Long-Chain Alkenones in the Shimosa Group Reveal Palaeotemperatures of the Pleistocene Interglacial Palaeo-Tokyo Bays

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Research article

Keywords: Alkenone palaeothermometer, Interglacial periods, Shimosa Group

Posted Date: September 14th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-880095/v1>

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Abstract

The Shimosa Group, middle- to late-Pleistocene sedimentary succession, has been the focus of stratigraphic attention because it is beneath the Tokyo metropolitan area of central Japan. It is also of palaeoclimatic significance because it contains important interglacial marine strata of the past 450,000 years. Since the marine strata of the Shimosa Group were formed in the fluvial, estuary, and shallow inner bay known as Palaeo-Tokyo Bay, few occurrences of marine microfossils, make it difficult to quantitatively reconstruct the palaeotemperatures. Here, we extracted long-chain alkenones from the core GS-UR-1 penetrating the Shimosa Group to Marine Isotope Stage (MIS) 11. We found that the alkenone unsaturation ratio appears to reflect the sea surface temperatures (SSTs) of Palaeo-Tokyo Bays formed during MIS 5e, 7e, 9, and 11, which might be recorded around the peak of each interglacial period. The palaeo-SSTs during each interglacial period were 2–3 °C higher than the palaeo-SSTs of Tokyo Bay in the pre-industrial era, seemed to reach the similar level as the Holocene thermal maximum. We suggest that the LCA-based proxy, which has not been utilized hitherto in studies on the Shimosa Group, demonstrates its potential to provide palaeoclimatic and stratigraphic information.

1 Introduction

The modern increase in greenhouse gas concentrations in the atmosphere and the weather catastrophes of recent years have stimulated growing public and scientific interest. Palaeotemperature reconstructions for the past interglacial periods are particularly important in palaeoenvironmental studies because they provide a basis for comparison with the present interglacial period (Holocene) and its future evolution under global warming (Tzedakis et al., 2009, 2012). Of particular importance is the last 450,000 years, when the 100-kyr eccentricity cycle characterising modern climate was established (the so-called mid-Brunhes event) because some of the interglacial periods during this era are characterised by high atmospheric CO₂ concentrations and have potentially been warmer than the present day (e.g., Droxler et al., 2003; Lüthi et al., 2008; Melles et al., 2012; Uemura et al., 2018). For example, the latest Intergovernmental Panel on Climate Change (IPCC) report states that the last interglacial period, that is Marine Isotope Stage (MIS) 5e, was 0.5–1.5°C higher in surface temperature than the preindustrial period when assessed on a global average and was a warmer environment approaching the current greenhouse Earth (Six Assessment Report, 2021). MIS 11 has also attracted attention because of its similarity in some orbital parameters to the Holocene and its warm climate (Candy et al., 2014). However, there are large diversities among these interglacial periods in terms of the regional variation in their intensity, which makes their climatic structure and controlling mechanism elusive (Lang and Wolf, 2011; Milker et al., 2013; Otto-Bliesner et al., 2013; Hoffman et al., 2017; Turney et al., 2020).

The climate in the centre of Honshu Island, Japan is controlled by unique oceanic conditions (Fig. 1a). It faces the Kuroshio extension and subarctic fronts, which generate a distinct sea surface temperature (SST) gradient in the latitudinal direction (Kida et al, 2016). It is also located near the northern limit of the westerly jet that bounds the East Asian summer monsoon front where temperatures and precipitation vary greatly at its boundaries (Sampe and Xie, 2010; Nagashima et al., 2013; Tada and Murray, 2016).

Because of these oceanic and atmospheric settings, the north-south anomaly in the climate of Honshu Island is very large, which means that it is sensitive to global climate change, and relatively large signals of palaeoclimatic and palaeoceanic change at various chronological scales has been often observed (e.g., Haneda et al., 2020; Kajita et al., 2020b).

Despite its high palaeoclimatic significance, there are not many geological samples that can be used for systematic and continuous palaeotemperature reconstructions for multiple interglacial periods after the mid-Brunhes event. Continuous and accurately dated long archives, such as lake and marine sediments, are promising for enhancing information. In the case of lakes, the sediment core recovered from Lake Biwa, the largest and oldest lake in Japan, has been recorded up to more than 450,000 years ago, which provides palaeoclimate information based on pollen indicators (Nakagawa et al., 2008; Tarasov et al., 2011). With respect to marine sediment cores, with the exception of a few sediment cores drilled in the Japan Sea at IODP Expedition 346 dating back to several million years (Tada et al., 2018; Sagawa et al., 2018), there are few promising archives especially on the Pacific side, which is affected by two large western boundary currents. Because it is relatively difficult to recover the continuous palaeoclimate records since the mid-Brunhes event using marine or lake sediment cores, we focused on the marine strata existing in the coastal subducting plains formed during the past sea-level highstands. Typical examples are distributed in the Osaka Plain and the Kanto Plain, which are called the Osaka Group and the Shimosa Group, respectively (Masuda, 2007). They are characterised by the cyclic deposition of shallow-marine and terrestrial strata related to glacial-interglacial sea-level changes during the middle to late Pleistocene. Previous palaeoenvironmental studies using pollen-based proxies have provided important information on climate change during the past interglacial periods (e.g., Okuda et al., 2002; Kariya et al., 2010; Kitaba et al., 2013). However, information on the marine environment, especially quantitative palaeo-SSTs, is scarce because of the few occurrences of planktic foraminifers in these successions.

Here, we found that organic biomarkers, long-chain alkenones (LCAs), are preserved in the marine strata of the Shimosa Group. LCAs contained in marine sediments are C_{37} – C_{39} unsaturated methyl and ethyl ketones with 2–4 double bonds and feature unique lipid biomarkers produced by Noelaerhabdaceae haptopytes inhabiting surface waters (Marlowe et al., 1984). The degree of unsaturation in C_{37} alkenones is strongly correlated with the growth in temperature and has been widely used as one of the most quantitative and well-established proxies for SST (Prahl et al., 1988; Sawada et al., 1996). Using the LCA-based palaeotemperature proxy, we attempted to quantitatively reconstruct the SSTs during MIS 5e, 7e, 9, and 11 that were recorded in the Shimosa Group.

2 Geological Setting

The Kanto Plain, which covers the Tokyo metropolitan area of Japan, is formed as part of the tectonic basin developed in response to the subduction of the Pacific and the Philippine Sea plates beneath the North American plate. This tectonic setting has resulted in a continuously subsiding basin with an uplifting and tilting margin relative to the basin centre. The Kanto tectonic basin is now buried with

Neogene to Quaternary sediments up to 3000 m thick, forming the widest plain (ca. 17000 km²) in Japan (Suzuki, 2002) (Fig. 1b). The present-day Kanto Plain is underlain by the middle to late Pleistocene Shimoua Group, which consists of fluvial–coastal depositional cycles (Tokuhashi and Kondo, 1989) related to sea level changes from MIS 12 to 5e (Nakazato and Sato, 2001). The marine strata greatly accumulated in the Kanto Plain (Palaeo-Tokyo Bay), when the relative sea level rose during each interglacial period. They can be subdivided into the Jizodo, Yabu, Kamiizumi, Kiyokawa, Yokota, and Kioroshi formations in ascending order, which are bounded by discontinuity formed during the sea-level lowstands (Tokuhashi and Endo, 1984; Nakazawa and Nakazato, 2005; Nakazawa et al., 2006; Nakazawa and Tanabe, 2011) (Fig. 2). The Kioroshi Formation which was deposited during the last interglacial period (MIS5e), can be observed in the shallow subsurface part of the upland areas that have not been subjected to fluvial erosion since the latest Pleistocene (Fig. 1b).

3 Materials And Methods

Sediment core GS-UR-1 was obtained from Saitama City, Saitama Prefecture in the Omiya Upland (139°39'25"E, 35°51'13"N) with an elevation of 16.29 m. The core was recovered using a triple-tube sampler 116 mm in diameter and attained a total length of 101.95 m. Sedimentary facies analysis and identification of tephra beds indicate that this core reaches the Jizodo Formation deposited during MIS 11, which also contains marine strata formed during the subsequent interglacial periods (Nakazawa and Nakazato, 2005). In a previous study, benthic and planktic foraminifers were detected from the marine strata above the bay ravinement surface of each formation to discuss the palaeoceanographic environment during MIS5e, 7e, 9, and 11 (Kaneko et al., 2018).

In this study, we obtained silty to sandy mud samples from stratigraphic levels similar to those of the foraminiferal analysis and carried out organic geochemical analysis following the procedures of Ohkouchi et al., (2005). Approximately 6 g of the dried sediments were crushed into fine powder and lipids were extracted by sonification using a mixed solvent of dichloromethane/methanol (70:30, v/v). The lipids were saponified with 0.5 M KOH in MeOH. The saponified samples were then extracted with n-hexane to obtain the neutral components. The neutral lipids were separated into four subfractions by silica gel column chromatography. The N-1 fraction (hydrocarbons) was extracted using n-hexane/dichloromethane (95:5, v/v). The N-2 fraction (ketones, esters, and aldehydes) was collected using n-hexane/dichloromethane (4:6, v/v). For the identification of LCAs, the N-2 fraction was introduced into an Agilent Technologies (Santa Clara, CA) model 7890A GC connected to a mass-selective (MS) detector with a non-polar VF-5ms fused silica column (J&W Scientific, 30 m/0.25 mm internal diameter 5% phenyl-dimethylpolysiloxane liquid phase) and Instant Connect Programmable Temperature Vaporizing Injector (Thermo Fisher Scientific). Helium was used as the carrier gas, and the column flow rate was 36 cm s⁻¹. The oven temperature was programmed with an initial temperature of 40°C (held for 2 min), ramp at 30°C min⁻¹ to 120°C, and then at 6°C min⁻¹ to 320°C (held for 20 min). The samples were dissolved in 50 µL of hexane of which 1 µL was injected. The detection limit of LCAs was 0.8 ng which was estimated by repeated injection of the external standard of 2-nonadecanone. For the samples

where LCAs were detected, they were then quantified using an Agilent Technologies (Santa Clara, CA) model 6890A GC with a flame ionisation detector (FID) using mid-polar VF-200ms fused silica columns (J&W Scientific, 60 m/0.25 mm internal diameter, trifluoropropylmethylsiloxane lipid phase), which exhibited adequate LCA separation (Longo et al., 2013). Hydrogen was used as the carrier gas, and the column flow rate was maintained at 36 cm s^{-1} . The oven temperature was then programmed with an initial temperature of 60°C (held for 1 min), ramp at $20^\circ\text{C min}^{-1}$ to 250°C (held for 48 min), and then at $20^\circ\text{C min}^{-1}$ to 310°C (held for 15 min). The samples were dissolved in 10–50 μL of hexane of which $3\mu\text{L}$ was injected. The detection limit of LCAs was 1.4 ng, which was estimated by the repeated injection of the external standard of 2-nonadecanone.

4 Results

GC-MS analysis showed that LCAs were preserved in almost all the marine strata where foraminiferal shells were found, whereas they were not detected in strata without foraminiferal shells. For many of the samples where LCAs were detected, $U_{37}^{K'}$ (defined as $=[\text{C}_{37:2}]/[\text{C}_{37:2}]+[\text{C}_{37:3}]$, where $[\text{C}_{37:2}]$ and $[\text{C}_{37:3}]$ represent the concentrations of di-unsaturated and tri-unsaturated C_{37} alkenones, respectively) were obtained from the GC chromatograms (Fig. 3). However, in some cases, reliable $U_{37}^{K'}$ values could not be obtained because of the small peak intensities or the coelution of other substances on the GC chromatogram. For only the samples for which good chromatograms were obtained, palaeo-SSTs were calculated from $U_{37}^{K'}$ using the following conversion formula based on culture experiments of *Gephyrocapsa oceanica* isolated from the inner bay of Japan (Sawada et al. 1996), which showed values from 22.1°C to 25.3°C (Fig. 4, Table 1).

Table 1
Results of all analysed samples of the core GS-UR-1

Core depth (m)	Extracted sediment (g)	GC/MS	C ₃₇ concentration (ng/g)	K' U ₃₇ '-SST (°C)
22.85-87	4.131	u.d.	< 9.7	-
23.83-85	5.505	u.d.	< 7.3	-
24.40-42	5.096	u.d.	< 7.8	-
26.20-23	6.005	□	27.2	24.7
26.78-80	6.014	□	76.9	23.7
28.70-72	6.002	□	219.3	24.2
29.20-22	6.618	□	263.1	24.7
29.88-90	6.062	□	102.2	24.7
30.34-36	6.056	□	52.1	24.7
30.40-42	6.062	□	60.2	24.0
30.80-82	6.223	□	153.9	24.4
31.78-80	6.008	□	> 6.7	-
32.18-20	4.992	□	> 8.0	-
32.30-32	6.011	u.d.	< 6.7	-
32.58-60	6.005	□	> 6.7	-
32.70-72	6.019	u.d.	< 6.6	-
33.30-32	3.863	□	> 10.4	-
33.90-92	5.643	u.d.	< 7.1	-
35.60-62	3.376	u.d.	< 11.8	-
35.88-90	6.074	u.d.	< 6.6	-
49.60-62	5.774	□	> 49.7	22.3
49.88-90	6.024	u.d.	< 6.6	-
50.5-7	6.004	□	> 6.7	-
50.20-22	6.004	□	> 6.7	-
50.46-48	6.006	u.d.	> 6.7	-
50.90-92	6.091	□	181.1	22.1

Core depth (m)	Extracted sediment (g)	GC/MS	C ₃₇ concentration (ng/g)	$\frac{K'}{U_{37}}$ -SST (°C)
51.20–22	6.023	□	267.1	22.8
51.50–52	6.013	□	198.5	23.4
51.88-90	6.082	u.d.	71.1	24.6
52.40–42	6.035	u.d.	80.1	24.3
52.78-80	6.029	u.d.	139.8	23.6
53.30–32	6.097	u.d.	139.4	25.0
53.80–82	6.497	u.d.	36.6	23.9
71.90–92	6.326	u.d.	< 6.3	-
72.30–32	6.170	u.d.	< 6.5	-
73.68-70	6.056	u.d.	< 6.6	-
74.20–22	6.044	u.d.	< 6.6	-
74.95-97	6.071	u.d..	< 6.6	-
75.23-25	6.026	□	> 6.6	-
75.34-36	6.020	□	10.6	23.5
75.70–72	6.079	□	71.9	23.7
76.25-27	6.092	□	116.9	23.8
76.65-70	6.073	□	17.0	23.4
77.25-27	6.112	□	42.6	25.3
77.50–52	6.003	□	72.7	24.6
77.80–82	6.038	□	71.8	24.9
78.8–10	6.023	□	73.3	25.2
78.30–32	6.017	□	43.1	25.2
78.80–82	6.005	u.d.	< 6.7	
94.20–22	6.076	u.d.	< 6.6	
95.20–22	5.010	u.d.	< 8.0	
96.52-54	6.019	u.d.	< 6.6	
96.78-80	6.009	u.d.	< 6.7	

Core depth (m)	Extracted sediment (g)	GC/MS	C ₃₇ concentration (ng/g)	$U_{37}^{K'}$ -SST (°C)
97.0–02	6.013	□	72.3	23.3
97.60–62	6.037	□	> 6.6	
98.42–44	6.047	□	> 6.6	
98.82–84	6.080	□	110.6	23.6
99.08–10	6.044	□	261.4	24.2
99.38–40	4.009	□	151.3	22.7
99.78–80	6.047	□	37.5	24.2
101.7–9	6.075	□	28.3	23.4
101.40–42	6.012	□	35.3	24.8

$$SST (°C) = (U_{37}^{K'} + 0.204) / 0.044$$

5 Discussion

5.1 Assessment of the $U_{37}^{K'}$ -SST

In this study, we showed for the first time that LCAs were preserved in the marine strata of the Shimosa Group. Although foraminifer assemblages have already been used as an indicator of the marine environment in Palaeo-Tokyo Bay, the information obtained from them was limited to a qualitative one (Kaneko et al., 2018). $U_{37}^{K'}$ -SST is a useful tool for reconstructing quantitative palaeotemperatures in the coastal shallow sea because the Noelaerhabdaceae haptophytes, which specifically synthesises LCAs in marine settings, can reproduce even in coastal and inland bay environments (e.g., Kajita et al., 2018; 2020b). In estuarine to coastal environments, LCAs have been potentially synthesised by Isochrysidaceae haptophytes living in brackish water which have different characteristics from Noelaerhabdaceae haptophytes (e.g., Salacup et al., 2019). Most Isochrysidaceae haptophytes are characterised by the abundant synthesis of C_{37:4} (Araie et al., 2018; Salacup et al., 2019; Plancq et al., 2019; Kajita et al., 2020a), but this was not evident in the analysis of this study (Fig. 3). Therefore, LCAs contained in the marine sediments of the Shimosa Group are likely to be derived mostly from Noelaerhabdaceae haptophytes, which enables us to calculate quantitative palaeo-SSTs using the calibration based on the culture experiments of Noelaerhabdaceae haptophytes (Sawada et al., 1996).

It is expected that the LCAs in the Shimosa Group are preserved because of the small degeneracy of the Shimosa Group, which has not been subjected to strong compaction and diagenesis since the time of deposition (Nakazawa and Nakazato, 2007). Well-preserved LCAs have also been detected in the

underlying Kazusa Group, which has experienced a deeper burial depth than the Shimosa Group (Kajita et al., 2021). Nevertheless, for some samples with low LCA concentrations, it was difficult to quantify $C_{37:2}$ and $C_{37:3}$ on the chromatogram, even when using a column suited for LCA separation. We interpret that the degradation was strongly promoted by the influence of groundwater and biological activities after the deposition of these strata (Rontani et al., 2013). Except for these samples, we obtained quantitative $U_{37}^{K'}$ -SST for Palaeo-Tokyo Bay formed during each interglacial period. In the following sections, we discuss the palaeotemperature variations, especially in relation to foraminiferal production proposed by Kaneko et al. (2018).

5.2 Comparison with the foraminifer assemblages

The stratigraphic levels at which LCAs were detected were roughly the same as those where ocean-dwelling benthic foraminifers were found, suggesting that LCA producers began to inhabit the core site when seaward expansions of Palaeo-Tokyo Bays were sufficiently advanced (Fig. 4). We compared $U_{37}^{K'}$ -SSTs with the benthic foraminiferal assemblages for the strata where the total number of benthic foraminifers reached 200 individuals, which is commonly required for environmental change analysis (Fig. 5). We focused on the production of species that are relatively abundant in the core, that is, *Ammonia japonica*, *Pseudorotalia gaimardii* (*Rotalinoides gaimardii*), *Buccella frigida*, and *Elphidium clavatum*. Many of these species can also be found in present-day Tokyo Bay (Kosugi et al., 1991). Of them, *A. japonica* and *P. gaimardii* are found in a wide range of areas along the coast of Japan but indicate a relatively warm water environment, including the Kuroshio Current (Hasegawa, 1993). In contrast, *B. frigida* and *E. clavatum*, which are abundant in subarctic neritic faces under the influence of Oyashio water (Ishiwada, 1964; Hasegawa, 1993), and suggest a relatively colder environment. The benthic foraminiferal assemblage is influenced not only by water temperature but also by the nutrient and redox environment of the sea floor (Murray, 2001), however, it has been the only proxy that provides information on continuous marine environmental change from the Shimosa Group. Their fluctuations broadly support the $U_{37}^{K'}$ -SST changes (Fig. 5); therefore, we believe that $U_{37}^{K'}$ -SSTs in the Shimosa Group are robust and provide quantitative palaeotemperatures.

5.3 Interglacial environments of (Palaeo-) Tokyo Bays

The examined samples were obtained from the marine strata formed during the relative sea-level highstands of MIS 5e, 7e, 9, and 11. Assuming that the maximum sea-level rise in Palaeo-Tokyo Bay is almost linked to global ice sheet volume fluctuations, the LCA-based palaeotemperatures reconstructed in this study can be interpreted as reflecting SSTs around the peak of each interglacial period. The key tephra bed of TE-5a which accumulated at the peak of MIS11 (Kameo et al., 2006; Nakazawa et al., 2009) can be recognised within the marine strata of the Jizodo Formation (Nakazawa and Nakazato, 2005), which supports our interpretation. $U_{37}^{K'}$ -SSTs in each formation generally showed decreasing trends toward the upper part, which might indicate the SST decrease during each sea-level highstand and afterward. As for the Kioroshi Formation, the lower part (ca. 30.1–38.0 m in core depth) with poor preservation of LCAs and foraminifers seemed to be formed in a restricted inner-bay environment as

incised-valley fills, which possibly corresponds to the peak of MIS 5e (Nakazawa et al., 2006). LCAs are poorly preserved in this stratigraphic section, likely due to the narrow-drowned valley with salinity too low for oceanic plankton to thrive.

Although data was not available for the lower part of the Kioroshi Formation (MIS 5e), which was in a special marine environment, and the Jizodo Formation (MIS 11), which was out of the core GS-UR-1, $U_{37}^{K'}$ -SSTs suggested that Palaeo-Tokyo Bays in each interglacial period seemed to reach similar SSTs around their sea-level highstand. These temperatures are 2–3 °C higher than the $U_{37}^{K'}$ -SSTs of the pre-industrial level of Tokyo Bay recovered from the sediment core KT12-06-2B (Kajita et al., 2020b) and possibly equivalent to the values of the Holocene thermal maximum (5–7 ka), which was previously estimated to be at least 2 °C higher than the pre-industrial level (Matsushima and Ohshima, 1974; Matsushima, 1979). These results indicate that Palaeo-Tokyo Bay and Tokyo Bay formed after the mid-Brunhes event experienced warmer conditions than present-day Tokyo Bay. Previous palaeoenvironmental studies based on ice and marine sediment cores worldwide suggest that the last five major interglacial periods that occurred after the mid-Brunhes event are warmer than those occurred before it (Yin and Berger, 2010; Lang and Wolff, 2011; Candy et al., 2014). Of them, MIS 5e and 11 have been sometimes referred to as “super-interglacials” because the sea levels exceeded that of the Holocene and surface temperatures were also higher in some places (Dutton and Lambeck, 2012; Raymo and Mitrovica, 2012; Melles et al., 2012; Turney et al., 2020). The results of this study demonstrate a comparable magnitude of warmth in Palaeo-Tokyo Bays among the last five interglacial periods, including MIS 7e, with relatively low marine isotope ratios. Despite the short recovery range and coarse time resolution, MIS 9 seems to be slightly warmer than MIS 5e, 7e, and 11. Such tendencies were also observed in the pollen records of a sediment core from Lake Biwa, located approximately 500 km west of Tokyo Bay (Tarasov et al., 2011). Honshu Island including the Kanto area, is influenced by the Kuroshio Current, which transports heat from the West Pacific Warm Pool. We interpret that the strength of the Kuroshio Current reached a similar level during all the last five interglacial periods, which may have caused a slightly different temperature trend compared to that of the global averages.

The $U_{37}^{K'}$ -SSTs revealed in this study will provide useful information not only for palaeoclimatology but also for stratigraphic studies in the Shimosa Group, which is important for revealing the subsurface structure of the Kanto Plain, where the capital of Japan is located (Nakazawa et al., 2017). Because the sequences of the Shimosa Group are not always rich in interbedded key tephra beds, information on palaeoenvironmental changes mainly based on pollen assemblages has been used to estimate stratigraphic correlations between cores and outcrops in other regions (e.g., Nakazawa et al., 2006; Nakazawa et al., 2017). However, pollen assemblages preserved in coastal sediments do not always accurately reflect the local climate of the catchment area because of the wide variety of sedimentary processes involved (e.g., Igarashi et al., 2015). Compared to the pollen-based indices, $U_{37}^{K'}$ -SST has the advantage that it can be expected to show similar variations in a wide range of contemporaneous strata. Consequently, $U_{37}^{K'}$ -SST is useful for elucidating the stratigraphy of the Shimosa Group and for extracting palaeoenvironmental information from Palaeo-Tokyo Bays.

6 Conclusions

We detected LCAs in the marine strata of the Shimosa Group and succeeded in reconstructing the SSTs of Palaeo-Tokyo Bays formed during the past interglacial periods after the mid-Brunhes event. The $U_{37}^{K'}$ -SSTs can be a new indicator that are useful for stratigraphic and palaeoceanographic studies in the Shimosa Group. The $U_{37}^{K'}$ -SSTs in Palaeo-Tokyo Bays around the peak of MIS5e, 7e, 9, and 11 were estimated to be 2–3 °C higher than those of Tokyo Bay during the pre-industrial era. Although MIS 5e and MIS 11 have been sometimes referred to as “super interglacials”, in Palaeo-Tokyo Bays which lies at the northern limit of the Kuroshio Current, there was no signal that these interglacial periods were particularly warm compared to MIS 1, 7e, and 9.

Abbreviations

IPCC

Intergovernmental Panel on Climate Change; LCAs:long-chain alkenones; MIS:marine isotope stage; SST:sea surface temperature

Declarations

Availability of data and material

The datasets supporting the conclusions of this article are included within the article.

Competing interests

The authors declare that they have no competing interest.

Funding

This work was supported by JSPS KAKENHI Grant Numbers 18J21788, 20H01981, and 21J00133.

Authors' contributions

H. Kajita proposed the topic and designed the study. N.T. drilled the core and performed stratigraphic study. H. Kajita carried out the experiments and wrote the manuscript. N.O., N.H., and H. Kawahawa organised the analytical devices and helped with the interpretation. M.S. assisted with the laboratory analysis. All authors read and approved the final manuscript.

Acknowledgements

We would like to thank the researchers at JAMSTEC (Y. Takano, H. Suga, N.O. Ogawa, Y. Isaji, Y. Sasaki, and M. Noguchi) for their helpful advice and in organising the analytical devices. We also thank Y. Nishikura and K. Sakata who helped us with the laboratory work.

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Figures

Figure 1

Maps showing the overall setting of the drill site of core GS-UR-1. (a) The marine and atmospheric environment around Japanese islands including the study site is shown in this figure. The blue and red arrows represent the paths of the Oyashio and Kuroshio currents. This base map was generated using Generic Mapping Tools. (b) The topography and geology around the core site. The sampling location of

the core KT12-06-2B (Kajita et al., 2020b) was also shown. The base map was generated using the Seamless Digital Geological Map of Japan (Geological Survey of Japan, AIST, 2020).

Figure 2

Stratigraphic summary of the Pleistocene Shimosa Group and correlation with marine isotope stages. The stratigraphic framework and depositional age summarized in Nakazawa and Tanabe (2011) are shown in the left column. Among the wide-spread tephra beds in the Shimosa Group, those detected in

core GS-UR-1 (J4, Km2, Km4 and TP) are shown in bold (Nakazawa and Nakazato, 2005). The Yokota and Kiyokawa formations shown in shaded boxes lack due to the erosion during MIS 6 at the core site of GS-UR-1 (Nakazawa and Nakazato, 2005). The marine oxygen isotope curve is adapted from Lisiecki and Raymo (2005).

Figure 3

A partial GC chromatogram of LCAs detected from the core GS-UR-1. It was obtained from a sample at a depth of 99.38–99.40 m corresponding to the Jizodo Formation.

Figure 4. Results of LCAs concentration and U_{37}^{K} -SST. The stratigraphic horizons examined in this study are shown in the left column with the columnar section of core GS-UR-1 described in Nakazawa and Nakazato (2005). (a–c) Variations in the total number of benthic and planktic foraminifers along with their relative abundance (P/T ratio) (Kaneko et al. 2018). (d–e) Variations in the LCAs concentrations and U_{37}^{K} -SSTs shown in this study. The white dots represent the samples in which LCAs were identified by GC/MS analysis, but clearly separated peaks could not be obtained by GC equipped with VF-200ms column.

Figure 4

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Figure 5. Variations of U_S -SST and the abundance of benthic foraminifer in present-day Tokyo Bay and Palaeo-Tokyo Bays. (a) Variation of U_S -SSTs in Tokyo Bay over the past 4200 years (late of MIS 1) recovered from the sediment core KT12-06-2B (Kajita et al., 2020b). The 11 points running average (black line) with standard error ranges (grey lines) is presented in this figure. The pre-industrial level (21.9°C) obtained by averaging the values from 1850 CE to 1950 CE is shown in red dotted line. The benthic foraminifer assemblage in the surface sediment at almost the same location as KT12-06-2B core site (K5 site in Kosugi et al., 1991). (b-e) Variations of U_S -SSTs (this study) and benthic foraminiferal abundances in Palaeo-Tokyo Bays (Kaneko et al., 2018).

Figure 5

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