Calcareous nannofossil biostratigraphy of the Lower–Middle Pleistocene boundary of the GSSP, Chiba composite section in the Kokumoto Formation, Kazusa Group, central Japan, and implications for sea-surface environmental changes

Koji Kameo1*, Yoshimi Kubota2, Yuki Haneda3, Yusuke Suganuma4,5 and Makoto Okada6

Abstract

The Chiba composite section (CbCS), in the middle of the Boso Peninsula in central Japan, was ratified as the Global Boundary Stratotype Section and Point (GSSP) for the Lower–Middle Pleistocene boundary, accompanied by the Matuyama–Brunhes (M–B) paleomagnetic polarity boundary in January 2020. This study examined the calcareous nannofossil biostratigraphy of the CbCS to describe potential nannofossil events and discuss sea-surface environments around the M–B paleomagnetic polarity boundary. There are no clear biohorizons at the M–B paleomagnetic polarity boundary, although a temporary disappearance of *Gephyrocapsa* specimens (≥ 5 μm in diameter), an important calcareous nannofossil genus in the Pleistocene, occurs just above the Lower–Middle Pleistocene boundary. Although this is a characteristic event around the M–B paleomagnetic polarity boundary, it is unclear whether the event is globally traceable.

Changes in the environmental proxy taxa of calcareous nannofossils in the CbCS revealed that sea-surface environments were driven by glacial-interglacial and millennial-scale climate forces. The time-transgressive change of the Tn value, a calcareous nannofossil temperature index, is mostly concordant with the planktonic foraminiferal oxygen isotope fluctuation. Abundant occurrences of a warm-water species, *Umbilicosphaera* spp., indicate that the Kuroshio Current was strong after ~ 783 ka. Even the strong influence of the Kuroshio Current, cooling events related to southward movements of the Kuroshio Front occurred every 10,000 years based on the presence of a cold-water taxon, *Coccolithus pelagicus*. Additionally, the inflow of coastal waters strengthened after ~ 778 ka because of abundant occurrences of *Helicosphaera* spp. Millennial-scale sea-surface changes were also inferred from detected floral fluctuations of less than 10,000 years.

Keywords: Calcareous nannofossils, Chiba composite section, Lower–Middle Pleistocene boundary, M–B paleomagnetic polarity boundary, *Gephyrocapsa*, Kuroshio Current

© The Author(s). 2020 Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.
Introduction
Calcareous nannofossils are major phytoplankton fossils that are used to determine the geologic age of strata and to infer past marine environmental changes. Many calcareous nannofossil biohorizons, corresponding to the appearance and disappearance of species, are known because calcareous nannofossils have rapidly evolved since the Late Triassic (e.g., Bown et al. 2004). Comparative studies between these biohorizons and other chronostratigraphic data have been used to construct a biochronological framework. The framework of the Neogene–Quaternary biohorizons exists in the eastern equatorial Pacific, the western equatorial Atlantic, and the Mediterranean (summarized by Raffi et al. 2006). However, useful biohorizons and their relationship to marine isotope stages have not yet been established in the North Pacific deep-sea cores because of the rarity of calcareous sediments caused by a shallow calcite compensation depth (CCD) (e.g., Pälike et al. 2012) from the Neogene to the Quaternary.

The marine Kazusa Group is a Japanese Pleistocene unit on the Boso Peninsula (central Pacific Japanese coast; Fig. 1) that yields abundant microfossils including pollen and spores, planktonic and benthic foraminifers, calcareous nannofossils, diatoms, and radiolarians (e.g., Oda 1977; Sato et al. 1988). These microfossils have been used to determine the age of the Group and the paleoceanographic conditions. However, the time resolution of these studies was relatively low (i.e., a minimum of tens of kyrs). Therefore, further biochronostratigraphic analyses of the formations in the Group are required to obtain suitable Quaternary age models and to discuss past climatic changes around the NW Pacific.

This paper reviews previous studies of the calcareous nannofossil biostratigraphy of the Kazusa Group and discusses the calcareous nannofossil assemblages in the Chiba composite section (CbCS), which is the ratified Global Boundary Stratotype Section and Point (GSSP) for the Lower–Middle Pleistocene boundary. Furthermore, detailed assemblage data of the calcareous nannofossils across the Matuyama–Brunhes (M–B) paleomagnetic polarity boundary are described, and the variability of calcareous nannofossils related to paleoceanographic changes in sea-surface waters is discussed. It is expected that the GSSP for the Lower–Middle Pleistocene boundary should provide good climatic information for understanding recent climatic changes because the boundary is situated within the interglacial Marine Isotope Stage (MIS) 19 (e.g., Head and Gibbard 2005). The orbital configuration in MIS 19 is considered to be similar to the current interglacial MIS 1 (e.g., Tzedakis et al. 2012); thus, orbitally induced climatic and paleoceanographic changes within MIS 19 should be investigated to clarify their effects on the recent marine biosphere. Calcareous nanoplankton, one of the most important marine primary producers, is a suitable tracer for environmental changes which occurred at the sea surface, especially within the photic zone.

Geological setting and chronostratigraphic analyses of the Kazusa Group
The Lower to Middle Pleistocene Kazusa Group is composed of thick siliciclastic sediments in the Boso Peninsula on the Pacific side of the Japanese islands (e.g., Ito 1998; Kazaoka et al. 2015; Ito et al. 2016). The basin where the Kazusa Group was deposited developed as a forearc basin in response to the northward or northwestward subduction of the Pacific Plate against the Japanese islands (e.g., Seno and Takano 1989). The Group consists of deep-sea to shallow-shelf sediments and is divided into ten formations on the eastern part of the Peninsula; namely, in chronological order from oldest to youngest: the Kurotaki, Katsuura, Namihana, Ohara, Kivada, Otadai, Umegase, Kokumoto, Kakinokidai, Chonan, and Kasamori Formations (Fig. 1; e.g., Suzuki et al. 1995; Kazaoka et al. 2015). Shallowing-upward successions and deepening successions eastward of the basin are recognized in the Group, suggesting a northeastward paleocurrent direction (e.g., Ito et al. 2016). Generally, all formations are composed of mostly continuous, undeformed sediments; however, in the eastern part of the Boso Peninsula, the sequence is disrupted by NNE-SSW-trending faults.

On the Yoro River, in the middle part of the Boso Peninsula, a thick succession of the Kazusa Group is present (Figs. 1 and 2). Several chronostratigraphic and chronological studies have been carried out in this sequence. Planktonic foraminifera (Oda 1977), calcareous nannofossils (Takayama 1973; Sato et al. 1988), diatoms (Cherepanova et al. 2002), magnetostratigraphic (Niitsuma 1971; Niitsuma 1976), and δ18O (Okada and Niitsuma 1989; Pickering et al. 1999; Tsuji et al. 2005) studies estimate the age of the Group to span ca. 2.4–0.45 Ma (see summary by Ito et al. 2016). Many interbedded tephra layers allow the correlation of different facies among the formations not only within the Group but also in other formations in Japan (e.g., Satoguchi and Nagahashi 2012). Sedimentological analyses revealed the depositional environments of the formations, and sequence stratigraphic analysis was applied to clarify their formation processes and relationship to sea-level changes (e.g., Ito and Katsuura 1992). As a result, glacioeustatic variability during the Quaternary has primarily controlled the deposition of the formations of the Kazusa Group, even in the active margin setting (Ito 1992).
The Chiba Composite Section (CbCS) is in the middle part of the Kokumoto Formation, which is the upper formation of the Group (e.g., Suzuki et al. 1995). This formation is mainly composed of massive mudstones interbedded with sandstones, indicating deposition in shelf-edge and slope environments (e.g., Ito 1992). No evidence of hiatuses or unconformities is present in the CbCS (Nishida et al. 2016).

Oceanographic conditions on the Pacific side of the Japanese islands
Oceanic waters flowing around the Pacific side of Japanese islands are composed of two main surface currents, the warm Kuroshio and the cold Oyashio currents, which are northeast- and southwest-flowing surface currents, respectively (Fig. 1). The Kuroshio Current is warm, with high-salinity surface water. It is the western boundary current of the subtropical
gyre in the North Pacific Ocean (e.g., Qiu 2001; Yasuda 2003) and flows northward from the western equatorial Pacific region. This current is less than 100 km wide and approximately 1000-m deep (Gallagher et al. 2015) and flows along the Pacific coast of the western part of the Japanese islands and becomes an eastward flow—the Kuroshio Extension—after separating from the coast (Fig. 1).
The Oyashio Current is the southwestern extension of the East Kamchatka Current, which is itself the western extension of the Western Subarctic Gyre from the North Pacific (e.g., Qiu 2001; Yasuda 2003). The Oyashio Current originates in the subarctic region. A mixed water regime between the Kuroshio and Oyashio currents is present off the coast of northeastern Japan, and the boundary between the two currents is either the Kuroshio Front or the Subarctic Front (Qiu 2001). In the mixed water region, the Oyashio Current generally flows beneath the warmer Kuroshio Current; generating complex warm and cold eddies in the surface waters (e.g., Unoki and Kubota 1996; Yasuda 2003). These eddies bring eutrophic surface waters to the mixed water region, whereas the Kuroshio Current is oligotrophic. Regional variations in both currents strongly influence the marine environments and organisms around the NW Pacific because physical and chemical conditions, such as sea-surface temperature, salinity, and nutrient richness, are strongly controlled by the strength of both currents (e.g., Kimura et al. 2000).

The Tsugaru Current is another surface water mass along the Pacific coast of Japan, which is a southward current flowing along the NE Japanese coast (Fig. 1; e.g., Qiu 2001; Gallagher et al. 2018; Yasuda 2003). This current flows between the coast and the Oyashio Current and originates in the Japan Sea as the Tsushima Current, which branches from the Kuroshio Current around the eastern part of the East China Sea off the west coast of the Tokara Islands, small islands to the south of Kyushu (Fig. 1). The Tsushima Current enters the Japan Sea through the shallow (< 140 m) Tsushima Strait (Fig. 1). It then passes through the Tsugaru Strait—a shallow (< 130 m) strait between Hokkaido and Honshu, and finally flows southward along the Pacific side of the Japanese islands (Gallagher et al. 2018; Yasuda 2003).

**Previous studies on calcareous nannofossil biostratigraphy of the Kazusa Group**

Several biostratigraphic studies on calcareous nannofossils from Japanese strata have been conducted since Takayama (1967) first described calcareous nannofossils from the Neogene and Quaternary sections in the southern Kanto region of Japan. In the Boso Peninsula, Takayama (1973) studied the calcareous microfossil biostratigraphy of the uppermost Cenozoic formations on the Japanese islands and from a sediment core taken near the northwestern region of the Pacific Ocean and described the biohorizons of planktonic foraminifera and calcareous nannofossils. In 1987, Takayama and Sato established 11 calcareous nannofossil datums (biohorizons) composed of the first and last occurrences of calcareous nannofossil taxa using the North Atlantic Quaternary sediment cores (Takayama and Sato 1987; Sato and Takayama 1992). Around the same time, similar Quaternary nannofossil biohorizons have been proposed by several authors, such as Raffi et al. (1993) and Matsuoka and Okada (1989). Sato et al. (1988) and Sato (1989) dated the formations in the Kazusa Group along the Yoro River in order to locate the Plio-Pleistocene boundary in the uppermost Japanese Quaternary sequences (Table S1). Subsequently, Sato et al. (1999) re-vised the calcareous nannofossil biostratigraphy detected in the Kazusa Group. Samples used in these papers were obtained along the Yoro, Heizo, and Hirasawa Rivers (Fig. 2), and the eastern part of the Boso Peninsula. Tsuji et al. (2005) established a high-resolution chronostratigraphy based on oxygen isotope stratigraphy, magnetostratigraphy, and calcareous nannofossil biostratigraphy in portions of the Otadai and Umegase Formations in the JNOC TR-3 sediment core (Fig. 2). Based on these studies, the following ten datums (= biohorizons) are recognized in the Kazusa Group (Fig. 3):

1. The LAD (last appearance datum: equivalent to the last occurrence or highest occurrence) of *Discoaster brouweri* in the middle part of the Ohara Formation (Sato et al. 1988). The numerical age for this biohorizon is 1.93 Ma by GTS2012 scaling (Anthonissen and Ogg 2012 in Gradstein et al. 2012). This biohorizon is in the eastern part of the Boso Peninsula; however, it is not in the Yoro River.

2. The FAD (first appearance datum: equivalent to the first occurrence or lowest occurrence) of *Gephyrocapsa caribbeaica* above the Kd38 tephra in the lower part of the Kiwada Formation (Sato et al. 1988). The biohorizon is situated just above the magnetochron C2n, the Olduvai Subchron zone (Niitsuma 1976). This biohorizon corresponds to the first occurrence of medium *Gephyrocapsa* spp. The biohorizon is correlated with MIS 59 (Wei 1993; Berger et al. 1994) or a transition of MIS 58/59 (Lourens et al. 2004; Anthonissen and Ogg 2012). The numerical age is 1.73 Ma (Anthonissen and Ogg 2012).

3. The FAD of *Gephyrocapsa oceania* is just below the Kd25 tephra in the Kiwada Formation (Sato et al. 1988, 1999). The LAD of *Calcidiscus macintyrei* also occurs in the same horizon. The FAD of *G. oceania* was defined by Takayama and Sato (1988) and Sato and Takayama (1992) and is situated into MIS 57 in the Ontong Java Plateau (Berger et al., 1994). No age data by GTS2012 scaling for the biohorizon has been calculated.

4. Large forms of *Gephyrocapsa* specimens first appear close to the Kd19 tephra in the Kiwada Formation (Sato et al. 1988, 1999). They are composed of large
specimens, which are over 6 μm in diameter with an oblique bridge to the short axis (Takayama and Sato, 1987). On the other hand, some authors treated large specimens over 5.5 μm in diameter as large Gephyrocapsa (e.g., Raffi et al. 1993). The first occurrence of Gephyrocapsa over 6 μm in diameter corresponds to MIS 50 in the Ontong Java Plateau (Berger et al. 1994) and MIS 45 in the North Atlantic Ocean (Sato et al. 2009). Its first occurrence seems to be slightly diachronous as same as that of specimens over 5.5 μm in diameter (e.g., Wei 1993; Raffi et al. 2006). The numerical age of the biohorizon based on the GTS2012 scaling has not been estimated.

(5) Helicosphaera sellii disappears prior to the Kd8 tephra in the upper part of the Kiwada Formation (Sato et al. 1988, 1999). Lourens et al. (2004) and Anthonissen and Ogg (2012) indicated that the biohorizon corresponds to MIS 49 in the eastern equatorial Pacific. This biohorizon is also situated into MIS 47 in the Ontong Java Plateau (Berger et al. 1994). However, it seems to be diachronous (e.g., Lourens et al. 2004) because the biohorizon is situated in MIS 37/38 boundary in the North Atlantic (Sato et al. 2009). The numerical age of this biohorizon is calculated at 1.34 Ma (Anthonissen and Ogg 2012).
(6) The LAD of large forms of Gephyrocapsa is in the upper part of the Kiwada Formation (Sato et al. 1988, 1999). The stratigraphic position of the biohorizon, however, could shift due to the relatively low-resolution analysis of nanofossils across the Kiwada and Otadai Formation boundary. Corresponding oxygen isotope stage is MIS 37 (e.g., Berger et al. 1994; Lourens et al. 2004; Anthonissen and Ogg, 2012). However, the biohorizon is slightly later in the North Atlantic, in MIS 35 (Sato et al. 2009). Its numerical age is 1.24 Ma (Anthonissen and Ogg 2012).

(7) The FAD of Reticulofenestra asanoi was initially described below the O22 tephra in the Otadai Formation (Sato et al. 1988). Later, its stratigraphic range was extended below the O23 tephra (Sato et al. 1999). The biohorizon is correlated with MIS 35 (e.g., Wei 1993; Berger et al. 1994; Raffi et al. 2002) or MIS 34 in the North Atlantic (Sato et al. 2009). The age of this biohorizon is 1.14 Ma (Anthonissen and Ogg 2012).

(8) Gephyrocapsa parallela first appears in the uppermost Otadai Formation. The first occurrence of this species is considered to be the reentrance of medium Gephyrocapsa specimens, usually over 4 μm in diameter (Raffi 2002), with a parallel bridge to the short axis. Larger forms (≥ 5.5 or ≥ 6 μm in diameter) of this species are sometimes found above its first occurrence, but they differ from large forms of Gephyrocapsa due to having a parallel bridge to the short axis. The biohorizon is between the tephras O1 and O7. A high-resolution chronological analysis of the JNOC TR-3 core—near Kamishiki, Otaki, in the north of Kazusa-Nakano (Fig. 2), by Tsuji et al. (2005) revealed that this biohorizon is in the middle part of the core, between tephras TR-3B and TR-3C. The first occurrence corresponds to MIS 29 (Anthonissen and Ogg 2012) or MIS 30 (Berger et al. 1994; Tsuji et al. 2005) but slightly later stages in the North Atlantic (e.g., Sato et al. 2009; Wei 1993). This biohorizon was also recognized within the magnetochron C1r.1n (Jaramillo Subchronzone) (Berger et al. 1994; Tsuji et al. 2005). The age of this biohorizon is 1.04 Ma (Anthonissen and Ogg 2012).

(9) The LAD of R. asanoi is below the tephra U4 in the Umegase Formation (Sato et al. 1999). This biohorizon can be correlated with MIS 22 and/or MIS 23 (e.g., Wei 1993; Berger et al. 1994; Raffi et al. 2002). The numerical age is 0.91 Ma (Anthonissen and Ogg 2012).

Based on Sato et al. (1988), the Chonan Formation, an uppermost formation of the Kazusa Group, can be situated below the LAD of Pseudoemiliania lacunosa (0.44 Ma; Anthonissen and Ogg 2012).

**Biogeography of modern calcareous nanoplanktons from the Japanese islands**

The ecological preferences of several nanofossil taxa in the CbCS were mainly interpreted from previous ecol-

ogic and biogeographic studies of calcareous nanno-

plankton around the Japanese islands (e.g., Tanaka 1991; Hagino 1997). Tanaka (1991) examined calcareous nanofossil species in 437 surface sediments from the Pacific Ocean, the Japan Sea, and the East China Sea, and clarified 10 biotopes based on the Q-mode cluster analysis of nanofossil assemblages. The distribution patterns of coccolith thanatocoenosis follow changes in the environmental conditions of surface currents around the Japanese islands, and several diagnostic nannoplankton taxa are recognized in specific surface currents and within oceanic areas. Aizawa et al. (2004) summarized the ecology and biogeography of the main Quaternary calcareous nanoplankton species in order to evaluate calcareous nanofossil assemblages during the last 144 ka in a piston core off the Kashima coast, north of the Boso Peninsula. Ecological information on these modern calcareous nanoplankton species in other oceans enables us to discuss paleoceanographic changes based on calcareous nanofossils.

A nanofossil tracer of the Kuroshio Current (Fig. 1) is Umbilicosphaera sibogae, because extant Umbilicosphaera sibogae is dominant in the main route of the Kuroshio Current (Tanaka 1991). Recently, Pleistocene Umbilicosphaera was classified into several species (e.g., Young et al. 2017). U. sibogae consists of two species, U. sibogae, and Umbilicosphaera foliosa; however, this study follows the definition used by Tanaka (1991) and treats them uniformly as U. sibogae.

Common Coccolithus pelagicus in thanatocoenosis is associated with cooler surface waters from the Kuroshio (Subarctic) Front and the mixed water region off the northeastern coast of the Japanese islands (Tanaka 1991). This taxon may include C. pelagicus pelagicus and C. pelagicus braarudii. Based on their ecological preferences in the Atlantic Ocean (e.g., Cachão and Moita 2000), C. pelagicus pelagicus corresponds to colder conditions than C. pelagicus braarudii (Narciso et al. 2006). C. pelagicus braarudii is common in Atlantic upwelling areas, where surface waters are cool and eutrophic. Based on Aizawa et al. (2004), C. pelagicus is abundant in surface waters under low-temperature and high-nutrient conditions.

Tanaka (1991) suggested that the dominance of Helico-
sphaera spp. in thanatocoenosis is typical of coastal wa-
ter from the East China Sea. This taxon is present from the East China Sea to off the Boso Peninsula,
which is off the southwestern coast of the Japanese islands. Tanaka (1997) indicated that this taxon occurred abundantly in sediment trap samples from the continental shelf slope in the East China Sea. Aizawa et al. (2004) summarized that the presence of this taxon may presumably be affected by nutrient levels.

A lower photic taxon, *Florisphaera profunda*, has been utilized to reconstruct nutrient dynamics around the equatorial regions (e.g., Molino and McIntyre 1990), water transparency, and/or turbidity (surface stratification) in the NW Pacific (Ahangon et al., 1993). According to Tanaka (1991), *F. profunda* occurs in more stable, stratified, warm offshore waters and gradually increases in number farther from the Japanese coast (Tanaka 1991). Another offshore taxon, *Calcidiscus leptoporus*, is more abundant to the east of the Izu-Ogasawara Ridge, in the northeastern part of the Pacific Ocean (Tanaka 1991). There has been no relationship established between the occurrence of this species and the Kuroshio and/or Oyashio currents.

*Rhabdosphaera clavigera, Syracosphaera spp.*, *Calciosolenia spp.*, and *Umbllosphaera* spp. are observed mainly south of the Kuroshio Front (Tanaka 1991), although these are considered as very rare taxa in the nannoplankton thanatocoenosis.

### Materials and methods

We used mudstone samples from Suganuma et al. (2018) from the CbCS of the Kokumoto Formation on the Yoro River (Fig. 2) to investigate potential bioevents of calcareous nannofossils across the M–B paleomagnetic polarity boundary and environmental changes in detail. Previous studies (Sato et al. 1988, 1999) suggest that there is no characteristic change in the occurrence of nannofossil species across this boundary (Fig. 3). The interval is between the last occurrences of *Reticulofenestra asanoi* and *Pseudoemiliania lacunosa*, and previous studies in other oceans (e.g., Raffi et al. 2006) have no apparent diagnostic biohorizons.

The analyzed intervals, including the tephra Byk-E (Takeshita et al., 2016), are in the middle part of the Kokumoto Formation. The formation mainly contains massive mudstones with thin sandstones and occasional mudstone/sandstone interbeds. This study adds 12 samples to those presented by Suganuma et al. (2018); the total number of samples was 75. The time resolution in this study is less than one thousand years, on average.

Typical smear slides and permanent slides were prepared and observed using a light-polarized microscope (Olympus BX51) at ×1500 magnification. Smear slides were used to estimate the relative abundance of each calcareous nannofossil species based on the count of 200 specimens per slide. Additional transects of each smear slide were observed to detect rare species outside 200 counts. According to Suganuma et al. (2018), specimens of *Gephyrocapsa*, *Pseudoemiliania*, and *Florisphaera* comprise approximately 90% of the total flora in the section. Thus, the frequencies of other rare taxa related to sea-surface conditions are obscured. In this study, we applied additional counting of subordinate taxa (Okada and Wells 1997) after 200 counts. The subordinate taxa in this study are nannofossil specimens except for major taxa (*Gephyrocapsa*, *Pseudoemiliania*, and *Florisphaera*). Permanent slides were made following the simplified method of Flores and Sierra (1997) to obtain the count data for subordinate taxa. The overall preservation of calcareous nannofossils in each sample was visually evaluated using the following criteria modified after that of Takayama and Sato (1987): good (i.e., most fossils have little or no evidence of dissolution and/or overgrowth), moderate (i.e., fossil specimens are partly etched, but all taxa can be identified), and poor (i.e., most specimens are etched, and it can be difficult to identify each species).

To avoid taxonomic problems, *Gephyrocapsa* specimens were subdivided into several morphotypes based on the maximum diameter of the coccolith. At the same time, a bridge angle to the diameter was also observed. The maximum diameter of a specimen was measured at 1 μm intervals using an eyepiece graticule under a light microscope. Based on the measurements, *Gephyrocapsa* specimens were subdivided into four categories (<3 μm, 3–4 μm, 4–5 μm, and ≥5 μm). Most *Gephyrocapsa* species over 4 μm in diameter in the CbCS are likely to be *Gephyrocapsa parallela* or *Gephyrocapsa omega*, with a parallel bridge to the short axis.

This study basically follows the age model of the CbCS established by Suganuma et al. (2018), which combines oxygen isotope stratigraphy and magnetostratigraphy. Oxygen isotope data of planktonic and benthic foraminifera revised by Haneda et al. (2020) were also used in this study. Marine isotope stages MIS 20 to MIS 18 were recognized, and high-resolution oxygen isotope records enabled us to identify three substages within MIS 19 (MIS 19c–19a). A chronologic uncertainty of the age model is approximately 4 kyr (Haneda et al. 2020).

In order to estimate sea-surface temperatures during the deposition of the CbCS, we calculated the nannofossil temperature index (Tn value) proposed by Aizawa et al. (2004). Tn values were estimated by using the relative abundances of subordinate counts, as mentioned above. Tn was estimated as follows:

\[
Tn = \frac{\text{warm taxa}}{(\text{warm taxa} + \text{cold taxa})} \times 100
\]

Originally, warm taxa were considered as Kuroshio taxa (Aizawa et al. 2004). These are composed of *Umbllicosphaera* spp., *Rhabdosphaera clavigera*, *Oolithotus* spp., *Syracosphaera* spp., and *Umbllosphaera* spp., which are all recognized in the Kuroshio region (Tanaka...
On the other hand, cold nannofossil taxa consist of *Coccolithus pelagicus pelagicus* and *C. pelagicus braarudii*. As mentioned above, Tanaka (1991) did not divide *C. pelagicus* into two subspecies and considered *C. pelagicus* as an Oyashio taxon. However, a few occurrences of this species were recognized just south of the Kuroshio Front, indicating the presence of locally low-temperature and nutrient-rich areas near the Front. Considering geographic distributions and ecological preferences in other oceans, they are likely to be *C. pelagicus braarudii*.

**Results**

**Calcareous nannofossil assemblages of the Chiba composite section**

The middle part of the Kokumoto Formation generally contained well preserved, abundant calcareous nannofossils, while some samples yielded fewer nannofossil specimens in the upper part of the section. Dominant *Gephyrocapsa*, *Pseudoemiliania*, and *Florisphaera* characterized the calcareous nannofossil assemblages (Figs. 4 and 5, Table S2); comprising 90% of the total flora in the section. Small forms of *Gephyrocapsa* (<3 μm in longer diameter) commonly reached over 70% of the total flora below sample TB3-43 in the lower part. This taxon, however, decreased from samples TB3-38 to TB14 and reached an average abundance of 45% above sample TB10.

In contrast, *Gephyrocapsa* specimens (from 3 to 4 μm in diameter) slightly increased above sample TB3-38 and replaced the smaller forms. The specimens over 5 μm in diameter were sporadically observed in the section; however, they were absent, in TB2-44 to KG30 samples between tephra Byk-A and an unnamed tephra layer in the middle of the Kokusabata section (Fig. 4). Within the lower part of this interval (TB2-44 to KG34), specimens from 4 to 5 μm in diameter were less numerous than those in other intervals. The interval with minor *Gephyrocapsa* (4–5 μm in diameter) and absent *Gephyrocapsa* over 5 μm in diameter corresponded to ~770–760 ka (Fig. 6). Most of the *Gephyrocapsa* (>4 μm in diameter) specimens in the CbCS had a bridge parallel to the short
axis of the specimen; thus, they were named *Gephyrocapsa parallela* or *Gephyrocapsa omega*.

*Florisphaera profunda*, another common species, typically replaced small forms of *Gephyrocapsa* above samples TB3-38 (Fig. 4). Here, the relative abundance of the taxon was over 15%, whereas its abundance was 5% or less below this level. *Pseudoemiliania lacunosa*, a common species in the Pliocene–Pleistocene sediments, was present throughout this section and became more abundant above sample TB18 (approximately 4% on average). *Umbilicosphaera sibogae* increased in samples above TB3-38, although its average percentage was approximately 2% of the total flora. *Helicosphaera* spp., *Calcidiscus leptoporus*, and *Coccolithus pelagicus* are considered key taxa typical of the uppermost part of the Neogene and Quaternary and were also present in the CbCS with an average continuous presence of ~ 1–2%. Thus, their variability in abundance was not revealed in standard counts.

**Occurrence of environmental indicators**

*F. profunda*, one of the most common species in the nannofossil assemblages, is a lower photic taxon in low-to middle-latitude oceans (Fig. 4). This taxon became abundant above sample TB3-30, ~ 787 ka (Fig. 7). As a possible Kuroshio water taxon, *Umbilicosphaera* spp. (mostly *U. sibogae*) was also abundant within subordinate taxa at almost the same time when its average abundance changed from ~ 20 to 40% (Table S3). This taxon was most abundant from ~ 787 to ~ 776 ka (TB65–TB18) (Fig. 7). Subsequently, its abundance slightly decreased until ~ 769 ka (TB2-48), before increasing again. Short-term variabilities of this taxon from ten thousand to a
few thousand years were also present. As a temperate and offshore taxon, *C. leptoporus* had a relative abundance within subordinate taxa of 9–40%. This taxon occurred prior to ~787 ka (TB65) and rapidly decreased at ~786 ka (TB61). Subsequently, a gradual increase of this taxon was observed after ~776 ka (TB14). Fluctuations in the abundance of this taxon with different cycles were recognized on the scale of twenty thousand and a few thousand years.

*C. pelagicus braarudii*, a cool and nutrient-rich water taxon, was abundant before ~783 ka (TB50) and from ~764 to ~762 ka (KG38–KG32). This subspecies predominated when *Umbilicosphaera* spp. decreased, except for the period from ~787–784 ka (TB3-38–TB54) and reached a 29% maximum within subordinate counts at 791 ka (YN12). At the same time, *C. pelagicus pelagicus* (a colder-water taxon) was also recognized but generally had fewer occurrences than *C. pelagicus braarudii*. *C. pelagicus pelagicus* was occasionally present approximately every ten thousand years (~801–795, ~787–783, ~772, ~764–761, and ~753 ka) (Fig. 7) and was most abundant around ~772 ka (TB2-16).

*Helicosphaera* spp., another abundant and characteristic taxon within the subordinate species, increased before ~787 ka (TB3-30) and after ~778 ka (TB26) (Fig. 7). *Helicosphaera* spp. mainly consisted of *Helicosphaera carteri*, *Helicosphaera hyalina*, and *Helicosphaera pavimentum* with rare *Helicosphaera wallichii*. Average values before ~787 ka and after ~778 ka were 16% and 24% in the subordinate taxon, respectively. Between these intervals, corresponding to the early part of MIS 19c, fewer occurrences—approximately 10% on average—were recorded. The sequential pattern of this taxon was dissimilar to that of other calcareous nannofossil specimens. Small fluctuations with a duration of several thousand years of this taxon were also observed throughout the studied intervals. Other nannofossil taxa in subordinate counts included *Rhabdosphaera clavigera*, *Syracosphaera pulchra*, *Oolithotus fragilis*, and other minor and extremely rare species (see Table S3).

The Tn value, which is the calcareous nannofossil temperature index, shows warm-cold fluctuation within the Chiba composite section (Fig. 7). Tn values were relatively low before ~783 ka, after which higher values were recorded. The fluctuation of Tn values was similar to that of the oxygen isotope of a planktonic species, *Globigerina bulloides*, in that Tn values were characteristically low at ~772 and ~763–761 ka.

**Discussion**

Possible bioevent around the M–B paleomagnetic polarity boundary at the Chiba composite section

There are no apparent useful nannofossil bioevents in the Chiba section across the M–B paleomagnetic polarity
boundary (e.g., Raffi et al. 1993; Takayama and Sato 1987). This makes it difficult to constrain the M–B paleomagnetic polarity boundary with calcareous nannofossils.

In the Quaternary strata, the significance of size variations of *Gephyrocapsa* has been recognized elsewhere around the world (e.g., Rio et al. 1990). Appearances and disappearances of *Gephyrocapsa* of different sizes and morphologic characters can be correlated globally and used to date marine sediments. Matsuoka and Okada (1990) demonstrated the size and morphological changes of *Gephyrocapsa* species in the Quaternary strata of the Indian Ocean and recognized several morphotypes. The first and last occurrences of these morphotypes are global and have been utilized as biohorizons. Across the M–B boundary, *Gephyrocapsa* specimens are typified by abundant smaller forms (< 4 μm) and medium to large-sized specimens with a higher bridge angle (nearly parallel to the short axis) called *Gephyrocapsa omega* (Bukry 1973), *Gephyrocapsa parallela* (Hay and Beaudry, 1973), *Gephyrocapsa* sp. 3 (Rio 1982), and/or *Gephyrocapsa* sp. C (Matsuoka and Okada, 1990; Hagino et al. 2011). In the CbCS, specimens over 4 μm in diameter correspond to these forms. In the middle part of the section, fewer medium-sized specimens (4–5 μm) and no specimens over 5 μm in diameter occurred (Figs. 4 and 6), which represents characteristic changes of *Gephyrocapsa* in the CbCS.

Maiorano et al. (2004) described the calcareous nannofossil biostratigraphy of the Lower to Middle Pleistocene in the Montalbano Jonico section and a Mediterranean Ocean Drilling Project (ODP) site (Site 964). Maiorano and Marino (2004) also provided quantitative data on the temporal and spatial distributions of *Gephyrocapsa* and *Reticulofenestra* from the Early to Middle Pleistocene, including across the M–B paleomagnetic polarity boundary in the North Atlantic Ocean (Site 607) and the Mediterranean (Sites 964, 967, and 977). These studies revealed temporal disappearances of medium-sized *Gephyrocapsa* (4–5.5 μm in size) around MIS 22 (td1) and MIS 20–19 (td2). Based on these patterns, both temporal disappearances are characteristic, but they seem to be diachronous (Maiorano and Marino 2004). In the CbCS, no intervals with a complete absence of medium-sized specimens (4–5 μm) were observed. However, there is a characteristic interval with fewer
occurrences of medium-sized *Gephyrocapsa* (4–5 μm) and a temporal disappearance of *Gephyrocapsa* specimens over 5 μm in diameter. This interval in the CbCS may correspond to a later part of td2 (Maiorano and Marino 2004). One possibility is that the end of td2 might be correlated with the top of the absent interval of *Gephyrocapsa* over 5 μm in diameter at ~ 760 ka because of re-occurrence of them at the same time (Fig. 6).

The presence of *Gephyrocapsa* over 5 μm in diameter in the CbCS suggests that this horizon corresponds to the latest occurrence of *Gephyrocapsa* sp. C identified by Matsuoka and Okada (1990) and Hagino et al. (2011). Across the M–B paleomagnetic polarity boundary, between the tops of *Reticulofenestra asanoi* (0.889 Ma) and *Pseudoemiliania lanunosa* (0.443 Ma), *Gephyrocapsa* sp. C (a medium to large *Gephyrocapsa* specimen with a comparatively high angle bridge nearly parallel to the shorter axis), disappeared. Although the exact timing of the last occurrence of *Gephyrocapsa* sp. C has not been determined, *Gephyrocapsa* specimens (≥ 5 μm) only occurred just prior to the disappearance of *Gephyrocapsa* sp. C in the upper part of the Pleistocene of the Indian Ocean (Hagino et al. 2011). *Gephyrocapsa* specimens over 5 μm in diameter in the lower CbCS may correlate with the uppermost occurrence of *Gephyrocapsa* sp. C. To correlate these *Gephyrocapsa* events identified in the CbCS with other oceans, studies on size variations and morphologic changes of *Gephyrocapsa* must be conducted across the M–B paleomagnetic polarity boundary.

**Sea-surface environmental changes based on calcareous nanofossils**

The stratigraphic distribution of certain major nannofossil taxa and their time-series variability revealed that sea-surface conditions, including surface currents, changed during the deposition (Fig. 7).

Prior to 788 ka, during MIS 20, warm-water taxa, *Florisphaera profunda*, and *Umbilicosphaera* spp., were not common. Instead, the abundance of *Coccolithus pelagicus braarudii* with *C. pelagicus pelagicus*, a colder, subarctic taxon (e.g., Cachão and Moita 2000), suggests cold and eutrophic surface conditions (Fig. 7). *C. pelagicus* deposited within surface sediments around the Japanese islands may include both subspecies (Tanaka, 1991), and the dominant area of *C. pelagicus* coincides with the distribution areas of the cool mixed water region and the cold Oyashio Current from Sanriku to Hokkaido coast. The continuous occurrence of *C. pelagicus* suggests that the influence of Kuroshio water was weak during MIS 20 and that cold and eutrophic waters from the north of the Kuroshio Front invaded the Kazusa Basin. Tn values are low during this interval, indicating low sea-surface temperatures. The presence of small forms of *Gephyrocapsa* during MIS 20 (Figs. 4 and 6) also supports this interpretation, as an abundance of smaller forms generally demonstrates a high nutrient supply in the upper photic zone (e.g., Okada and Wells 1997; Chiyonobu et al. 2012).

Around 790 ka, extreme decreases in a lower photic taxon, *F. profunda*, indicate the collapse of sea-surface stratification (Fig. 7) because this species is more likely to be abundant in stable surface conditions. At the same time, increases in small *Gephyrocapsa* (< 3 μm) (Fig. 4) and *C. pelagicus braarudii* also indicate a turbulent photic zone, resulting in cool and nutrient-rich sea-surface conditions. This suddenly disturbed horizon corresponds to the Ydt1 (Younger Dryas-type event 1: Suganuma et al., 2018; Haneda et al., 2020) which is a characteristic cooling event at the latest MIS 20. Another cooling event, called Ydt2, was not clearly detected, even though there was a small reduction in the Tn value around 788 Ka (Fig. 7).

*Umbilicosphaera* spp. became abundant around 787 ka and persisted until 776 ka, suggesting that the strong ingress of the Kuroshio Current during MIS 19 was associated with a northward retreat of the Kuroshio Front. This interval almost corresponds to the full-interglacial conditions in MIS 19 (785.0–775.1 ka; Suganuma et al. 2018) when the Boso Peninsula was strongly influenced by southern surface waters and the Kuroshio Current. However, Tn values suggest the beginning of warming of sea-surface waters was during early MIS 19c, around ~ 783 ka. The Tr value, a sea-surface temperature index calculated by radiolarians (Suganuma et al. 2018), also supports the timing of warming. During 787–783 ka, co-occurrences of Kuroshio water taxa and cool-water taxa (Fig. 7) suggest that the study area was possibly situated around the Kuroshio Front and seasonal movements of the Front around the CbCS may have largely fluctuated.

In the early MIS 19c, *F. profunda* and *C. leptoporus* increased in abundance, although *F. profunda* began to increase earlier than *C. leptoporus*. Recently, *F. profunda* was found to have mainly lived outside the Kuroshio Current, to the south of 32–34° N (Tanaka 1991). Conversely, *C. leptoporus* is relatively abundant in the eastern part of the offshore areas, from 142° E. Thus, a gradual increase in both species signifies the stronger influence of offshore waters and the relative deepening of the basin.

After ~ 783 ka, the Kuroshio Current was common throughout the study area because of the abundant occurrences of warm-water taxa. Moreover, the gradual increase and common occurrences of *Helicosphaera* spp. after ~ 778 ka suggest the influence of coastal waters. This taxon is abundant in the East China Sea and coastal areas along the Pacific side of Japanese islands (Tanaka 1991; Tanaka 1997) and may relate to the inflow of fresh
coastal waters (Tanaka 1991). In the CbCS, however, *Umbilicosphaera* spp. and *Florisphaera profunda* were still common (Fig. 7) at the same time. Their occurrences suggest that the influence of coastal water near the coast of the Japanese islands may have increased along with the Kuroshio Current after the full interglacial during MIS 19. In Japan Sea, subtropical Tsushima Warm Current radiolarian species were rapidly decreased in Hole U1427 (Sagawa et al. 2018). Sagawa et al. (2018) suggested that shallowing the Tsushima strait due to lowering sea-level prevented the Tsushima Warm Current from flowing into Japan Sea after interglacial maxima. It has possibly influenced on common occurrences of the Kuroshio Current nannofossil taxa and increases of a coastal nannofossil taxon at the CbCS.

Although the study area has been under the strong Kuroshio Current regime, climatic fluctuations shorter than the glacial-interglacial cycle were found for each taxon. In particular, strong Kuroshio Current and comparatively cooler water regimes were regularly repeated (Fig. 7). *C. pelagicus pelagicus* and *C. pelagicus braarudii* seem to occur approximately every 10,000 years at ~ 801–795 ka, ~ 787–783 ka, ~ 772 ka, ~ 764–761 ka, and ~ 753 ka. Preliminary spectrum analysis of *C. pelagicus* (Fig. S1) also shows approximately 10,000 periodicity throughout the section, indicating cyclic southward invasions of the Kuroshio Front. These cold invasions mostly coincide with the larger oxygen isotope values of surface-dwelling *Globigerina bulloides*. On the basis of the occurrences of *C. pelagicus pelagicus*, the durations and influences of cold waters seem to be shorter and weaker, respectively. Haneda et al. (2020) suggested millennial-scale oceanographic variations, possibly influenced by North Atlantic climate variability and tropical insolation. They indicated that the millennial-scale oscillation during MIS 19b–19a corresponds to four stadial-interstadial cycles (Fig. 7; Haneda et al. 2020). These patterns indicate that the oscillatory movement of the Kuroshio Front may have controlled abrupt, millennial-scale increases and decreases in surface temperature. Two stadial periods (S1 and S3 by Haneda et al., 2020) correspond to these cooler intervals indicated by calcareous nannofossils at ~ 772 ka and ~ 764–761 ka, respectively. However, other climatic changes (stadal periods S2 and S4) indicated by oxygen isotope data were only shown by small reductions in Tn values (Fig. 7). Further examination of a higher-resolution analysis of calcareous nannofossils would be needed in order to discuss millennial-scale changes in surface waters.

**Conclusions**

This study examined calcareous nannofossil assemblages of the CbCS of the Kokumoto Formation of the Kazusa Group in order to extract the calcareous nannofossil index for the Lower–Middle Pleistocene boundary and to consider environmental changes in sea surface conditions along the southwest Pacific side of the Japanese islands around the M–B paleomagnetic polarity boundary. This paper reviews previous calcareous nannofossil investigations and introduces the detailed calcareous nannofossil biostratigraphy of the CbCS, as follows. In addition, local bioevents and floral changes associated with oceanographic conditions were found using high-resolution analysis of calcareous nannofossils:

1. Previous results of the calcareous nannofossil biostratigraphy of the Kazusa Group (e.g., Sato et al. 1988, 1999) and resultant nannofossil biohorizons (datums) were summarized. Quaternary calcareous nannofossil biohorizons established in the North Atlantic (Takayama and Sato 1987; Sato and Takayama 1992) were applied in the Group. Similar biohorizons were also found in other Quaternary sequences (e.g., Raffi et al. 1993), and thus, the worldwide utility of the nannofossil biohorizons was demonstrated.

2. Based on high-resolution calcareous nannofossil biostratigraphy of the CbCS, there are no apparent bioevents of calcareous nannofossil species around the M–B paleomagnetic polarity boundary. *Gephyrocapsa* specimen (≥ 5 μm in diameter), with a higher bridge angle (nearly parallel to the short axis), may have temporarily disappeared from ~ 770–760 ka, just after the M–B paleomagnetic polarity boundary appears in the sequence. This event could be related to the temporary disappearance of medium-sized *Gephyrocapsa* in MIS 20–19 (td2: Maiorano and Marino 2004). Moreover, the presence of large specimens of *Gephyrocapsa* corresponds to the latest occurrence of *Gephyrocapsa* sp. C (Matsuoka and Okada, 1990). Further investigation of calcareous nannofossils around the M–B paleomagnetic polarity boundary will be needed because it is unclear if this event can be traceable to other areas.

3. Floral changes in the environmental proxy taxa of calcareous nannofossils enable us to infer changes in surface currents around the M–B paleomagnetic polarity boundary. Before 787 ka, the influence of the Kuroshio Current was weak around the Kazusa Basin, and cool and eutrophic conditions were inferred because of the presence of *Coccolithus pelagicus*. Generally, abundant occurrences of *Umbilicosphaera* spp. and *Florisphaera profunda* indicate that the Kuroshio Current affected the Kazusa Basin after 787 ka.
After ~ 783 ka, the Kuroshio Current was common until MIS 18, but sea-surface temperatures fluctuate shorter than the glacial-interglacial cycle. Moreover, periodic southward invasions of the Kuroshio Front occurred approximately every 10,000 years based on the presence of a cold-water species. Shorter-term fluctuations of flora were also observed and correspond to millennial-scale environmental changes.

Supplementary information
Supplementary information accompanies this paper at https://doi.org/10.1186/s40645-020-00355-x.

Additional file 1: Table S1. Counts of calcareous nanofossils of the Kazusa Group by Sato (1989).

Additional file 2: Table S2. Counts of overall calcareous nanofossils of the Chiba composite section (This study and Suganuma et al. 2018).

Additional file 3: Table S3. Counts of subordinate taxa of calcareous nanofossils of the Chiba composite section.

Additional file 4: Fig. S1. Spectral power of Coccolithus pelagicus based on REDFIT method (Schulz and Mudelsee 2002) using the PAST4 software (Hammer et al. 2001). A blue dotted line shows 95% confidence level and a red dotted line indicates the first-order autoregressive (AR1) red noise model fit. A periodic change of 11 kyr is characteristically extracted from sequential occurrence of C. pelagicus in the CBGs.

Abbreviations
CBGs: Chiba composite section; FAD: First appearance datum; GSSP: Global Boundary Stratotype Section and Point; LAD: Last appearance datum; M-B: paleomagnetic polarity boundary; Matuyama–Brunhes paleomagnetic polarity boundary

Acknowledgements
We would like to thank Mr. Kento Watanabe, who co-operated with KK in conducting the preliminary studies of the calcareous nanofossils of the CBGs. Mr. Daisuke Kuwano at Chiba University gave us important advice for conducting the preliminary studies of the calcareous nannofossils of the Chiba composite section. We would also like to thank all those who assisted us in this project from the Tabuchi district, Ichihara City, Chiba Prefecture, and Ministry of Education. We wish to thank Prof. Dr. Stephen J. Gallagher, anonymous reviewers, and Dr. Takuya Sagawa for their constructive and useful comments, which significantly improved our manuscript. We would like to thank Editage (www.editage.com) for English language editing.

Authors’ contributions
KK conducted an overall investigation of calcareous nannofossils including sample treatments, counting, interpretation of data, writing of the manuscript, drawing of figures and tables, and creation of other additional files. YK, YH, YS, and MO assisted with the data interpretation for sample treatments, counting, interpretation of data, writing of the manuscript, drawing of figures and tables, and creation of other additional files. YH supported the drawing of the figures related to lithostratigraphy, the identification of samples, and their stratigraphic locations. YT conducted a overall investigation of calcareous nannofossils including magnetostratigraphy and oxygen isotopes. The authors read and approved the final manuscript.

Funding
JSPS KAKENHI Grant Number 18K03771 supported this work. MO was partly funded by JSPS KAKENHI, Grant Number 16H04068 and 19H00710.

Availability of data and materials
The counting data of calcareous nanofossils of this article are included within the article and its additional files.

Competing interests
The authors have no competing interests to declare.

Received: 22 September 2019 Accepted: 19 July 2020
Published online: 08 August 2020

References
Ahagon N, Tanaka Y, Uijie H (1993) Florisphaera profunda, a possible nanoplankton indicator of late Quaternary changes in sea-water turbidity at the northwestern margin of the Pacific. Mar Micropaleontol 22:255–273. https://doi.org/10.1016/0377-8896(93)90047-2

Aizawa C, Oba T, Okada H (2004) Late Quaternary paleoceanography deduced from coccolith assemblages in a piston core recovered off the central Japan coast. Mar Micropaleontol 52:277–297. https://doi.org/10.1016/j.marmicro.2004.05.005

Anthonissen DE, Ogg JG (2012) Appendix 3 Cenozoic and Cretaceous biochronology of planktonic foraminifera and calcareous nanofossils. In: Gradstein FM, Ogg JG, Schmitz M, Ogg G (eds) The Geologic Time Scale 2012. Elsevier, Boston, USA 2:1103–1124

Berger WH, Yasuda MK, Bickert T, Wefer G, Takayama T (1994) Quaternary time scale for the Ontong Java Plateau: Milankovitch template for Ocean Drilling Program Site 806. Geology 22:463–467. https://doi.org/10.1130/0991-7613(1994)022<0463:QTSFTO>2.3.CO;2

Brown PR, Lees JA, Young JR (2004) Calcareous nanoplankton evolution and diversity through time. In: Thierstein HR, Young JR (eds) Coccolithophores. Springer, Berlin, Heidelberg, pp 481–508

Brown E, Colling A, Park D, Phillips J, Rothery D, Wright J (2001) Chapter 3-Ocean Currents, Ocean Circulation (Second Edition). Butterworth-Heinemann, Oxford, pp 37–78

Bakry D (1973) Low-latitude coccolith biostratigraphic zonation. In: Edgar NT, Saunders JB, et al. Initial Reports, DSDP 15. Washington, US Government Printing Office, 685–703. https://doi.org/10.3979/jcproc.15.116.1973

Cachão M, Moita MT (2000) Coccolithus pelagicus, a productivity proxy related to moderate fronts off Western Iberia. Micropaleontology 39:131–155. https://doi.org/10.1016/S0377-8980(00)00018-9

Cherepanova MV, Pushkar VS, Raskina AV, Kumai H, Koizumi I (2002) Diatom biostratigraphy of the Kazusa Group, Boso Peninsula, Honshu, Japan. Quat Res (Daiysonki Kenkyu) 41:1–10. https://doi.org/10.4116/jaqua41:1

Chiyonobu S, Mori Y, Oda M (2012) Reconstruction of paleoceanographic conditions in the northwestern Pacific Ocean over the last 500 kyr based on calcareous nannofossil and planktic foraminiferal assemblages. Mar Micropaleontology 96(7/9):29–37. https://doi.org/10.1016/j.marmicro.2012.07.002

Flores JA, Sinton FJ (1997) Revised technique for calculation of calcareous nanofossil accumulation rates. Micropaleontology 43:321–324

Gallagher SJ, Itami K, Koizumi I (2002) The Pliocene to recent history of the Kuroshio and Tsushima warm currents: a multi-proxy approach. Prog Earth Planet Sci 2:1–17. https://doi.org/10.1186/s40645-015-0045-6

Gallagher SJ, Sagawa T, Henderson AGG, Saavedra-Pellittero M, De Vleeschouwer D, Black H, Itaki T, Toucanne S, Bassetti M-A, Clemens S, Anderson W, Alvears-Zarikian C, Tada R (2018) East Asian monsoon history and paleoceanography of the Japan Sea over the last 460,000 years. Paleoceanogr. Paleoclimatol. 33: 683–702. https://doi.org/10.1029/2018PA003331

Gradstein FM, Ogg JG, Schmitz M, Ogg G (2012) The Geologic Time Scale 2012. Elsevier, Boston, USA. https://doi.org/10.1016/C2011-0-08249-8

Hagino K (1997) Distribution of living coccolithophores in the western Pacific Ocean off the coast of Northwest Japan. Fossil 65:1–19 (in Japanese with English abstract)

Hagino K, Horiguchi T, Takano Y, Matsuoka H (2011) Geological and biological approaches of speculation with size variation in coccolithophores. Bull. Plank. Soc. Japan 58:73–80 (in Japanese with English abstract)
