Alkenone-sea surface temperatures in the Japan Sea over the past 36 kyr: warm temperatures at the last glacial maximum

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Abstract

The Japan Sea experienced bottom water anoxia at the last glacial maximum (LGM) since it is surrounded by four shallow straits, the sill depths of which are close to, or shallower than, the drop in sea level (~120 m) that occurred then. A distinctive negative δ18O excursion of planktonic foraminifera also took place during the LGM. This excursion has been interpreted from foraminiferal data as recording a drop in the paleosalinity of surface waters on the assumption of a constant low sea surface temperatures between 34 and 11 ka. We present here a profile of alkenone-based sea surface temperatures (alkenone-SSTs) over the past 36 kyr. Our results suggest that SSTs during the LGM were much higher than those previously assumed. After considering the factors that might affect estimation of alkenone-SSTs and comparisons of core-top alkenone-SSTs values with values for modern seawater we conclude that the higher alkenone-SSTs during the LGM are reliable and reasonable. These warm SSTs were probably caused by radiative equilibrium associated with the development of stable water stratification in the Japan Sea during the LGM.

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1. Introduction

During the late Quaternary, the Japan Sea, which is a semi-isolated marginal sea located between Japan and the Asian continent and connected to the Pacific Ocean through shallow straits with sill depths of less than 130 m, experienced significant changes in sea-level (e.g. Oba et al., 1991, 1995; Ishiwatari et al., 1994, 1999; Tada et al., 1999). During the last glacial interval, the Japan Sea became almost isolated from the open ocean as sea-level dropped by approximately 120 m at the last glacial maximum (LGM).

Oba and his coworkers discovered a negative excursion in oxygen isotopic composition of planktonic foraminifera at site L-3 (Oki ridge) in the Japan Sea, where the δ18O became gradually lighter by ~2.7‰ between 33 and 17.5 ka, the latter corresponding to the end of the LGM [~19–18 ka (calendar age) is used for the LGM around the Japan Sea (Oba et al., 1995)]; and then shifted to heavier values by ~3.3‰ until 1.2 ka (Oba et al., 1991; 1995). Oba et al. (1991) assumed that the negative δ18O excursion of planktonic foraminifera during the 33–17.5 ka period was caused only by the decrease in paleosalinity of surface seawater. They estimated that the paleosalinity dropped from 33 to 20 during this interval, using a temperature-δ18O relationship of foraminifera (cited in Section 4.1.2.) and assuming that the paleo-SST remained constant at 4.4±1°C, together with assumptions about the δ18O values of seawater and freshwater for...
mixing (Matsui et al., 1998). A paleosalinity of 20 is ~14 less than the modern level.

However, their conclusion was based on an interpretation of oxygen isotope analysis of planktonic and benthic foraminifera. No paleo-SSTs have been measured to date. Nevertheless, the model of depleted paleosalinity and low-SSTs during the LGM seems accepted in the scientific community (e.g. Keigwin and Gorbarenko, 1992; Crusius et al., 1999), although CLIMAP estimates give higher community (e.g. Keigwin and Gorbarenko, 1992; Crusius et al., 1999) during the LGM. A paleosalinity of 20 was inferred for other parts of the world using oxygen isotope analysis of planktonic and benthic foraminifera. No paleo-SSTs have been measured to date. Nevertheless, the model of depleted paleosalinity and low-SSTs during the LGM seems accepted in the scientific community (e.g. Keigwin and Gorbarenko, 1992; Crusius et al., 1999), although CLIMAP estimates give higher community (e.g. Keigwin and Gorbarenko, 1992; Crusius et al., 1999) during the LGM. A paleosalinity of 20 was inferred for other parts of the world using oxygen isotope analysis of planktonic and benthic foraminifera. No paleo-SSTs have been measured to date. Nevertheless, the model of depleted paleosalinity and low-SSTs during the LGM seems accepted in the scientific community (e.g. Keigwin and Gorbarenko, 1992; Crusius et al., 1999), although CLIMAP estimates give higher community (e.g. Keigwin and Gorbarenko, 1992; Crusius et al., 1999) during the LGM. A paleosalinity of 20 was inferred for other parts of the world using oxygen isotope analysis of planktonic and benthic foraminifera. No paleo-SSTs have been measured to date. Nevertheless, the model of depleted paleosalinity and low-SSTs during the LGM seems accepted in the scientific community (e.g. Keigwin and Gorbarenko, 1992; Crusius et al., 1999), although CLIMAP estimates give higher community (e.g. Keigwin and Gorbarenko, 1992; Crusius et al., 1999) during the LGM. A paleosalinity of 20 was inferred for other parts of the world using oxygen isotope analysis of planktonic and benthic foraminifera. No paleo-SSTs have been measured to date. Nevertheless, the model of depleted paleosalinity and low-SSTs during the LGM seems accepted in the scientific community (e.g. Keigwin and Gorbarenko, 1992; Crusius et al., 1999), although CLIMAP estimates give higher community (e.g. Keigwin and Gorbarenko, 1992; Crusius et al., 1999) during the LGM. A paleosalinity of 20 was inferred for other parts of the world using oxygen isotope analysis of planktonic and benthic foraminifera.
collection and was almost in an air-dried state. No appreciable effect of sample storage at room temperatures on $U_{37}^{c}$ values has been reported (Sikes et al., 1991), nor is it seen in core L-3 (described later).

2.2. Total organic carbon and total nitrogen analysis

Subsamples taken from these cores were freeze-dried and ground to powder for total organic carbon (TOC) and total nitrogen (TN: total organic nitrogen plus ammonium nitrogen) analysis. Duplicate determination used HCl-treated sediment samples (~100 mg) analysed by dry combustion using a Fison NA1500-NCS elemental analyzer. The relative standard deviation of these measurements was better than 10% for both TOC and TN.

2.3. Alkenone and alkenoate determination

Free lipids were extracted by ultrasonication of wet samples (ca. 4 g) in 50 ml Pyrex glass centrifuge tubes containing benzene/methanol (6:4 v/v). The extracts were collected after centrifugation (10 min, 3000 rpm), and saponified with 5% NaOH-methanol. Distilled water was added to the solvent extracts after their transference to separatory funnels and the neutrals were extracted with n-hexane/diethyl ether (9:1 v/v). The neutrals were fractionated on a silica gel column (silica gel: Mallinckrodt Inc. 100 mesh; column size: 50 x 5 mm i.d.). Long-chain alkenones were obtained as the third (benzene) eluate after hexane (1st eluate containing saturated hydrocarbons) and hexane/benzene (2nd eluate containing unsaturated and/or aromatic hydrocarbons) elutions. The 1st and 2nd eluates were stored for later study. The third eluates were evaporated to small volumes and analyzed by gas chromatography (GC) or gas chromatography/mass spectrometry (GC/MS).

GC analysis of alkenones used an HP 5890 instrument fitted with a splitless injector and a DB-5 fused-silica capillary column (60 m x 0.32 mm i.d.). The oven temperature was programmed from 50 to 150°C at 30°C min⁻¹ and then to 325°C at 3°C min⁻¹. Quantitation was achieved by integration of FID peak areas; 1-docosene was used as a reference (injection) standard. GC/MS analysis used a Finnigan INCOS 50 MS/Varian 3400 GC, with analytical conditions similar to those for GC analysis. Alkenone-SSSTs were calculated in this study using the empirical equation given by Prahl et al. (1988): $U_{37}^{c} = 0.034 T (°C) + 0.039$, where $U_{37}^{c} = [C_{37:2}] / [C_{37:2} + C_{37:3}]$.

Alkenones were analyzed by a similar procedure used for the alkenones except for elimination of the NaOH-methanol saponification.

2.4. Micropaleontological analysis

Coccolith assemblages were analyzed on smear slides using a polarizing microscope with 1250 times magnification. The abundance of coccoliths was measured only qualitatively, and ranked into four categories: very rare, rare, few and common. For the samples containing rare to common coccoliths, 200 specimens were identified to species or genus level, and their numbers were recorded. Occurrences of Florisphaera profunda and reworked specimens were counted separately.

3. Results

3.1. TOC and alkenone/alkenoate analytical data

The vertical profiles for TOC concentrations were useful for correlating the sediment cores L-3, PC-9 and KI-5 (Fig. 2). The TOC profiles for cores PC-5 and KI-5 were very similar, even though the two cores were taken in different years (1994 and 1993). Since the sampling location for core PC-9 is close to that for core KI-5, this result indicates the good reproducibility of TOC profiles in this region. TOC concentrations in core PC-9 slightly decreased upward from 500 cm (37 ka) to 357 cm (28 ka), became uniform until 214 cm (17.5 ka), and then increased upward. At 128.5 cm (11.3 ka: TL-1 layer), TOC concentrations exhibited a maximum and then decreased again slightly followed by nearly constant values. This vertical profile matches well that in core L-3.

In both cores L-3 and PC-9, a considerable amount of C$_{37}$ alkenones was detected in the Holocene section (C$_{37}$ conc.: 1.7±0.3 µg g⁻¹ for L-3, 1.2±0.7 µg g⁻¹ for PC-9). For the sections below the top of TL-2 (17.5 ka), however, the abundance of alkenones in core L-3 was extremely low (C$_{37}$ conc.: <0.1 µg g⁻¹), compared with that in core PC-9 (0.4±0.2 µg g⁻¹). This result suggests that coccolithophore production was higher in the region where core PC-9 was taken compared to the region of core L-3 during the glacial period.

Crossplots of EE/K$_{37}$ (a ratio of C$_{36:2}$ ethyl alkenoate to C$_{37}$ alkenones) versus $U_{37}^{c}$ and EE/K$_{38}$ (a ratio of C$_{36:2}$ ethyl alkenoate to C$_{38}$ alkenones) versus $U_{37}^{c}$ have been proposed by Sawada et al. (1996) from culture experiments to estimate the extent of production of Emiliania huxleyi relative to Gephyrocapsa oceanica in seawater. This is based on their result that the regression curves for EE/K$_{37}$ vs. $U_{37}^{c}$ and EE/K$_{38}$ vs. $U_{37}^{c}$ in the two species are different. Although the results of Sawada’s culture experiment are not necessarily supported by their own and other microscopic observations of sediment samples (e.g. Herbert et al., 1998), we carried out both alkenone analyses and microscopic observation to check the coincidence of the two kinds of results.

We measured the concentrations of C$_{36:2}$ ethyl alkenoate, C$_{37}$ and C$_{38}$ alkenones in selected samples from PC-9. All the data plotted on the same curve, consistent with $E$. huxleyi being the major contributor of these alkenones (Fig. 3). This observation, however,
is in conflict with the results of microscopic analysis, as described below.

3.2. Coccolith data

Out of 20 sections examined for core PC-9, 14 sections yielded sufficient concentration of coccoliths for analysis. In most samples, the assemblage was dominated by *E. huxleyi* and *G. oceanica*, but *Braarudosphaera bigelowii* was the dominant species in the 339.0 and 363.0 cm sections (26.4 and 28.1 ka, respectively). *Coccolithus pelagicus* that dwells in cold waters was rare in the upper sections down to section 131.5 cm (11.5 ka) and became abundant below section 151.0 cm (12.9 ka). This observation reflects the increased influence of the Tsushima Warm Current over the last 12 kyr.
The relative abundances of *E. huxleyi* and *G. oceanica* coccoliths are shown in Fig. 4. The highest concentration of coccoliths was observed in the section at 131.5 cm (12.9 ka), which corresponds to the maximum TOC concentration (Fig. 2). Although the alkenone/alkenoate-type analysis suggests that the major contributor to the sedimentary alkenones is *E. huxleyi*, the coccolith data indicate that *G. oceanica* comprised the dominant part (~93%) of the haptophyte species in the sections at 19.3 and 20.6 ka (Fig. 4). The discrepancy between molecular analysis and microscopic observation is discussed in Section 4.2.1.

3.3. Sea surface temperatures (SSTs) obtained from alkenone analyses

Fig. 5 displays the temporal profiles of alkenone-SSTs calculated from the empirical equation given by Prahl et al. (1988) for cores L-3, PC-9, and KI-5. The profile of alkenone-SST for core PC-9 [Fig. 5(b)] is similar to that for core KI-5 [Fig. 5(c)], demonstrating that the results for alkenone-SSTs through time are reproducible.

The profiles for cores PC-9 and KI-5 indicate that SSTs were ~12°C at ~36 ka [Fig. 5(b)], increased from 12°C to 18–19°C between 36 and 30 ka, and remained almost constant until ~17.5 ka. The water column became stratified at this time due to restricted vertical mixing as a result of sea-level drop during the LGM. With the deglacial rise in sea level, SST decreased from 18–19 to ~12°C at site PC-9 at 17-12 ka. Between 12 and 9 ka, SSTs increased from ~12 to 18°C, remained almost constant until 7 ka and then decreased to ~16°C and fluctuated around 16–17°C thereafter.

The time resolution for the SST profile of core L-3 [Fig. 5(a)] is low compared to those for cores PC-9 and KI-5, but the following common features can be identified among those SST profiles: (i) relatively high SSTs at 17.5 ka, (ii) an SST drop between 17 and 12 ka, and (iii) an SST rise after 12 ka. This suggests that the SST variations described above occurred over the whole area of the Japan Sea.

During the 12–11 ka interval, the SST at site L-3 shows a sharp rise from 15 to 19°C, probably as the warm seawater from the south began to flow into the Japan Sea through the Tsushima Strait (Oba et al., 1991). In the same interval, the rise in SST at site PC-9 was more gradual than that at site L-3, probably reflecting changes in the hydrodynamics in the Japan Sea.

4. Discussion

As described above, we obtained relatively high alkenone-SSTs in the Japan Sea during the LGM, which is consistent with our previous results (Ishiwatari et al., 1999). However these estimated alkenone-SSTs at the LGM are much higher than SST values previously assumed by Oba et al. (1991) and Matsui et al. (1998). Before going into a discussion of the possible reasons for this, we need to establish the reliability of the alkenone method. We have done this from a comparison with the other data in modern and late Holocene (0–7 ka) sediments when the Japan Sea was probably under relatively stable oceanographic conditions. We also discuss some uncertainties associated with the alkenone method.

4.1. Assessment of core-top and late Holocene alkenone-SSTs

4.1.1. Core-top alkenone-SSTs

The shallowest samples we analyzed were the 5–10 cm section (0.7 ka) of core L-3, the 0–6 cm Section (0.3 ka) from core PC-9 and the 2–4 cm section (0.1 ka) from KI-5. The sample from core L-3 is clearly not a core-top sample. The temperature estimated from $U_{137}$ was
19.1°C for L-3, 16.2°C for PC-9 and 15.2°C for KI-5. The modern mean annual SSTs obtained from the compiled data of JODC (Japan Oceanographic Data Center: on a 1° square grid) give 17.6±5.3°C for the region near L-3 site and 16.3±5.8°C for that near PC-9 site, respectively. Therefore, the alkenone-SST value for L-3 is 1.5°C higher than the modern mean annual SST, while the alkenone-SST values for PC-9 and KI-5 are close to the modern mean annual SST. The coincidence between the alkenone-SSTs and modern mean annual SSTs at two sites implies that the $U_{37}^{13}$ data provide reliable estimates of SST in this region.

4.1.2. Comparison between alkenone-SSTs and $\delta^{18}O$-derived SSTs in the late Holocene

Oba and his coworkers determined oxygen isotopic compositions of planktonic (mainly Neogloboquadrina pachyderma and Globigerina umbilicata) and benthic foraminifera (mainly Cassidulina japonica) in core L-3 (Oba et al., 1991; 1995). Later they reported vertical variations in $\delta^{18}O$ of planktonic foraminifera in cores PC-9 and KI-5 (Okumura et al., 1996). These data are shown in Fig. 5(d).

$N. pachyderma$ (right-coiling), which is a major species in the Holocene, is thought to live at depths shallower than 100 m, while the life style of $G. umbilicata$, which is the most abundant species in the glacial interval, is unknown since it is an extinct species (Oba, per. comm. 1999). Oba and his coworkers estimated SSTs ($\delta^{18}O$-SST is used hereafter) over the past 60 kyr except for the interval 16–30 ka when benthic foraminifera were absent in the sediments, using those oxygen isotopic compositions. For this estimation they ignored difference in the species of planktonic foraminifera present and assumed that: (i) bottom water temperatures were constant at 0.2°C which is the same as the present temperature over the periods studied, and (ii) vertical profiles of oxygen isotopic composition of seawater as a function of water depth were the same as those in the present time; i.e. $O_2$ in shallow sea water was assumed to be isotopically heavier by 0.2‰ than that in bottom water (below 1000 m in depth) (Oba et al., 1980). Thus, they calculated $\delta^{18}O$-SSTs to be 16.6–17.7°C for 0–10 ka, 8.2–11.5°C for 10–17 ka and 8.0–9.7°C for the period before 2.5 ka.

Although uncertainties are present in estimating SSTs using oxygen isotopic compositions of benthic and planktonic foraminifera, we calculated $\delta^{18}O$-SSTs using the same assumptions as cited above, and compared these with alkenone-SSTs using new microfossil analyses (Oba et al., 1995). The sediment sections which we examined are limited to those before 7 ka (0–75 cm in depth), because we excluded extinct species such as $G. umbilicata$. For the calculation of $\delta^{18}O$-SST, we used the same equations of temperature-$\delta^{18}O$ relationship as those used by Oba et al. (1980):

$$T(°C : 0.2) = 16.9 - 6.17(\delta_{df} - \delta_{sw}) + 0.52(\delta_{df} - \delta_{sw})^2$$

$$SST(°C) = 21.4 - 4.19(\delta_{df} - \delta_{sw}) + 0.05(\delta_{df} - \delta_{sw})^2$$
where \( \delta_{\text{uf}} - \delta_{\text{dw}} \) is the oxygen isotopic difference between calcite of benthic foraminifera and deep water, and \( \delta_{\text{uf}} - \delta_{\text{sw}} \) is the oxygen isotopic difference between calcite of planktonic foraminifera and surface water. Eq. (1) is used for benthic foraminifera (C. japonica) and Eq. (2) is used for planktonic foraminifera (N. pachyderma). We did not use the temperature–\( \delta^{18} \)O relationship \( [T (\degree C) = 16.9 - 4.38 (\delta_{\text{uf}} - \delta_{\text{sw}}) + 0.10 (\delta_{\text{uf}} - \delta_{\text{dw}})^2] \) of Matsui et al. (1998) for estimating paleosalinity variations, because the \( \delta^{18} \)O-SST obtained from this equation for the core-top sample of core L-3 (12.7\degree C for 0–1 cm section) was about 5\degree C lower than the modern mean annual SST at site L-3 (17.6\degree C).

It is clear from Table 1 that the agreement between \( \delta^{18} \)O-SSTs and alkenone-SSTs is good, although the former is slightly lower by about \(-0.4\degree C \pm 0.4\degree C (n = 5)\). This result seems in favor of the reliability of the alkenone-SSTs at least in late Holocene. A possible explanation for the slight difference in estimated SSTs is a difference in the depth of water inhabited by coccolithophores and planktonic foraminifera. From a study of long-chain alkenones in suspended materials during well defined thermocline conditions, Bentaleb et al. (1999) concluded that the \( C_{37} \) alkenone record reflects the temperature of highest primary production (maximum algal growth) which occurred at 30 m depth in their study. Herbert et al. (1998) found that alkenone-temperatures agree closely with mean annual SSTs in surface waters (0 m) and nearly as well with the warmest month (September) temperatures at 30 m depth along the California margin. Coccolithophores generally live in the upper photic zone, but planktonic foraminifera generally migrate vertically in the water column through their life cycle and thus reflect temperature changes through the surface water mass (Weaver et al., 1999). Oba et al. (1980) assumed that the planktonic foraminifera lived at depths shallower than 200 m. These facts suggest that temperatures estimated from \( \delta^{18} \)O of planktonic foraminifera reflect temperatures in waters deeper than those in which coccolithophores live. This might be particularly so at the time of development of strongly stratified surface waters in the Japan Sea at the LGM.

### 4.2. Problems related to the estimation of alkenone-SSTs

#### 4.2.1. Effects of haptophyte species on alkenone-SST

*E. huxleyi* and the closely related species *G. oceanica* are known to synthesize \( C_{37} \)-\( C_{39} \) methyl and ethyl alkenones and related alkenoates (Marlowe et al., 1990). The difference in the \( U_{37}^k \) vs. SST relationship between the two species is controversial. Volkman et al. (1995) and Sawada et al. (1996) claimed from culture experiments that a linear equation expressing the \( U_{37}^k \) vs. SST relationship is different between the two species; SST estimated for *G. oceanica* being higher than that for *E. huxleyi* at the same \( U_{37}^k \) value.

Recently, however, Conte et al. (1998) showed from culture experiments using a variety of strains of *E. huxleyi* and *G. oceanica* that the \( U_{37}^k \) vs. SST relationship for *G. oceanica* falls within the range of those observed for cultured strains of *E. huxleyi*. In addition, Conte et al. (1998) argued against the idea of Sawada et al. (1996) of distinguishing *G. oceanica* production from *E. huxleyi* from their alkenoate/alkenone ratio relative to \( U_{37}^k \), by presenting evidence that the ratio reflects a different cell physiology rather than genetics. Alkenone/alkenone analysis for core PC-9 would indicate that the major contributor of alkenoates and alkenones is *E. huxleyi* if we adopt the ideas of Sawada et al. (1996). But this result does not agree with the microscopic observations of haptophyte species in our samples. A similar observation was reported by Herbert et al. (1998) for California margin sediments. Their core top data fall closest to the Prahl et al. (1988) temperature calibration derived from laboratory cultures of *E. huxleyi*, although the smear slide data for selected samples show that *G. oceanica* comprises an important part of haptophyte flora. They claimed that the *G. oceanica* culture calibration of Volkman et al. (1995) does not seem to accurately reflect natural conditions. Moreover, if we adopt the \( U_{37}^k \) vs. SST relationship obtained for *G. oceanica* reported by Volkman et al. (1995) or Sawada et al. (1996), alkenone-SSTs should be higher than those obtained from Prahl et al. (1988) equation. Therefore, SSTs obtained after correction for the presence of *G. oceanica* would be higher than the uncorrected SSTs.

#### 4.2.2. Effects of postdepositional conditions on alkenone-SST

Thick laminated sections called TL-2 are observed between 26 and 17.5 ka. This fact together with other evidence, such as the disappearance of most benthic fauna (at least for site L-3: Oba et al., 1991), presence of highly \(^{13} \)C-depleted diploptene (Yamada et al., 1997), and high sulfur contents (Ishiwatari et al. 1999 unpublished data), collectively indicate the prevalence of anoxic bottom water conditions during this interval. Therefore, if strongly sulfate-reducing conditions in bottom water and sediments play a role in the reduction of alkenones, then the abundance of \( C_{37,2} \) and \( C_{37,3} \) alkenones might be modified by reduction or sulfurization. However, since no distinct change in the distribution of \( C_{37,2} \) and \( C_{37,3} \) alkenones has been observed in the anoxic Black Sea sediments (Sun and Wakeham, 1994), anoxic bottom water condition does not seem to produce abnormal \( U_{37}^k \) values.

Some studies have shown that \( U_{37}^k \) tends to be higher in oxic sediments as a result of preferential degradation of \( C_{37,3} \) alkenone relative to \( C_{37,2} \) alkenone and bioturbation mixing (Hoefs et al., 1998; Gong and Hollander, 1999). On the other hand, other investigators could not recognize any difference in \( U_{37}^k \) value between
4.2.3. Salinity effects on alkenone-SST in Japan Sea sediments.

There exist a possibility that the growth temperatures at least higher than 6°C below ~6°C, and moreover, the increase of %37:4 corresponds to the decrease in salinity (~1.5) for the Nordic sea core.

If SSTs were steady at ~4°C and paleosalinity decreased to 22 in the Japan Sea during the 33–17.5 ka interval as claimed by Matsui et al. (1998), and if the relationship between %37:4 and salinity found by Rosell-Melé (1998) is valid for the Japan Sea, then a high %37:4 content should be observed for the sediment samples in the 33–17.5 ka interval. The temporal variation in %37:4 over the last 36 kyr is displayed in Fig. 6. Evidently, no high %37:4 values for core PC-9 are observed in the 33–17.5 ka interval, suggesting that the SST cannot be so low. In the light of the findings of Rosell-Melé (1998), SSTs at site PC-9 must have been at least higher than ~6°C.

4.2.4. Other uncertainties

There are still several possible uncertainties disturbing the estimation of accurate SSTs. It is known that long-chain alkenones preserved in sediments are synthesized essentially at the depths of highest primary production (Bentaleb et al., 1999; Weaver et al., 1999). However, there exist a possibility that the growth temperatures at which the C_{37} alkenones were produced might have been influenced by changes in the glacial-interglacial

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Table 1

Data of benthic and planktonic foraminifera, their oxygen isotope composition and comparison between δ^{18}O-SSTs and alkenone-SSTs in late Holocene for core L-3

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Calendar age (Ka)</th>
<th>Benthic foraminifera</th>
<th>Surface water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Species</td>
<td>δ^{18}O (‰) (calculated)</td>
<td>Species</td>
</tr>
<tr>
<td>1</td>
<td>C. jap.</td>
<td>4.20</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>C. jap.</td>
<td>3.74</td>
<td>–0.44</td>
</tr>
<tr>
<td>11</td>
<td>C. jap.</td>
<td>4.04</td>
<td>–0.14</td>
</tr>
<tr>
<td>15</td>
<td>C. jap.</td>
<td>4.00</td>
<td>–0.18</td>
</tr>
<tr>
<td>21</td>
<td>C. jap.</td>
<td>4.00</td>
<td>–0.18</td>
</tr>
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<td>C. jap.</td>
<td>3.73</td>
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</tr>
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</tr>
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<td>–0.27</td>
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</tr>
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<td>4.00</td>
<td>–0.11</td>
</tr>
<tr>
<td>65</td>
<td>C. jap.</td>
<td>3.97</td>
<td>–0.21</td>
</tr>
</tbody>
</table>

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a Data from Oba et al. (1995). C. jap: Cassidulina japonica; N. pac: Neogloboquadrina pachyderma.

b δdw was calculated from T(°C) = 16.9 – 6.17 (δdf–δdw) + 0.52 (δdf–δdw)^2 (Oba et al., 1980) on the assumption that bottom water temperature is 0.2°C.

c δsw was assumed to be isotopically heavier by 0.2‰ than that of bottom water (Oba et al., 1980).

d SST was calculated from SST (°C) = 21.4 – 4.19 (δsf–δsw) + 0.05 (δsf–δsw)^2 (Oba et al., 1980).

e SST was calculated from U_{37}^{C} = 0.034 T(°C) + 0.039 (Prahl et al., 1998).
climatic regime or by changing oceanographic conditions caused by severely stratified surface seawaters. As discussed by Herbert et al. (1995), if the season of maximal production of haptophyte microalgae were to shift with climatic regime, it would produce alkenone-SSTs anomalies. Although it is difficult to rule out such potential anomalies, we have no evidence to suggest that they are important here.

4.3. Environmental changes in the Japan Sea

Notwithstanding the possibility that $U_{37}^{C}$ values are controlled by unknown factor(s), we conclude that the temporal variations in mean annual SST over the past 36 kyr, as shown in Fig. 5, are reasonable. Thus we conclude that the following environmental changes occurred in the Japan Sea over the past 36 kyr.

- 36–17.5 ka: During the interval 36-17.5 ka, the water column of the Japan Sea became stratified as sea-level dropped. As vertical mixing and upward transport of nutrients became restricted, deep waters [deeper than ~400 m from the sea surface as suggested by Ikehara et al. (1994)] became anoxic, leading to the formation of laminated sediment layers of TL-2. Evidence for anoxic deep waters was presented in Section 4.2.2. The high mean annual SSTs (18–19°C) may have occurred under heavily stratified surface seawater where thermal energy due to solar radiation is trapped in shallow waters. A similar phenomenon of radiative equilibrium is observed in brackish lakes (Yoshimura, 1976).

According to Oba et al. (1991), *Thalassiosira lacustris*, a diatom species common in the less saline waters of coastal areas, became abundant in the sedimentary sections during the 32–17.5 ka interval. This suggests that paleosalinity was lower in this interval. Therefore, a realistic scenario for environmental changes in the Japan Sea is that both SST rose and paleosalinity fell during this interval. Further studies are needed to develop a method of extracting signals of paleosalinity from those preserved in the Japan Sea sediments.

- 17.5-8 ka: Between 17.5 and 12 ka, the SST decreased and then increased between 12 and 9 ka at sites PC-9 and L-3. The decrease in SSTs is interpreted to have been caused by the onset of vertical mixing of seawater by the inflow of seawater from the north (Oyashio Current: Oba et al., 1991), or the south (Keigwin and Gorbarenko, 1992). The vertical mixing of seawater led to the disappearance of anoxic deep water. This is shown by the positive shift in $\delta^{13}C$ values of diploptene from $-57$ to $-25\%$ (Yamada et al., 1997), the disappearance of laminae.

The lowering of SST during 17–12 ka is qualitatively supported by the diatom fossil analysis where the ratio of warm-current species (*Pseudoeunotia doliolus, Paralia sulcata, Thalassiosira oestrupii*) to total species [warm-current region sp. + cold-current region sp. (*Denticulopsis seminai, Thalassiosira trifiltula, Thalassiosira nordenskioldii*)] dropped from about 0.8–0.9 at 17 ka to 0.4–0.5 at 12 ka for core C-3 taken at the site L-3 (Koizumi, 1984). This result also demonstrates that the constant $-4^\circ C$ model of Matsui et al. (1998) at the LGM is not realistic.

The SST rise in the 12–11 ka interval were probably caused by the inflow of warm seawater from the south through the Tsushima Strait (Oba et al., 1991).

- 8–0 ka. The present oceanographic regime became established at about 8 ka, and conditions since then have been similar to what is observed today.

5. Conclusions

A marked negative $\delta^{18}O$ excursion of planktonic foraminifera during the LGM observed in the Japan Sea.
sediment cores has been interpreted as recording a drop in paleosalinity of surface waters on the assumption of constant low sea surface temperatures between 34 and 11 ka. This assumption has now been checked and our results for alkene-SSTs over the past 36 kyr at Sites L-3, PC-9 and KI-5 indicate that SSTs during the LGM were much higher than those previously assumed. Comparisons of core-top alkene-SSTs values with values for modern seawater in the Japan Sea suggest that SSTs estimated from alklenes are reliable. The warm SSTs were probably the result of equilibrium of thermal energy due to solar radiation in stratified surface seawaters under conditions where the Japan Sea was largely isolated from the open ocean when sea level was lowest at the LGM. Physical modeling of the warm SSTs of the Japan Sea at the LGM, and magnitudes of paleosalinity change remain to be studied.

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