Biogeosciences Discuss., 10, 7677–7726, 2013
www.biogeosciences-discuss.net/10/7677/2013/
doi:10.5194/bgd-10-7677-2013

Biogeosciences Discussions
Open Access

Summer and winter living coccolithophores in the Yellow Sea and the East China Sea

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Received: 19 March 2013 – Accepted: 5 April 2013 – Published: 3 May 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

To date, very little information on living coccolithophores species composition and distribution, especially the vertical profile has been reported around the world. This paper tries to fill this gap by descripting on living coccolithophores (LCs) distribution in the Yellow Sea and the East China Sea in summer and winter time in detail, and its relationship among enviromental factors by canonical correspondence analysis (CCA). We carried out the investigations on LC distribution in the Yellow Sea and the East China Sea in July and December 2011. 210 samples from different depths were collected from 44 stations in summer and 217 samples were collected from 45 stations in winter. Totally 20 taxa belonging to coccolithophyceae were identified using a polarized microscope at the 1000 × magnification. The dominant species of the two seasons were *Gephyrocapsa oceanica, Emiliania huxleyi*, *Helicosphaera carteri*, and *Algirosphaera robusta*. In summer the abundance of cells and coccoliths ranged $0 \sim 176.40$ cells mL^{-1}, and $0 \sim 2144.98$ coccoliths mL^{-1}, with the average values of 8.45 cells mL^{-1}, and 265.42 coccoliths mL^{-1}, respectively. And in winter the abundance of cells and coccoliths ranged $0 \sim 71.66$ cells mL^{-1}, and $0 \sim 4698.99$ coccoliths mL^{-1}, with the average values of 13.91 cells mL^{-1} and 872.56 coccoliths mL^{-1} respectively. In summer the LCs in surface layer were mainly observed on the coastal belt and southern part of the survey area. The highest abundance was found at the bloom station. In winter the LCs in surface layer had high value in the continental shelf area of section P. The comparison among section A, section F, section P and section E indicated lower species diversity and less abundance in the Yellow Sea than those of the East China Sea in both seasons. Temperature and the nitrate concentration may be the major environmental factors controlling the distribution and species composition of LCs in the studying area based on CCA.

1 Introduction

As an important phytoplankton functional group in the ocean, by conducting both photosynthesis to absorb CO_2 from the atmosphere and calcification to form calcium carbonate coccoliths and release CO_2 back to the atmosphere, living coccolithophores usually flourish in the open ocean, and sometimes form large blooms that can be viewed by satellites for the white lights reflection from the coccolith both detached and been enclosed in the coccospheres (Holligan et al., 1983; Brown and Yoder, 1994). Thus, coccolithophores take major roles in the marine carbon cycle and it is necessary to understand the ecological distribution of individual species of living coccolithophores (Sun, 2007).

As West Pacific marginal seas, East China Sea and Yellow Sea not only have the eutrophic-water near the coast, but also the oligo-trophic water mainly caused by the Kuroshio current; moreover, the phytoplankton productivity is in general high in these areas, supporting the important fishery in the near shore and the slope sea. There have been many studies on the phytoplankton assemblages since mid-20 century (e.g. Riley, 1957; Okada, 1971), especially Hulburt (1962, 1963a,b, 1964, 1970, 1990) and Marshall (1966, 1968, 1969a,b, 1973, 1976), but few studies on modern coccolithophores had been carried out in these areas.

In the current research, we reported the abundance, composition and correlation between species and environmental parameters from a cubic view of the water layers from two seasons in order to understand the ecological role of living coccolithophores in these regions.

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2 Material and methods

2.1 Survey area and sampling method

We carried out the comprehensive investigations including hydrology, geology, chemistry and biology in the Yellow Sea and East China Sea (27.4° N ~ 36.4° N, 121.3° E ~ 127.3° E) from 6–24 July 2011 and 20 December 2011–12 January 2012, respectively. A total of 44 stations in summer and 45 stations in winter were investigated (Fig. 1).

Water samples from each station were taken by a sampler with attached CTD (conductivity temperature device) device. For each sample 300 mL to one liter of seawater was filtered onto polycarbonate filters (25 mm diameter, 0.22 µm pore diameter) under less than 30 mm Hg filtration pressure. The filters were then transferred onto plastic Petri dishes for air-drying. The dried filters were clipped and then immobilized on glass slides using Neutral balsam for laboratory microscopic analysis.

2.2 Coccolith data analyses and statistical methods

The samples were investigated using a Motic Inverted microscope (PM, BA300) under 1000 × magnification with more than 300 coccoliths or 100 coccospheres being identified and counted per filter according to Bollmann et al. (2002).

Coccolith/coccosphere abundance was calculated following the methodology described in Sun et al. (2011) as the equation:

$$A = \frac{a \times S}{N \times b \times s}$$

where A is the abundance of the species; N is the number of fields counted in each filter; a is the number of total cells of a species in the whole viewing fields of a filter; b is the volume of the water filtered (mL); S is the effective filtration area; and s is the area of per field under 1000 × magnification.

Coccolith/coccosphere dominance index (Y), relative abundance (P) calculation was calculated respectively following the methodology of Sun et al. (2003, 2011):

$$Y = \frac{n_i}{N} f_i$$

$$P = \frac{n_i}{N}$$

Where Y is the dominance index; N is the total number of cells of all species counted; n_i is the number of cells of the species; P is the relative abundance; and f_i is the frequency of occurrence of the species in each sample.

In this survey, we used a multivariate analysis, the canonical correspondence analysis (CCA), to infer the relationship between a set of environmental factors (temperature, salinity, nitrate, nitrite, ammonium, phosphate, silicate, and water depth) and the species abundance (Braak, 1986). In the CCA diagram, the environmental factors are indicated by different arrow lines. The length of the arrow line represents the correlation between a certain environmental factor and the distribution of the community and species. The longer the line is, the larger the correlation is. The angle of the arrow line and the axes stands for the correlation between a certain environmental factor and the axes. The smaller the angle is, the larger the correlation is.

3 Results

3.1 Environmental factors

The surface temperature and salinity distribution are shown in Fig. 2. The Yellow Sea has lower temperature and salinity than the East China Sea. The Yangtze River Estuary coast was affected by the Yangtze River diluted water with low temperature and low salinity, especially in summer. And the offshore of the East China Sea has the high temperature and high salinity water mainly caused by the Kuroshio current. Thus both

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of the low temperature, low salinity eutrophic-water near the coast and the high temperature and high salinity oligo-trophic water caused by the Kuroshio current determine the basic hydrological pattern in the East China Sea areas.

The temperature and salinity vertical distribution of four major sections in the two seasons are shown in Figs. 3 and 4, respectively. In summer, the distribution of the temperature and salinity presented an obvious stratification phenomenon. And below 40 m in the north of Section A, the Yellow Sea Cold Water Mass is formed with the low temperature and high salinity relatively ($T < 9\,^{\circ}\mathrm{C}$, $S > 32$) (Fig. 3). In winter, the temperature and salinity shared the similar tendency increasing from the coast to the offshore. And due to the intensive vertical mixing, the temperature and salinity showed little difference in the water column (Fig. 4).

3.2 LC species in survey area

In summer, a total of 13 taxa were identified (not including undetermined species) in this survey area. The common taxa observed were as followed: *Gephyrocapsa oceanica, Emiliania huxleyi*, *Helicosphaera carteri*, *Algirosphaera robusta* and *Calcidiscus leptoporus*. For coccoliths, *Gephyrocapsa oceanica* and *Emiliania huxleyi* were absolutely dominant with the high frequency of 93.07 % and 92.08 %, the sum relative abundance of 98.65 %. Besides, *Helicosphaera carteri* had a high frequency of 50.00 %, while the relative abundance was as low as 1.07 %. *Gephyrocapsa oceanica* and *Emiliania huxleyi* coccosphere were the dominant species, with high frequencies of 68.81 % and 55.94 %, respectively (Table 1).

In winter, 20 taxa were identified totally and the common taxa were as the same as in summer. *Gephyrocapsa oceanica* and *Emiliania huxleyi* were still the dominant species. Besides, *Braarudosphaera bigelowii* had a higher frequency in winter (Table 2).

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3.3 Horizontal distribution of common species

In summer the abundance of coccoliths and cells ranged $0 \sim 2144.98$ coccoliths mL^{-1}, and $0 \sim 176.40$ cells mL^{-1}, with the average values of 265.42 coccoliths mL^{-1} and 8.45 cells mL^{-1}, respectively. The abundance of *Gephyrocapsa oceanica* coccoliths ranged $0 \sim 1729.09$ coccoliths mL^{-1}, with the average of 156.56 coccoliths mL^{-1}; the abundance of *Emiliania huxleyi* coccoliths ranged $0 \sim 1029.00$ coccoliths mL^{-1}, with the average value of 105.27 coccoliths mL^{-1}; and the abundance of *Helicosphaera carteri* coccoliths was $0 \sim 36.75$ coccoliths mL^{-1}, with the average of 2.83 coccoliths mL^{-1}. As for the cell abundances, *Gephyrocapsa oceanica* ranged $0 \sim 69.83$ cells mL^{-1}, with the average value of 4.38 cells mL^{-1}; the abundance of *Emiliania huxleyi* cells ranged $0 \sim 58.80$ cells mL^{-1}, with the average of 2.12 cells mL^{-1}; and the cell abundance of *Algirosphaera robusta* ranged $0 \sim 47.78$ cells mL^{-1}, with the average of 1.11 cells mL^{-1}.

In winter, the abundance of coccoliths and cells ranged $0 \sim 4698.99$ coccoliths mL^{-1}, and $0 \sim 71.66$ cells mL^{-1}, with the average values of 872.56 coccoliths mL^{-1} and 13.91 cells mL^{-1}, respectively. The abundance of *Gephyrocapsa oceanica* coccoliths ranged $0 \sim 2370.38$ coccoliths mL^{-1}, with the average of 484.89 coccoliths mL^{-1}; the abundance of *Emiliania huxleyi* coccoliths ranged $0 \sim 2260.13$ coccoliths mL^{-1}, with the average value of 365.00 coccoliths mL^{-1}; and the abundance of *Braarudosphaera bigelowii* coccoliths was $0 \sim 16.54$ coccoliths mL^{-1}, with the average of 1.02 coccoliths mL^{-1}. As for the cell abundances, *Gephyrocapsa oceanica* ranged $0 \sim 51.45$ cells mL^{-1}, with the average value of 7.05 cells mL^{-1}; and the abundance of *Emiliania huxleyi* cells ranged $0 \sim 31.85$ cells mL^{-1}, with the average of 4.84 cells mL^{-1}.

As for the surface layer, in summer, the abundance of *Gephyrocapsa oceanica* coccoliths ranged from $0 \sim 463.05$ coccoliths mL^{-1}, with the average abundance of 29.71 coccoliths mL^{-1}; the abundance of *Emiliania huxleyi* coccoliths ranged $0 \sim 286.65$ coccoliths mL^{-1}, and the average value was 16.55 coccoliths mL^{-1}. *Gephyrocapsa oceanica* and *Emiliania huxleyi* presented obvious ribbon distribution in the coastal area of the Yellow Sea and East China Sea, and the highest value was observed in stations northeast to Yangtze River Estuary. For *Helicosphaera carteri*, the highest value was found southwest to Jeju Island (Fig. 5). The abundance of dominant species *Gephyrocapsa oceanica* cells ranged from 0 ~ 23.28 cells mL^{-1}, with the average value of 2.35 cells mL^{-1}; the abundance the other dominant species *Emiliania huxleyi* cells ranged from 0 ~ 7.35 cells mL^{-1}, with the average of 0.90 cells mL^{-1} (Fig. 6). Higher values were mainly observed in the southern parts of the survey area. The abundance distribution of the two dominant species showed similar trend of increasing from north to south.

In winter, as to the surface layer, the abundance of *Gephyrocapsa oceanica* coccoliths ranged from 0 ~ 1405.69 coccoliths mL^{-1}, with the average abundance of 413.04 coccoliths mL^{-1}; the abundance of *Emiliania huxleyi* coccoliths ranged 0 ~ 1455.30 coccoliths mL^{-1}, and the average value was 301.68 coccoliths mL^{-1}. The higher values were observed in stations northwest to Jeju Island and southeast to Yangtze River Estuary. For *Helicosphaera carteri*, the high values presented obvious ribbon distribution along the outside of the survey region (Fig. 7). The abundance of dominant species *Gephyrocapsa oceanica* cells ranged from 0 ~ 19.60 cells mL^{-1}, with the average value of 6.08 cells mL^{-1}; the abundance the other dominant species *Emiliania huxleyi* cells ranged from 0 ~ 18.38 cells mL^{-1}, with the average of 3.77 cells mL^{-1} (Fig. 8). Higher values were mainly observed in the off-sea and the southwest corners of the survey area.

3.4 Vertical distribution of LCs at different sections

3.4.1 Vertical distribution of LCs at section A

Section A located from north of the Yellow Sea to northeast of the East China Sea, across the Yellow Sea. In summer, the abundance of coccoliths ranged 0 ~ 1679.48 coccoliths mL^{-1}, with the average of 215.57 coccoliths mL^{-1}. The abundance of coccoliths was in general less than 200 coccoliths mL^{-1}, increasing from north to south and from surface to depth at this section (Fig. 9). The relative higher values were found in southern part of the section. The cell abundances ranged 0 ~ 53.29 cells mL^{-1}, with the average of 7.98 cells mL^{-1} (Fig. 10). The sum abundance had similar trend with the coccoliths above. However, a high abundance of *Algirosphaera robusta* was observed in the low temperature and high salinity region with the abundance more than 3 cells mL^{-1}. The number of species identified increased from 3 along the coast to 8 in the southeast with a general increasing trend from north to south.

In winter, the abundance of coccoliths ranged 0 ~ 3698.89 coccoliths mL^{-1}, with the average of 924.17 coccoliths mL^{-1}. The abundance of coccoliths was in general focused in southern part of the section (Fig. 11). The cell abundances ranged 0 ~ 40.23 cells mL^{-1}, with the average of 9.75 cells mL^{-1} (Fig. 12). The relative high values also found in the southern part with a general increasing trend from north to south. However, an obvious abundance was observed in the north with the abundance more than 3 cells mL^{-1}. The number of species identified increased from 3 along the coast to 9 in the southeast.

3.4.2 Vertical distribution of LCs at section F

Section F is affected by the Yangtz River diluted water. In summer, the abundance of coccoliths ranged from 0 to 1492.05 coccoliths mL^{-1}, with the average value of 294.68 coccoliths mL^{-1}. And the cell abundance ranged 0 ~ 26.95 cells mL^{-1}, with the average value of 6.78 cells mL^{-1}. The distribution of coccoliths abundance presented obvious layering phenomenon, increasing with depth (Fig. 13); and the distribution of coccosphere cells was similar to that of coccoliths (Fig. 14).

In winter, the abundance of coccoliths ranged from 159.86 to 2451.23 coccoliths mL^{-1}, with the average value of 1130.42 coccoliths mL^{-1}. And the cell abundance ranged 3.68 ~ 36.75 cells mL^{-1}, with the average value of 14.65 cells mL^{-1}. The distribution of coccoliths sum abundance mainly presented increasing trend with depth (Fig. 15); while the high values of coccosphere cells presented plaque distribution (Fig. 16).

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3.4.3 Vertical distribution of LCs at section P

Along section P, in summer, the abundance of coccoliths ranged from $0 \sim 2144.98$ coccoliths mL^{-1}, and the average value was 362.86 coccoliths mL^{-1}, with an obvious trend of increasing coccolith abundance from surface to bottom (Fig. 17). The areas with high values were mainly around continental shelves. The abundance of coccosphere was $0 \sim 30.63$ cells mL^{-1}, with the average value of 8.93 cells mL^{-1}. The abundance in vertical direction presented plaque distribution (Fig. 18). The number of species identified increases from 3 along the coast to 10 in the off-sea stations with a general increasing trend from near-shore to off-sea.

In winter, the abundance of coccoliths ranged from $18.38 \sim 4698.99$ coccoliths mL^{-1}, and the average value was 1270.67 coccoliths mL^{-1}, with a decreasing trend when it comes to off-sea (Fig. 19). The areas with high values were also mainly around continental shelves. The abundance of coccosphere was $1.23 \sim 53.29$ cells mL^{-1}, with the average value of 17.93 cells mL^{-1}. The abundance in vertical direction presented plaque distribution and the high values found near the surface layer (Fig. 20). The number of species identified increases from 4 along the coast to 16 in the off-sea stations with a general increasing trend from near-shore to off-sea.

3.4.4 Vertical distribution of LCs at section E

E section locates in the southernmost part of the survey area. In summer, the abundance of coccoliths and cells ranged $0 \sim 1804.23$ coccoliths mL^{-1} and $0 \sim 39.47$ cells mL^{-1}, with the average of 178.83 coccoliths mL^{-1} and 10.92 cells mL^{-1}, respectively. The abundance of coccoliths was relatively higher in-shore and declined suddenly away from the shore (Fig. 21). *Gephyrocapsa oceanica* was the absolutely dominating species with the abundance ranging from 0 to 1729.09 coccoliths mL^{-1}, and the average value was 131.04 coccoliths mL^{-1}. The abundance distribution of coccosphere cells was mainly affected by distribution of *Gephyrocapsa oceanica*, similar to

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coccoliths. High *Helicosphaera carteri* coccosphere cell abundance was found off-sea (Fig. 22).

In winter, the abundance of coccoliths and cells ranged 7.35 ~ 1413.04 coccoliths mL^{-1} and 1.05 ~ 71.66 cells mL^{-1}, with the average of 422.77 coccoliths mL^{-1} and 22.50 cells mL^{-1}, respectively. The abundance of coccoliths was relatively higher in-shore and around the edge of continental shelves (Fig. 23). *Gephyrocapsa oceanica* and *Emiliania huxleyi* were the dominating species with the abundance ranging from 5.25 ~ 1029.00 coccoliths mL^{-1} and 2.1 ~ 679.88 coccoliths mL^{-1}, with the average value of 206.28 coccoliths mL^{-1} and 212.87 coccoliths mL^{-1}, respectively. *Braarudosphaera bigelowii* was found in the surface around the edge of continental shelves. The high values of coccosphere cells was also observed the same area. High *Helicosphaera carteri* coccosphere cell abundance was found in-shore (Fig. 24).

4 Discussion

In this study for the two seasons, the two dominated species identified were both *Gephyrocapsa oceanica* and *Emiliania huxleyi*, consistent with some previous studies as shown in Table 2.

In summer, in the coccolith CCA diagram (Fig. 25), axis 1 mainly related to depth and temperature while axis 2 mainly relates to ammonium. As shown in Fig. 13, *Gephyrocapsa oceanica*, tropical or warm water coccolithophore, and *Emiliania huxleyi,* eurythermal species (Okada, 1971; Paasche, 2001) were bound up with each environmental factor in the some degree, indicating that they are able to survive in various environmental conditions. Therefore, *Gephyrocapsa oceanica* and *Emiliania huxleyi* have absolute advantages in the Yellow Sea and East China Sea. Similarly, *Helicosphaera carteri*, with a high frequency, widely survives in the survey area, and *Calcidiscus leptoporus* tends to occur in cool waters and nutrient-rich environment. *Syracosphaera spp.* expressed a tendency towards cool waters and rather oligotrophic conditions.

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Umbilicosphaera sibogae had obvious positive correlation with depth. And in the coccosphere CCA diagram (Fig. 26), axis 1 related to depth and temperature while axis 2 related to nutrients with nitrogen. For the dominant species, *Gephyrocapsa oceanica* and *Emiliania huxleyi*, the correlation between the main species and the environmental factors were similar to those of the coccoliths. However, *Syracosphaera spp.*, *Helicosphaera carteri Calcidiscus leptoporus* and *Umbilicosphaera sibogae* had obvious positive correlation with depth. These differences with the coccoliths were possibly caused by the sampling season, station locations or sample numbers.

In winter, in the coccolith CCA diagram (Fig. 27), axis 1 mainly related to nitrate and temperature while axis 2 mainly relates to depth and phosphate. As shown in Fig. 13, Similarly with that in summer, *Gephyrocapsa oceanica*, *Emiliania huxleyi* and *Helicosphaera carteri*, with a high frequency, widely survives in the survey area, and *Braarudosphaera bigelowii* tends to occur in rather oligotrophic conditions. And in the coccosphere CCA diagram (Fig. 28), axis 1 related to salinity, temperature and phosphate while axis 2 related to depth and ammonium. *Gephyrocapsa oceanica*, *Emiliania huxleyi* and *Calcidiscus leptoporus* were bound up with most environmental factors in the some degree while *Helicosphaera carteri* showed obvious positive correlation with phosphate.

Okada and Honjo (1975) reported that the distribution of coccolithophores was associated with nutrient concentrations, especially nitrate; Winter et al. (2002) found the high abundance of LCs on the surface, above the nitrate halocline and in the photic zone under the DCM (Deep Chlorophyll Maximum) in the Caribbean Sea; Andruleit et al. (2003) believed that the mixing layer depth was the decisive factor to the abundance of LCs and the competition with diatoms in the northern Arabian Sea; Yang et al. (2004) suggested that the distribution of LCs was mainly affected by the temperature and salinity; the study of Mohan et al. (2008) found the abundance and species of LCs was inversely linked to the silicate concentration in the Indian sector of the Southern Ocean.

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In this study, according to the Figs. 25 to 28, the distribution of LCs in Yellow Sea and East China Sea had various connections with temperature and the nutrients.

In summer, the abundance of coccolith on the surface layer increased from north to south of the survey area, associated with the environment characteristics. In the Yellow Sea, the temperature, salinity and nutrient concentrations are in general low in summer (Liu and Hu, 2009; Zhang, 2009), which limit the survival and growth of the LCs. As for the East China Sea, the temperature and salinity are significantly higher (Zou and Xiong, 2001) and the input by the Yangtze River runoff and the Kuroshio waters greatly increased the nutrient concentrations (Wang, 2008). The abundance of coccoliths reached a high value along P section. The abundance of the coccosphere cells in the survey area presents plaque distribution mainly focusing on the Yangtze River diluted water region and the south part of East China Sea, resulted from the distribution of temperature, salinity and nutrients in various water masses. As the figure shown, the nutrients enrichment is beneficial to the survival and growth of the LCs (Baumann et al., 2005), so the maximum abundance of the LCs is found at the 20 m depth layer of station T09 where the phytoplankton blooms, consistent with what observed by Jin and Sun (2013).

In winter, the Yellow Sea had low temperature and high salinity, and the particularly low temperature limited the growth of LCs. In the East China Sea, the nutrients were enriched with the influence of the Yangtze River runoff. And the Kuroshio waters brought high temperature. As a result, the LCs in the East China Sea had fast growth rates than in the Yellow Sea. And the maximum abundance of the LCs was also found in the continental shelf of section P, consistent with the study by Zhang (2011).

In summer, axis 1 is depth-dependent (Figs. 25 and 26). Because of the stratification effect, the temperature has strong correlation with the depth by linear regression. Besides ocean currents invasion, the depth is the main factor leading to the temperature changes. Therefore, the water layer depth as well as the nutrients (mainly nitrate) is the decisive factor in summer. The abundance of coccoliths at all sections increased in various degrees as the depth increased. The high value always appeared at the bottom,

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similar with the pattern reported by Sun et al. (2011) in the area of depth less than 200 m in the South China Sea, by deriving from the resuspension of bottom sediment coccoliths and the coccoliths exfoliation after the dead cells settled to the bottom.

In winter, under the effect of monsoon, the temperature had intensive vertical mixing and the nutrients welled up with the upwelling. And the vertical distribution of coccoliths was relatively uniform. Moreover, the high coccosphere abundance presented not only in the bottom, but also in the upper layers So the depth is not the significant environmental factor (Figs. 27 and 28).

The P section, from the Yangtze River Estuary to southeast of the survey area, is affected by Yangtze River diluted waters and the Kuroshio waters, with complicated changing pattern of thermocline, halocline and nutrients. It is always an important section for conducting research on the phytoplankton community dynamics (Liu, 2001). In summer, the increasing trend of coccoliths at section P from surface to bottom is quite obvious, with *Gephyrocapsa oceanica* as the absolutely dominating species. The high value area (station P08) of both coccoliths and coccospheres is near the bottom of the continental shelf, with high temperature, salinity and nutrient concentrations. Meanwhile, the coccospheres have an obvious sudden increase tendency in the off-sea due to the high nutrient value on the bottom caused by the Kuroshio and its branch Taiwan warm current invading to the East China Sea (Wang et al., 1998). In winter, *Gephyrocapsa oceanica* and *Emiliania huxleyi* were the dominant species. The coccoliths increased slightly from the top to the bottom and the had an obvious sudden decrease in the offshore. While the coccosphere present the plaque distribution and the high values found upper layers under the effect of upwelling.

5 Conclusions

In conclusion, based on the study in the two seasons of 2011, the dominant species of coccolithophroes in the Yellow Sea and the East China Sea areas were *Gephyrocapsa oceanica*, *Emiliania huxleyi*, *Helicosphaera carteri* and *Algirosphaera robusta*.

Temperature and the nitrate concentration may be the major en- vironmental factors controlling the distribution and species composition of LCs in the studying area according to CCA.

At present, research on LCs in a wide range of Yellow Sea and the East China Sea of all seasons is still rare. And the correlation between the dominated species as well as its abundance and the nutrients, environmental factors is not absolutely clear. Further studies on the seasonal distribution of coccolithophores, its connections with the environmental factors, and the succession between coccolithophores and other phytoplankton groups, such as diatoms, are still necessary for a comprehensive understanding of LCs distribution in these areas in the future.

Acknowledgements. This research was supported by National Program on Key Basic Research Project of China (Nos. 2009CB421202 and 2011CB409804), and National Natural Science Foundation of China (Nos. 41176136, 40776093 and 41050110436) to Jun Sun. The authors would like to thank the captain and crew of Research Vessel *Dong Fang Hong II* for cruise helping on sampling for the National Program on Key Basic Research Project of China (2010CB428900).

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Table 1. Living coccolithophore species composition of the Yellow Sea and East China Sea in summer 2011

Species	Frequency of occurrence (fi)	Relative abundance (P)	Dominance index (Y)
Coccolith dominant species			
Gephyrocapsa oceanica	93.07 %	59.04 %	0.5494561
Emiliania huxleyi	92.08 %	39.61 %	0.3647127
Helicosphaera carteri	50.00 %	1.07 %	0.0053287
Calcidiscus leptoporus	17.33 %	0.16 %	0.0002719
Coccolithophore dominant species			
Gephyrocapsa oceanica	68.81 %	50.97 %	0.3507418
Emiliania huxleyi	55.94 %	24.63 %	0.1377727
Algirosphaera robusta	31.19 %	12.88 %	0.0401645
Helicosphaera carteri	15.84 %	4.24 %	0.0067235
Calcidiscus leptoporus	11.39 %	2.56 %	0.0029089
Umbilicosphaera sibogae	5.94 %	1.48 %	0.0008770
Syracosphaera spp.	5.94 %	1.45 %	0.0008590

Table 2. Living coccolithophore species composition of the Yellow Sea and East China Sea in winter 2011.

Species	Frequency of occurrence (fi)	Relative abundance (P)	Dominance index (Y)
Coccolith dominant species			
Gephyrocapsa oceanica	98.62 %	56.72 %	0.5593388
Emiliania huxleyi	96.31 %	41.83 %	0.4028726
Helicosphaera carteri	68.66 %	1.08 %	0.0073966
Calcidiscus leptoporus	40.09 %	0.15 %	0.0006089
Braarudosphaera bigelowii	27.65 %	0.12 %	0.0003242
Umbilicosphaera sibogae	19.35 %	0.06 %	0.0001172
Coccolithophore dominant species			
Gephyrocapsa oceanica	80.65 %	50.69 %	0.4087761
Emiliania huxleyi	68.66 %	34.82 %	0.2390601
Algirosphaera robusta	29.95 %	6.47 %	0.0193885
Helicosphaera carteri	19.35 %	3.36 %	0.0065052
Calcidiscus leptoporus	6.45 %	0.74 %	0.0004788
Umbilicosphaera sibogae	6.45 %	0.85 %	0.0005461
Braarudosphaera bigelowii	4.15 %	0.44 %	0.0001812

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Table 3. Historical data of living coccolithophores assemblage in Yellow Sea and East China Sea.

Sampling time	Method[a]	Dominant species	Abundance (cells mL^{-1})	Region	Reference
Dec 2011 ~ Jan 2012	PM	*E. huxleyi*, *G. oceanica*	0 ~ 40.4	Yellow Sea and East China Sea (surface)	This study
Jul 2011	PM	*E. huxleyi*, *G. oceanica*	0 ~ 30.6	Yellow Sea and East China Sea (surface)	This study
Nov 2010	PM	*E. huxleyi*, *G. oceanica*	18.6	East China Sea	Jin et al. (2013)
Dec 2009 ~ Feb 2010	PM	*E. huxleyi* *G. oceanica*	3.84	Yellow Sea and East China Sea	Zhang (2011)
Jul ~ Sep 2009	PM	*E. huxleyi* *G. oceanica*	2.84	Yellow Sea and East China Sea	Zhang (2011)
Jul ~ Aug 2009	SEM/PM	*E. huxleyi* *G. oceanica*	8.41	Yellow Sea and East China Sea	Luan (2010)
Dec 1997	SEM	*E. huxleyi*, *G. oceanica*	0 ~ 56.4	East China Sea (surface)	Yang et al. (2004)
Jul 1996	SEM	Uncertain[b]	11.5 ~ 19.7	Northwest Taiwan (surface)	Yang et al. (2001)
Apr 1996	HPLC	Unclear	–	PN Section	Furaya et al. (2003)
Jul ~ Aug 1994	HPLC	Unclear	–	PN Section	Furaya et al. (2003)
Jan ~ Mar 1993	IM/SEM	*E. huxleyi*, *G. oceanica*	–	PN Section	Furaya et al. (1996)
Jul 1992	SEM	*E. huxleyi*, *G. oceanica*	0 ~ 64.5	East China Sea (surface)	Yang et al. (2004)
Aug 1981	SEM/PM	*E. huxleyi*, *G. oceanica*	–	PN Section	Wang et al. (1988)
Oct ~ Dec 1969	PM	Unclear	–	Two stations in East China Sea	Okada et al. (1975)

[a] IM: Inverted microscope; PM: Polarized microscope.
[b] Uncertain dominant species at different stations.

Table 4. Abbreviations.

LCs	living coccolithophores
CCA	canonical correspondence analysis
DCM	deep chlorophyll maximum

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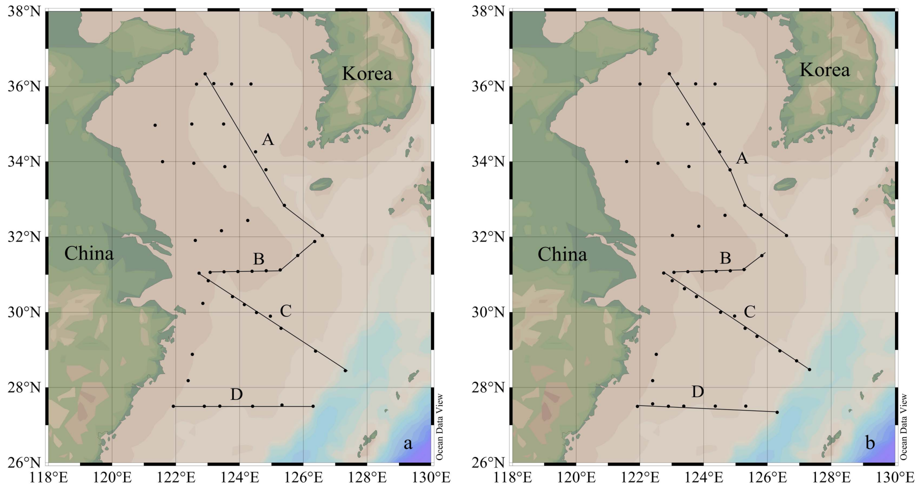

Fig. 1. Sampling stations of living coccolithophores in the Yellow Sea and East China Sea in summer and winter, 2011. A: A section; B: F section; C: P section; D: E section. **(a)** in summer; **(b)** in winter.

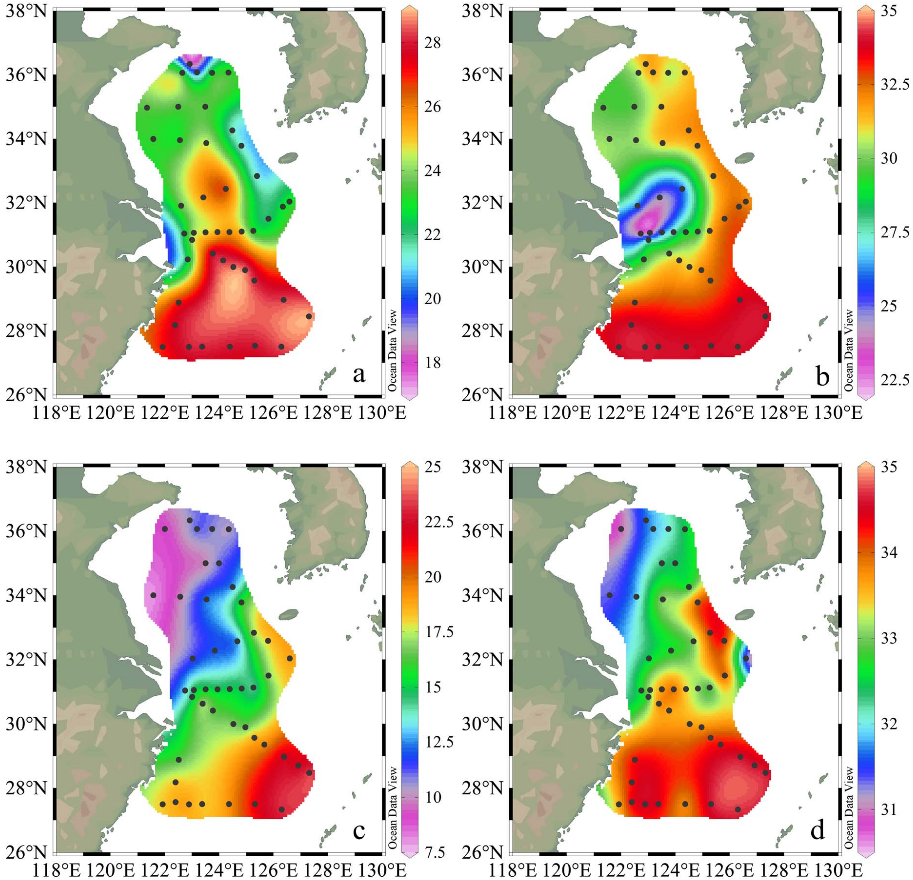

Fig. 2. The distribution of temperature and salinity in the surface layer in summer and winter. **(a)** Temperature distribution in summer (°C); **(b)** salinity distribution in summer (psu); **(c)** temperature distribution in winter (°C); **(d)** salinity distribution in winter (psu).

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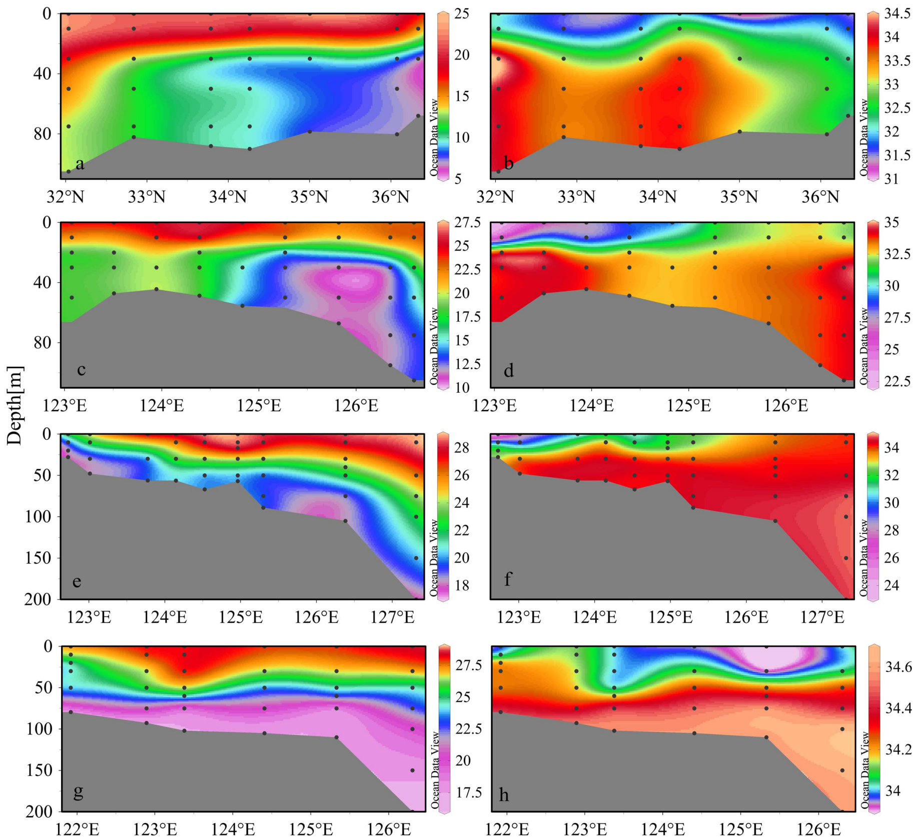

Fig. 3. Vertical distribution of temperature and salinity along the four sections in summer. **(a)** Temperature distribution along section A (°C); **(b)** salinity distribution along section A (psu); **(c)** temperature distribution along section F (°C); **(d)** salinity distribution along section F (psu); **(e)** temperature distribution along section P (°C); **(f)** salinity distribution along section P (psu); **(g)** temperature distribution along section E (°C); **(h)** salinity distribution along section E (psu).

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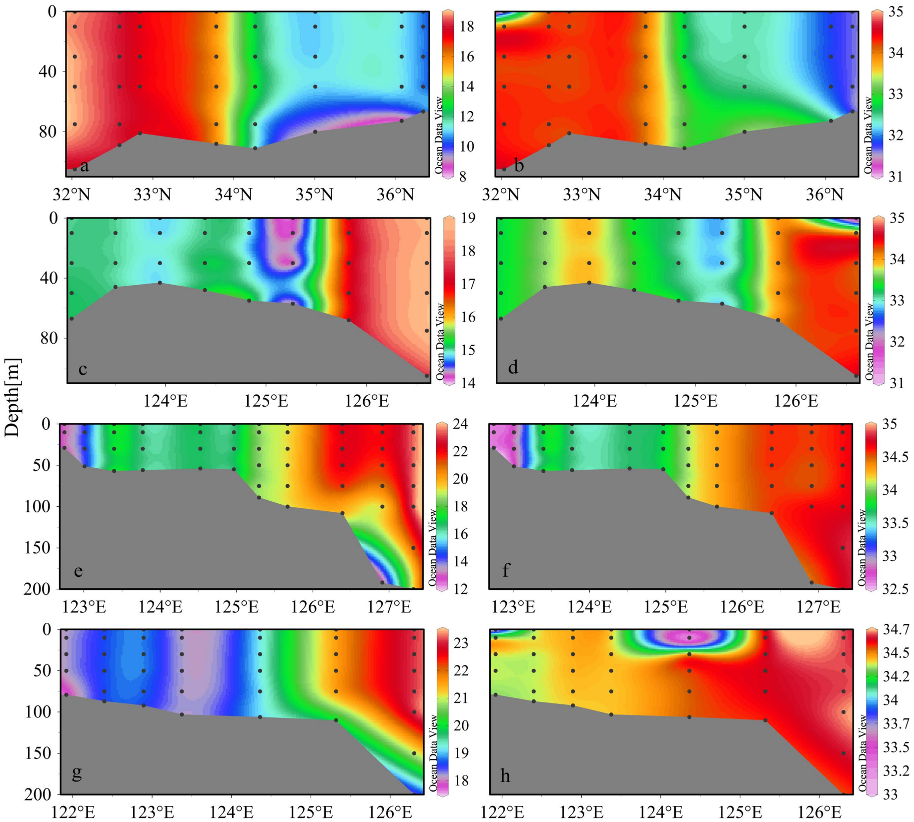

Fig. 4. Vertical distribution of temperature and salinity along the four sections in winter. **(a)** Temperature distribution along section A (°C); **(b)** salinity distribution along section A (psu); **(c)** temperature distribution along section F (°C); **(d)** salinity distribution along section F (psu); **(e)** temperature distribution along section P (°C); **(f)** salinity distribution along section P (psu); **(g)** temperature distribution along section E (°C); **(h)** salinity distribution along section E (psu).

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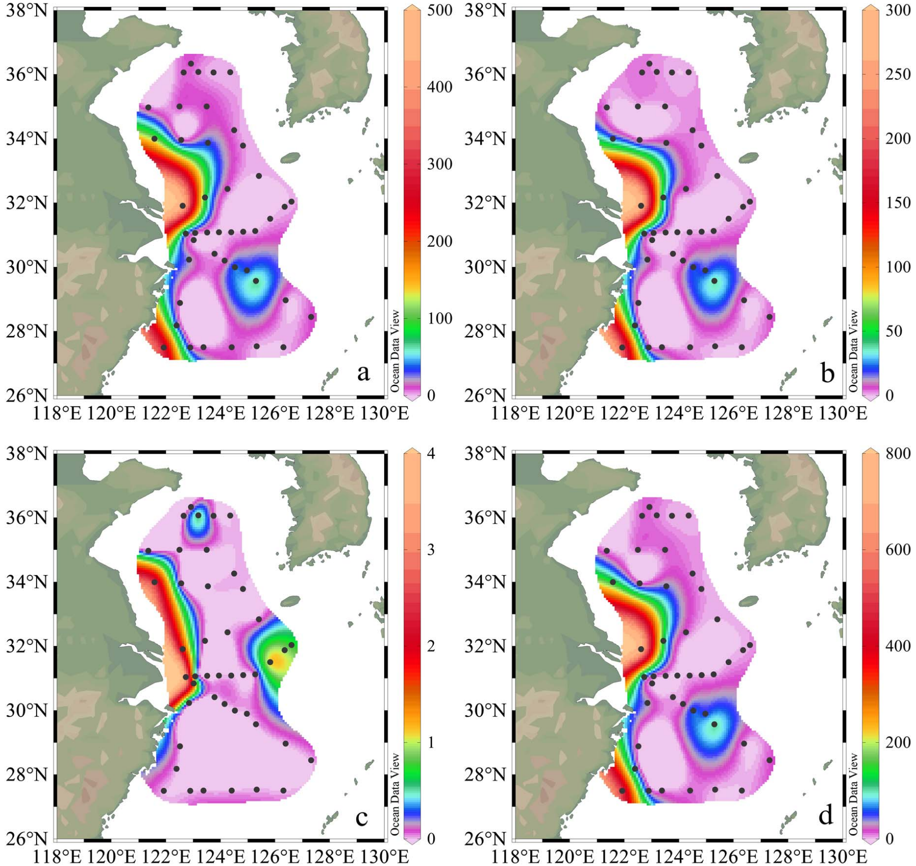

Fig. 5. The abundance distribution of coccolith on surface layer in summer. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Helicosphaera carteri*; and **(d)** sum.

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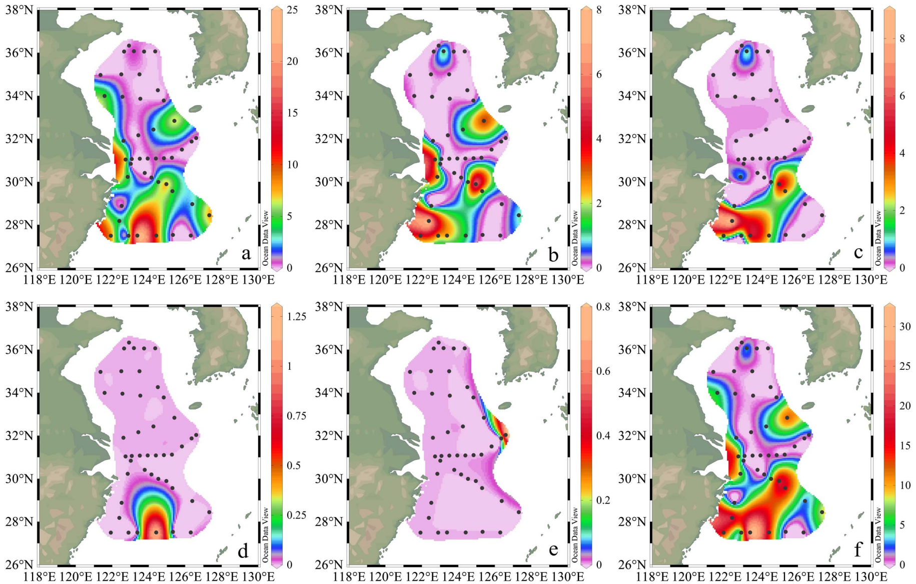

Fig. 6. The abundance distribution of coccosphere on surface layer in summer. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Algirosphaera robusta*; **(d)** *Calcidiscus leptoporus*; **(e)** *Helicosphaera carteri*; and **(f)** sum.

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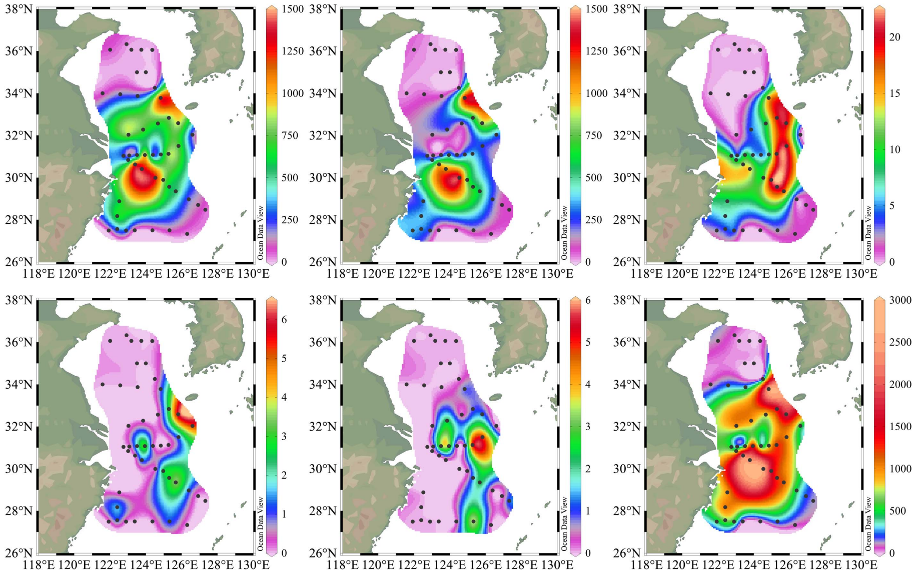

Fig. 7. The abundance distribution of coccolith on surface layer in winter. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Helicosphaera carteri*; **(d)** *Calcidiscus leptoporus*; **(e)** *Braarudosphaera bigelowii*; and **(f)** sum.

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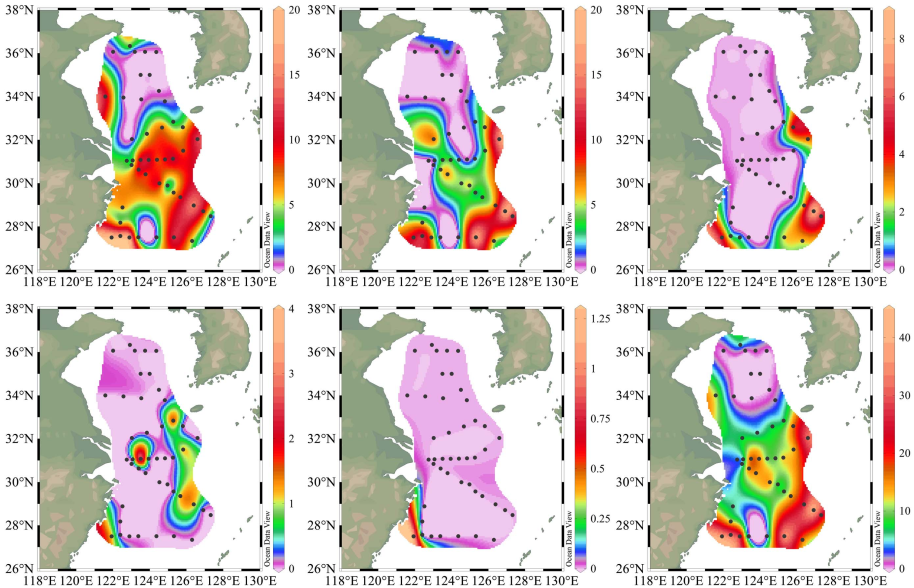

Fig. 8. The abundance distribution of coccosphere on surface layer in winter. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Algirosphaera robusta*; **(d)** *Helicosphaera carteri*; **(e)** *Calcidiscus leptoporus*; and **(f)** sum.

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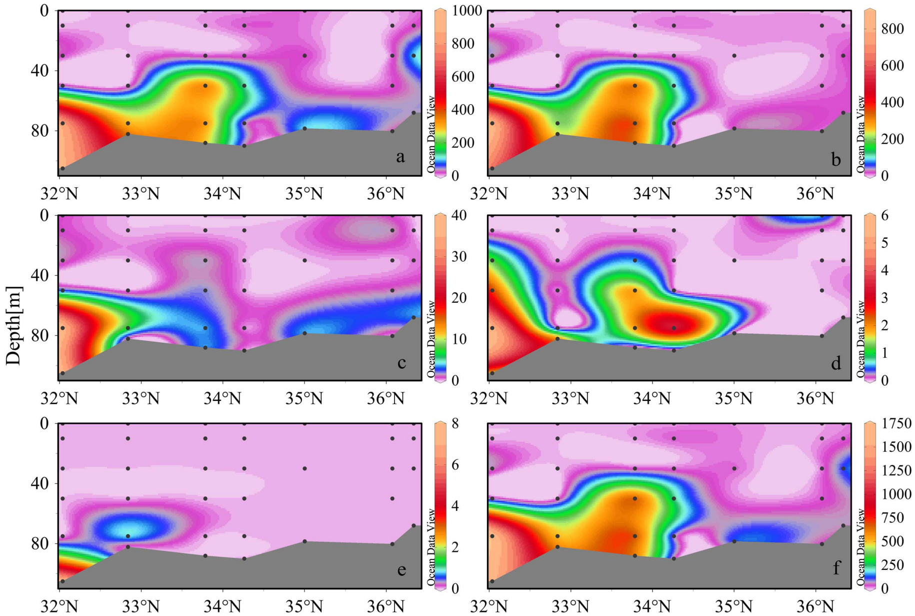

Fig. 9. Vertical distribution of coccolith abundance along the section A in summer. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Helicosphaera carteri*; **(d)** *Calcidiscus leptoporus*; **(e)** *Braarudosphaera bigelowii*; and **(f)** sum.

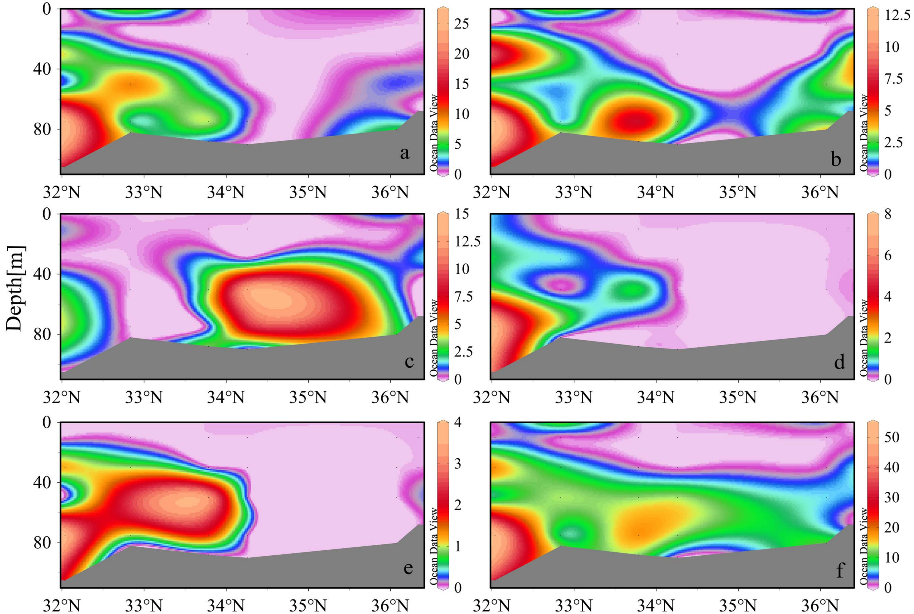

Fig. 10. Vertical distribution of coccosphere abundance along the section A in summer. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Algirosphaera robusta*; **(d)** *Helicosphaera carteri*; **(e)** *Calcidiscus leptoporus*; and **(f)** sum.

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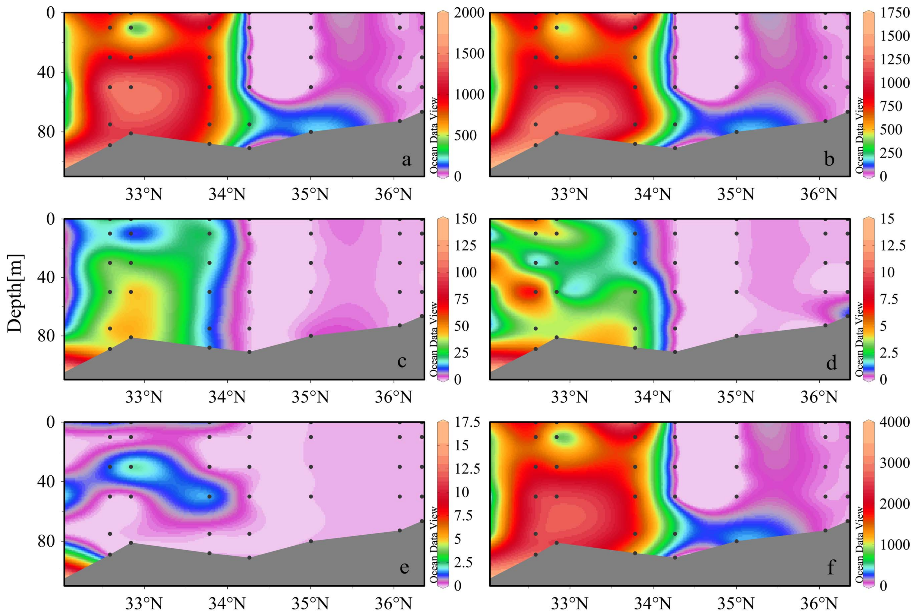

Fig. 11. Vertical distribution of coccolith abundance along the section A in winter. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Helicosphaera carteri*; **(d)** *Calcidiscus leptoporus*; **(e)** *Braarudosphaera bigelowii*; and **(f)** sum.

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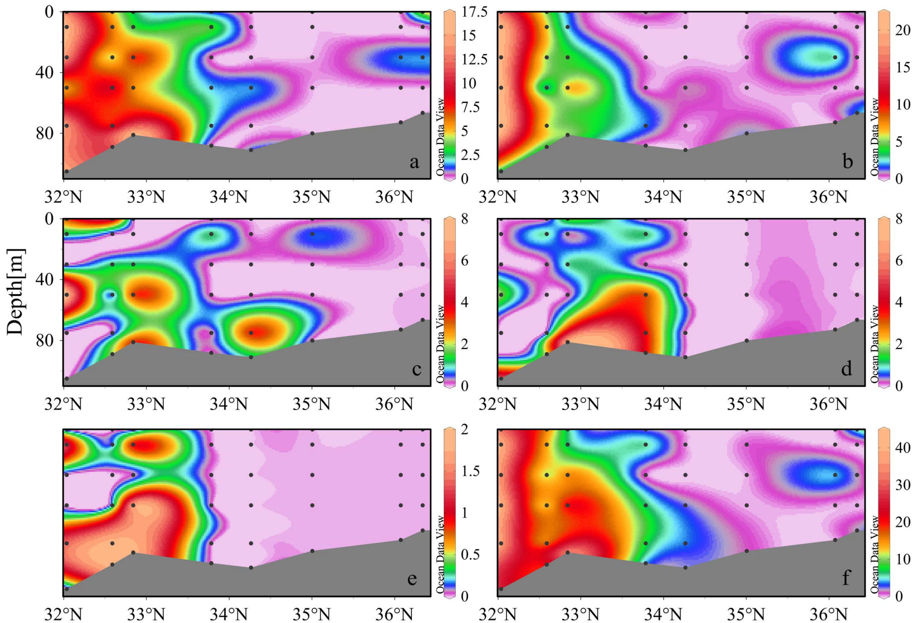

Fig. 12. Vertical distribution of coccosphere abundance along the section A in winter. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Algirosphaera robusta*; **(d)** *Helicosphaera carteri*; **(e)** *Calcidiscus leptoporus*; and **(f)** sum.

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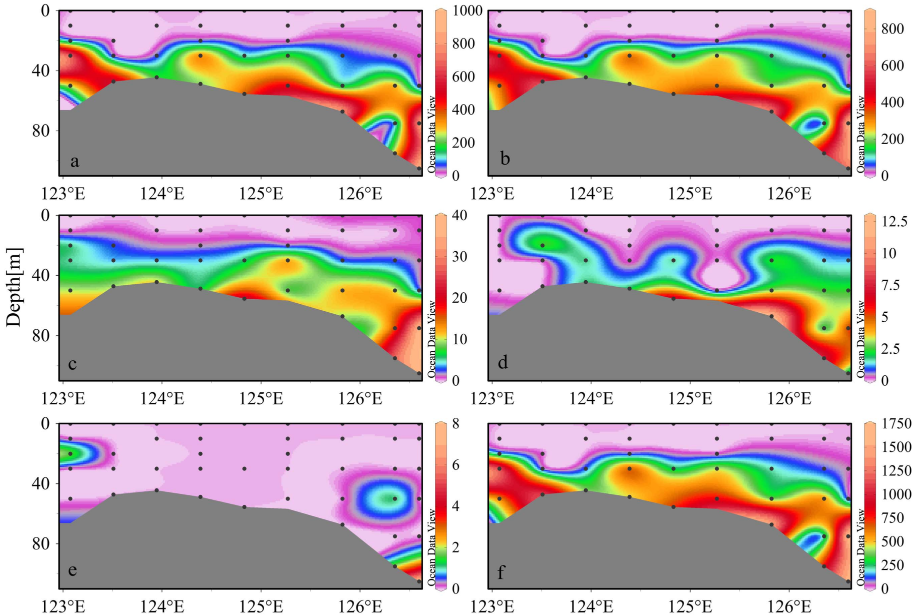

Fig. 13. Vertical distribution of coccolith abundance along the section F in summer. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Helicosphaera carteri*; **(d)** *Calcidiscus leptoporus*; **(e)** *Braarudosphaera bigelowii*; and **(f)** sum.

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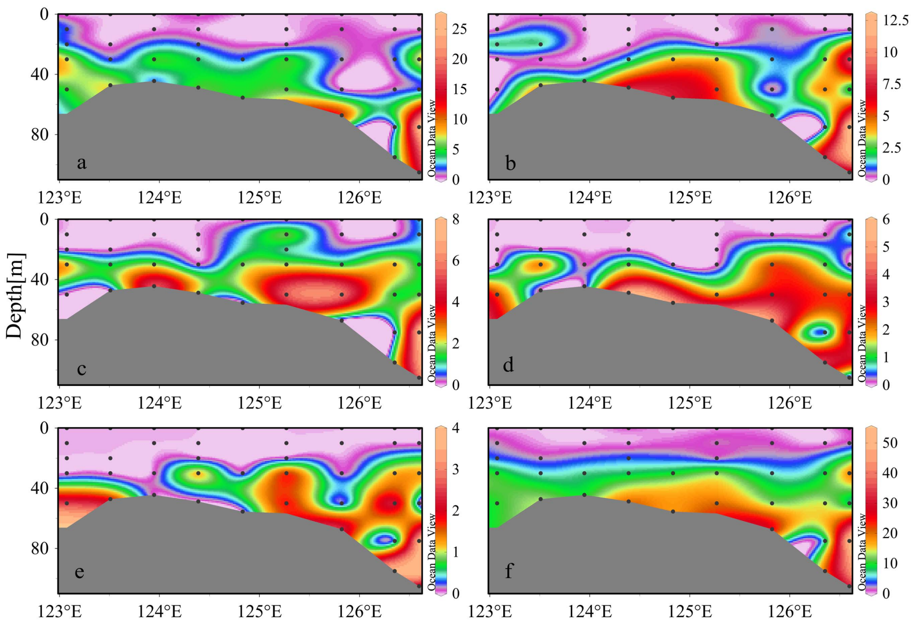

Fig. 14. Vertical distribution of coccosphere abundance along the section F in summer. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Helicosphaera carteri*; **(d)** *Algirosphaera robusta*; **(e)** *Calcidiscus leptoporus*; and **(f)** sum.

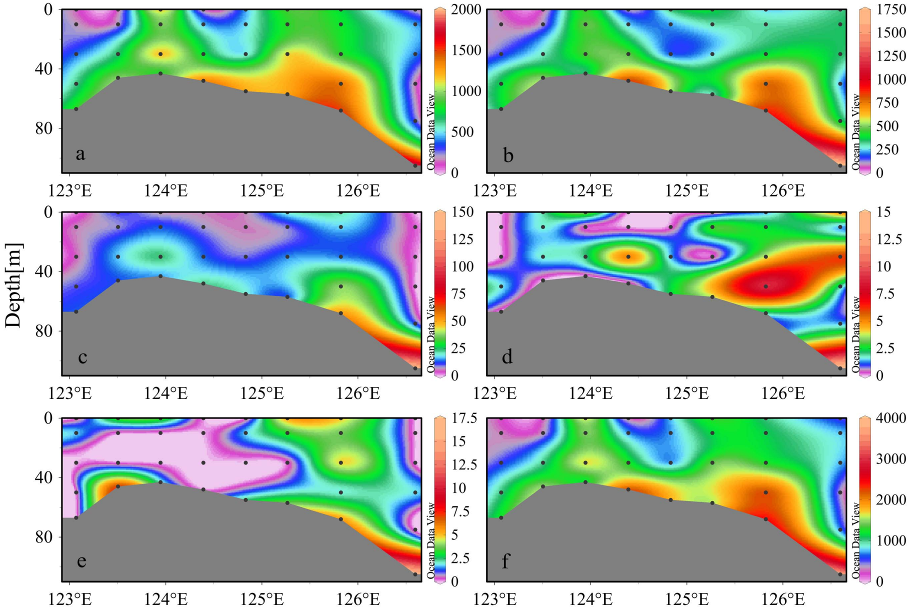

Fig. 15. Vertical distribution of coccolith abundance along the section F in winter. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Helicosphaera carteri*; **(d)** *Calcidiscus leptoporus*; **(e)** *Braarudosphaera bigelowii*; and **(f)** sum.

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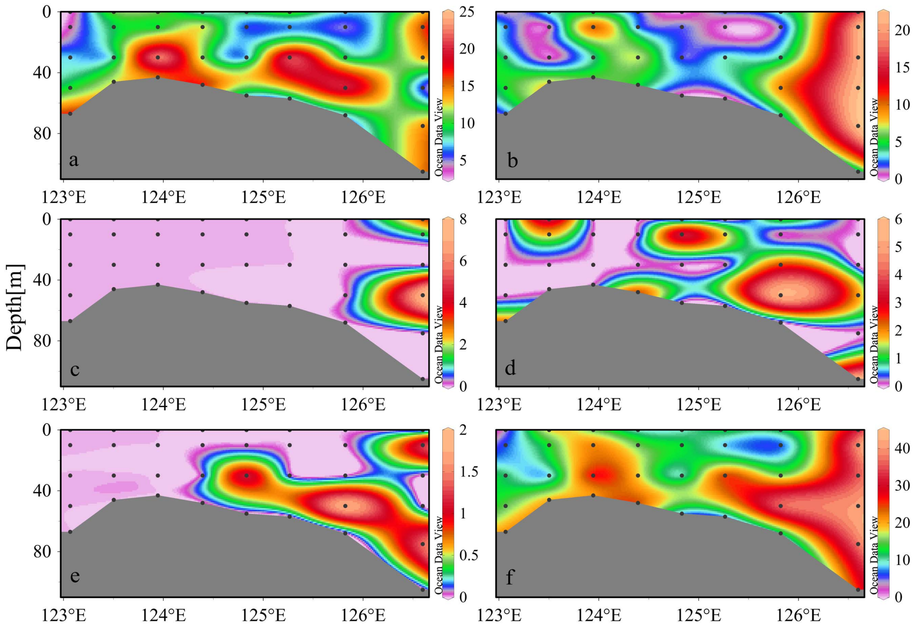

Fig. 16. Vertical distribution of coccosphere abundance along the section F in winter. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Algirosphaera robusta*; **(d)** *Helicosphaera carteri*; **(e)** *Calcidiscus leptoporus*; and **(f)** sum.

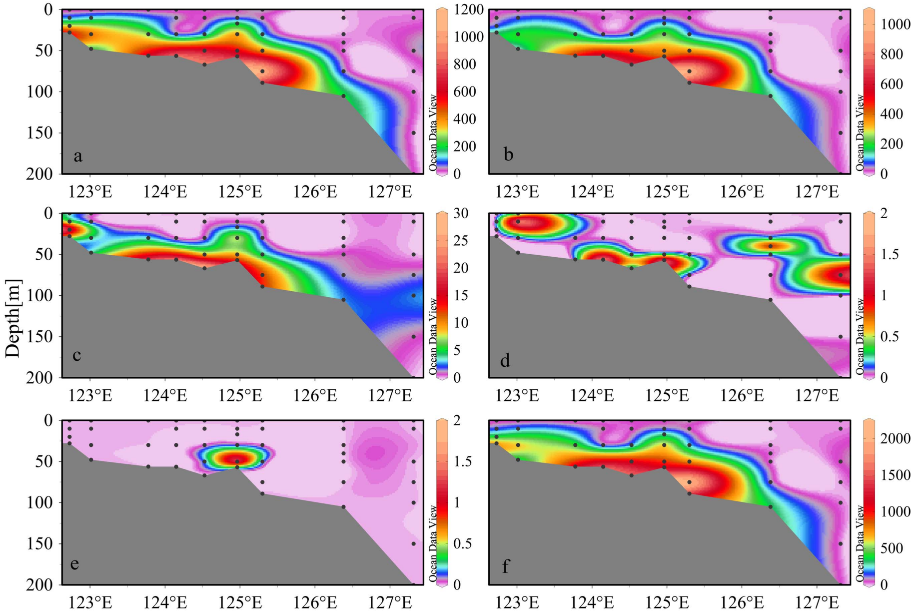

Fig. 17. Vertical distribution of coccolith abundance along the section P in summer. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Helicosphaera carteri*; **(d)** *Calcidiscus leptoporus*; **(e)** *Braarudosphaera bigelowii*; and **(f)** sum.

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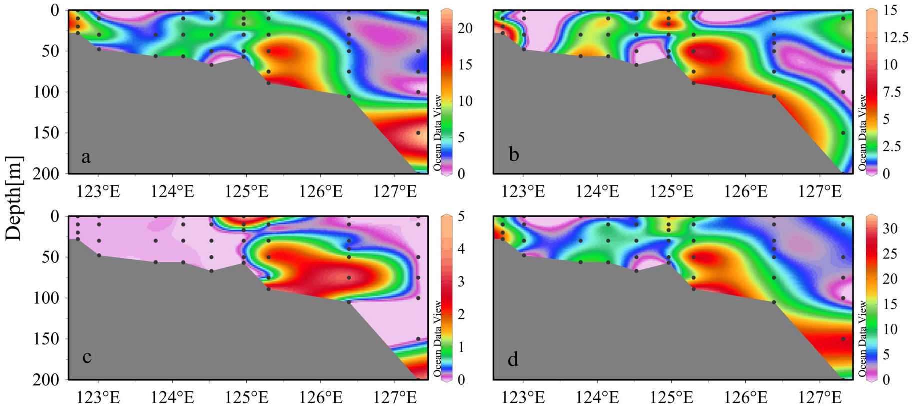

Fig. 18. Vertical distribution of coccosphere abundance along the section P in summer. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Algirosphaera robusta*; and **(d)** sum.

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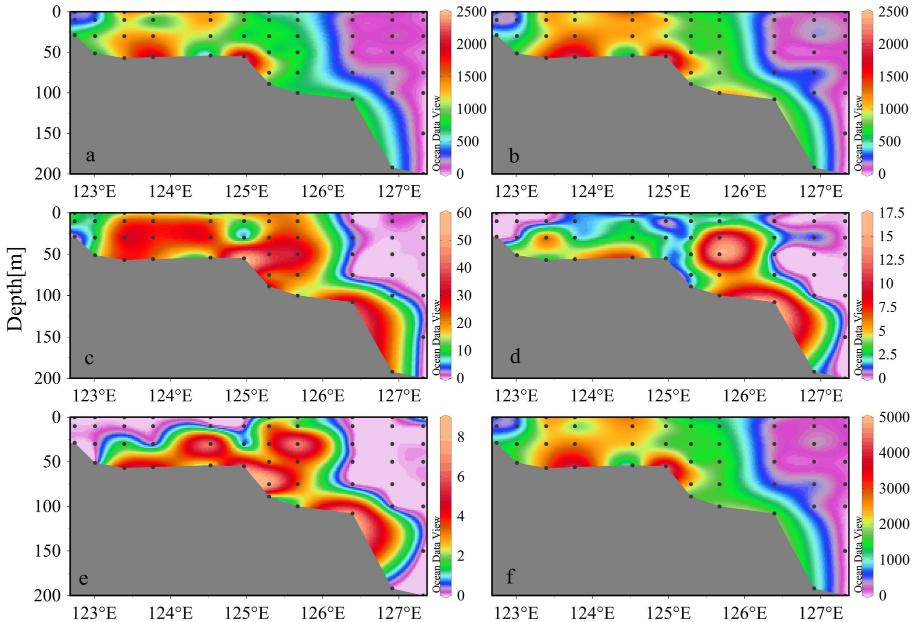

Fig. 19. Vertical distribution of coccolith abundance along the section P in winter. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Helicosphaera carteri*; **(d)** *Calcidiscus leptoporus*; **(e)** *Braarudosphaera bigelowii*; and **(f)** sum.

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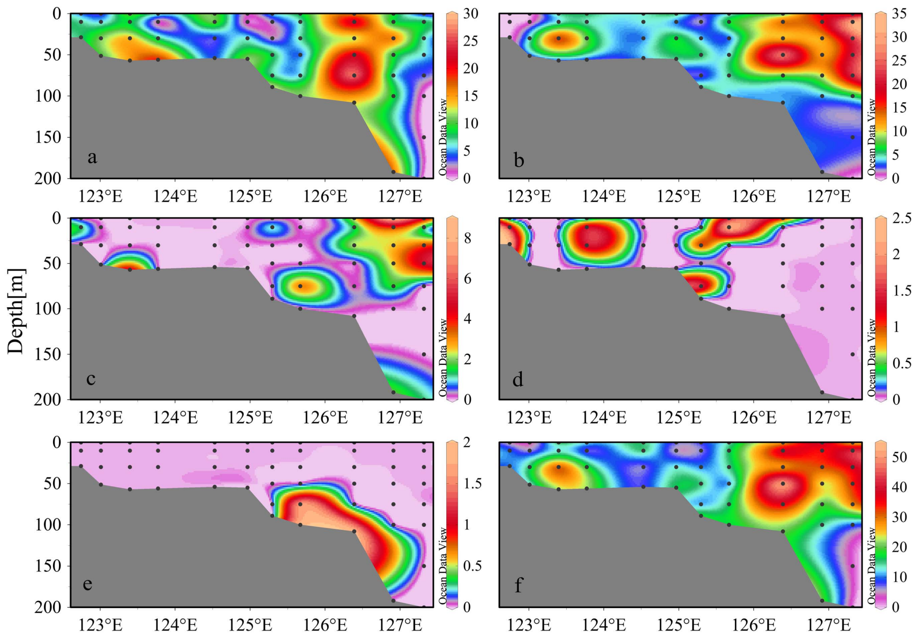

Fig. 20. Vertical distribution of coccosphere abundance along the section P in winter. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Algirosphaera robusta*; **(d)** *Helicosphaera carteri*; **(e)** *Calcidiscus leptoporus*; and **(f)** sum.

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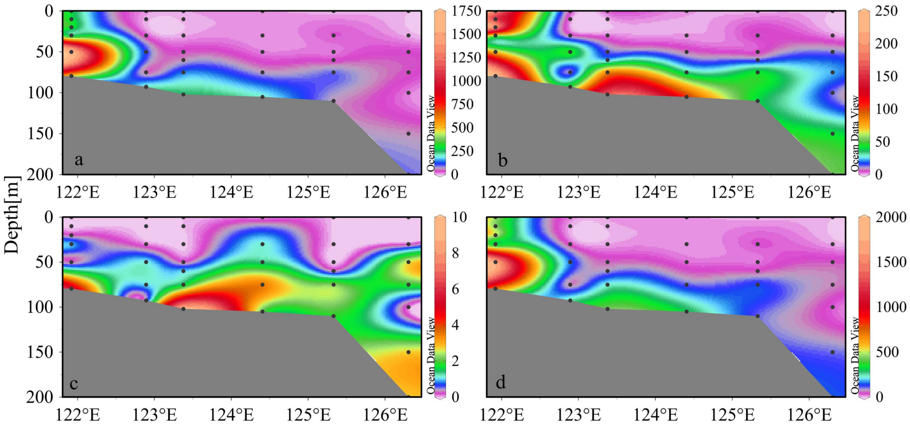

Fig. 21. Vertical distribution of coccolith abundance along the section E in summer. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Helicosphaera carteri*; and **(d)** sum.

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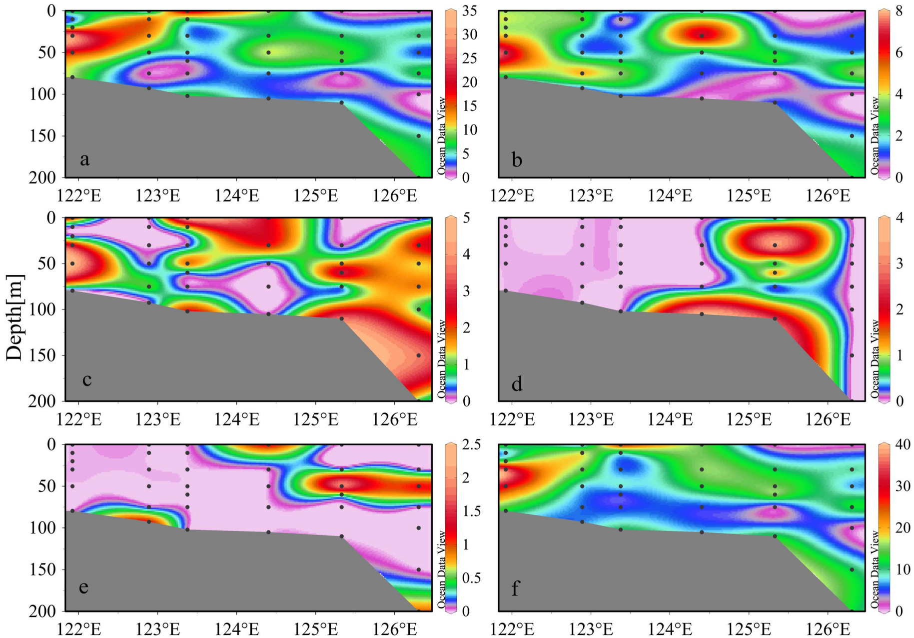

Fig. 22. Vertical distribution of coccosphere abundance along the section E in summer. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Algirosphaera robusta*; **(d)** *Helicosphaera carteri*; **(e)** *Calcidiscus leptoporus*; and **(f)** sum.

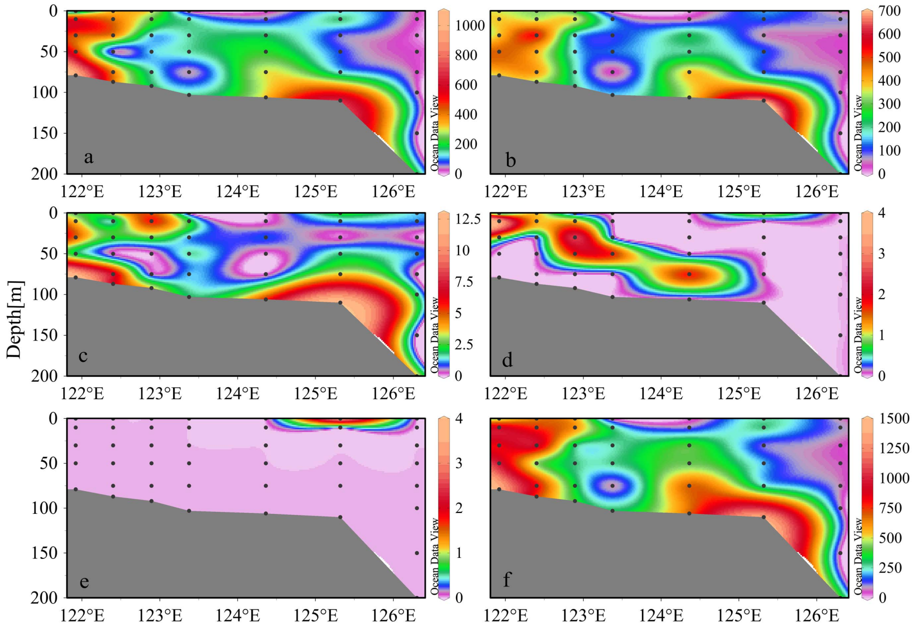

Fig. 23. Vertical distribution of coccolith abundance along the section E in winter. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Helicosphaera carteri*; **(d)** *Calcidiscus leptoporus*; **(e)** *Braarudosphaera bigelowii*; and **(f)** sum.

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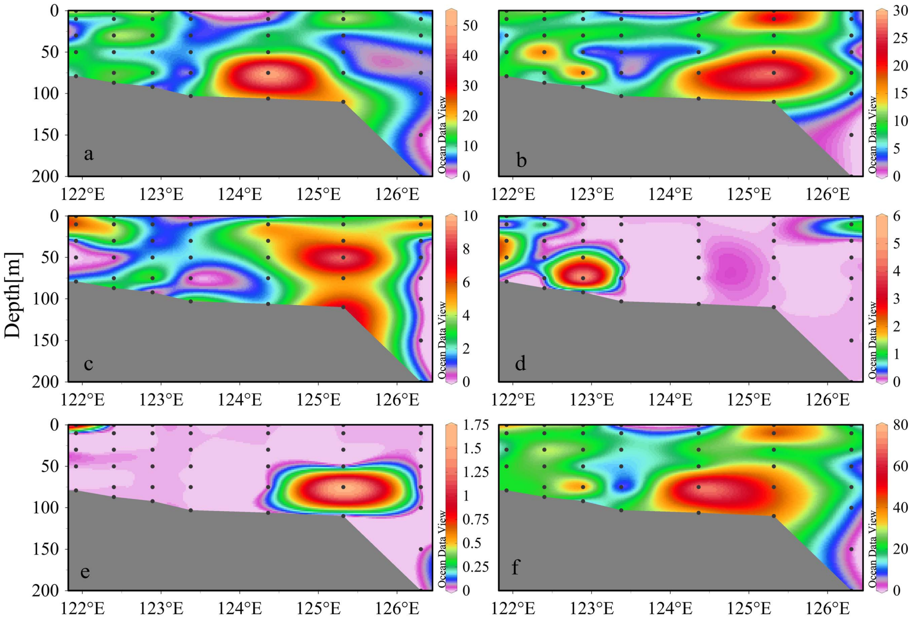

Fig. 24. Vertical distribution of coccosphere abundance along the section E in winter. **(a)** *Gephyrocapsa oceanica*; **(b)** *Emiliania huxleyi*; **(c)** *Algirosphaera robusta*; **(d)** *Helicosphaera carteri*; **(e)** *Calcidiscus leptoporus*; and **(f)** sum.

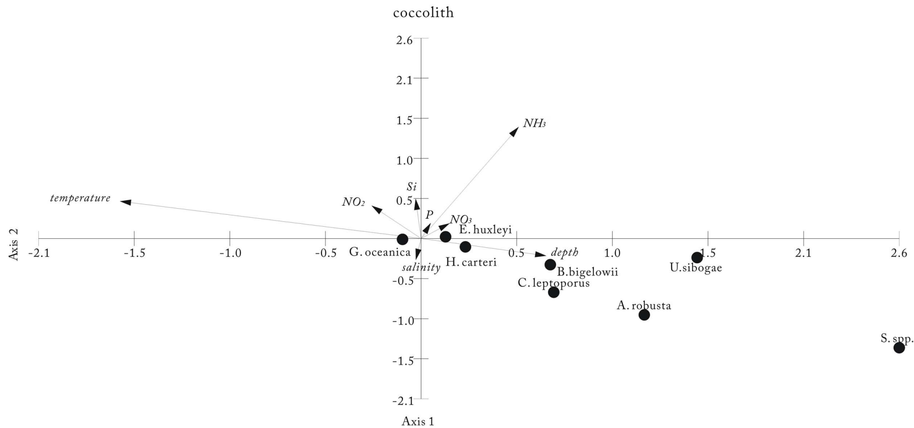

Fig. 25. Results of the CCA of coccolith abundance vs. environmental factors in summer. (NO_2: Nitrite; NO_3: Nitrate; NH_3: Ammonium; Si: Silicate; P: Phosphate; G. oceanica: *Gephyrocapsa oceanica*; E. huxleyi: *Emiliania huxleyi*; H. carteri: *Helicosphaera carteri*; B. bigelowii: *Braarudosphaera bigelowii*; A. robusta: *Algirosphaera robusta*; C. leptoporus: *Calcidiscus leptoporus*; U. sibogae: *Umbilicosphaera sibogae*; S. spp.: *Syracosphaera* spp.)

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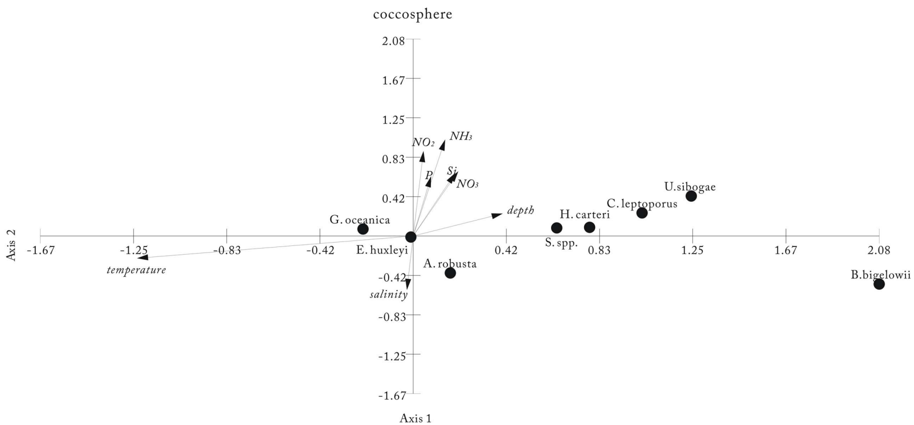

Fig. 26. Results of the CCA of coccosphere abundance vs. environmental factors in summer. (NO_2: Nitrite; NO_3: Nitrate; NH_3: Ammonium; Si: Silicate; P: Phosphate; G. oceanica: *Gephyrocapsa oceanica*; E. huxleyi: *Emiliania huxleyi*; H. carteri: *Helicosphaera carteri*; B. bigelowii: *Braarudosphaera bigelowii*; A. robusta: *Algirosphaera robusta*; C. leptoporus: *Calcidiscus leptoporus*; U. sibogae: *Umbilicosphaera sibogae*; S. spp.: *Syracosphaera* spp.)

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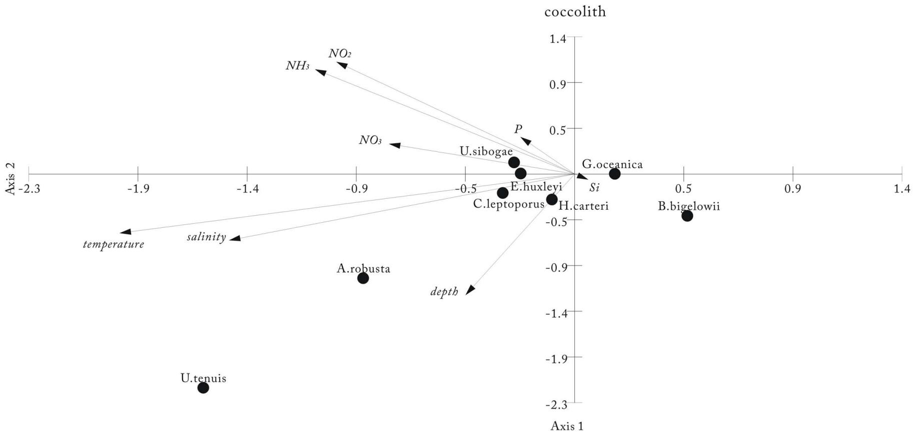

Fig. 27. Results of the CCA of coccolith abundance vs. environmental factors in winter. (NO_2: Nitrite; NO_3: Nitrate; NH_3: Ammonium; Si: Silicate; P: Phosphate; G. oceanica: *Gephyrocapsa oceanica*; E. huxleyi: *Emiliania huxleyi*; H. carteri: *Helicosphaera carteri*; B. bigelowii: *Braarudosphaera bigelowii*; A. robusta: *Algirosphaera robusta*; C. leptoporus: *Calcidiscus leptoporus*; U. sibogae: *Umbilicosphaera sibogae*; U. tenuis: *Umbellosphaera tenuis*)

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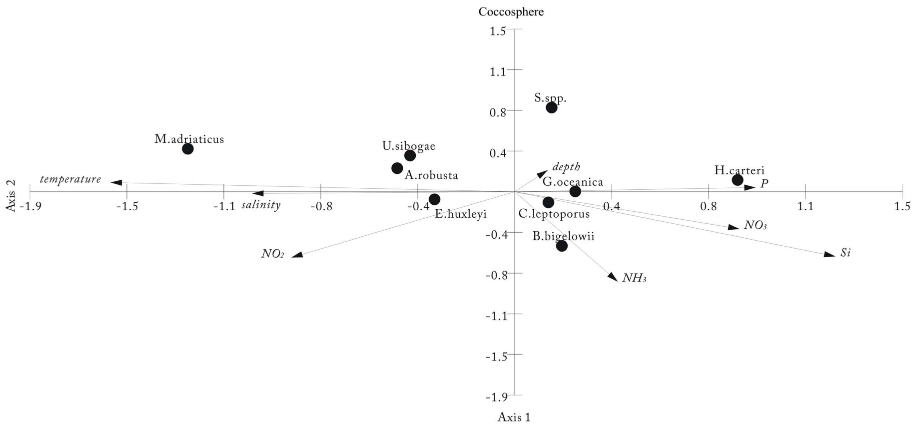

Fig. 28. Results of the CCA of coccosphere abundance vs. environmental factors in winter. (NO_2: Nitrite; NO_3: Nitrate; NH_3: Ammonium; Si: Silicate; P: Phosphate; G. oceanica: *Gephyrocapsa oceanica*; E. huxleyi: *Emiliania huxleyi*; H. carteri: *Helicosphaera carteri*; B. bigelowii: *Braarudosphaera bigelowii*; A. robusta: *Algirosphaera robusta*; C. leptoporus: *Calcidiscus leptoporus*; U. sibogae: *Umbilicosphaera sibogae*; M. adriaticus: *Michaelsarsia adriaticus*; S. spp.: *Syracosphaera* spp.)

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