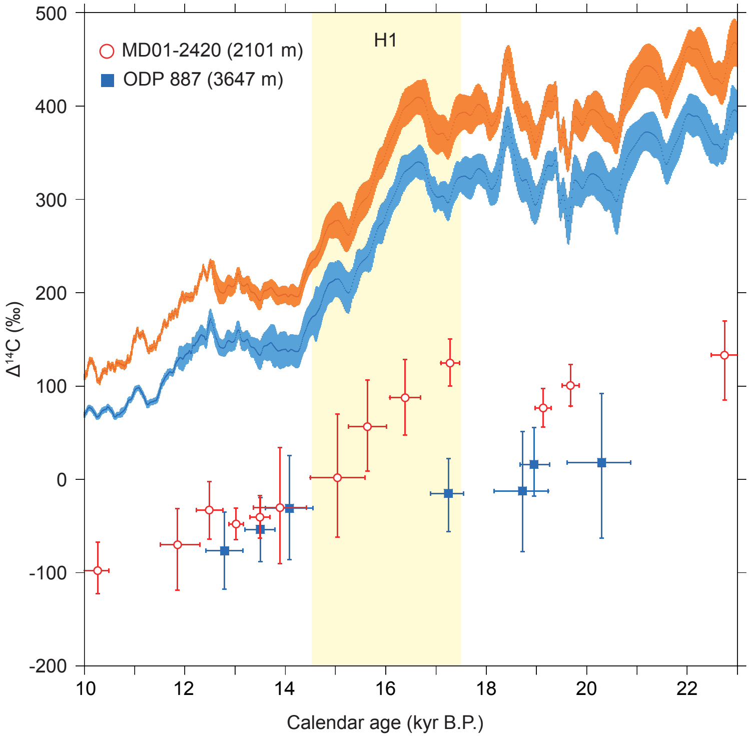

Fig. 5. $\Delta^{14}C$ change in core MD01-2420 (this study) and core ODP 887 in the Gulf of Alaska (3647 m, Galbraith et al., 2007) between 23 and 10 kyr BP along with Intcal09 and Marine09 curves (Reimer et al., 2009).