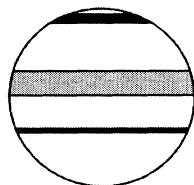


Millennial-scale variability of Holocene hydrography in the southwestern Okhotsk Sea: diatom evidence

Chieko Shimada,^{1*} Ken Ikehara,² Yoshihiro Tanimura³
and Shiro Hasegawa⁴

(¹Graduate School of Life and Environmental Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba 305-8572, Japan; ²Institute of Geoscience and Geoinformation/Geological Survey of Japan, the National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Higashi, Tsukuba 305-8567, Japan; ³Department of Geology, National Science Museum, 3-23-1 Hyakunincho, Shinjuku-ku, Tokyo 169-0073, Japan; ⁴Graduate School of Science and Technology, Kumamoto University, 2-39-1 Kurokami, Kumamoto 860-8555, Japan)

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Abstract: Diatom analysis of two submarine cores off eastern Hokkaido Island, northern Japan, provides insights into the Holocene palaeoenvironmental history of the southwestern Okhotsk Sea. Diatom flora was mainly composed of open-water and/or high-productivity-related *Thalassionema nitzschioides*, *Neodenticula seminae* and sea-ice-related species such as *Bacterosira fragilis* and *Fragilariopsis cylindrus*, suggesting millennial-scale alternation of dominant hydrographic regimes. Great abundances of *T. nitzschioides* and *N. seminae*, in particular, together with the ice-related species, from the early Holocene onward show that this biota was the major contributor to productivity in the southwestern Okhotsk Sea. On the other hand, faint but important occurrences of warm-water species such as *Fragilariopsis doliolus* were observed during 6.3–5.5, 4.2–2.7 and 1.1–0.2 ka. Such rhythmic occurrences of warm-water species as a sensitive indicator of the Soya Warm Current and the terminal branch of the subtropical Kuroshio Current reflect this history. The presence of this warm species is probably in tune with pulses of the Tsushima Warm Current that have been documented in Holocene sediments of the Japan Sea. These floral results, which might imply the millennially paced variability in palaeoclimate regimes in both Subarctic and subtropical regions, are well documented in these cores from the southwestern Okhotsk Sea.

Key words: Diatom, Holocene, millennial-scale variability, sea ice, Soya Warm Current, palaeoceanography, Okhotsk Sea, Japan.

Introduction

The modern Okhotsk Sea is one of the most important seas to which interdisciplinary attention has been paid, in order to decode global environmental signals in this unique oceanographic setting. Much of its importance derives from this sea's ice concentration, which can be an informative proxy of broader climatic change. For example, some workers have suggested that sea-ice concentrations in the Okhotsk Sea reflect atmospheric circulation: the Pacific/North American (PNA)

pattern with intensified Siberian High and southward development of the Aleutian Low, which accompany anomalous southward shifts of the entire Subarctic gyre (Cavaliere and Parkinson, 1987; Sekine, 1988; Parkinson, 1990). Secondly, since North Pacific Intermediate Water (NPIW; Talley, 1993) is thought to have originated in this sea (Talley, 1991) and/or from a biological pump (Sorokin and Sorokin, 1999), the Okhotsk Sea is inferred to be a significant sink for greenhouse gases (Tsunogai *et al.*, 1993; Honjo, 1997). Despite such significance, difficulties such as severe weather and political conditions have prevented oceanographic investigations. Shiga and Koizumi (2000), Gorbarenko *et al.* (2002), Ternois *et al.*

*Author for correspondence (e-mail: cshim@arsia.geo.tsukuba.ac.jp)

(2000) and Koizumi *et al.* (2003) have presented micropalaeontological and biogeochemical data from this sea for the interval since the last glacial period, but few studies with higher resolution have been conducted, even though analyses of submarine biotas can provide abundant palaeoceanographic information for predicting future climate regimes.

Data and samples have recently become available, including two Holocene diatomaceous submarine cores from the southwestern part of the Okhotsk Sea. This material allows us not only to reconstruct palaeoceanography, but also to present better correlations with adjacent terrestrial regions for which abundant palaeoclimatic information has been generated. In this study, we describe marine environmental changes in the southwestern Okhotsk Sea during the Holocene, using diatoms as sensitive palaeohydrographic proxies.

Materials and methods

Oceanographic setting of the Okhotsk Sea

The Okhotsk Sea on the margin of the northwestern Pacific Ocean is $1.53 \times 10^6 \text{ km}^2$ in area and 838 m in mean water depth (Figure 1). Its primary surface oceanographic feature is seasonal sea-ice coverage, which is the lowest-latitude such feature in the Northern Hemisphere. Ice formation generally starts in the northwestern part of the sea in November, whereas its southwestward development along eastern Hokkaido Island does not occur until January (Figure 2). After attaining its maximum extent in late March, the sea ice recedes northward and completely disappears in June (Parkinson, 1990; Japan Meteorological Agency, 2001). No permanent ice cover exists today. Wakatsuchi (1996) emphasized development of the Siberian High and huge freshwater runoff from the Amur River as major factors to explain sea-ice formation at such a low latitude.

The Okhotsk Sea is characterized secondly by an anti-clockwise surface-water gyre. Its comparatively warm water, which makes the southeastern part of the sea ice-free, flows from the Pacific Ocean through the Kruzshsterna Strait (1900 m depth), turns around in the northernmost part of the sea to flow south as the East Sakhalin Current, and is then

ventilated through the Bussol' Strait (2300 m depth). Water ventilated to the North Pacific mixes with the East Kamchatka Current, flows southward along the fore-arc area of the Kurile Islands, and is then named the Subarctic Oyashio Current (Ohtani, 1989). Meanwhile, the Tsushima Warm Current (TWC), a branch of the subtropical Kuroshio Current, partly flows northward off of northern Japan. This current terminates in the Okhotsk Sea through the Soya Strait and this successive southeastward current along Hokkaido Island is defined as the Soya Warm Current (SWC) and is the only warm current in the Okhotsk Sea (Figure 1). The SWC is characterized by a remarkable interannual variation of current velocity (greater in summer, to a maximum of $0.6\text{--}0.7 \text{ m s}^{-1}$), volume transport ($> 1.0 \text{ Sv}$ in summer at Soya Strait) and SST (max. $> 20^\circ\text{C}$ in late summer), which is driven by the sea-level difference between the Japan and Okhotsk Seas (Aota, 1985; Ohshima, 1994; Matsuyama *et al.*, 1999; Itoh and Ohshima, 2000). In contrast, salinity is more stable throughout the year ($> 33.6 \text{ psu}$; Aota, 1985). In winters with complete sea-ice coverage, the SWC is an undercurrent below 200 m depth with high temperature and salinity despite its disappearance at the surface (Aota, 1985). Recently, Watanabe and Wakatsuchi (1998) inferred a significant contribution of the SWC (in particular, the forerunner of this current), with greater density and higher temperature in early spring (Takizawa, 1982); $2\text{--}5^\circ\text{C}$ in SST, $26.8 \leq \sigma_\theta \leq 27.2$; Matsuyama *et al.*, 1999) and also of the denser, warmer and more oxenic NPIW source water located out of the Kurile arc. Although strong cooling and ejection of more-saline brine during sea-ice formation has also been presented as another mechanism (Kitani, 1973; Alfulit and Martin, 1987; Talley, 1991; 1993), no water with more than $26.7 \sigma_\theta$ potential density has actually been observed in the northwestern part of the sea, in spite of the necessity for denser water in the formation of NPIW source water. Noting that the NPIW is thought to be a major CO_2 sink, these suggestions imply that both sea-ice formation and the strength of the SWC might relate to global as well as regional climatic changes. More than 50 km offshore, the colder and fresher East Sakhalin Current flows southward, especially in late autumn to winter, owing to the influence of fresh water from the Amur River (Aota, 1985).

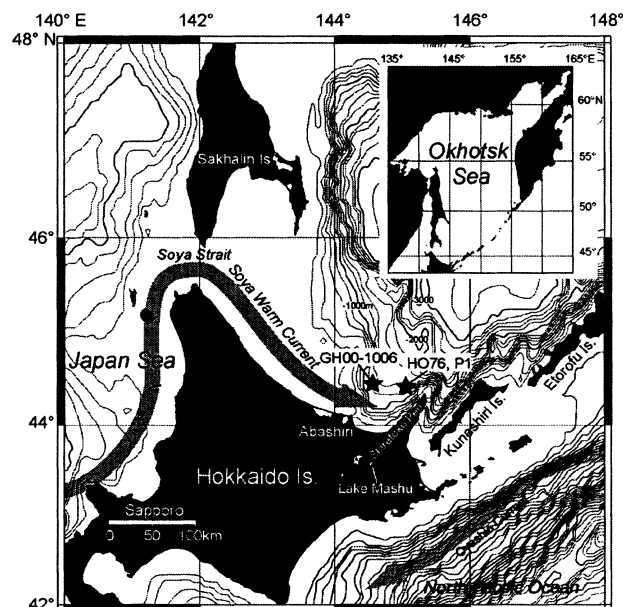


Figure 1 Map showing localities for the study cores.

Lithology of the cores

The submarine cores HO76-P1 and GH00-1006 were recovered from the southwestern Okhotsk Sea, off eastern Hokkaido Island (Figure 1; Table 1), during the cruises of R/V *Hokusei-maru* of Hokkaido University and R/V *Hakurei-maru No. 2* of the Geological Survey of Japan. Both cores are composed mainly of olive-grey, diatomaceous, silty clay with few sedimentary structures with several tephra layers. No clear erosional surface was found in either core by visual observation and/or X-ray radiography. Core P1 contains more abundant burrows at 430–170 cmbsf than does core 1006, and also contains several identifiable tephra layers at 139–133 cmbsf in layers and at 28–26 cmbsf in patches. For core 1006, we carried out onboard stratigraphic colour measurements using a colour spectrometer (Minolta CM-2022) at each 1 cm interval after being split. As a result of these observations, dark and thin lamination thresholding at < 40 of the L^* value (= brightness; rightness; higher values indicate a lighter tone) was observed at 340–320 and 300–0 cmbsf.

Age model

Diatomaceous lithofacies overall contain little calcareous material, particularly planktonic foraminifers, so afford few chances to conduct AMS radiocarbon dating. In addition,

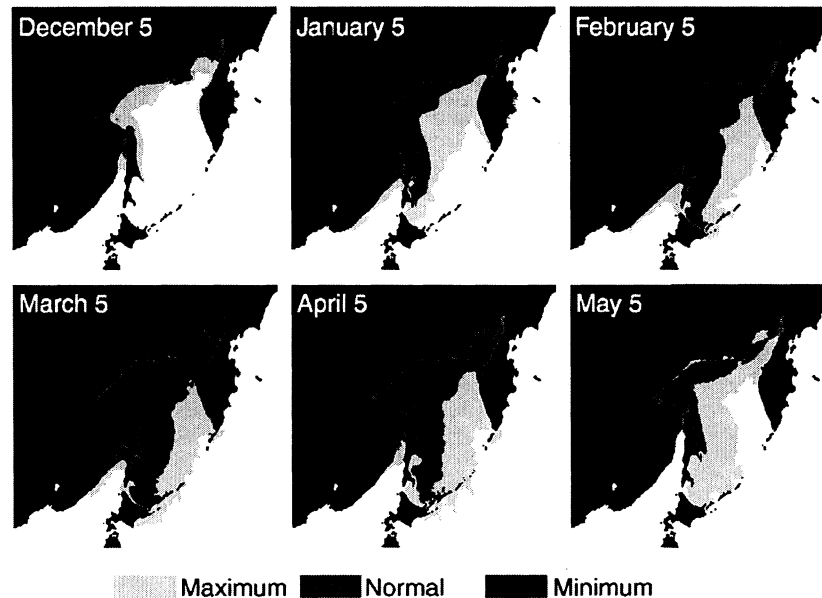


Figure 2 Normal, maximum and minimum sea-ice extent for 30 days (Japan Meteorological Agency, 2001). Normal ice extent is defined as gridpoints where sea ice has existed more than 10 years during the 30-year interval from 1971 to 2000. Maximum ice extent is defined as gridpoints where sea ice has existed for more than one year. Minimum ice extent is defined as gridpoints where sea ice has existed during all years.

stable oxygen isotope stratigraphy is not a useful method for Holocene age control. We inferred chronology from mollusc shells, bulk organic carbon and tephra (Table 2).

Three time-control points were available for core P1, based on AMS ^{14}C measurements of a molluscan shell near the core base, and tephra identification: 7260 ± 130 ^{14}C yrs BP (NUTA-5818) at 760 cmbsf for a mollusc shell, 980 ± 100 ^{14}C yrs BP (Gak-3139; Shoji and Katsui, 1974) for the Ma-b (Mashu-b) tephra at 136 cmbsf and 1739 yrs AD at 28 cmbsf for the Ta-a (Tarumai-a) tephra (Figure 3a; Shimada *et al.*, 2000). The ^{14}C age of the molluscan shell was converted into a calibrated age on INTCAL98 (Stuiver *et al.*, 1998) and calculated at 7242 yrs cal BP. The reservoir effect was considered using the value of 950 years from Keigwin (1998), which we estimated for the Okhotsk Sea (Shimada *et al.*, 2000). However, the age of Ma-b was redetermined as 1025 cal. yrs BP using Calib 4.3 (available at <http://depts.washington.edu/qil/dloadcalib/>). In this treatment, the typical stable isotopic carbon value of mid-latitude terrestrial plants, 25‰ (Sakai and Matsuhisa, 1996), was used. The extrapolated age of the basal part of core P1 is estimated as 7360 cal. yrs BP with a sedimentation rate as much as 105 cm/kyr.

To establish age control for core 1006, we obtained conventional radiocarbon ages (CRA) and followed Ikehara's (2000) concept to yield an age-depth relationship for bulk organic-radiocarbon dating (Table 2). First of all, note that all these determined CRAs are systematically about 2600 years older than expected, except those from the laminated unit (Figure 3b). We interpret the intercept of the regression on the age axis as a reflection of a time gap between the estimated depositional age (^{14}C years BP) and the raw CRA of the dated

bulk organic matter (^{14}C years BP) probably because of much older matter inputs. Using these corrected conventional radiocarbon ages (^{14}C years BP) for the estimated depositional ones (except for those from the laminated unit), we interpolated sedimentation rates between the dated horizons. The ^{13}C values of bulk organic carbon for core 1006 range from -22.3 to -24.9 ‰ (Table 2) and imply a major marine contribution to the sediments. There are problems in converting CRAs into calendar ages due to the uncertainty of the reservoir ages and the contribution of marine organic constituents in the 1006 core sediments, so we adopted the corrected CRA for this core. The bottom of core 1006 was estimated to date as 2780 yrs BP in corrected conventional ^{14}C age.

Diatom analysis

For diatom analysis, *c.* 20 mg of dried material at each horizon was acid-treated to remove organic and calcareous matter. After washing with purified water and settling for 4–5 hours to make pH-neutral, the diluted suspension was put onto a cover slip. A minimum of 200 diatom valves were counted to compile data sets. Special attention was paid to environmental markers and major taxa that had statistically significant percent abundances ($\alpha = 5\%$) at a given horizon. Important environmental markers were categorized into some groups to make them significant as representatives (Table 3). Percent abundance at 0.7% was remarked as statistically significant when 400 counts (=200 valves) were made. The floral information was *Chaetoceros* resting spores free.

Results

Percent abundances of major species are shown in Figures 4 and 5. Optical microscopy of 94 and 58 horizons in cores P1 and 1006, respectively, show that the dominant species in both cores were *Thalassionema nitzschioides* (Grunow) H. and *M. Peragallo* (up to 40–45% in each core), which is common in neritic areas, and *Neodenticula seminae* (Simonsen and Kanaya) Akiba and Yanagisawa (10–15%), the most important contributor to the ecosystem and exclusive to Subarctic

Table 1 Sample profiles of the studied cores

Core	Latitude (N)	Longitude (E)	Water depth (m)	Recovery (cm)	Coring gear
HO76-P1	44°31.74'	145°01.57'	1248	771	Piston
GH00-1006	44°35.54'	144°26.11'	1378	373	Gravity

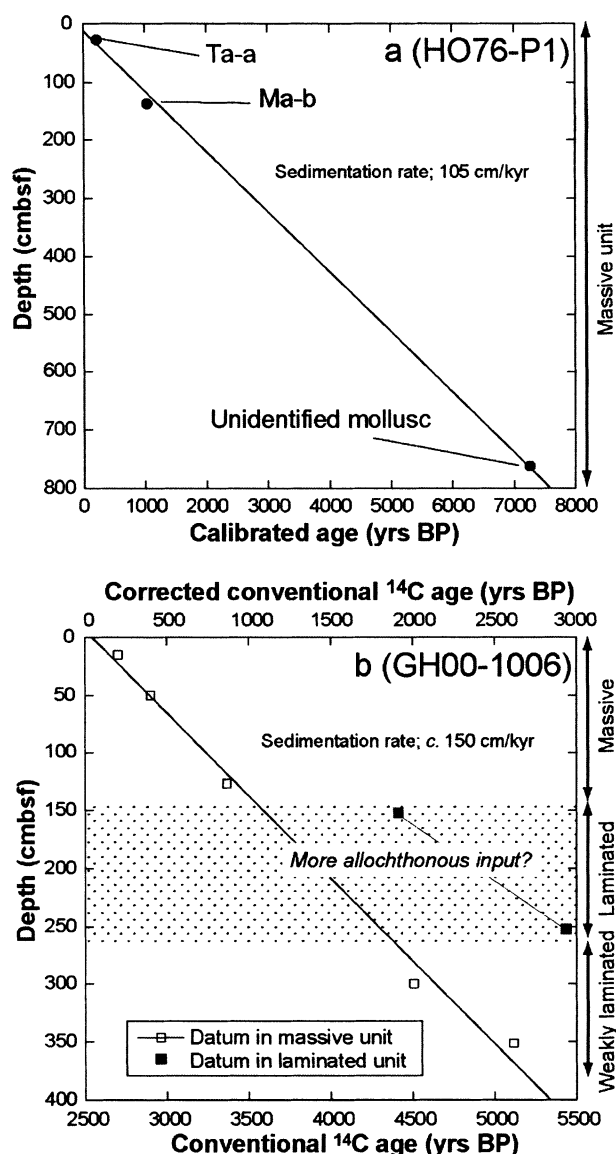


Figure 3 Age control for the study cores. (a) P1; (b) 1006.

seas. *Fragilariopsis cylindrus* (Grun) Krieger, *F. oceanica* (Cleve) Hasle and *Bacterosira fragilis* (Gran) Gran are reported to occur in polar or high-latitude neritic waters with the strongly implied presence of sea ice (Hasle, 1990; Poulin, 1990; Kang and Fryxell, 1992). In both cores, these three ice-related species were secondarily significant constituents of the flora, with up to an aggregate of c. 40% abundance. As

one clearly allochthonous factor, we frequently observed extinct *N. kamtschatica* (Zabelina) Akiba and Yanagisawa. *Denticulopsis* spp. (*D. simonsenii* Yanagisawa and Akiba, *D. hyalina* (Schrader) Simonsen and others), and *Thalassiosira* (in particular *T. antiqua* (Grunow) Cleve-Euler and *T. nidulus* (Tempère and Brun) Jousé) were present in lesser abundances. We also observed *Fragilariopsis doliolus* (Wallich) Medlin and Sims, *Nitzschia bicapitata* Cleve, *Azpeitia nodulifera* (Schmit) Fryxell and Sims and *T. lineata* Jousé, as warm-water species that occur in lower abundances. *Fragilariopsis doliolus* has been regarded as a typical temperate-subtropical species, based on analyses using both water-column and surface sediments (Kanaya and Koizumi, 1966; Hasle, 1976; Sancetta and Silvestri, 1986; Hasle and Syvertsen, 1997). This species is sensitive to the TWC, based on micropalaeontological analyses of Japan Sea sediments (Tanimura, 1981; Koizumi, 1989). *Nitzschia bicapitata*, *A. nodulifera* and *T. lineata* have also been cited as warm-water dwellers (Kaczmarek *et al.*, 1986; Fukuyo *et al.*, 1990; Tanimura, 1992; Hasle and Syvertsen, 1997). Although most of the individual warm-water species were less abundant, *F. doliolus* shows a clearer pulse-like occurrence in core P1 (Figure 4). This species alone in core 1006 presented more spotty and insignificant occurrence. A greater number of warm or extinct species were found in the more nearshore core P1. The pelagic species *Actinocyclus curvatulus* Janish in Schmidt and *Thalassiosira trifulta* Fryxell are also present.

As a general trend in temporal percent abundances, we recognized that ice-related and allochthonous species have decreasingly fluctuated in millennial order since 7.3 ka; the following periods during 6.3–5.5, 4.2–2.7 and 1.1–0.2 ka offer comparatively lower abundances, but by contrast open-water species, such as warm-water species *T. nitzschioides* and *N. seminae*, were more abundant during the periods (Figures 6 and 7).

Both cores contain a rich assortment of undamaged valves at most horizons. In particular, core 1006 generally had better preservation and higher valve concentrations per 1 g of dry sediment (VC; #·g⁻¹), and the mean value of VCs at analysed horizons of core 1006 is 1.6 times that in core P1. As reflected in the percent abundances, the VCs of *T. nitzschioides* and *N. seminae* were mostly responsible for the total VC variation in both cores, being more abundant in core P1 than in the more offshore core 1006. Although an accurate peak-to-peak correlation in total VCs of the two leading species is somewhat difficult between the cores, there is rough agreement at about 1.7 and 0.6 ka (Figures 6 and 7).

The detailed relationship between the VCs of warm *F. doliolus* and ice-related species in core 1006 was unclear due to very poor occurrences of the former. However, out-of-phase, or somewhat different-phase, occurrences among those species in P1 might be likely, particularly since around

Table 2 Profiles of radiocarbon measurements for chronology

Core	Depth interval (cmbsf)	Depth (cmbsf)	^{14}C age (^{14}C yrs BP)	Deviation	$\delta^{13}\text{C}$ (per mil)	Conventional age (^{14}C cal. yrs BP)	Accession no.
HO76-P1	139–133	136	980	100	–25	–	Gak-3139
	–	760	7260	130	0.95	7242	NUTA-5818
GH00-1006	15–17	16	2680	50	–23.7	2700	Beta-151546
	50–52	51	2870	40	–23.3	2900	Beta-151547
	125–127	126	3340	40	–23	3370	Beta-161977
	150–152	151	4390	40	–23.7	4410	Beta-151548
	250–252	251	5410	40	–23.9	5430	Beta-151549
	300–302	301	4480	40	–22.9	4510	Beta-161978
	349–351	350	5100	40	–23.9	5120	Beta-151550

Table 3 Summary of grouping of the major environment-indicative species

Group	Species
Ice-related	<i>Bacterosira fragilis</i> (Gran) Gran <i>Fragilariopsis cylindrus</i> (Grun) Krieger <i>F. oceanica</i> (Cleve) Hasle
Warm-water	<i>Azpeitia nodulifera</i> (Schmit) Fyxeil and Sims <i>F. doliolus</i> (Wallich) Medlin and Sims <i>Nitzschia bicipitata</i> Cleve <i>Thalassiosira lineata</i> Jousé
Extinct	<i>Denticulopsis</i> spp. <i>Neodenticula kamtschatica</i> (Zabelina) Akiba and Yanagisawa <i>Thalassiosira antiqua</i> (Grunow) Cleve-Euler <i>T. nidulus</i> (Tempère and Brun) Jousé
Brackish	<i>Paralia sulcata</i> (Ehrenberg) Cleve <i>Cyclotella</i> spp.

the mid-Holocene; there is an occurrence variation of *F. doliolus* on a millennial scale with peaks in around (7300), 5800, 3500 and 700 yrs cal. BP (Figure 6). Warm-water species made a very poor contribution to the total VC in the southwestern Okhotsk Sea.

Discussion

Millennial-scale variability of Holocene hydrography in the southwestern Okhotsk Sea

The presence of warm-water species in the floral array is faint but important. In the modern surface-current system, even if warm core rings cut off the subtropical Kuroshio Current, a direct migration of warm water from the North Pacific would be very unlikely. Thus, the occurrences of warm-water species in our cores imply input by the SWC, the extension of the subtropical Kuroshio Current water via the Japan Sea. Using the same P1 core, Kawahata *et al.* (2003) noted the presence of temperate *Cryptomeria*, temperate, evergreen, broadleaved *Cyclobalanopsis* and *Castanopsis* pollen (good indices of transportation by the TWC and not living on Hokkaido Island during the Holocene) in rough agreement with the warm diatom occurrences, except for the last 1000 years. They also stated that the palynological results were in accord with the Holocene pollen stratigraphy of Kunashiri Island (Korotky *et al.*, 2000) and central Japan (Sakaguchi, 1995). An especially warm climate optimum around 6 ka is well documented by the occurrence of warm-water molluscs such as *Meretrix lusoria* (Röding). These species, with a modern northern geographical limit in northeastern Honshu Island, Japan, are present in shell mounds along the coast at Abashiri City located in the eastern Hokkaido (Akamatsu, 1969).

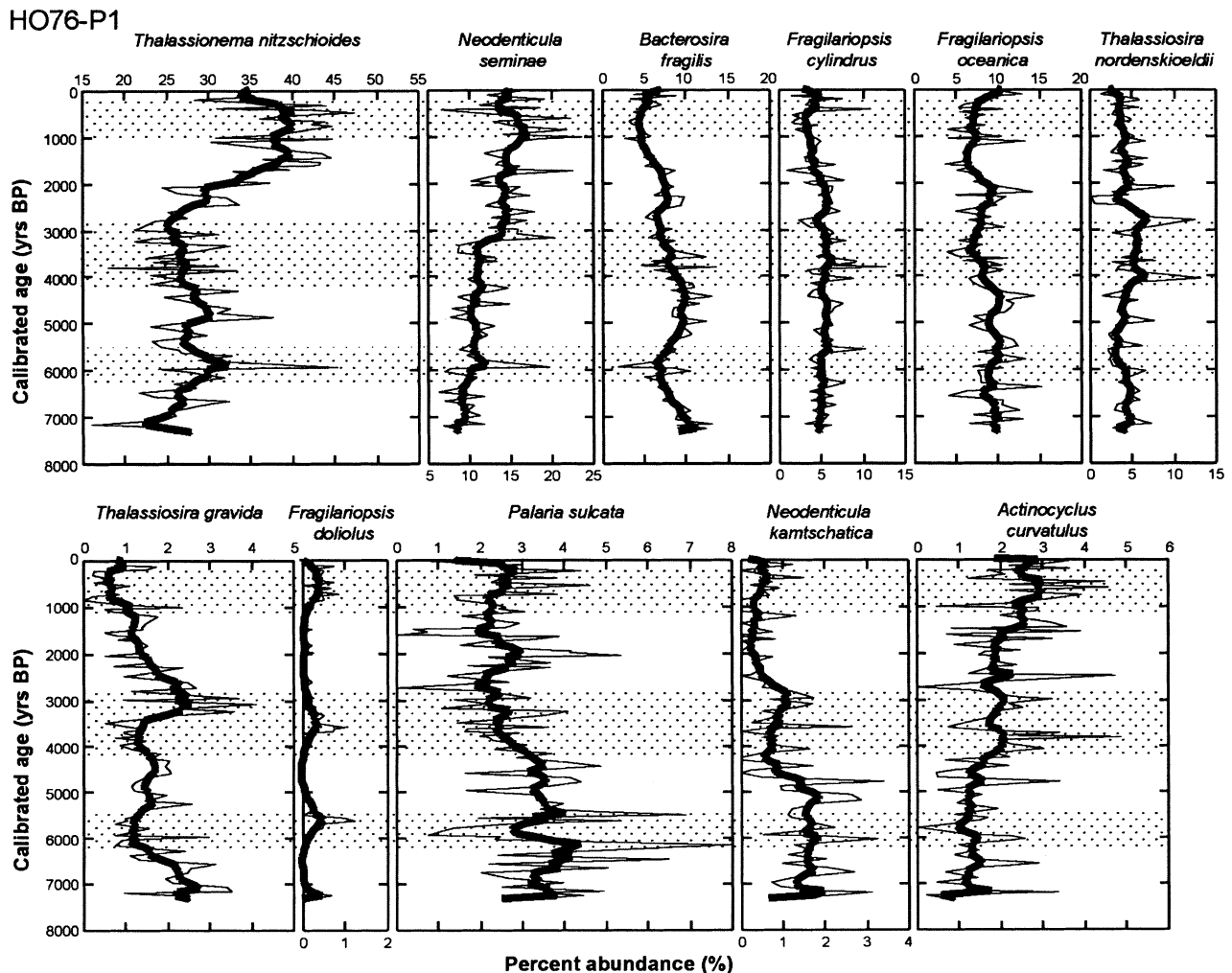


Figure 4 Percent abundances of major species in core P1.

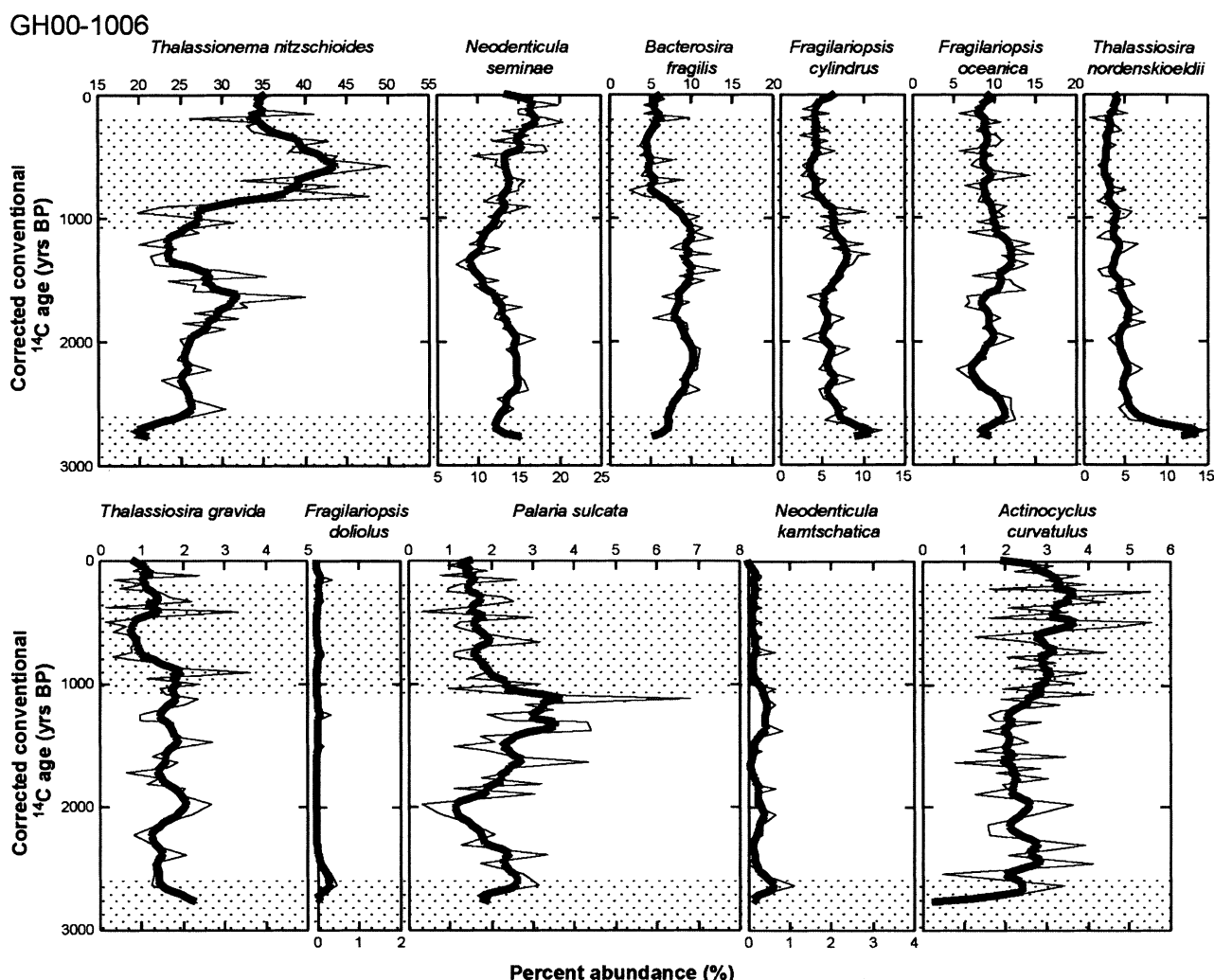


Figure 5 Percent abundances of major species in core 1006.

For some time it has been believed that the Holocene environments were more stable than those of the last glacial period (Johnsen *et al.*, 1972; Fronval and Jansen, 1997). However, tentative but well-documented evidence of Holocene environmental fluctuations has been accumulated more recently (O'Brien *et al.*, 1995; Sirocko *et al.*, 1996; Bond *et al.*, 1997; Campbell *et al.*, 1998; Bianchi and McCave, 1999). As pointed out in Burckle (1992), who detected a distinct appearance during the Holocene in the southwestern part of the Japan Sea, and in other works, *F. doliolus* has been revealed to be representative of the TWC. Based on downcore records of *F. doliolus*, the TWC that began the intrusive flow into the Japan Sea at 9.0 ka had a rhythmic variation with *c.* 1800-yr-long periodicity (Koizumi, 1989), which approximately correlates with terrestrial pollen records in Japan (Sakaguchi, 1995). Our diatom records off Shiretoko Peninsula in the southwestern Okhotsk Sea might be subject to small temporal discrepancies, but at least seem to be synchronous with records from other areas around Japan (Figure 6). Our floral data documented at least three warmer episodes during the last 7.3 ka including successful detecting of the mid-Holocene climate optimum around 6 ka (Figure 6). Not all climatic episodes in our results are correlative with those of the Japan Sea and Japanese mainland.

Holocene diatom stratigraphy recently worked out by Koizumi *et al.* (2003) using two cores from the central and

eastern parts of the sea appears to be approximately parallel to those of our representative species in percent abundances. Millennial-scale alternation of dominant hydrographic regimes between open water and sea ice seems to be reflected in both our and their cores. Specifically, an open-water regime is suggested to have gradually increased since 7.3 ka. By contrast, ice-related species have become minor in particular since 5.0–4.5 ka, with the lowest record in abundance around 0.5–0.4 ka. Further, a decrease of *P. sulcata*, a representative of littoral input, is also analogous in abundances since 3.0 ka. Thus, variations of some representative diatom abundances would roughly seem to be spatially correlative and isochronous, but higher resolution is hardly expected at this time. Note that *T. nitzschioides*, a 'warm-water species' in Koizumi *et al.* (2003), was not treated as such in our study. Since *T. nitzschioides s. l.* are known to distribute almost all over the neritic seas except the polar regions as acknowledged with very wide temperature/salinity tolerance, few studies have succeeded in palaeoceanographic reconstruction focusing on this species (Tanimura, 1999). Taxonomic information at variety level should be viewed with serious caution if using this species as a sensitive palaeoenvironmental indicator for a study in higher resolution.

Cores from near the southernmost front of average sea-ice extent (Figure 2) were expected to reflect the spatial dynamics of sea-ice concentrations and signals of the SWC. Such a

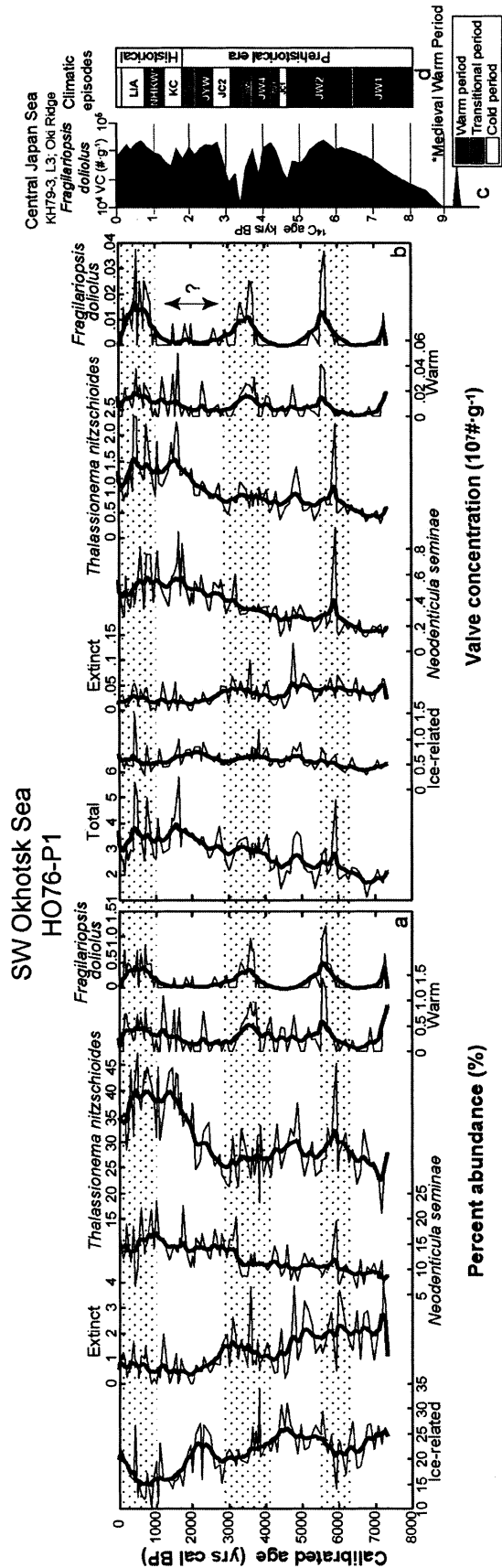


Figure 6 Percent abundances (a) and valve concentrations (b) of major species and species groups in core P1. Taxa grouping follows Table 3. Schematic correlations with past studies are also shown; (c) the diatom records in the Japan Sea (Koizumi, 1989); (d) terrestrial climate reconstruction based on palynology by Sakaguchi (1995). Chronology of these past studies are given as ^{14}C dates. Note that a strict correlation between these studies is not done here.

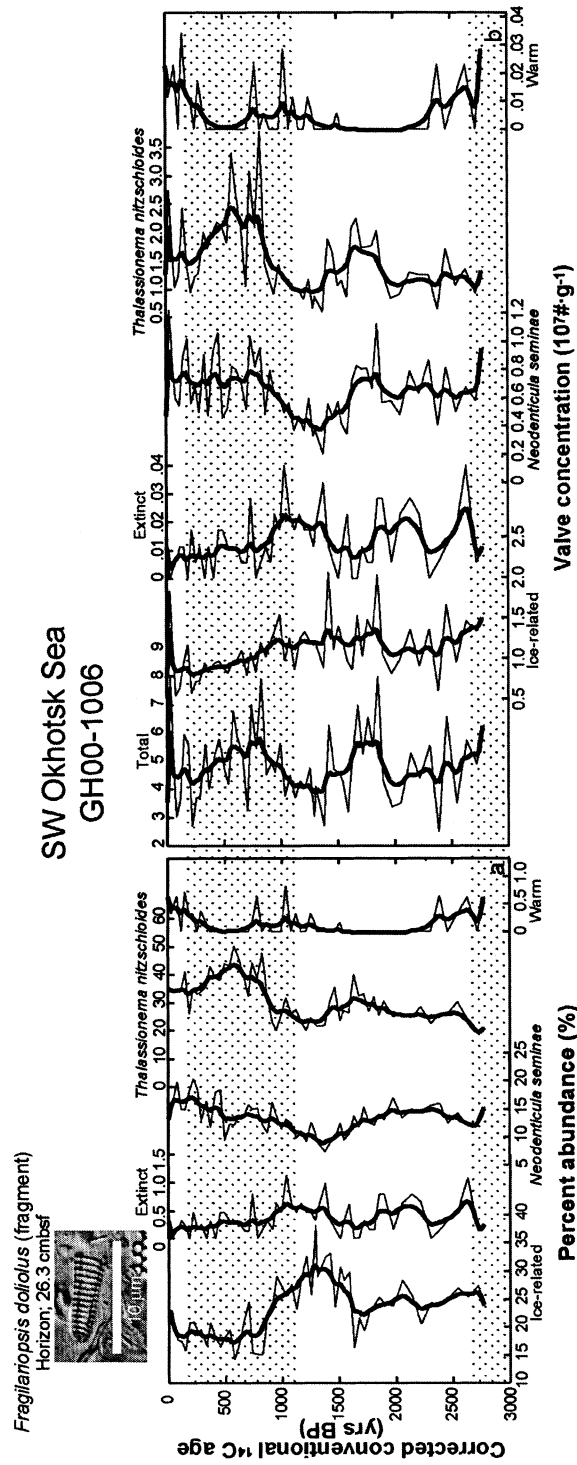


Figure 7 Percent abundances (a) and valve concentrations (b) of the major species and species groups in core 1006. Taxa grouping follows Table 3.

geographical setting would calibrate the different floral profiles into identical time slices for the two cores. Overall, sea-ice zones (except in late spring) exhibit lower productivity than do open-water zones (Alexandar, 1980). In both our study cores, *T. nitzschioides* and *N. seminae* were the most abundant species (which shows that ice-related species were not primary contributors to productivity, especially in nearshore core P1).

Perspective on further palaeoclimatological reconstruction

Actually, neither observations nor numerical experiments have shown any direct relationship between sea-ice concentration in the Okhotsk Sea and volume transport of the subtropical Kuroshio Current. Although a detailed relationship between them is still an open question, Tachibana *et al.* (1996) reported a synchronous and drastic decrease of sea-ice concentration in the southern Okhotsk Sea and the intensity of the Aleutian Low, accompanied by a decrease in intensity of the Siberian High (winter monsoon) and temperatures around Japan, based on a lag correlation analysis before the early 1990s. This implies for (sub)tropical regions that the PNA pattern inhibits development of the Pacific Subtropical High, with lower-volume transport in accord with weakened trade winds during the El Niño mode (Yasunari, 1991; Akitomo *et al.*, 1996). If longer-lasting fluctuations of such marine and atmospheric regimes had occurred due to certain mechanisms in the past, this might explain the series of floral variations we see in our study cores. Of course, more environmental investigations are required to clarify in higher resolution whether the palaeoclimatic variations both in subtropical and Subarctic regions were synchronously periodic with each other because the temporal profiles in VC for warm-water and ice-related species in our study do not always show a 'perfect' negative correlation.

Anyway, it is important to note that such changes in the climatic subsystems would cause corresponding shifts in the biosphere, due to variations in water temperature and/or nutrient supply. Here, we stress that the Holocene biotic responses preserved in the southwestern Okhotsk Sea suggest interactions among the climatic subsystems not only in the Subarctic but also in the subtropical North Pacific, even though warm signals reflected by the flora are very subtle because the SWC was distant from the Kuroshio Current. Even if the SWC signal and its impacts on sea ice concentration in the Okhotsk Sea were faint and very localized, the warm species are crucial and conspicuous indicators of warming among the otherwise overwhelmingly dominant cold and ice-related species.

Conclusions

In order to reconstruct the Holocene palaeoenvironmental evolution of the southwestern Okhotsk Sea, we focused on diatom evidence from two submarine cores, and discovered the following: (1) abundant *Thalassionema nitzschioides* and *Neodenticula seminae* and other ice-related species have been present since the early Holocene, and this biota (these two species in particular) was the major contributor to productivity; (2) there are rhythmic occurrences of warm-water species such as *Fragilariopsis doliolus* (a sensitive indicator of the Soya Warm Current, the terminal branch of the subtropical Kuroshio Current in the Okhotsk Sea), with three major peaks at around 5500, 3500 and 700 cal. yrs BP. The ice-related species show occurrences out of phase with the warm species. We infer that occurrences of the warm species were in tune with pulses of the Tsushima Warm Current known from Holocene sediment records in the Japan Sea. Our results suggest that

phytobiotic processes with millennially paced variability of palaeoclimate regimes for both Subarctic and subtropical provinces are present in submarine sediments in the Okhotsk Sea.

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