

An Anoxic Sea of Japan by 2200?

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Abstract. It has been reported that the Sea of Japan was anoxic during the last glacial period and did not become oxic until early in the Holocene. Studies have shown that the thickness of the bottom layer decreased between 1969 and 1984 and that the bottom oxygen concentration dropped between 1977 and 1984. Recent data have further confirmed those earlier observations that properties in the deep waters of the Sea of Japan have been changing since 1969. Researchers recently reported an increase in the potential temperature of the deep waters, a deepening of the oxygen minimum layer, and a decrease in the thickness of the adiabatic bottom water as well as in the oxygen concentrations. These temporal variations were interpreted as being transient and probably caused by the recent reduction or cessation of new bottom water formation in the northern Sea of Japan. Here, it is shown that this stagnation started at least as early as 1950 and is continuing. This is consistent with the heat flow data. It was also shown that the interpreted oxygen consumption rate and the phosphate and nitrate regeneration rates since the stagnation began have remained consistent with the rates calculated from the one dimensional advection-diffusion and the mass balance models. These rates average $0.8 \pm 0.4 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ for oxygen, $0.007 \pm 0.003 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ for phosphate and $0.10 \pm 0.04 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ for nitrate. If the stagnation continues, the Sea of Japan could become anoxic below 2000 m 180-530 years from now.

Introduction

More and more evidence points to the fact that the oceanic environment is changing. For instance, *Read and Gould* (1992) found support to a cooling and freshening of the sub-polar North Atlantic Ocean since the 1960s. Earlier, *Freeland* (1990) found evidence of a warming trend in the sea surface temperature along the coast of British Columbia, Canada. Such findings may well reflect global environmental changes.

The Sea of Japan is one of the major marginal seas in the world with an area of $1 \times 10^6 \text{ km}^2$ and an average depth of 1350 m. The rather deep sea, however, is almost a closed basin because the deepest strait connecting the basin to the outside is only 135 m deep. As a result, this isolated body of seawater is an ideal place to observe temporal changes.

It has been reported that the Sea of Japan was anoxic during the last glacial period and that not until early in the Holocene did it become oxic (*Masugawa and Kitano*, 1984; *Oba et al.*, 1991; *Uematsu et al.*, 1996). *Gamo et al.* (1986) have shown that the thickness of the bottom layer decreased by 400 m between 1969 and 1984 and that the bottom oxygen concentration also decreased by $5\text{-}7 \mu\text{mol kg}^{-1}$ between 1977 and 1984.

Recent data have further confirmed the earlier observations of *Gamo et al.* (1986) that properties of the deep waters of the Sea of Japan have been changing since 1969. To illustrate, *Kim* (1997) reported a more than 0.1°C increase in potential temperature of the deep waters, a deepening of the oxygen minimum layer from less than 1000 m in the late 60s to below 1500 m in 1996, and a decrease in the thickness of the adiabatic bottom water and in the oxygen concentrations by $20 \mu\text{mol kg}^{-1}$.

These temporal variations were interpreted to be transient, probably caused by the recent reduction or cessation of new bottom water formation in the northern Sea of Japan. What follows supports the view that the stagnation started at least as early as 1950 and is ongoing. It is also shown that the interpreted oxygen consumption rate since the stagnation began is consistent with the rate calculated from the one-dimensional advection-diffusion and the mass balance models. Finally, it is pointed out that if such stagnation continues, the bottom layer in the Sea of Japan could become anoxic within 200 years.

Sources of Data

Two cruises were carried out aboard the *R/V Akademik M. Lavrentjev* in 1995. The April-May cruise occupied 22 stations in the Sea of Japan, while the November-December cruise occupied 16 stations. A Neil Brown MK3 CTD/Rosette system was used to carry out the conductivity, temperature, and depth (CTD) measurements and to collect water samples. Temperatures and depths were checked by reversing thermometers. A Guildline Autosol 8400 salinometer was used to measure the salinities of the bottled samples. The IAPSO batch P121 standard seawater was used for calibration. The modified Winkler technique with colorimetric endpoint detection was used for oxygen determination (*Dickson*, 1994). Nutrients were measured by a Technicon Autoanalyzer.

For comparison, the Russian data collected in 1950 and 1954 (onboard the *R/V Vityaz*), Japanese data collected in 1969, 1977, 1979, 1984 (*Gamo et al.*, 1986), KEEP-MASS data collected in 1992 (*Chen et al.*, 1992) along with CREAMS data collected in 1996 (*Kim*, 1997) were used. Selected sampling stations are shown in Figure 1.

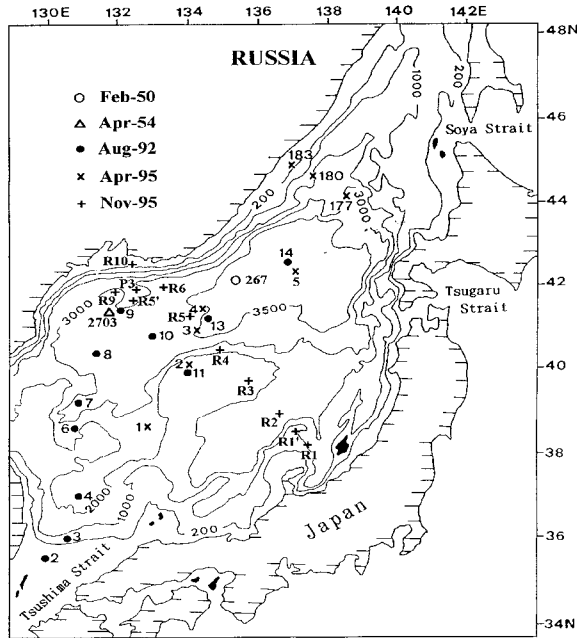


Figure 1. Study area and station locations in the Sea of Japan.

Secular Trends

The secular variations of temperature, dissolved oxygen and phosphate for stations in the same general region are plotted in Figures 2a-2c. As reported earlier (*Gamo et al.*, 1986; *Kim*, 1997) there is an 0.07°C increase in the potential temperature below 2000 m which is only slightly lower than the value of 0.1°C reported by *Kim* (1997). It should be noted that systematic and random errors in the measurements

as well as changes in temperature scale may all have contributed to the observed differences. However, both the 1950 and the April-May 1995 cruises also occupied stations in the Sea of Okhotsk. There is no clear systematic difference in those two temperature data sets. In fact, other data collected around 1950 in the Sea of Okhotsk show similar trends (Fig. 3a). The implication is that the temporal increase in temperature in the Sea of Japan is real. In addition, it is quite certain that the thickness of the homogeneous bottom water has decreased since 1950. Taking the basement heat flow at 95 mW m^{-2} (*Tamakik*, 1986), a stagnation of an average of 500 m - thick water mass below 2000 m would increase the temperature by 0.064°C . This is entirely consistent with the observed temperature increase of 0.007°C .

The temporal variations of oxygen profiles are plotted in Figure 2b. Clearly noted is that the depth of the oxygen minimum layer and the oxygen concentration in the bottom layer have been decreasing since the 1950s. The thickness of the bottom layer has also declined. Again the 1950 and 1995 cruises also measured oxygen in the Sea of Okhotsk (Figure 3b). These and other data collected around 1950 in the same general region point to no clear differences within the combined analytical errors, rendering support to the conclusion that the secular decrease in the oxygen concentration in the Sea of Japan since 1950 is real.

Not as much data are available for nutrients, but it is evident that the phosphate concentrations in the bottom layer have also been increasing (Figure 2c), consistent with the suggestion that the Sea of Japan started to stagnate as early as 1950. As a result, the end products of organic material decomposition, such as phosphate, have been accumulating in the bottom layer. On the other hand, a reduced supply of newly formed bottom water has been unable to resupply oxygen, causing its concentration to decrease.

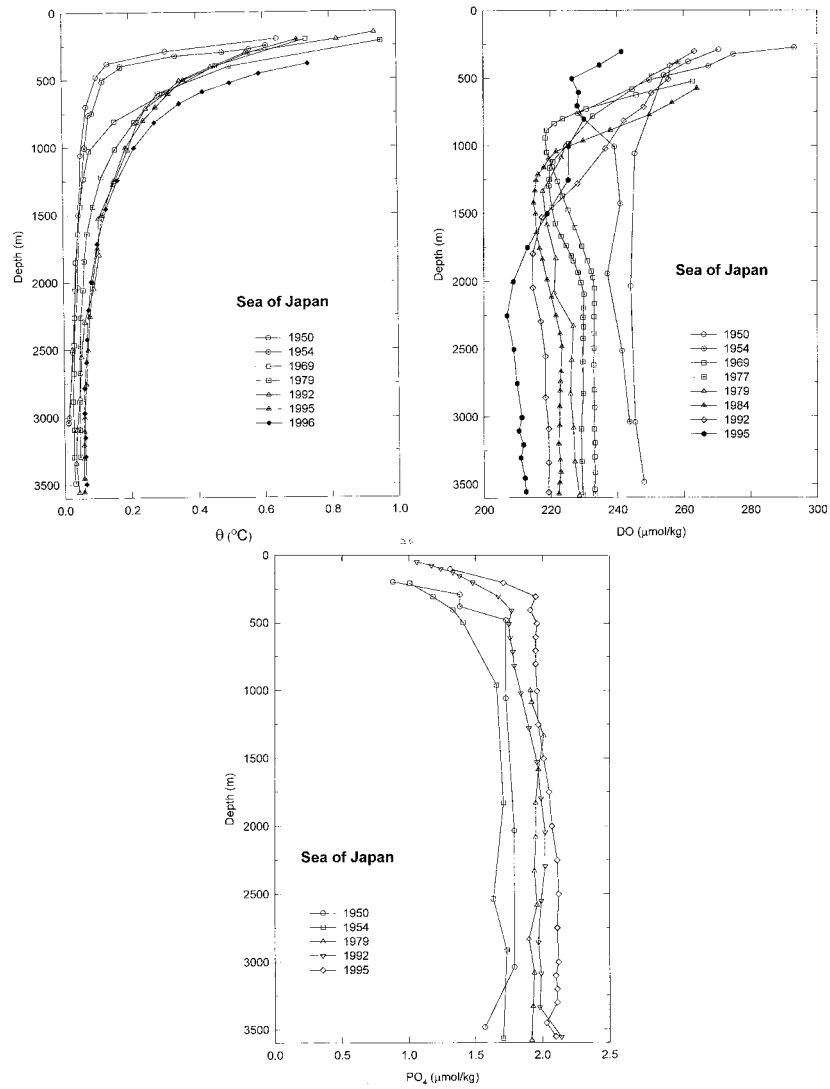


Figure 2. Vertical distribution of (a) potential temperature, (b) dissolved oxygen and (c) phosphate in the Sea of Japan from 1950 to 1996.

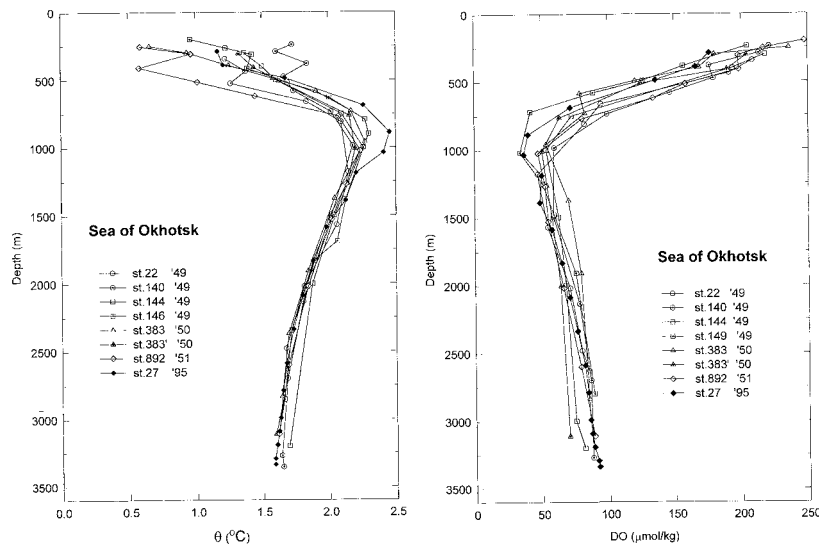


Figure 3. Vertical distribution of (a) potential temperature and (b) dissolved oxygen in the Sea of Okhotsk from 1949 to 1995.

Oxygen Consumption and Nutrient Regeneration Rates

Assuming that the bottom water has not received any new input of oxygen since 1950, and based on data presented in Figure 2b, the oxygen consumption rate is approximately $0.8 \pm 0.1 \mu\text{mol kg}^{-1} \text{yr}^{-1}$. The corresponding phosphate production rate is $0.0058 \pm 0.0007 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ supposing there is a phytoplankton O/P ratio of 138. According to data presented in Figure 2c, the observed PO_4 production rate is $0.0075 \pm 0.0015 \mu\text{mol kg}^{-1} \text{yr}^{-1}$, which is in close agreement with the value estimated from oxygen consumption.

It has also been possible to further check the internal consistency of the above data. First, the one dimensional advection-diffusion model (Craig, 1969) was used to calculate the oxygen consumption rate, and the phosphate and nitrate production rates. Accordingly,

$$K \left(\frac{d^2C}{dz^2} \right) - w \left(\frac{dC}{dz} \right) + J = 0 \quad (1)$$

where K is the vertical eddy diffusion coefficient; C is the concentration; z is the upward distance from the lower boundary; w is the upwelling velocity, and J is the term representing the non-conservation nature of the physiochemical parameter under consideration.

The salinity and temperature data in the depth range of 600 and 2000 m were used to calculate K/w . In so doing, the θ/S plot is linear. The resultant value of 0.4-0.6 km is lower than the value of 0.8-1.0 km found in the North Pacific (Chung, 1975). This is because the Sea of Japan turns over rather quickly, in fact, in the order of 120 years for waters deeper than 2000 m (Chen et al., 1995). This turnover rate corresponds to an average upwelling velocity of 17 m/yr, which is much higher than the value of 4 m/yr found in the Pacific (Munk, 1966; Broecker and Peng, 1982). Smaller w makes K/w higher.

By fitting the 1995 Russian and the 1992 KEEP-MASS oxygen data and considering the probable upwelling velocity in this depth range to Eq. (1), the oxygen consumption rate of between 2.63 ± 0.29 and $0.40 \pm 0.04 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ was obtained. Chen et al. (1996) used a mass balance model to calculate the oxygen consumption rate, and they determined a value of $5.1 \pm 0.3 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ for the depth range of 300-600 m. This is about a factor of 2 higher than the high value of $2.63 \pm 0.29 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ obtained from the 1-D model. This discrepancy might be expected as the 1-D model was applied to a deeper depth range where less organic matter is left to be decomposed, resulting in a lower oxygen consumption rate.

Chen et al. (1996) obtained an oxygen consumption rate of $1.13 \pm 0.04 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ for the waters below 2000 m. This is again greater than the low value of $0.40 \pm 0.04 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ as determined by the 1-D model by a factor of 3. These rates bracket the value obtained by assuming stagnation in the bottom water, i.e., $0.8 \pm 0.1 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ (Table 1). Chen et al. (1996) found a total carbon production rate of $1.05 \pm 0.10 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ in the bottom water. The organic carbon production rates are 3.7 ± 0.4 and $0.89 \pm 0.05 \mu\text{mol kg}^{-1} \text{yr}^{-1}$, respectively, between 300-600 m below 2000 m (Table 1). The ratios of organic carbon production and oxygen consumption rates are thus 0.73 ± 0.5 and $0.79 \pm 0.11 \mu\text{mol kg}^{-1} \text{yr}^{-1}$, respectively. These are in good agreement with the Redfield ratio.

It has been also possible to repeat the above calculations for phosphate (Table 1). The 1-D model results in a high value of $0.028 \pm 0.006 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ for the range of 600-2000 m. The value is 50% lower than the consumption rate of $0.042 \pm 0.002 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ obtained from the mass balance model for the depth range of 300-600 m (Chen et al., 1996). The mass balance model was applied at a shallower depth range; thus, more organic matter was available for decomposition, meaning that there was a higher phosphate production rate.

The 1-D model results in a low phosphate regeneration rate of $0.004 \pm 0.001 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ which is a factor of 2 lower than that obtained from the mass balance model for waters below 2000 m, i.e. $0.009 \pm 0.004 \mu\text{mol kg}^{-1} \text{yr}^{-1}$. On assuming stagnation between 1950 and 1995 in the bottom layer, the phosphate production rate is $0.0075 \pm 0.0015 \mu\text{mol kg}^{-1} \text{yr}^{-1}$. This value happens to be the average of the two values obtained from the above two independent methods.

Finally, in this study the 1-D model was applied to the 1995 nitrate data, and the nitrate regeneration rate of $0.05 \pm$

$0.008 - 0.33 \pm 0.055 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ between 600 and 2000 m was obtained (Table 1). Again, the higher value of $0.33 \pm 0.055 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ is about a factor of two lower than that determined by the mass balance model for the depth range of 300-600 m ($0.62 \pm 0.06 \mu\text{mol kg}^{-1} \text{yr}^{-1}$, *Chen et al.*, 1996). This difference may also be expected for the same reason as that accounting for phosphate. The lower nitrate production rate based on the 1-D model is $0.05 \pm 0.008 \mu\text{mol kg}^{-1} \text{yr}^{-1}$.

Table 1. Consumption or production rates of carbon, oxygen, and nutrients in the Sea of Japan ($\mu\text{mol kg}^{-1}\text{yr}^{-1}$)

Depth	300~600 m ¹	600~2000 m ²	below 2000 m
Total carbon production rate	3.7±0.8	0.40±0.07~2.63±0.44	1.05±0.10 ¹
Organic carbon production rate	3.7±0.4		0.89±0.05 ¹
Oxygen consumption rate assuming stagnation from 1-D model	5.1±0.3	0.40±0.04~2.63±0.29	1.13±0.04 ¹ 0.8±0.1 ²
PO ₄ production rate assuming stagnation from 1-D model	0.042±0.002	0.004±0.001~0.028±0.006	0.009±0.004 ¹ 0.0075±0.0015 ²
NO ₃ production rate assuming stagnation and N/P ratio of 16/1 from 1-D model	0.62±0.06	0.05±0.008~0.33±0.055	0.12±0.008 ¹ 0.12±0.014 ²

¹ Based on mass-balance model (*Chen et al.*, 1996)

² This work

The lower nitrate production rate based on the 1-D model is $0.05 \pm 0.008 \mu\text{mol kg}^{-1} \text{yr}^{-1}$. There were no high quality nitrate data around 1950, but if it is assumed that the phytoplankton N/P ration was 16, then the nitrate production rate could be estimated based on the phosphate production rate. Assuming stagnation between 1950 and 1995 the nitrate regeneration rate thus obtained is $0.12 \pm 0.014 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ for the bottom water. This value is the same as that obtained from the mass balance model ($0.12 \pm 0.008 \mu\text{mol kg}^{-1} \text{yr}^{-1}$; *Chen et al.*, 1996), but higher than the low value obtained from the 1-D model (Table 1).

Discussion and Conclusions

The mass balance method and 1-D model rely upon knowledge of the turnover time of the deep water, which *Chen et al.* (1995) estimated at 120 years. Some physicist, however, could not account for such a rapid turnover rate based on the ice production and chimney formation (*Nagata et al.*, 1996). Although no quantitative rates are given, these estimates were based on recent observations of the hydrographic data collected after the stagnation started. It is, thus, not surprising that lower rates were obtained. On the other hand, the deep Sea of Japan waters probably acquired most of the chemical signals before the stagnation started, thus yielding higher turnover rates.

Nevertheless, it should still be pointed out that because of the small vertical gradients of dissolved oxygen, nitrate and phosphate, the 1-D model gives rise to large uncertainties. The consumption or production rates calculated by assuming stagnation also suffer two major uncertainties: one is that we are not certain that the stagnation started around 1950 because we do not have high quality, pre-1950 data to compare with. If the stagnation actually started before 1950 then the rates calculated are too high. The other uncertainty is that although evidence provided above did indicate stagnation we cannot be sure that the bottom water is entirely unventilated. A certain amount of the oxygen-rich, nutrient-poor dense water formed in a severe winter in the northern Sea of Japan and could have penetrated into the bottom layer. In this case, the rates calculated would be too low.

Bearing these uncertainties in mind, it is still sufficient to say that the Sea of Japan has started to stagnate at least since 1950. The oxygen consumption rate calculated based on the mass-balance method, the one dimensional advection-diffusion model, and direct comparison of the 1950 and 1995 data is $0.8 \pm 0.4 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ below 2000 m. The average phosphate and nitrate regeneration rates are 0.007 ± 0.003 and $0.10 \pm 0.04 \mu\text{mol kg}^{-1} \text{yr}^{-1}$, respectively. With continued stagnation the Sea of Japan bottom water could become anoxic between 180 and 530 years from now.

Acknowledgment. This work was partially supported by the NSC/ROC (87-2611-M-110-116-GP)

References

- Broecker, W. S., and T. H. Peng, *Tracers in the Sea*, 690 pp. Eldigo Press, 1982.
- Chen, C-T. A., S-L. Wang, and A. S. Bychkov, Carbonate chemistry of the Sea of Japan., *J. Geophys. Res.*, 100 (C7), 13, 737-13,745, 1995.
- Chen, C-T. A., G. C. Gong, S-L. Wang, and A. S. Bychkov, Redfield ratios and regeneration rates of particulate matter in the Sea of Japan as a model of closed system, *Geophys. Res. Lett.*, 23 (14), 1785-1788, 1996.
- Chen, M. P., C. C. Huang, F. L. Lin, C. C. Liu, H. W. Li, G. C. Gong, J. J. Hung, and Y. L. Lee, The KEEP-MASS data report, 358 pp., NSC R.V. Ocean Researcher 1 Regional Instrument Center, 1992.
- Chung, Y., Aerial extent of the benthic front and variation of the scale height in Pacific deep and bottom waters, *J. Geophys. Res.* 80, 4169-4178, 1975.
- Craig, H., Abyssal carbon and radiocarbon in the Pacific, *J. Geophys. Res.* 74, 5491-5506, 1969.
- Dickson, A. G., Determination of dissolved oxygen in seawater by winter titration, in *WOCE Operations Manual, WHP Operations and Methods, WOCE report, No. 68/91*, 11pp., 1994.
- Freeland, H. J., Sea surface temperatures along the coast of British Columbia: regional evidence for a warming trend, *Can. J. Fish. Aquat. Sci.*, 47, 346-350, 1990.
- Gamo, T., Y. Nogaki, H. Sakai, T. Nakai, and H. Tsubota, Spatial and temporal variations of water characteristics in the Japan Sea bottom layer, *J. Mar. Res.*, 44, 781-793, 1986.
- Kim, K. R., The East Sea (Japan Sea): A miniature test ground for global changes? Recent chemical observations during CREAMS 93-96, in *Biogeochemical Processes in the North Pacific*, edited by S. Tsunogai, pp. 41-51, Japan Marine Science foundation, Tokyo, 1997.
- Masugawa, T., and Y. Kitano, Appearance of H₂S-bearing bottom waters during the last glacial period in the Japan Sea, *Geochem. J.*, 18, 167-172, 1984.
- Munk, W.H., Abyssal recipes, *Deep-Sea Res.*, 13, 707-730, 1966.
- Nagata, Y., V. B. Lobanov and L. D. Talley (editors), Proceedings of the Workshop on the Okhotsk Sea and adjacent areas, *PICES Scientific Rep. 6*, 426 pp., 1996.
- Oba, T., M. Kata, H. Kitazatao, I. Koiaumi, A. Osmra, T. Sakai, and T. Takayama, Paleoenvironmental changes in the Japan Sea during the last 85,000 years, *Paleoceanography*, 6, 499-518, 1991.
- Read, J. F., and W. J. Gould, Cooling and freshening of the subpolar North Atlantic Ocean since the 1960s, *Nature*, 360, 55-57, 1992.
- Tamiki, K., Age estimation of the Japan Sea on the basis of stratigraphy, basement depth, and heat flow data, *J. Geomag. Geoelectr.*, 38, 427-446, 1986.
- Uematsu, M., H. Minam, Y. Hijikata, and Y. Kata, Paleoenvironmental change estimated from the concentration of major composition in the sediments of the northern Japan Sea, *Sea Research*, 5, 143-150, 1996, (in Japanese with English abstract).