Late Quaternary Paleoceanography of the Japan Sea : An Update

Ryuji Tada*

Because the Japan Sea is a semi-enclosed marginal sea surrounded by a continent and an island arc, its oceanographic condition during late Quaternary has been influenced by many factors including climate in central to east Asia and Japan, oceanographic condition of northwestern Pacific, and glacioeustatic sea level changes. Consequently, its sedimentary record is complicated and difficult to interpret. However, the record preserves a wealth of information both terrestrial and marine, and is suited for linking the terrestrial climate in central to east Asia and the oceanography of the Japan Sea and surrounding oceans. Recent progress revealed intimate linkage between the Asian climate and the Japan Sea paleoceanography on millennial time-scale.

Key Words : Japan Sea, paleoceanography, late Quaternary, sea level changes

I. Introduction

The Japan Sea is a semi-enclosed marginal sea connected with other seas through five shallow and narrow straits. Among the five straits, the Tsushima and Tsugaru Straits are two of the deepest with the present sill depths of only 130 m, which is close in magnitude to the amplitude of the glacioeustatic sea level drops during the late Quaternary (e.g. Fairbanks, 1989; Chappell, 1994). Consequently, drastic changes in paleoceanographic condition is expected in association with the glacioeustatic sea level oscillations. Especially, possibility for the complete isolation of the sea and establishment of the land bridge between Asian continent and the Japanese Islands during the Last Glacial Maximum [LGM] has been discussed repeatedly because it is closely related with the problems such as origin of the people and evolution of the culture in Japan (Sato and Mogi, 1982; Kamei *et al.*, 1988; Ohshima, 1990; Tada, 1995). Another major interest on the late Quaternary paleocean-

ography of the Japan Sea is the paleoenvironmental changes recorded in the alternations of dark and light colored layers, which characterize the hemipelagic facies of the Japan Sea sediments (Ichikura and Ujiie, 1973; Oba *et al.*, 1991; Tada *et al.*, 1992, 1999). In spite of these major topics on late Quaternary paleoceanography of the Japan Sea, the research progress was slow until early 80s when Oba and his colleagues carried out the comprehensive study on the piston core recovered from the Oki ridge (Oba *et al.*, 1991). In this short review, I will describe the recent progress on the late Quaternary paleoceanography in Japan after the review work of Oba (1991) with special emphasis on the Japan Sea.

II. Surface water condition of the Japan Sea

1. The last glacial period

Through their comprehensive work on late Quaternary paleoceanography of the Japan Sea using multiple proxies including isotopic records of planktonic and benthonic fora-

Received January 30, 1999. Accepted April 3, 1999.

* Geological Institute, Graduate School of Science, the University of Tokyo. 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan.

minifers, Oba *et al.* (1991, 1995) showed that paleoceanographic condition of the Japan Sea did change drastically during the last 80 kys. Especially, they discovered positive excursion of the $\delta^{18}\text{O}$ of planktonic foraminifers during the LGM¹⁾ which suggests that the surface water salinity dropped significantly probably due to isolation of the sea in response to the glacioeustatic sea level drop during the LGM.

Although the negative $\delta^{18}\text{O}$ peak during the LGM strongly indicate development of lower salinity surface water (Oba *et al.*, 1991), it does not necessarily indicate complete isolation of the sea. Using a simple salinity balance model, Matsui *et al.* (1998) explored the possibility for isolation of the Japan Sea during the LGM. They demonstrated that salinity excursion of the surface water implied by $\delta^{18}\text{O}$ of planktonic foraminifers can be explained by glacioeustatic sea level drop and consequent decrease in the influx of the Tsushima Warm Current [TWC]. Assuming that the influx volume through the Tsushima Strait have been that proportional to the cross sectional area of the strait that has been regulated by glacioeustatic sea level changes, they showed that the decrease in surface water salinity of the sea becomes evident when the sea level dropped by more than approximately 90 to 100 m below the present level. At this point, the importance of net fresh water input to the sea becomes significant relative to sea water influx through the Tsushima Strait. They also suggest that the Japan Sea was probably not isolated completely but shallow strait of approximately 10 m depth and 10 km width should have remained to maintain the surface water salinity at the level suggested by planktonic $\delta^{18}\text{O}$ value (Fig. 1). This estimation is consistent with the estimated sill depth of 10 to 30 m during the LGM based on the presence of submarine terraces of approximately 18 calendar ka²⁾ at 110 to 120 m depth within the Tsushima Strait (Yoo and

Fig. 1 Oxygen isotopic ratio of planktonic foraminifera at KH-94-15, PC-9 and KH-79-3, C-3 by Oba *et al.* (1991, 1995), estimated surface water salinity based on $\delta^{18}\text{O}$ data, and reconstructed sill depth changes by Matsui *et al.* (1998) during the last glacial period

Park, 1997), which suggests the magnitude of the relative sea level drop as 100 to 120 m during the LGM.

Comparison of the oxygen isotope data between the northern and southern sites within the sea (Oba *et al.*, 1991 ; Okumura *et al.*, 1996) also suggest that the temperature difference between the northern and southern sites decreases with the decrease in the influx rate, and the surface water temperature became almost the same throughout the Japan Sea between 19

1) In their earlier studies, timing of negative $\delta^{18}\text{O}$ peak was considered as older than the LGM since their earlier age model was based on ^{14}C dates of bulk carbonate in the sediments, which consistently gave older ages because of significant contribution of dead carbon to the sediments through the eolian input. Later, Oba *et al.* (1995) revised the age model based on AMS dates of planktonic foraminifers. With the new age model, the negative $\delta^{18}\text{O}$ peak agree with the LGM.

2) Ages in this article is expressed as calendar ages which are converted from ^{14}C ages based on Bard *et al.* (1993) between 8.5 and 20 ka and Kitagawa and van der Plicht (1998 a, b) before 20 ka.

Fig. 2 Schematic illustration showing the hypothesized behavior of land-ocean systems in central to eastern Asia and in the Japan Sea in response to millennial-scale wet and dry cycles possibly associated with Dansgaard-Oeschger (D-O) cycles (Tada *et al.*, 1999)

and 15.5 calendar ka when the global sea level was at its minimum (Fig. 1). This is another evidence that the Japan Sea was nearly isolated and the TWC ceased during the LGM. The good age constraint of the oxygen isotope data of Oba *et al.* (1995) gives further useful information on the timing of eustatic sea level changes. Namely, according to reconstruction of temporal changes in the influx using the salinity balance model, the continuous decrease in sea level started from approximately 33 calendar ka, which reached its maximum approximately at 19 calendar ka and the lowest sea level stand lasted for 3.5 k.y. until the abrupt increase in sea level occurred approximately at 15.5 calendar ka (Matsui *et al.*, 1998).

Tada *et al.* (1999) examined variations in assemblage and number of diatoms in the Japan Sea sediments during the last 150 k.y. Especially, they paid special attention to warm-water diatoms indicative of the TWC and a coastal-water diatom *Palaría sulucata* indicative of the East China Sea Coastal Water [ECSCW]. They found orbital and suborbital-scale (millennial-scale) variations in their abundance and relative ratio, which they interpret as reflecting variation in relative contribution of the ECSCW to the total influx. They further speculated that millennial-scale variation in the relative contribution of the ECSCW during the last glacial period was reflecting millennial-scale variation of precipitation in inland east Asia that modulated the discharge of the

Huanghe and Changjiang Rivers (Fig. 2), whereas the orbital-scale variation was reflecting glacioeustatic sea level change that caused the changes in distance between the mouths of the Huanghe and Changjiang Rivers and the entrance of the Tsushima Strait.

2. The last deglacial period

Oba and his colleagues also suggested the possibility of influx of the Oyashio Current from the northeastern Tsugaru Strait during deglaciation from 15.5 to 11 calendar ka based mainly on benthic foraminiferal assemblage (Oba *et al.*, 1991). Their planktonic $\delta^{18}\text{O}$ data also show the heaviest values indicative of very cold SST comparable to the LGM. In addition, there is no evidence for the influx of the TWC during this period (Tada *et al.*, 1999). Since global sea level rise already started during this period, it is unlikely that the Tsushima Strait was closed during this time. On the other hand, it is difficult to find a good reason to explain why TWC did not flow into the sea. One possibility is that sea level at the entrance of Tsugaru Strait was higher relative to that at Tsushima Strait during this period because salinity of the surface and intermediate water in the northwest Pacific Oyashio region was lower than that in southern Kuroshio region. Based on $\delta^{18}\text{O}$ of benthic foraminifers in the Pacific side of Japan, Oba and Yasuda (1991) demonstrated good evidence that salinity of the intermediate and surface waters in the northern Pacific was significant-

ly lower than the global average during the last glacial period and such lower salinity condition lasted until 12 calendar ka off central Japan and even younger at the entrance of Tsugaru Strait. This timing is consistent with planktonic $\delta^{18}\text{O}$ records in the Pacific side (Chinzei *et al.*, 1987), which suggest that the Kuroshio Front migrated to the north since 15 calendar ka and Holocene condition established at 8 calendar ka. This explanation is also consistent with the idea of presence of well ventilated intermediate water with lower salinity during the LGM (Keigwin, 1998).

Although there is a paleontological evidence of the influx of the Oyashio water to the Japan Sea during the last deglaciation, it is doubtful whether the volume of influx of Oyashio Current to the sea was significant. If the influx of the Oyashio Current to the Japan Sea was significant, its influence should have appeared in the northeastern part of the East China Sea. However, planktonic $\delta^{18}\text{O}$ data in that area did not show any evidence of the increase in $\delta^{18}\text{O}$ during this period suggesting that outflux of the cold surface water from the Tsushima Strait was not significant during deglaciation (Oba, 1991). Comparison of the oxygen isotope data between the northern and southern sites within the sea also suggest that the temperature difference between the northern and southern sites was small during this period (Fig. 1). Diatom assemblage in the Japan Sea sediments during this period is dominated by *Paralia sulcata* indicative of the influence of the ECSCW. Thus, it is most likely that the Japan Sea during the deglaciation period was influenced by the cold Oyashio water but its net outflux through the Tsushima Strait was not significant.

3. Holocene

The surface water condition of the Japan Sea has been more or less stable during Holocene (after 10 ka) with its southern half having been under the continuous influence of the TWC. However, detailed examination of diatom assemblage by Koizumi (1989) revealed millennial-scale pulses of the TWC during this period with the average interval of approximately 2,000 years. This pulses of the TWC could be associated with millennial scale regional to

hemispheric climatic changes as will be discussed later.

III. Deep water condition of the Japan Sea

Masuzawa and Kitano (1984) and Oba *et al.* (1991) suggested the possibility that deep water became anoxic during the LGM possibly due to the development of low salinity surface water. Tada *et al.* (1992, 1999) further examined this possibility based on the degree of preservation of varve-like lamination and pyrite-S/org-C. Presence of lamination suggest elimination of bottom-dwelling macrofauna when dissolved O_2 within the bottom water is below 0.1 ml/l (Savirde *et al.*, 1984) whereas S/C ratios higher than 0.36 suggest euxinic (highly reducing condition with considerable amount of H_2S developed within a water column) bottom water conditions (Berner, 1982). They demonstrated that the deep water of the sea approximately below 500 m water depth became euxinic during the low salinity event of the LGM when thick laminated dark layer with <2% org-C was deposited. This interpretation is further supported by Yamada *et al.* (1997) who showed enhanced activity of methanotrophic bacteria within the water column based on carbon isotopic study of biomarkers.

Tada *et al.* (1992, 1999) further demonstrated that the deep water condition of the Japan Sea have fluctuated drastically between hyper-oxic and euxinic during the last 0.8 m.y. According to them, the bottom water condition of the sea has been controlled primarily by glacioeustatic sea level changes that control the relative importance of the excess freshwater input to the sea versus sea water influx through the Tsushima Strait, and secondarily by changes in salinity of the sea water influx through the Tsushima Strait. Namely, during interglacial highstands such as present, the high salinity TWC flows strongly into the sea, which sinks when cooled during winter and ventilates the deeper part of the sea. During intervals of intermediate (−20 to −60 m) to low (−60 to −90 m) sea levels, the deep water ventilation of the sea becomes sensitive to the salinity of the influx. When the influx had stronger contribution from the lower salinity ECSCW,

the deep water production within the sea was reduced. In addition, the ECSCW is also characterized with higher nutrients compared with the TWC, which was regenerated from the bottom of the Yellow Sea (Hong *et al.*, 1995). Consequently, the surface water productivity was enhanced in spite of reduced upwelling as a result of the reduced deep water production within the sea, which led to suboxic to euxinic bottom water conditions and deposition of

org-C rich thin dark layers. When the influx was dominated by higher salinity TWC, deep water was well ventilated due to the high production level of the deep water, which led to deposition of the light layers. During the very low sea levels (lower than -90 m), low salinity water cap developed and the bottom water became strongly euxinic as is described above.

Fig. 3 Correlation of the dark and light layers in C-3 core from the Japan Sea, its organic carbon contents, and $\delta^{18}\text{O}$ records of Greenland ice cores (Matsui *et al.*, 1998). Interstadial numbers are illustrated on right side of GISP2 $\delta^{18}\text{O}$ peaks.

IV. Linkage with the continental climate

Based on the correlation of the dark and light layers of the Japan Sea sediments with $\delta^{18}\text{O}$ records of the Greenland ice cores, Tada *et al.* (1999) suggest that alternations of the dark and light layers in the Japan Sea sediments are associated with Dansgaard-Oeschger climatic cycles with dark layers corresponding to the interstadials of the Dansgaard-Oeschger cycles (Fig. 3). They further speculated that deposition of the dark layers during the last glacial period reflected expansion of the ECSCW to the mouth of the Tsushima Strait, which was caused by increased discharge of the Huanghe and Changjiang Rivers due to the development of wet climate in central to east Asia (Fig. 2). To test this hypothesis, they quantified content of the eolian dust derived from inland arid area of central to east Asia within the Japan Sea sediments based on Q-mode factor analysis of major element composition (Irino and Tada, 1995; Tada *et al.*, 1999). They found higher eolian dust content during glacial periods and lower content during interglacial periods. In addition, they found millennial-scale variations of the eolian dust content during the last glacial period with lower contents coincide with the dark layers. This support their hypothesis that alternations of the dark and light layers in the late Quaternary sediments in the Japan Sea reflect wet-dry cycles in central to east Asia, which probably was associated with Dansgaard-Oeschger climatic cycles. Their result also suggests that similar millennial-scale oscillation in eolian dust content was also present during Holocene with lower eolian dust contents tend to coincide with spikes of TWC suggested from diatom assemblage.

V. Summary

Late Quaternary paleoceanography of the Japan Sea was strongly controlled by glacioeustatic sea level changes as well as wet and dry climatic cycles in central to east Asia. During interglacial highstands ($+10 > \text{sea level} > -20\text{m}$), significant and stable influx of the Tsushima Warm Current [TWC] introduced

warm, saline, and relatively nutrient-poor surface water, enhanced deep water production, and resulted in hyperoxic bottom water condition within the sea. During intermediate to low sea level periods ($-20 > \text{sea level} > -90\text{m}$), the influx through the Tsushima Strait was reduced but still significant enough to control the condition of the surface water of the Japan Sea. When inland east Asia was wet, the less saline and nutrient-enriched East China Sea Coastal Water [ECSCW] was expanded to the entrance of the Tsushima Strait and introduced into the sea, which reduced deep water production, enhanced surface productivity, and resulted in suboxic to euxinic bottom water conditions. When inland east Asia was dry, the ECSCW shrank and the TWC was introduced into the sea, deep water production was enhanced, and the bottom water became oxic. During glacial lowstands ($-90 > \text{sea level} > -120\text{m}$), the sea became semi-isolated and the surface water condition was strongly influenced by the excess fresh water input through precipitation and discharge from the surrounding rivers. As a result, the surface water salinity was drastically decreased to form a stable surface water cap, and resulted in euxinic bottom water conditions.

Millennial-scale wet and dry climatic cycles in central to east Asia probably associated with Dansgaard-Oeschger climatic cycles, was faithfully recorded as alternations of the dark and light layers in the Japan Sea sediments during the last glacial period. Influx of the Oyashio cold water into the Japan Sea during deglacial period previously postulated by Oba *et al.* (1991) could be explained by development of lower salinity North Pacific Intermediate Water during the last glacial period which stayed near the entrance of the Tsugaru Strait until 11 calendar ka.

References

- Bard, E., Arnold, M., Fairbanks, R.G. and Hamelin, B. (1993) ^{230}Th - ^{234}U ages obtained by Mass Spectrometry on corals. *Radiocarbon*, 35, 191-199.
- Berner, R. A. (1982) Burial of organic carbon and pyrite sulfur in the modern ocean : its geochemical and environmental significance. *Amer. Jour. Sci.*, 282, 451-473.
- Chappell, J. (1994) Upper Quaternary sea levels, coral

- terraces, oxygen isotopes and deep-sea temperatures. *Jour. Geogr. (Chigaku-zasshi)*, 103, 828–840.
- Chinzei, K., Fujioka, K., Kitazato, H., Koizumi, I., Oba, T., Oda, M., Okada, H., Sasaki, T. and Tanimura, Y. (1987) Postglacial environmental change of the Pacific Ocean off the coasts of Central Japan. *Marine Micropaleontology*, 11, 273–291.
- Fairbanks, R.G. (1989) A 17,000-year glacio-eustatic sea level record : influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature*, 342, 637–642.
- Hong, G.H., Kim, S.H., Chung, C.S., Kang, D.J., Choi, J., Lee, T. S. and Chung, J. Y. (1995) Nutrients and biogeochemical provinces in the Yellow Sea. Tsunogai, S., Iseki, K., Koike, I. and Oba, T. (eds.) *Global fluxes of carbon and its related substances in the coastal sea-ocean-atmosphere system* : 114–128, M & J International.
- Ichikura, M. and Ujiie, H. (1973) Lithology and planktonic foraminifera of the Sea of Japan piston cores. *Bull. National Science Museum*, 2, 151–178.
- Irino, T. and Tada, T. (1995) Temporal variation of the Kosa flux at ODP Site 797, the Japan Sea during last 150 ka. Tsunogai, S., Iseki, K., Koike, I. and Oba, T. (eds.) *Global fluxes of carbon and its related substances in the coastal sea-ocean-atmosphere system* : 511–516, M&J International.
- Kamei, S., Taruno, H. and Kawamura, Y. (1988) Implication of mammal fauna for the Quaternary geohistory of the Japanese islands. *The Quat. Res. (Daiyonki-Kenkyu)*, 26, 293–303. (J+E)
- Keigwin, L.D. (1998) Glacial-age hydrography of the far northwest Pacific Ocean. *Paleoceanography*, 13, 323–339.
- Kitagawa, H. and van der Plicht, J. (1998 a) A 40,000 year varve chronology from lake Suigetsu, Japan : Extension of the radiocarbon calibration curve. *Radiocarbon*, 40, 505–516.
- Kitagawa, H. and van der Plicht, J. (1998 b) Atmospheric radiocarbon calibration to 45,000 yr B.P. : Late glacial fluctuations and cosmogenic isotope production. *Science*, 279, 1187–1190.
- Koizumi, I. (1989) Holocene pulses of diatom growths in the warm Tsushima Current on the Japan Sea. *Diatom Res.*, 4, 55–68.
- Masuzawa, T. and Kitano, Y. (1984) Appearance of H₂S-bearing bottom waters during the last glacial period in the Japan Sea. *Geochem. J.*, 18, 167–172.
- Matsui, H., Tada, R. and Oba, T. (1998) Low-salinity isolation event of the Japan Sea in response to eustatic sea-level drop during the LGM : Reconstruction based on salinity-balance model. *The Quat. Res. (Daiyonki-Kenkyu)*, 37, 221–233. (J+E)
- Oba, T. (1991) Oceanic paleoenvironmental studies in Japan. *The Quat. Res. (Daiyonki-Kenkyu)*, 30, 197–202.
- Oba, T., Kato, M., Kitazato, H., Koizumi, I., Omura, A., Sakai, T. and Takayama, T. (1991) Paleoenvironmental changes in the Japan Sea during the last 85,000 years. *Paleoceanography*, 6, 499–518.
- Oba, T., Murayama, M., Matsumoto, E. and Nakamura, T. (1995) AMS¹⁴C ages of Japan Sea cores from the Oki Ridge. *The Quat. Res. (Daiyonki-Kenkyu)*, 34, 289–296. (J+E)
- Oba, T. and Yasuda, H. (1991) Paleoenvironmental change of the Kuroshio region since the last glacial age. *The Quat. Res. (Daiyonki-Kenkyu)*, 31, 329–339. (J+E)
- Ohshima, K. (1990) The history of straits around the Japanese islands in the Late Quaternary. *The Quat. Res. (Daiyonki-Kenkyu)*, 29, 193–208. (J+E)
- Okumura, S., Minagawa, M., Oba, T. and Ikehara, K. (1996) Paleoenvironmental analysis of two sediment cores off Akita city in the Japan Sea based on oxygen, carbon and nitrogen isotopes. *The Quat. Res. (Daiyonki-Kenkyu)*, 35, 349–358. (J+E)
- Sato, T. and Mogi, A. (1982) Sea level change in the Japan Sea deduced from submarine terraces and buried shelf channels. *The Quat. Res. (Daiyonki-Kenkyu)*, 21, 203–210. (J+E)
- Savard, C. E., Bottjer, D. J. and Gorsline, D. S. (1984) Development of a comprehensive oxygen-deficient marine biofacies model : evidence from Santa Monica, San Pedro, and Santa Barbara basins, California continental borderland. *Amer. Assoc. Petrol. Geol. Bull.*, 68, 1179–1192.
- Tada, R. (1995) Land bridge between Japan and Asian continent during the last glacial period. Koizumi, I. and Tanaka, K. (eds.) *Ocean and civilization*, 10 : 31–48, Asakura-shoten. (J)
- Tada, R., Koizumi, I., Cramp, A. and Rahman, A. (1992) Correlation of dark and light layers, and the origin of their cyclicity in the Quaternary sediments from the Japan Sea. Pisciotto, K.A., Ingle Jr., J.C., von Breymann, M.T. and Barron, J. et al. (eds.) *Proc. ODP, Sci. Results, 127/128, Pt 1* : 577–601, College Station, TX (Ocean Drilling Program).
- Tada R., Irino, T. and Koizumi, I. (1999) Land-ocean linkages over orbital and millennial timescales recorded in late Quaternary sediments of the Japan Sea. *Paleoceanography*, 14, 236–247.
- Yamada, K., Ishiwatari, R., Matsumoto, K. and Naraoka, H. (1997) $\delta^{13}\text{C}$ records of diploptene in the Japan Sea sediments over the past 25 kyr. *Geochem. J.*, 31, 315–321.
- Yoo, D.G. and Park, S.C. (1997) Late Quaternary lowstand wedges on the shelf margin and trough region of the Korea Strait. *Sed. Geol.*, 109, 121–133.
- (J+E) in Japanese with English abstract, (J) in Japanese