Late Quaternary changes in intermediate water oxygenation and oxygen minimum zone, northern Japan: A benthic foraminiferal perspective

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[1] A strong oxygen minimum zone (OMZ) currently exists at upper intermediate water depths on the northern Japanese margin, NW Pacific. The OMZ results largely from a combination of high surface water productivity and poor ventilation of upper intermediate waters. We investigated late Quaternary history (last 34 kyr) of ocean floor oxygenation and the OMZ using quantitative changes in benthic foraminiferal assemblages in three sediment cores taken from the continental slope off Shimokita Peninsula and Tokachi, northern Japan, at water depths between 975 and 1363 m. These cores are well located within the present-day OMZ, a region of high surface water productivity, and in close proximity to the source region of North Pacific Intermediate Water. Late Quaternary benthic foraminiferal assemblages experienced major changes in response to changes in dissolved oxygen concentration in ocean floor sediments. Foraminiferal assemblages are interpreted to represent three main groups representing oxic, suboxic, and dysoxic conditions. Assemblage changes in all three cores and hence in bottom water oxygenation coincided with late Quaternary climatic episodes, similar to that known for the southern California margin. These episodes, in turn, are correlated with orbital and millennial climate episodes in the Greenland ice core including the last glacial episode, Bølling-Ållerød (B/A), Younger Dryas, Preboreal (earliest Holocene), early Holocene, and late Holocene. The lowest oxygen conditions, marked by dysoxic taxa and laminated sediments in one core, occurred during the B/A and the Preboreal intervals. Suboxic taxa dominated mainly during the last glacial, the Younger Dryas, and most of the Holocene. Dysoxic conditions during the B/A and Preboreal intervals in this region were possibly caused by high surface water productivity at times of reduced intermediate ventilation in the northwestern Pacific. Remarkable similarities are evident in the late Quaternary sequence of benthic foraminiferal assemblage change between the two very distant continental margins of northern Japan and southern California. The oscillations in OMZ strength, reflected by these faunal changes, were widespread and apparently synchronous over wide areas of the North Pacific, reflecting broad changes in intermediate water ventilation and surface ocean productivity closely linked with late Quaternary climate change on millennial and orbital timescales.

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1. Introduction

[2] The high latitudes of the North Pacific represent a key component of the earth's modern climate system as the terminus for the so-called "deep oceanic conveyor" and because of the affect of this region on global biogeochemical cycles through intense surface ocean biological productivity. Pacific intermediate circulation has also changed significantly in association with the late Quaternary climatic cycles. *Keigwin* [1998] found that intermediate waters in the far northwestern Pacific were well ventilated during the last glacial episode compared with today based on benthic foraminiferal stable isotopic data from the northern Emperor Seamounts and the Okhotsk Sea. Moreover, *Ahagon et al.* [2003] suggested that middepth ventilation of the northwestern Pacific was much reduced during the Bølling-Ållerød (B/A). Furthermore, evidence from laminated sediments in Santa Barbara Basin (SBB) suggest strong and rapid participation of upper intermediate waters with abrupt millennial-scale climate oscillations initially recorded in the Greenland ice sheet [*Kennett and Ingram*, 1995; *Cannariato et al.*, 1999; *Cannariato and Kennett*, 1999; *Hendy and Kennett*, 2003; *Kennett et al.*, 2000] initially recorded in the Greenland ice sheet [*Dansgaard et al.*, 1993]. In contrast to the northeast Pacific region, little is known about the late Quaternary history of intermediate water circulation and surface ocean productivity at the margins of northern Japan on millennial timescales.

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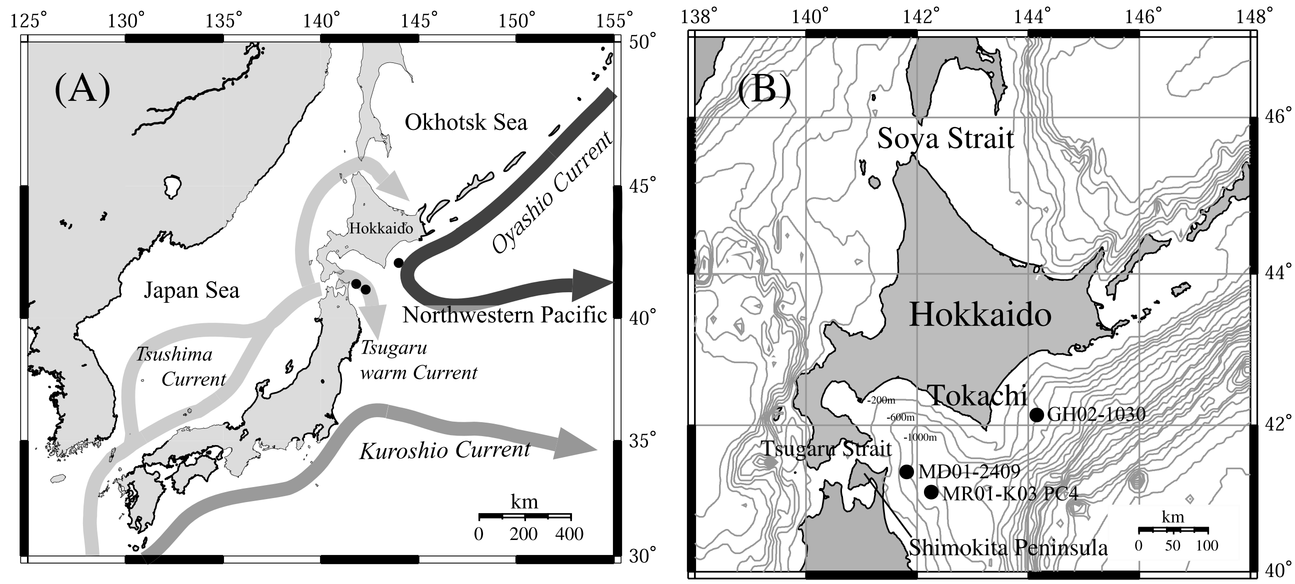

Figure 1. (a) Location of study area and coring sites with major currents illustrated. (b) Cores from study area including core MD01-2409 (41°33′N, 141°52′W; 975 m) from continental slope near the Tsugaru Strait, core PC4 (41°07′N, 142°24′W; 1363 m) from off Shimokita Peninsula, and core GH02-1030 (42°13′N, 144°12′W; 1212 m) from off Tokachi, eastern Hokkaido.

[3] Today, North Pacific Intermediate Water (NPIW), defined as the salinity minimum at depths of 300–800 m, is formed in the northwestern Pacific. The origin of NPIW is a low-salinity cold intermediate water, likely formed in the Sea of Okhotsk [*Yasuda*, 1997; *Talley*, 1991]. The Okhotsk intermediate water is produced by brine rejection during the formation of sea ice on the continental shelf in winter and is exported by vertical mixing in the Bussol' Strait to ventilate the subpolar gyre of the open Pacific. Mixing of the Okhotsk water with the subpolar water in the open Pacific is essential for establishing properties of the NPIW. Thus the Oyashio Current region off northern Japan would have been directly affected by hydrographic changes in the Sea of Okhotsk and the open Pacific Ocean. At intermediate depths in the modern Oyashio Current region, there exists an oxygen minimum zone (OMZ), because of poor intermediate water ventilation and high surface water productivity [*Nagata et al.*, 1992]. The strength of this OMZ has been sensitive to changes in the ventilation of intermediate waters and surface water productivity during the late Quaternary. Changes in benthic foraminiferal assemblages in this region provide critical information on the relative strengths of the intermediate water circulation, ventilation and surface water productivity in the past.

[4] The primary goal of this investigation is to reconstruct the millennial-scale history of the OMZ on the continental margin of NE Japan during the last glacial through the Holocene, and to evaluate the potential effects on margin oxygenation of changes in ventilation by intermediate waters and of surface water productivity. Three piston cores were collected in the northwestern Pacific, near northern Japan (Figure 1) to reconstruct OMZ history using benthic foraminiferal census data. Benthic foraminifera are well known as suitable proxies for monitoring environmental changes related to the changing strength of the OMZ because of their rapid responses to changes in dissolved oxygen [*Bernhard et al.*, 1997; *Kaiho*, 1994] and organic carbon (food) availability. A number of experimental studies have also been conducted on the species distribution of benthic foraminifera in oxygenated (occasionally sulfurized) sediments [*Sen Gupta and Machain-Castillo*, 1993; *Alve and Bernhard*, 1995; *Bernhard et al.*, 1997; *Moodley et al.*, 1998]. As a result, foraminiferal assemblages can be ordered with respect to tolerance to oxygen depletion. This ranking has been established using observed relationships between modern benthic foraminiferal associations and oxygen levels, and by down-core comparison of changing assemblages with sediment parameters known to respond to changes in oxygenation state.

2. Core Locations

[5] Three piston cores (MD01-2409, PC4, and GH02-1030) were collected from the east side of Shimokita Peninsula and eastern Hokkaido, northern Japan (Figure 1). Core MD01-2409 (41°33′N, 141°52′W), is from a water depth of 975 m on the continental slope near the eastern entrance of the Tsugaru Strait (collected during the IMAGES VII–WEPAMA cruise (West Pacific Margin) of the R/V *Marion Dufresne*). Core PC4 (41°07′N, 142°24′W) is from a water depth of 1363 m on the continental slope 65 km southeast of site MD01-2409, off Shimokita Peninsula (collected during cruise MR01-K03 of the R/V *Mirai*). Core GH02-1030 (42°13′N, 144°12′W) was collected from a water depth of 1212 m on the continental slope off Tokachi, eastern Hokkaido

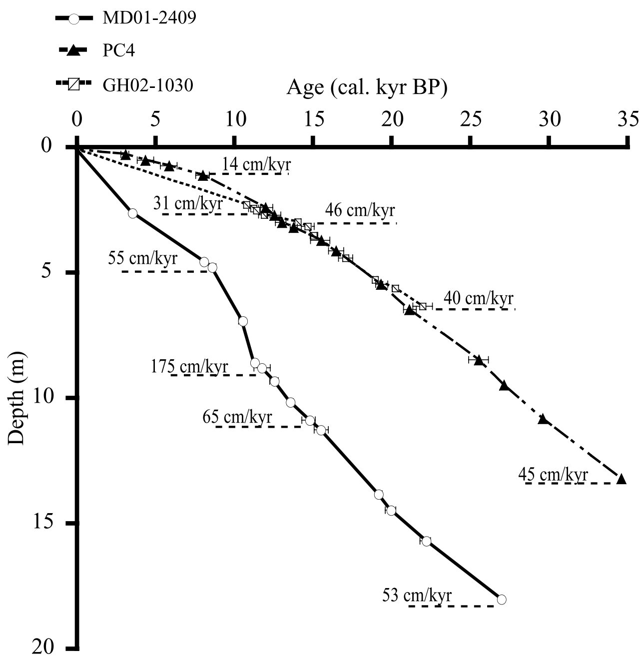

Figure 2. Age model of core MD01-2409 (circles), core PC4 (triangles), and core GH02-1030 (squares). Sedimentation rates in the three cores are also indicated. Age model for all cores were determined using accelerator mass spectrometry ^{14}C dating of planktonic foraminifera. All ^{14}C ages are calibrated to calendar ages. Bars show the 2σ range of calendar ages.

(collected during cruise GH02 of the R/V *Hakurei-Maru* number 2).

3. Oceanographic Setting

[6] Three major currents dominate modern surface waters in the region (the Tsugaru Warm Current, the Kuroshio Current, and the Oyashio Current; Figure 1). The Tsugaru Warm Current is an extension of the Tsushima Current that flows northward through the Japan Sea and in turn is a branch of warm, saline waters of the Kuroshio Current (Figure 1). The Tsugaru Warm Current transports warm, low-salinity waters eastward through the Tsugaru Strait, with a sill depth of 130 m. The maximum depth of the Tsugaru Warm Current is less than 200 m. As a result, cool waters of the Oyashio Current underlie those of the Tsugaru Warm Current where they intersect. The Kuroshio Current transports warm (>15°C), saline, and oligotrophic waters to the northeast along the southeast coast of Japan (Figure 1). The Oyashio Current, in contrast, transports cold, lower-salinity waters southwest along Hokkaido's east coast, representing the western part of subarctic circulation in the North Pacific [*Nagata et al.*, 1992]. An OMZ (500–1500 m) exists at intermediate depths in the modern Oyashio Current region, because of poor intermediate–water ventilation and high surface water productivity [*Nagata et al.*, 1992]. Today, the most oxygen depleted layer (about 50 μmol/L) occurs from 700 m to 1200 m.

4. Materials and Methods

[7] Core MD01-2409 consists of massive clayey silt. Three well-preserved laminated sediment horizons occur in the middle of this core: The upper laminated layer (694–860 cm core depth) is defined as laminated layer 1; the middle laminated layer (969–1018 cm) is laminated layer 2; and the lowest laminated layer (1031–1131 cm) is laminated layer 3. Samples for foraminiferal analysis were taken at 27 cm intervals in average. This represents a sampling interval of 400 years in average. Sampling resolutions in the middle of cores are high on average, because sedimentation rates in this period are relatively higher than other periods. Core PC4 consists of undisturbed hemipelagic sediment. Samples for foraminiferal analysis are taken at 27 cm intervals on average, representing intervals of 700 years on average. Core GH02-1030 consists of massive, homogeneous silty clay or clayey silt. Samples for foraminiferal analysis are taken at 17 cm intervals in average, representing intervals of 600 years in average.

[8] Samples each representing a 2 cm interval were taken from each core using plastic cubes and freeze-dried. Freeze-dried samples were disaggregated by soaking in hot water. Disaggregated samples were sieved using a 63 μm sieve. A microsplitter was used to obtain sample splits containing a minimum of ~100–200 specimens. All identified specimens were counted to determine changes in relative abundances of benthic foraminiferal taxa throughout each core. Thirty-four species, representing over two percent in relative abundances of the taxa are considered common species. Benthic foraminiferal accumulation rates (BFAR) were calculated on the basis of the sedimentation rate and benthic foraminiferal number.

[9] The age model for core MD01-2409 was developed using radiocarbon (^{14}C) ages of 15 planktonic foraminiferal samples that were measured using an accelerator mass spectrometry [*Kuroyanagi et al.*, 2006] (Figure 2). The age model for core GH02-1030 was constructed using ^{14}C of *Neogloboquadrina pachyderma* analyzed from 13 levels [*Ikehara et al.*, 2006]. The age model for core PC4 was developed using ^{14}C dates of 15 planktonic foraminiferal samples [*Ahagon et al.*, 2003]. These three dates were calibrated against INTCAL 04 [*Hughen et al.*, 2004] using CALIB software for dates younger than 24 ka and the equation of *Bard* [1998] for dates older than 24 ka with reservoir correction. Standard values of reservoir correction are ΔR = 376 yr for the northwestern Pacific region [*Kuroyanagi et al.*, 2006; *Ikehara et al.*, 2006], following *Kuzmin et al.* [2001]. On the basis of high-resolution radiocarbon dating for these cores, it is possible to achieve millennial-scale comparison of benthic foraminiferal assemblages among these cores. According to our age model, laminated layer 3 ranges from 15.6 ± 0.2 to 13.7 ± 0.1 ka; laminated layer 2 ranges from 13.5 ± 0.1 to 13.0 ±

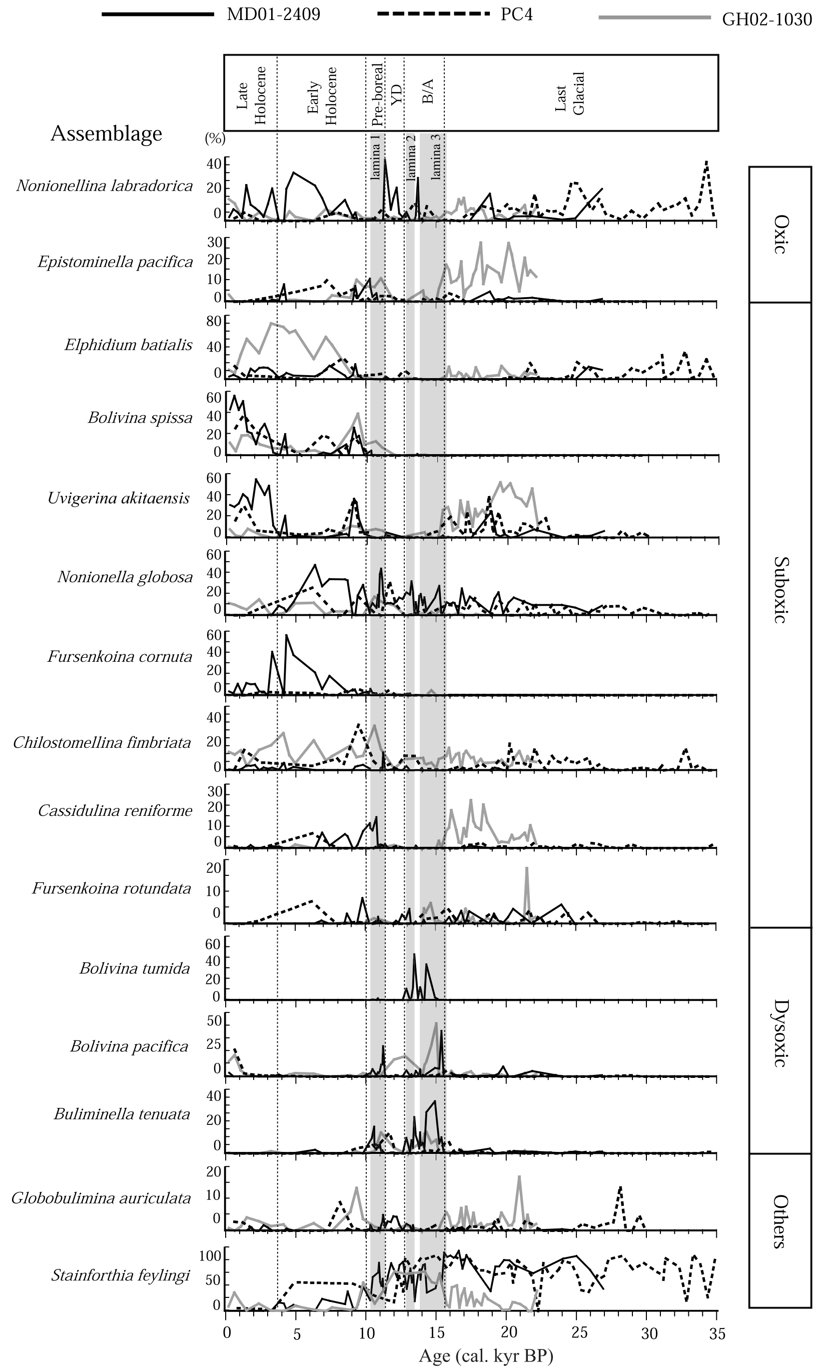

Figure 3. Changes in relative abundances of the 15 most abundant benthic foraminiferal species in three cores shown against primary climatic episodes of the late Quaternary. Taxa are grouped within their oxygenation preferences. Laminated sediments in core MD01-2409 are shown as shaded bands.

0.1 ka; and laminated layer 1 ranges from 11.3 ± 0.1 to 10.4 ± 0.1 ka.

5. Results

[10] Figure 3 shows changes in the relative abundances of major benthic foraminifera in the three cores. Distinct changes in benthic foraminiferal assemblages mark six intervals as follows: last glacial (from 34.0 ± 0.1 ka to 15.4 ± 0.1 ka); B/A (from 15.4 ± 0.2 ka to 12.8 ± 0.1 ka); Younger Dryas (from 12.8 ± 0.1 to 11.3 ± 0.1 ka); Preboreal (from 11.3 ± 0.1 to 10.0 ± 0.1 ka); early Holocene (from 10.0 ± 0.1 to 3.8 ± 0.1 ka); and late Holocene (from 3.8 ± 0.1 ka to 0 ka). Relative abundance changes of the 15 most abundant benthic foraminiferal species are compared

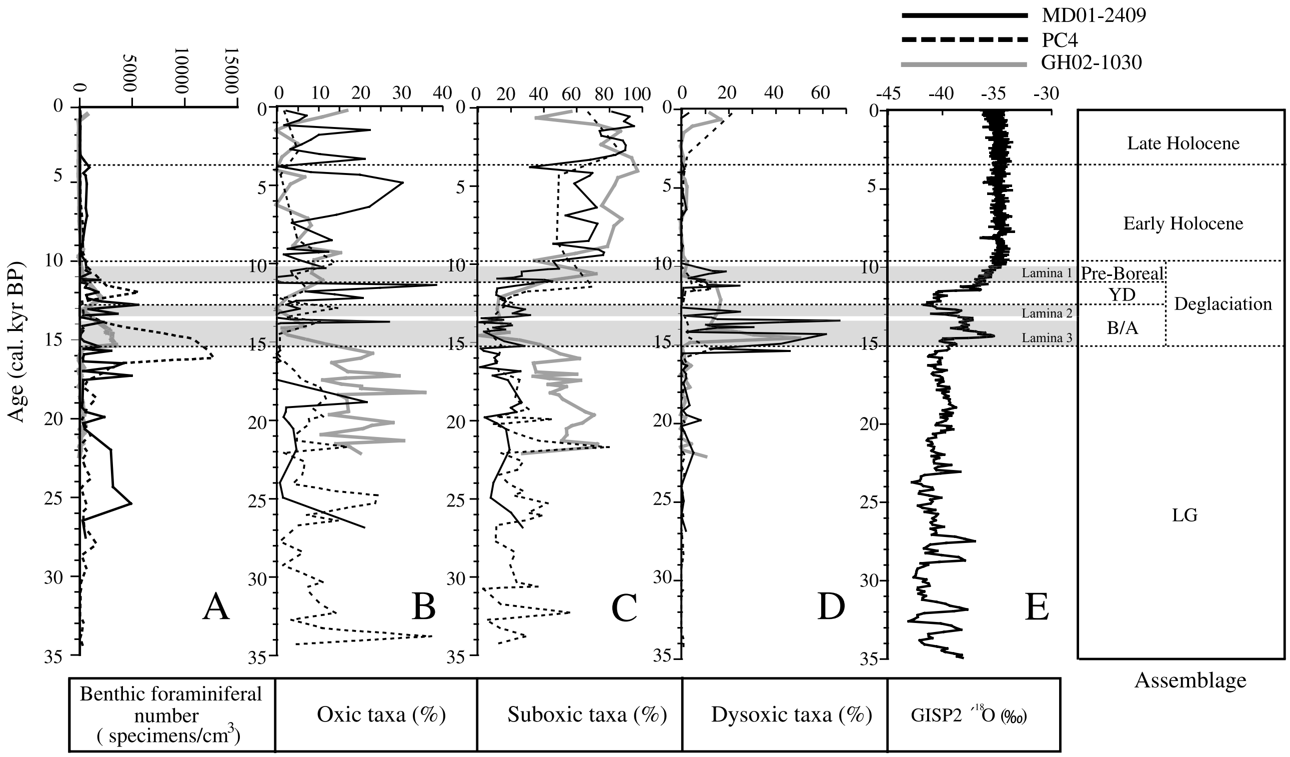

Figure 4. Changes in total benthic foraminiferal number and relative abundances of three oxygen-indicative benthic foraminiferal groups (oxic, suboxic, and dysoxic) relative to late Quaternary climate history in three cores: core MD01-2409 (solid line), core PC4 (dashed line), core GH02-1030 (shaded line). (a) Benthic foraminiferal number. (b) Total relative abundance of oxic taxa. (c) Total relative abundance of suboxic taxa. (d) Total relative abundance of dysoxic taxa. (e) The $\delta^{18}O_{ice}$ time series from Greenland ice core record (GISP 2) [*Grootes et al.*, 1993]. Shaded areas represent laminated sediments in core MD01-2409.

between the three cores (Figure 3). Several species exhibit intercore similarities in relative abundance oscillations.

[11] *Bolivina pacifica* is generally associated with laminated sediments in core MD01-2409, and the occurrence of this species is associated with other dysoxic taxa in all cores. This species is reported from thinly laminated intervals in the Japan Sea that presumably indicates low dissolved oxygen content [*Oba et al.*, 1991]. In consequence, this species is treated as a dysoxic form. *Bolivina tumida*, which occurs only in laminated sediments in core MD01-2409, is considered a dysoxic ($[O_2]$ = 0.1–0.3 mL/L) form being closely associated with strongly laminated sediments in SBB [*Cannariato et al.*, 1999] and associated with other dysoxic taxa in our cores. *Bolivina spissa* is abundant at depths within the modern OMZ in the Oyashio Current region [*Ishiwada*, 1964] and was described as a suboxic ($[O_2]$ = 0.3–1.5 mL/L) taxa by *Cannariato and Kennett* [1999]. *Buliminella tenuata* was reported as a dysoxic ($[O_2]$ = 0.1–0.3 mL/L) taxa by *Cannariato and Kennett* [1999] and *Cannariato et al.* [1999], occurring in close association with laminated sediments like *B. tumida*. This form occurs only in laminated intervals in the three cores and is presumed to be an indicator of dysoxic conditions. *Cassidulina reniforme* is a suboxic to oxic form occurring in association with glacial assemblages that include *Epistominella pacifica*, *Uvigerina akitaensis*, *Nonionellina labradorica* in *Ohkushi et al.* [2003]. *Cassidulina reniforme* was also reported to be suboxic by *Cannariato et al.* [1999]. *Elphidium batialis* is a modern deepwater form, occurring abundantly between ~2000–3000 m in the region of the Oyashio Current and its confluence with the Kuroshio Current [*Matoba*, 1976]. At depths greater than 1000 m dissolved-oxygen concentrations become higher compared with the central part of the OMZ. Thus *E. batialis* is considered to be a suboxic to oxic taxon [*Ohkushi et al.*, 2003]. In the studied core, *E. batialis* is abundant in the LGM and Holocene, rare during deglaciation and absent in laminated intervals. *Epistominella pacifica* was reported to be oxic by *Cannariato and Kennett* [1999] and *Cannariato et al.* [1999]. *Cannariato and Kennett* [1999] suggested *Nonionella globosa* to a suboxic taxon, while *Cannariato et al.* [1999], considered *Nonionellina labradorica* an oxic taxon. *Nonionella* was also described as oxic to suboxic by *Ishiwada* [1964] based on modern distributions in northern Japan. *Stainforthia feylingi* is the most dominant taxon throughout the cores. This species is widely distributed in the North Pacific, and is often a dominant species on the west coast of Canada, also in boreal waters. The reason for the broad, pervasive occurrence of this species is unclear, although it

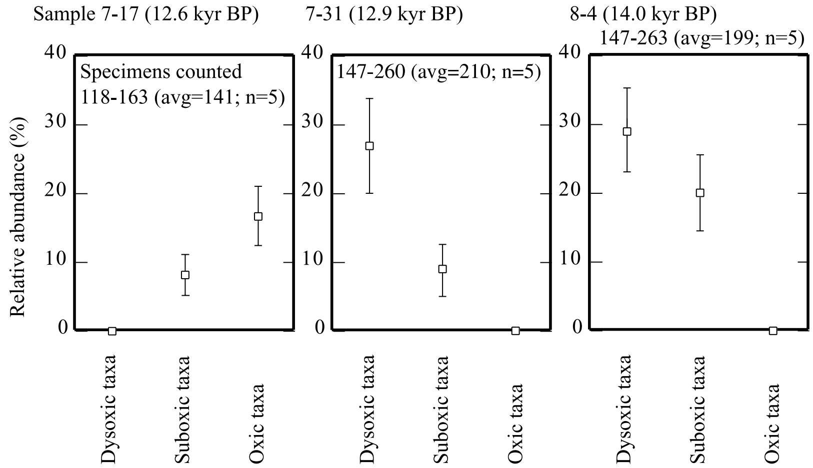

Figure 5. Average proportions of oxic, suboxic, and dysoxic assemblages of benthic foraminifera computed from the counting of five subsamples composed of at least 100 individuals each in three deglacial horizons of core MD01-2409. Bars show the 2σ error. Avg is average number of specimens counted; *n* is number of subsamples counted in each horizon.

seems to be highly tolerant of unstable conditions [*Knudsen and Seidenkrantz*, 1994]. A decrease in relative abundance of *S. feylingi* during the Holocene is striking and likely caused by greater dissolution rather than change (this form is easily dissolved because of its thin wall and small test) in the biocenosis. This taxon has broad tolerance for dissolved oxygen and thus appears unsuitable for monitoring oxygen levels. *Uvigerina* spp. was reported as a suboxic taxon by *Cannariato and Kennett* [1999]. *U. akitaensis* is a major element of the modern OMZ in the Oyashio Current region together with *B. spissa* [*Inoue*, 1989]. Comparison of abundance patterns between species discussed here suggests the following other forms to be characteristic of suboxic conditions: *Bolivina decussata*, *C. fimbriata*, *Fursenkoina cornuta*, and *Fursenkoina rotundata*.

[12] Figure 4 exhibits time series changes in each cumulative percent of oxic, suboxic, and dysoxic taxa. LGM assemblages composed of oxic (15–30%) and suboxic taxa (20 to 50%). Assemblages restricted to the Preboreal and B/A indicate dysoxic (<0.3 mL/L O_2) conditions. In addition, assemblages occurring mainly in Holocene sediments indicate suboxic (<0.5 mL/L O_2) conditions [e.g., *Sen Gupta and Machain-Castillo*, 1993]. As a consequence, changes in benthic foraminiferal assemblages clearly define six intervals resulting from climatically related changes in oxygen concentrations in the benthic environment. These changes appear to correlate well with climatic changes recorded in the Greenland ice core record (GISP 2) (Figure 4) and SBB [*Kennett et al.*, 2000] and exhibit the following sequence: (1) During the LGM, oxic to suboxic conditions marked the study region. (2) Subsequently, there were dysoxic conditions during the B/A associated with inferred maximum strength of the OMZ. (3) Suboxic conditions returned during the Younger Dryas. (4) Strong dysoxic conditions returned during the Preboreal. (5) Finally, suboxic conditions returned again during the Holocene.

[13] We considered that the low count numbers of about 100 specimens per sample for faunal analysis might introduce a significant error into paleoenvironmental estimates. We calculated the 2σ error of the relative abundances of oxic, suboxic, and dysoxic assemblages for five counts of 100–300 specimens each from three samples from the last deglacial (Figure 5). The results indicate that counts of 100–300 specimens are sufficient for estimating bottom water oxygenation changes. Abundance differences among oxic, suboxic, and dysoxic taxa in each sample are clearly larger than the counting error and thus reflect environmental changes. In two samples, from 12.9 and 14.0 kyr B.P. (B/A), dysoxic taxa were definitely dominant, and oxic taxa were dominant in the sample from 12.6 kyr B.P. (YD). Thus we confidently used the results of counts of 100–300 specimens.

[14] Bioturbational mixing could also introduce a significant error into paleoenvironmental estimates based on foraminiferal assemblages. Because the mixed layer thickness is approximately 10 cm in this region, the mixing coefficient (K) can be estimated from the sedimentation rate (SR) by using empirically derived functions [*Boudreau*, 1994; *Tromp et al.*, 1995]. The resultant value of K ranges from 150 to 1350 cm^2/kyr for the SR of 16.7 cm/kyr in the Holocene section in PC4 [*Ahagon et al.*, 2003]. This K value range suggests that the sediment was stirred to a depth of about 10 cm over a period of several hundred years. Thus 2 cm thick samples from glacial layers in PC4 and in the other cores with high sedimentation rates reflect a time-averaging effect of less than several hundred years. The time-averaging effect thus had little influence for our interpretation because we focused on millennial-scale paleoenvironmental changes. The environmental shifts observed

as changes in the abundances of oxic taxa (Figure 4) were often shown by single-point troughs and peaks. The troughs and peaks may be the result of century-scale background variability such as in primary productivity.

6. Discussion

6.1. Dysoxic Conditions During the Bølling-Ållerød and Preboreal Episodes

[15] Laminated sediments in core MD01-2409 during the B/A and Preboreal represent strong evidence for dysoxic condition because dysoxic conditions would exclude bioturbation activity of macrobenthic fauna (Figure 4). Therefore we conclude that foraminiferal taxa associated with laminated sediments represent dysoxic conditions. Furthermore, benthic foraminiferal assemblages in the other two cores during the B/A and Preboreal compare well with those in the laminated intervals of core MD01-2409. The OMZ (700 m to 1200 m) was more strongly developed at a water depth of 975 m, as represented by MD01-2409.

[16] On the basis of biogenic opal data in core CH84-14 at 978 m south of Hokkaido, *Crusius et al.* [2004] suggested that increased productivity in the open northwest Pacific possibly contributed to low-oxygen intermediate waters during the B/A in the northeast Pacific because of increased respiration of organic carbon. Likewise, deglacial productivity increases were observed in the Japan, Okhotsk Seas and subarctic Pacific [*Gorbarenko and Southon*, 2000; *Gorbarenko*, 1996; *Gorbarenko et al.*, 1995, 2002a, 2002b, 2004; *Keigwin et al.*, 1992; *Lee et al.*, 2003; *Ono et al.*, 2005]. *Tada et al.* [1999] suggested that inputs of nutrient-enriched coastal water from the East China Sea increased productivity in the Japan Sea during interstadials. Discharges from the Huanghe and Changjing rivers in the East China Sea are important sources of nutrients. Likewise, increased productivity in the Okhotsk Sea may have resulted from deglacial increased discharge of terrestrial inorganic matter from the Amur River. This occurred during rapid sea level rise [*Ono et al.*, 2005]. Thus nutrient input from marginal seas likely increased productivity in the Oyashio region during the B/A and PB.

[17] Furthermore, benthic-planktonic foraminiferal age differences in core PC4 suggest that ventilation of intermediate waters in the North Pacific was reduced during the B/A [*Ahagon et al.*, 2003], thus contributing to OMZ strength. Our benthic records are consistent with such ventilation changes, suggesting that the OMZ simultaneously and regionally expanded both off the Shimokita Peninsula and Tokachi. The strong deglacial OMZ may be explained by drastic decrease in intermediate water production in the subarctic Pacific including the Okhotsk and Bering Seas. Deglacial surface water warming and increase in fresh water input from the Eurasia and North America inhibited polynya formation in the coastal areas in the above marginal seas, decreasing brine rejection into intermediate depths. Core MD01-2409 is the only core containing a thick sequence of laminated sediments and is closest to the main depth of influence of NPIW. Thus combination of decreased intermediate water ventilation and increased productivity appears to have contributed to bottom water oxygen depletion off NE Japan during the late Quaternary.

[18] Similarly, deglacial ventilation changes of intermediate water occurred off the northeast Pacific [*Hendy and Kennett*, 2003]. According to *Hendy and Kennett* [2003], comparisons of δ^{18}O between benthic and planktonic foraminifera suggested that intermediate water warming preceded that of surface waters by 60–200 years during deglaciation. They concluded that "southern component" intermediate waters from subtropical areas, marked by low dissolved oxygen concentrations expanded northward during deglaciation. This interpretation is supported by ocean model simulation results that changes in NPIW in the northeastern Pacific were strongly influenced by an anomalous poleward flow at 300–1100 m depths [*Auad et al.*, 2003]. Such poleward expansion of low-oxygen intermediate waters likely affected intermediate waters in the northeastern Pacific during deglacial warming.

6.2. Suboxic Conditions During the Holocene

[19] Both last glacial and Holocene assemblages are represented by suboxic taxa (Figure 4). Although the primary suboxic form is *U. akitaensis* during the last glacial, suboxic faunas of the Holocene consist of *B. spissa* and *U. akitaensis*, at times forming as much as 60 to 80% of assemblages during the late Holocene (Figures 3 and 4). Both *B. spissa* and *U. akitaensis* were reported as major species of the modern "Oyashio oxygen minimum layer fauna" [*Inoue*, 1989], and simultaneous occurrence of these two species are apparent in modern strong OMZ around NE Japan [*Ikeya*, 1971]. Comparison with modern assemblages thus indicates that the OMZ during the LGM was weaker than that of today. This is consistent with results of previous studies that intermediate water ventilation in the glacial North Pacific was stronger than during the Holocene [*Keigwin*, 1998; *Kennett and Ingram*, 1995].

[20] Moreover, benthic foraminiferal assemblages and the inferred strength of the OMZ changed during the Holocene (Figures 3 and 4). Increases in *B. spissa* and *U. akitaensis* during the late Holocene suggest that the OMZ became stronger during the late Holocene. Inferred changes in oxygenation of intermediate waters during the Holocene have not previously been reported from the northwestern Pacific. However, *Takei et al.* [2002] suggested that surface water exchanges through the Tsugaru Strait between the Japan Sea and the open Pacific drastically changed during the Holocene. Although the Tsugaru Warm Current presently flows eastward through the Tsugaru Strait today, paleoceanographic reconstructions by *Takei et al.* [2002] suggest that Oyashio waters flowed into the Japan Sea during the early Holocene. By 8.3 ka, the Tsugaru Warm Current began to flow eastward from the Japan Sea to the open Pacific, and became dominant one-way flow after 4.8 ka. If this is correct, late Holocene surface ocean productivity on the east side of the Tsugaru Strait would have significantly strengthened because a front between the ocean currents is associated with strong surface water production. This might have indirectly affected the strength of the OMZ and benthic foraminiferal assemblages.

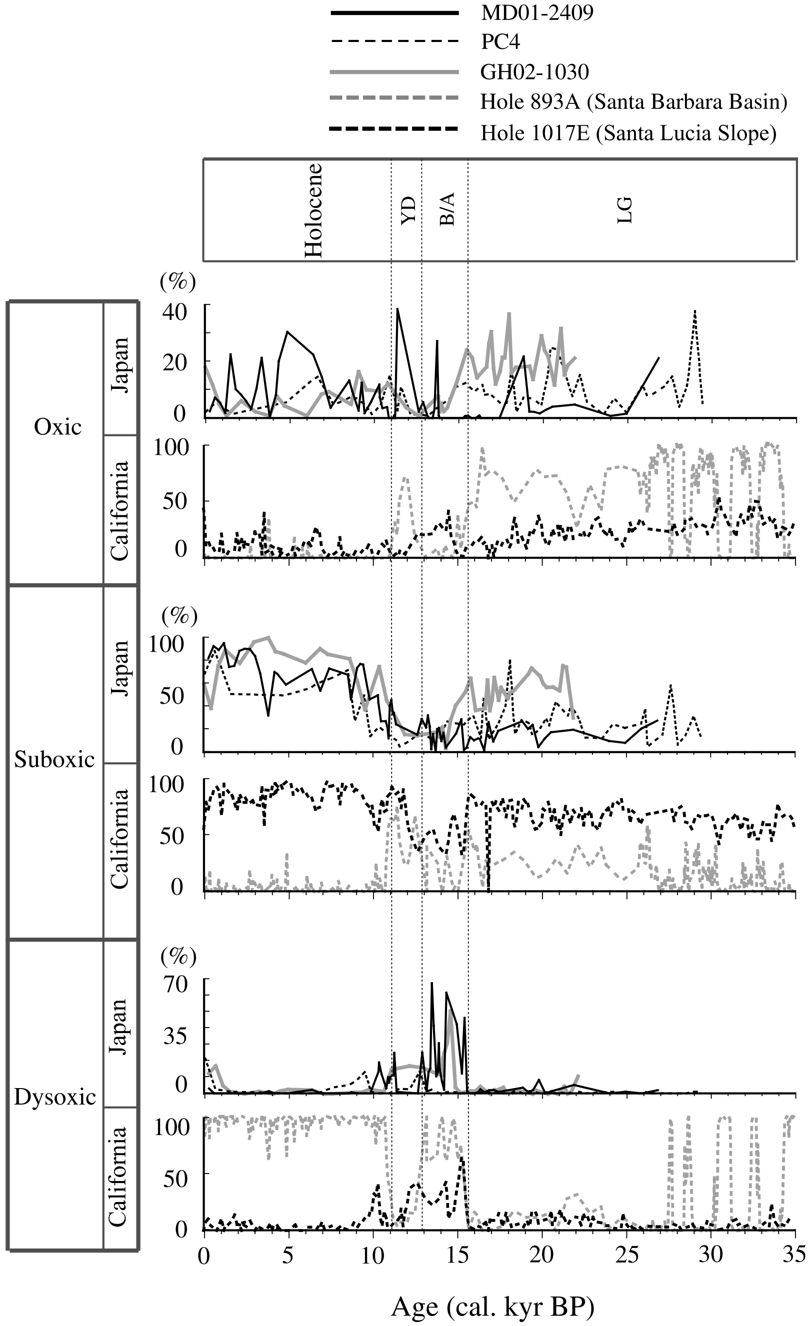

Figure 6. Comparison of variations in oxic, suboxic, and dysoxic assemblages observed in both northern Japan and southern California (Santa Barbara Basin and Santa Lucia Slope) margin: core MD01-2409 (solid line), core PC4 (thin dashed line), core GH02-1030 (shaded line), core 1017E (bold dashed line) core 893A (shaded dashed line).

[21] However, Holocene changes of benthic faunas in core GH02-1030 off Tokachi, eastern Hokkaido, were similar to those on the east side of the Tsugaru Strait. Surface waters off Tokachi would not have been affected by flow through the Tsugaru Strait, because of the overriding influence of the southwestward flow of the Oyashio Current. Instead, the hydrography of surface waters off Tokachi would mainly have been affected by surface waters of the Okhotsk Sea, as present Oyashio water is produced by mixing of the Okhotsk Seawater and subarctic gyre water. At present, a branch of the Tsushima warm Current from the Japan Sea flows into the Okhotsk Sea and is a major constituent of Okhotsk Seawater. Thus the Tsushima warm Current is indirectly related with the formation of Oyashio water. Paleontological records of mollusk in coastal areas of Hokkaido exhibit that the clockwise flow of the Tsushima warm Current migrated along Hokkaido coast from the early Holocene to the middle Holocene and thence

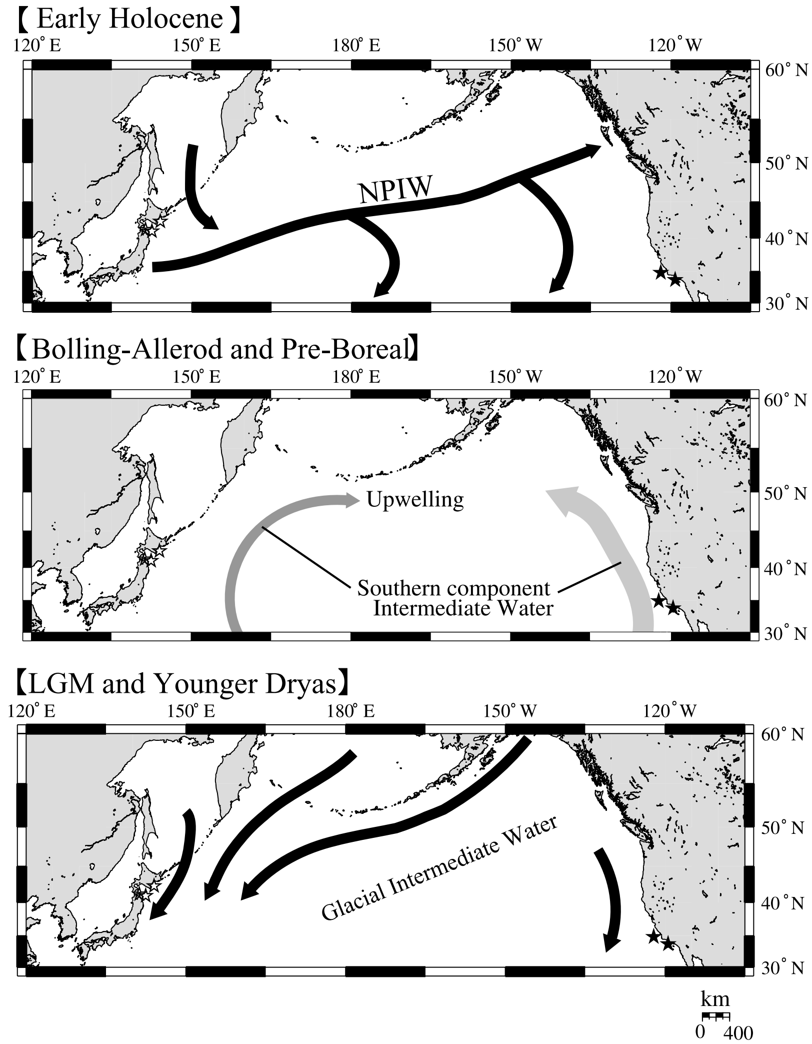

Figure 7. Simple circulation models for different late Quaternary climatic episodes in the North Pacific (open stars, coring site of northern Japan; solid stars, coring sites of southern California). During the LGM, intermediate waters originated from the Bering Sea with increased production compared with modern NPIW [e.g., *Ohkushi et al.*, 2003]. During deglaciation, surface ocean biological productivity increased, because of inferred deglacial deepwater upwelling associated with intensified global thermohaline circulation [*Sarnthein et al.*, 2004]. Furthermore, *Hendy and Kennett* [2003] inferred the northward expansion of southern component intermediate waters from subtropical areas to the California margin. During the early Holocene, NPIW originated from the northwestern Pacific spreads in the subtropical North Pacific as a salinity minimum zone.

to coastal areas around Tokachi during the middle Holocene [*Matsushima*, 1998]. Thus Holocene changes of benthic faunas in core GH02-1030 off Tokachi have been directly affected by these hydrographic changes in the Okhotsk and Japan Seas. Biogenic opal and organic carbon data indicate the highest productivity in the Okhotsk Sea during the late Holocene [*Ono et al.*, 2005; *Gorbarenko et al.*, 2002a, 2002b, 2004; *Seki et al.*, 2004]. Moreover, abundance changes in intermediate water-dwelling radiolaria suggest decreased ventilation in the Okhotsk Sea during the late Holocene [*Itaki and Ikehara*, 2004]. Changes in strength of the OMZ during the Holocene were affected by both intermediate water ventilation and productivity in the Oyashio region, reflecting influence of hydrographic changes in marginal seas.

6.3. Comparison of Slope Benthic Foraminiferal Assemblages Between Northern Japan and California Margins

[22] We now compare changes in the relative abundances of oxic, suboxic, and dysoxic assemblages in upper slope sequences between northern Japan and two sites (Santa Lucia Slope and SBB) of southern California (Figure 6). Age models of cores in both Californian margin and Northeast Japan were developed using high-resolution radiocarbon (^{14}C) ages of planktonic foraminiferal samples,

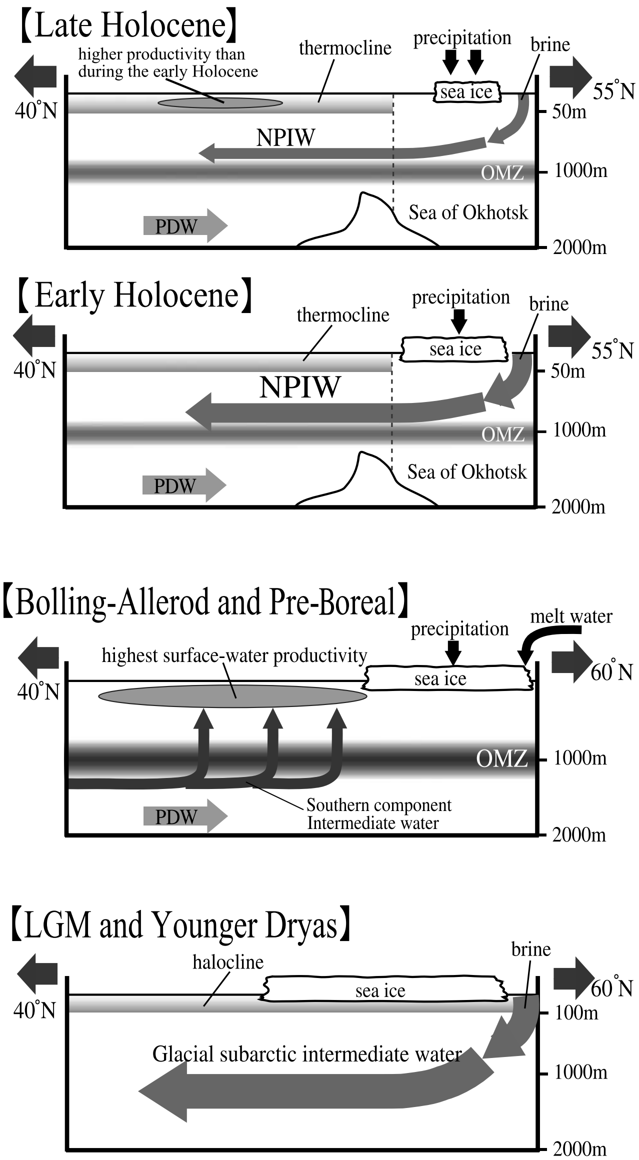

Figure 8. Simple paleoceanographic models for the North Pacific during the late Quaternary. The LGM was marked by cold, well-oxygenated intermediate waters produced at high latitudes in the North Pacific [e.g., *Ohkushi et al.*, 2003]. The glacial intermediate waters originated from the Bering Sea. During the B/A the formation of subarctic intermediate waters ceased or weakened. At that time, surface ocean biological productivity increased because of increase in nutrient input from the marginal seas, the influence of deglacial deepwater upwelling associated with intensified global thermohaline circulation [*Sarnthein et al.*, 2004], and northward expansion of southern component intermediate waters. During the early Holocene the formation of NPIW in the Okhotsk Sea started to increase. Thus during the early Holocene, increased strength of surface water stratification led to decreased surface water biological productivity [*Sarnthein et al.*, 2004].

and are of sufficient resolution for millennial-scale correlations. On the Santa Lucia Slope, *Cannariato and Kennett* [1999] generated benthic foraminiferal assemblage data for the past 60 kyr at Ocean Drilling Program (ODP) Site 1017 at a depth of 955 m (at a similar depth as core MD01-2409). Patterns of changes in Santa Lucia Slope assemblages are remarkably similar to those of the NE Japan upper slope at water depths close to, or deeper than 1,000 m, and within the present-day OMZ. For instance, suboxic assemblages dominate both NE Japan and Santa Lucia Slope during the Holocene. On the other hand, several similarities are apparent between records of NE Japan and SBB. For example, strongly laminated sediments (ODP Hole 893A) from 576 m water depth in SBB during the B/A also are associated with assemblages dominated (>90%) by dysoxic taxa [*Cannariato et al.*, 1999]. Oxic assemblages dominate during the Younger Dryas in both NE Japan and SBB indicating a major weakening of the OMZ. However, prominent differences occur between NE Japan and SBB assemblages during the Holocene. SBB Holocene assemblages are dominated (90%) by dysoxic taxa indicating the intense OMZ, while coeval assemblages in NE Japan are indicative of relatively weaker OMZ. This difference between these two sites results from the different depth range of the OMZ. In modern NE Japan, which is a source area of NPIW, the OMZ is centered close to 1000 m water depth [*Hakodate Marine Observatory*, 2003]. On the other hand, the OMZ in SBB is shallow as 450 m. The shallower OMZ in the NE Pacific is caused by intense biological productivity resulting from coastal upwelling, accounting for differences in the OMZ depth range and the intensity between NE Japan and SBB.

[23] Remarkable similarity is also apparent between dysoxic assemblages in core MD01-2409 and SBB. Dysoxic assemblages during the B/A in the SBB are dominated by *B. tumida* (together with *B. tenuata*) not known in modern basin assemblages. This assemblage is associated with the most strongly laminated sediments and the least diverse basinal benthic foraminiferal assemblages of the late Quaternary. The habitat of *B. tumida* was also ephemeral, and its temporal distribution and ecology indicate a rapid, opportunistic response during interstadials to favorable environmental conditions from refugia in more poorly ventilated zones such as nearby hydrocarbon seeps. The co-occurrence of *B. tumida* and *B. tenuata* together with laminated sediments has also been observed in core MD01-2409 in NE Japan. This is considered to indicate especially low oxygenated environments, because laminated sediments containing a combination of *B. tumida* and *B. tenuata* are rarely observed both in NE Japan and California, and the apparent existence of laminated sediments is almost certainly the result of drastic oxygen depletion.

[24] This apparent synchronization between the northwestern and northeastern Pacific assemblage changes suggests that benthic foraminiferal faunas reflect millennial-scale paleoceanographic changes in the North Pacific in response to large, abrupt changes in Arctic atmospheric temperature recorded in Greenland ice cores during the late Quaternary. The rapidity of the changes in these strongly linked regions indicates a dominance of atmospheric tele-

connections that affect intermediate waters and surface water productivity.

6.4. Ventilation Changes in the North Pacific Since the LGM

[25] Figures 7 and 8 show simple models of paleoceanographic changes during the late Quaternary in the North Pacific, based on our observations and those of others. Hydrographic characteristics of intermediate waters in the North Pacific during the glacial were different from the present NPIW. Microfossil assemblages indicate that intermediate waters were cold, well oxygenated and ventilated in the North Pacific during the LGM [*Ohkushi et al.*, 2003]. Because benthic δ^{13}C data [*Keigwin*, 1998; *Matsumoto et al.*, 2002] suggest higher nutrient levels at depths greater than 2 km in the glacial North Pacific, glacial intermediate waters seem to have been limited to depths shallower than 2 km. Glacial dominance of the radiolarian *Cycladophora davisiana*, indicative of cold, oxic intermediate waters, suggests origin of glacial intermediate waters from the Bering Sea. Increased intermediate water ventilation appears to have been widespread and synchronous throughout the North Pacific. Such young waters would have been relatively low in nutrients compared with the present [*Keigwin*, 1998; *Ohkouchi et al.*, 1994]. Furthermore, a strong vertical salinity gradient during the glacial would have increased stratification in the subarctic Pacific [*Sigman et al.*, 2004] reducing surface water productivity compared with the present [*Kienast et al.*, 2004; *Okazaki et al.*, 2005; *Seki et al.*, 2004].

[26] The first noticeable change in intermediate water oxygenation during the deglaciation was at the onset of B/A. The timing of the oxygenation change approximately corresponds to the meltwater discharge event (mwp-1A) from continental glaciers of Eurasia and North America. At this time, shifts in atmospheric circulation associated with Northern Hemisphere warming would have abruptly changed moisture transport associated with the east Asian monsoon in the North Pacific [*Wang et al.*, 2001]. The stalagmite δ^{18}O record, a proxy for precipitation in the Asian continent, from Hulu Cave in China, indicate intensified summer monsoon during the B/A. Both effects of meltwater discharge from Eurasia and North America, and increased precipitation associated with east Asian monsoon would decrease SSS in the North Pacific. The decreased SSS and increased SST led to cessation or weakening of intermediate water ventilation in the subarctic North Pacific. Thus millennial-scale thermohaline circulation in the subarctic North Pacific may be a principal cause of this antiphase relationship with the North Atlantic counterpart. The millennial-scale change of fresh water influx between the North Pacific and the North Atlantic may be one of main causes of the antiphase relationship.

[27] Moreover, shifts in atmospheric circulation associated with Northern Hemisphere warming would have abruptly changed the location and flux of intermediate water production in the North Pacific [*Dean et al.*, 1989]. Today, NPIW is largely formed in the Sea of Okhotsk [*Yasuda*, 1997] where polynyas develop as a result of strong northerly winds from Siberia. On the other hand, polynyas reduce when easterly winds from the Bering Sea and Kamchatka is prevalent [*Martin et al.*, 1998; *Itaki and Ikehara*, 2004]. The changes in wind direction and strength are largely controlled by winter atmospheric circulation involving geostrophic winds associated with changes in the relative position and strength of the Siberian High (SH) and Aleutian Low (AL) systems, especially that of the AL. The northerly winds dominate when the AL shifts its position to the north, while easterly winds flow when the AL shifts its position to the south. Thus the annual latitudinal shift of the winter AL affects the volume of brine rejection and intermediate water formation in the Sea of Okhotsk [*Martin et al.*, 1998; *Itaki and Ikehara*, 2004]. In contrast, during the LGM, model results of COHMAP [*COHMAP Members*, 1988] suggest the existence of a strong differential between an intensified AL and strong anticyclonic circulation on North America. The formation of polynya in the northeastern Bering Sea would have increased because of the intensification of strong dry northeasterly winds. Thus active brine production in the coastal surface waters would have caused increased intermediate water formation in the Bering Sea during the LGM [*Ohkushi et al.*, 2003].

[28] During the B/A, decreased sea surface density led to cessation or weakening of subarctic intermediate water production. At that time, surface water productivity abruptly increased, because of upwelling of nutrient-rich southern component intermediate waters, and increased nutrient input by meltwater from continents. This high productivity has been interpreted by *Sarnthein et al.* [2004] to result from deglacial deepwater upwelling associated with changes in global thermohaline circulation. High surface water productivity led to increased flux of organics to seafloor and resulting increased strength of the OMZ.

[29] Biological productivity decreased during the Younger Dryas cold event, but increased again during Preboreal warming. During the Preboreal to the early Holocene, decreased meltwater discharge from continents lead to decreased biological productivity. Moreover, *Sarnthein et al.* [2004] suggested that steep halocline and stratification typical of the present-day subarctic North Pacific surface ocean developed during the mid-Holocene. As a result, increased surface water stratification during the mid Holocene led to decreased biological productivity [*Sarnthein et al.*, 2004], and associated weakening of the OMZ off North Japan. During the Holocene, alkenone SST data indicate a temperature increase over almost the entire North Pacific [*Kim et al.*, 2004]. Production of NPIW seems to have gradually decreased from the mid-Holocene to the late Holocene [*Itaki and Ikehara*, 2004]. On the other hand, since 3 ka, biological productivity increased in northwest Pacific marginal seas, although the reason is unclear. Poor planktonic foraminiferal preservation indicates local carbonate dissolution in the Oyashio region after 3 ka, due to increased influence of CO_2-enriched intermediate waters from the south and increased organic decomposition at the seafloor.

[30] Our results imply the existence of a tight coupling of changes in atmospheric circulation and thermohaline circulation in the Northern Hemisphere during the last 30 ka. Millennial-scale thermohaline circulation in the subarctic North Pacific seems to have an antiphase relationship with

the North Atlantic counterpart. The reorganization of thermohaline circulation in the North Pacific appears to have had a large impact on ocean productivity, the intensity of the OMZ, biogeochemical cycles in the North Pacific and benthic communities at intermediate water depths.

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