Acta Oceanol. Sin., 2022, Vol. 41, No. 6, P. 41–53
https://doi.org/10.1007/s13131-021-1913-0
http://www.aosocean.com
E-mail: ocean2@hyxb.org.cn

Distribution of phytoplankton in the East China Sea and the southern Yellow Sea in spring in relation to environmental variables and dimethylsulfide compounds

Jiawei Zhang[1, 2, 5†], Yanghang Chen[4†], Xueyan Ren[1, 2], Vishal Patil[1, 2], Lin Sun[1, 2], Xuesong Li[1, 2], Junrong Liang[1, 2], Jun Zhang[1, 2], Yahui Gao[1, 2, 3*], Changping Chen[1, 2, 3*]

[1] School of Life Sciences, Xiamen University, Xiamen 361102, China

[2] Key Laboratory of the Coastal and Wetland Ecosystems of Ministry of Education, Xiamen University, Xiamen 361102, China

[3] State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen 361102, China

[4] Laboratory of Marine Biology and Ecology, Third Institute of Oceanography, State Oceanic Administration, Xiamen 361005, China

[5] Eco-Environmental Monitoring and Research Center, Pearl River Valley and South China Sea Ecology and Environment Administration, Ministry of Ecology and Environment, Guangzhou 510610, China

Received 19 February 2021; accepted 29 July 2021

Abstract

The coastal ecosystems are highly sensitive to climate change and are usually influenced by variations in phytoplankton communities and water physiochemical factors. In the present study, the phytoplankton community, chlorophyll *a* (Chl *a*) and their relationships with environmental variables and dimethylsulfide (DMS) and dimethylsulfoniopropionate (DMSP) were investigated in spring 2017 (March 24 to April 16) in the East China Sea (26.0°–33.0°N, 120.0°–128.0°E) and southern Yellow Sea (31.0°–36.0°N, 120.0°–125.0°E). The spatial distributions of phytoplankton species composition and cell density were investigated by qualitative and quantitative methods and were compared with historical data to study phytoplankton species succession in the survey area. The results showed that there were 275 phytoplankton species belonging to 90 genera and 6 phyla in the survey area, of which 208 species belonged to 62 genera of Bacillariophyta and 56 species belonged to 20 genera of Pyrrophyta. The dominant phytoplankton species were *Skeletonema dohrnii*, *Chaetoceros vanheurckii* and *Prorocentrum donghaiense*. The phytoplankton cell densities ranged from 0.06×10^4 cells/L to 418.73×10^4 cells/L, with an average value of 21.46×10^4 cells/L. In spring, the average ratio of Bacillariophyta/Pyrrophyta was 41.13 for the entire study area. The areas with high phytoplankton cell density were mainly distributed in the northern South Yellow Sea and offshore waters of the East China Sea. According to a canonical correspondence analysis among phytoplankton and environmental parameters, the water Chl *a* concentrations were notably consistent with phytoplankton cell density ($P<0.001$), and both showed significant negative correlations with salinity and nitrite ($P<0.05$) and significant positive correlations with dissolved oxygen and pH ($P<0.001$). There was a significant positive correlation between diatom (both in cell density and in dominant species) and DMS ($P<0.05$), which indicated that diatoms play a greater role in DMS production in this investigated area.

Key words: phytoplankton, distribution, East China Sea, southern Yellow Sea, dimethylsulfoniopropionate

Citation: Zhang Jiawei, Chen Yanghang, Ren Xueyan, Patil Vishal, Sun Lin, Li Xuesong, Liang Junrong, Zhang Jun, Gao Yahui, Chen Changping. 2022. Distribution of phytoplankton in the East China Sea and the southern Yellow Sea in spring in relation to environmental variables and dimethylsulfide compounds. Acta Oceanologica Sinica, 41(6): 41–53, doi: 10.1007/s13131-021-1913-0

1 Introduction

Phytoplankton are the main primary producers of marine ecosystems and account for nearly 95% of marine primary productivity (Koblentz-Mishke et al., 1970; Reynolds, 1984; Sun, 2011; Zhou, 2014) due to photosynthesis and the energy supply to other organisms (Falkowski et al., 1992; Noman et al., 2019), which are the foundations of marine ecosystems and food webs that sustain most oceanic life (Charlson et al., 1987; Sarmiento et al., 1988) and play a key role in marine ecosystems (Jia et al., 2014). Due to its short life cycle, phytoplankton is very sensitive to changes in environmental stress conditions, and the community structure of phytoplankton can reflect the nutritional status of marine ecosystems; therefore, phytoplankton are a critical indicator of changes in marine climates and environments (Norse, 1993; Hays et al., 2005; Torrisi and Dell'Uomo, 2006). For example, the eutrophication of seawater will lead to the miniaturization of phytoplankton, the different ratio of nitrogen to phosphorus will lead to the change of phytoplankton particle size structure, and the frequency of small-size diatom red tide will increase (Chen et al., 2010; Ma, 2018); the acidification of seawater

Foundation item: The National Key Research and Development Program of China under contract Nos 2016YFA0601302 and 2018FY100202.

*Corresponding author, E-mail: gaoyh@xmu.edu.cn; chencp@xmu.edu.cn

†These authors contributed equally to this work.

and the decrease of pH will lead to the decrease of diatom species (Ma, 2018); the inhibition of cryptophytes and diatoms was more significant at high salinities (Van Meerssche and Pinckney, 2017). Especially, with changes in the global environment, the structure of phytoplankton communities has changed markedly, which has been indicated by the change of diatom predominance to dinoflagellates and cyanobacteria predominance, and the proportion of toxic and harmful algal blooms (HAB) is increasing (Anderson et al., 2002; Wu and Kow, 2002; Taylor et al., 2007; Aubry et al., 2012).

In recent years, with frequent human activities and the intensification of industrialization, global environmental and climate change have created unprecedented challenges (Lammers et al., 2013; Hoegh-Guldberg et al., 2018; Sekerc and Ozarslan, 2020). These anthropogenically induced changes have altered terrestrial and aquatic environments and ecosystems (Lammers et al., 2013). Emissions of industrial waste gas, fossil fuel burning, deforestation and wetland destruction have led to ocean acidification and global warming (Zeebe, 2012). Global warming directly influences the increment of temperature at the ocean surface, which not only causes increased water vapor in the atmosphere (Schaffer et al., 2000), leading to a greenhouse effect, but also causes glacial melting (Najjar et al., 2000, 2010) and sea level rise (Nick et al., 2013), and thereby changing the marine environment. The change of marine environment has an important impact on the marine ecosystem starting from phytoplankton, which is mainly manifested in the succession of phytoplankton community structure, physiological and ecological response, primary productivity and biogeochemical cycle (Findlay et al., 1999; Zhao et al., 2020).

On the other hand, phytoplankton produce an organic compound, dimethylsulfoniopropionate (DMSP), which is important for regulating the global climate and environment. DMSP is one of the main carbon and sulfur sources in the ocean (Stefels and van Leeuwe, 1998; Simó, 2001; Stefels et al., 2007). It also plays a role in osmotic pressure regulation (Kirst, 1990) and resistance to freezing (Nishiguchi and Somero, 1992; Karsten et al., 1996) of phytoplankton. Acrylic acid, one of its degradation products, can promote phytoplankton to resist predation (Wolfe and Steinke, 1996), while dimethylsulfide (DMS), another degradation product, plays an important role in climate regulation. DMSP, as the precursor of DMS, is decomposed by DMSP lyase (DLA) to form DMS. DMS released from seawater accounts for 95% of natural marine sulfur emissions and plays an important role in the global sulfur cycle. Charlson et al. (1987) proposed the CLAW hypothesis, which states that DMS has the function of regulating global climate. There may be a negative feedback process between DMS emission and climate change. With global warming, the surface temperature of seawater increases, which promotes phytoplankton productivity and thus accelerates DMS release. Recently, Deng et al. (2021) reported that DMS concentrations were affected by the pH of phytoplankton photosynthetic processes; when the pH exceeded 8.1, DMS degradation accelerated, and its concentration decreased. Andreae and Crutzen (1997) stated that if the DMS flux changes one time, the global average temperature will change by several degrees Celsius.

The East China Sea (ECS) and Yellow Sea (YS) are important marginal seas in the Northwest Pacific Ocean (Chen, 2009). This area is one of the most typical continental shelf shallow seas in the world (Yu et al., 2017). The environmental status of this sea area is not only affected by inputs of land-based materials, but also is closely related to the water exchange process of the adjacent ocean. The main circulation system of the ECS is composed of the Taiwan Warm Current in the Kuroshio shelf area and the coastal current in the nearshore area (Guan, 1994; Chen, 2009). At the same time, large amounts of fresh water are transported to the ECS by runoff from of the Changjiang River, which has an important impact on the marine environment (Zhao et al., 2019a). The YS is a semiclosed shelf shallow sea. The warm current in the middle of the YS and the coastal currents on both sides are the main circulations in the YS. There are cold, seasonal water masses in the middle of the YS in summer (Guan, 1994; Zhang et al., 1996). These complex ocean circulations and abundant land-based material inputs affect the environment and ecosystem of the ECS and YS (Liu and Xu, 1963; Zhou et al., 2008; Chen, 2009; Chinese Society of Oceanography, 2015), which cause the marine environment to be eutrophic and have high primary productivity to produce more DMS, leading to significant impacts on global environmental change. Therefore, it is especially important to study phytoplankton in this sea area. After consulting the literature, we found that research on marine phytoplankton in the ECS and YS began in the late 1950s, and large volumes of data have been gathered (Zhu and Guo, 1959; Guo, 1963; Chen et al., 1980; Huang et al., 1984; Furuya et al., 1996; Chiang et al., 1999, 2004). To date, many studies by domestic and foreign scholars have covered many aspects, such as phytoplankton taxonomy, size fraction structure, floristic distribution, environmental adaptability and HAB (Lu and Goebel, 2001; Zhou et al., 2008; Song, 2010; Guo et al., 2011). Former studies have shown that the species composition and distribution of phytoplankton in the YS and ECS are largely controlled by the marine environment and oceanographic processes, such as the Yellow Sea Cold Water Mass, distribution of Changjiang River Diluted Water and invasion of Kuroshio into the ECS shelf area (Liu et al., 2012; Wang et al., 2014; Song et al., 2017; do Rosario Gomes et al., 2018; Zhao et al., 2018, 2019b). The community diversity of phytoplankton and the response of biogenic active gases to phytoplankton are the key areas of marine phytoplankton investigation in China.

At present, studies of DMS in this area are mainly focused on the concentration distribution, air sea flux estimation and relationship of phytoplankton with physical and chemical factors (Yang et al., 2015a; Liu et al., 2016; Jian et al., 2019). However, the contribution of phytoplankton community to DMS has been rarely studied. Moreover, most studies in China have concentrated on the local waters of Qingdao (Hu et al., 1995, 1997; Ma, 2004; Ma et al., 2004), Xiamen (Du et al., 1998; Jin et al., 2004), the Bohai Sea (Xu et al., 2019), the YS (Yang et al., 2015b; Liu et al., 2016), and the ECS (Yang et al., 2011), which have space coverage limitations. Few studies have examined the relationship between phytoplankton and DMS at the scale of the entire east shelf sea area. In this study, which is based on an investigation of the phytoplankton distributions in the ECS and the South YS (SYS) from March to April 2017, the chlorophyll *a* (Chl *a*) concentration and phytoplankton cell density, community structure and species diversity are studied. The aim of this study is to reveal the relationships between phytoplankton and environmental factors, and the DMS and DMSP concentrations across the entire ECS and SYS.

2 Materials and methods

2.1 *Study area*

From March 27 to April 15, 2017, the R/V *Dongfanghong 2* scientific research vessel established 10 sections in the ECS (26.0°–33.0°N, 120.0°–128.0°E) and the SYS (31.0°–36.0°N, 120.0°–125.0°E) to conduct a comprehensive hydrological, chemical and biological survey at 58 stations (Fig. 1).

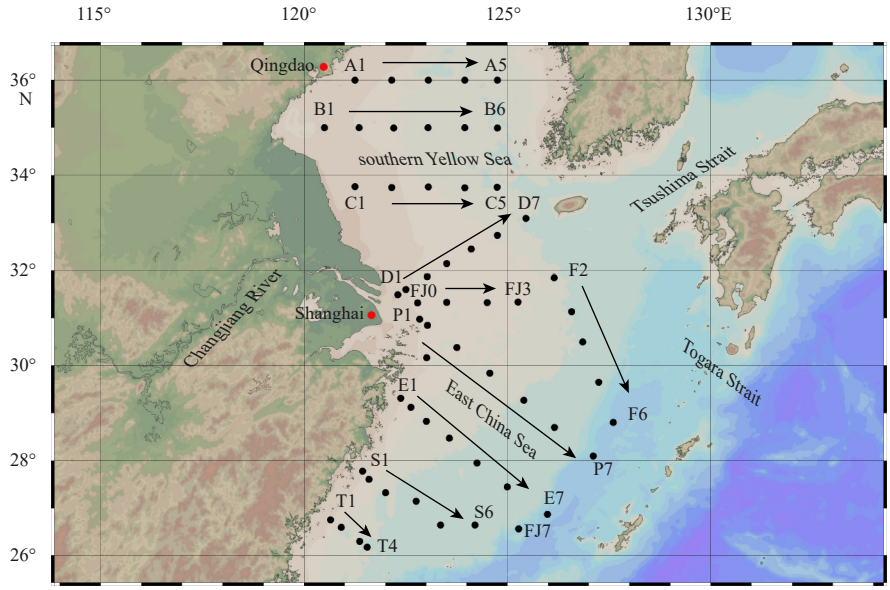

Fig. 1. Map of the location of phytoplankton survey stations in the East China Sea and the southern Yellow Sea.

2.2 *Sample collection and phytoplankton species identification*

Sample collection, processing and analysis of the phytoplankton community and Chl *a* concentration were carried out in accordance with General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China and Standardization Administration (2008). In this survey, seawater samples were collected by the R/V *Dongfanghong 2* in the ECS and SYS. Seawater was obtained at 58 stations using a series of 12 L Niskin bottles attached to a Seabird 911 plus conductivity-temperature-depth (CTD) sensor rosette (SEA-BIRD, America). Salinity, temperature and water depth were measured using the Seabird 911 CTD equipment. Chl *a* samples were filtered with a Whatman GF/F glass fiber filter membrane (diameter 25 mm) with a pore size of 0.70 μm under a pressure of less than 15 kPa. To prevent Chl *a* decomposition, 1 mL of the $MgCO_3$ suspension was added to the seawater samples before filtration. After filtration was completed, the filter membrane was folded in half, wrapped in aluminum foil and then frozen in liquid nitrogen. The Chl *a* concentration was determined by the fluorescence method (Parsons et al., 1984). The filters were extracted with 10 mL 90% acetone solution at low temperature (–20°C) for approximately 24 h and were then centrifuged at 4 500 r/min for 15 min, and the supernatant was determined by the Trilogy laboratory-type fluorescence analyzer 7200-000 (Turner Designs, America). A series of standard concentration gradient solutions were prepared with a pure Chl *a* product (Sigma, America) before sample determination. Fluorescence signals were measured using the Turner Designs system, and working curves were drawn according to the concentration and fluorescence signals.

Phytoplankton water samples (1 000 mL) from each representative layer was collected and poured into sample bottles. The samples were immediately fixed with Lugol's iodine solution at a ratio of 1.5%. All samples were statically deposited for 24 h, and the supernatant was removed by a siphon. A 0.1 mL water sample was placed into a counting box that was used for identification (Round et al., 1990; Guo and Qian, 2003; Huang and Lin, 2012; Cheng et al., 2013a, b; Yang et al., 2016a, b), and counting was performed used an Olympus BH-2 microscope. Each sample was counted twice, and the number of specimens per microscopic examination was more than 500 individuals. There were no significant differences between the two microscopic examinations of the same sample.

The DMS determination method is described in Zhang et al. (2014). DMSP determinations were carried out by pretreatment, which converted 1:1 DMSP into DMS (Dacey and Blough, 1987; Yang et al., 2011). Particulate DMSP (DMSPp) was calculated as the difference between total DMSP and dissolved DMSP (DMSPd) (Xu et al., 2019). The DMSP determinations were carried out by pretreatment, which converted 1:1 DMSOt and DMSOd into DMS. The particulate dimethylsulfoxide (DMSOp) levels were derived from the differences between DMSOt and dissolved DMSO (DMSOd) (Kiene and Gerard, 1994; Spiese et al., 2009). The determination of sulfide-related data was completed in the Ocean University of China (unpublished), and they were used for correlation analysis.

2.3 *Data processing and statistical analysis*

The Shannon-Wiener diversity index (H'), Pielou evenness index (J) and dominance index (Y) were used to analyze the phytoplankton community structure. The Shannon-Wiener diversity index formula (Shannon, 1948; Shannon and Weaver, 1949) is as follows:

$$H' = -\sum_{i=1}^{s} P_i \log_2 P_i, \tag{1}$$

in the formula, P_i is the ratio of the number of species i in the sample to the total number of samples, and S is the number of species in the sample.

The Pielou Uniformity Index Formula (Pielou, 1969) is as follows:

$$J = \frac{H'}{\log_2 S}, \tag{2}$$

where S is the number of species in the sample.

The dominance calculation formula (Lampitt et al., 1993) is as follows:

$$Y = \frac{n_i}{N} f_i, \tag{3}$$

where n_i is the number of species i in all samples; N is the number of species; and f_i is the frequency of occurrence of the species at each survey station.

Statistical Product and Service Solutions 11.0 and Canoco 4.5 were used to analyze the correlations between dominant species and environmental factors. Correlation analyses among phytoplankton density, diversity index, Bacillariophyta cell density/Pyrrophyta cell density (B/P), DMSO and environmental factors in the SYS and ECS in spring 2017 were performed using the R Programming Language software. The relationships between the phytoplankton community structure and the main environmental factors were analyzed with CANOCO software. As we considered dominant species, only those taxa that were observed in >10% of all samples were included in the analyses (Chen, 2017; Leira and Sabater, 2005). Species data and environmental parameters were transformed by $\log_{10}(x+1)$ and were then analyzed to obtain normal distributions. First, the species data were analyzed by detrended correspondence analysis to determine the appropriate ranking model. Then, corresponding ranking analysis was carried out, and the correlation among different stations, different species and environmental factors was analyzed by a double sequence diagram.

3 Results

3.1 *Characteristics of temperature and salinity in seawater*

The surface seawater temperatures of the SYS and the ECS are shown in Fig. 2a. The temperature range in this investigation is 6.91°C to 12.32°C for the SYS and 10.91°C to 23.17°C for the ECS, with average values of 9.40°C for the SYS and 16.98°C for the ECS. The average sea surface temperature of the entire investigated sea area is 13.97°C. It can be clearly observed that the surface temperature of this sea area is different from north to south and gradually rises from north to south. The water temperature gradually rises from northwest to southeast in the SYS and from north to south in the ECS.

The average salinity of the whole eastern shelf sea area in this investigation is 32.60 compared to 30.82 in the Changjiang River Estuary and 34.38 in the open sea area. The salinity range in the SYS is 25.81 to 33.84, with an average of 32.23, and that in the ECS is 28.22 to 35.10, with an average of 32.84. The surface salinities of the SYS and ECS fluctuate greatly from 28.81 to 35.10, and the lowest value appears near the Changjiang River Estuary and gradually increases (Fig. 2b).

3.2 *Distribution of Chl a concentration*

The mean Chl *a* concentration in the investigated sea area is 1.097 μg/L and ranges from 0.028 μg/L to 8.805 μg/L. The high-value areas mainly occur in the southern Shandong Peninsula of the YS and offshore areas of the ECS. The Chl *a* concentration at the Stations E3 (8.805 μg/L), A2 (7.691 μg/L) and S2 (7.416 μg/L) are relatively high. The lowest Chl *a* concentration is 0.028 μg/L at the Station E7. The Chl *a* concentration decreases from alongshore to offshore (Fig. 3a). The peak Chl *a* values are relatively higher in the southern waters of the Shandong Peninsula of the YS and offshore waters of Zhejiang and Fujian in the ECS (35.0°–37.0°N, 27.0°–31.0°N, 121.0°–124.0°E) (Fig. 3a).

3.3 *Species composition in phytoplankton*

In total, 275 species of phytoplankton belonging to 90 genera and 6 phyla of algae were identified in this study, including 208 species belonging to 62 genera of Bacillariophyta, accounting for 75.636% of the total number of species; 56 species, 20 genera, and 20.364% for Pyrophyta; 4 species, 4 genera, and 1.455% for Cyanophyta; 4 species, 2 genera, and 1.455% for Prymnesiophyta; 2 species, 1 genus, and 0.727% for Chlorophyta; and 1 species, 1 genus, and 0.363% for Cryptophyta (Fig. 4).

Bacillariophyta and Pyrrophyta were the main phylum of phytoplankton species in the survey area. The areas with high B/P ratios were generally consistent with the phytoplankton cell densities and distributions of the dominant population (Figs 3b, c). In spring, the average B/P ratio was 41.13 in the entire study area, of which the average for the SYS was 16.31, with the lowest value at Station B5 (0.71) and highest value (231.00) at Station D5; the average value in the ECS was 57.44, of which the highest was 550.86 (Station E3) and the lowest was 0.10 (Station E5).

3.4 *Phytoplankton cell density*

The phytoplankton cell densities ranged from 0.06×10^4 cells/L

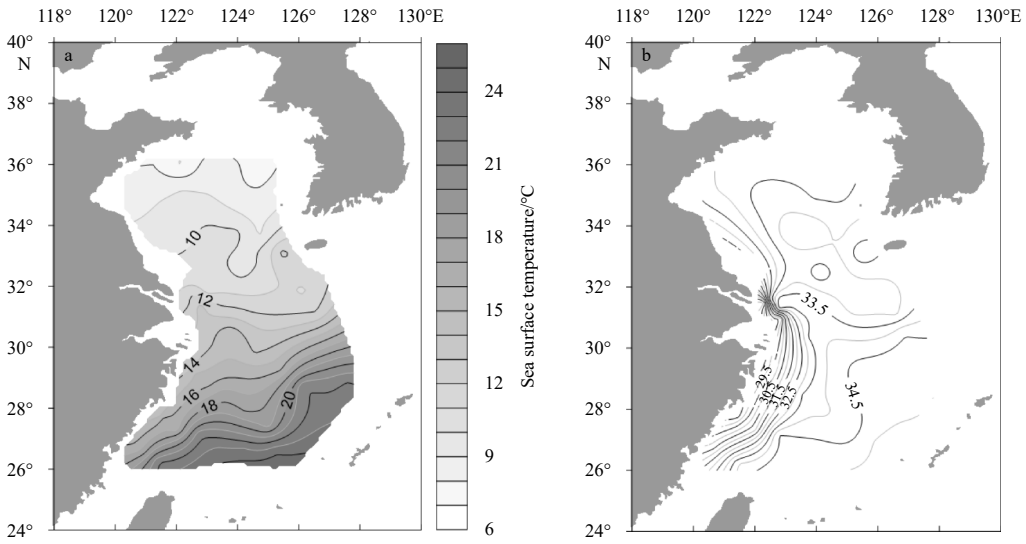

Fig. 2. Distributions of sea surface temperature (°C, a) and salinity (b) in the investigated areas of the East China Sea and southern Yellow Sea.

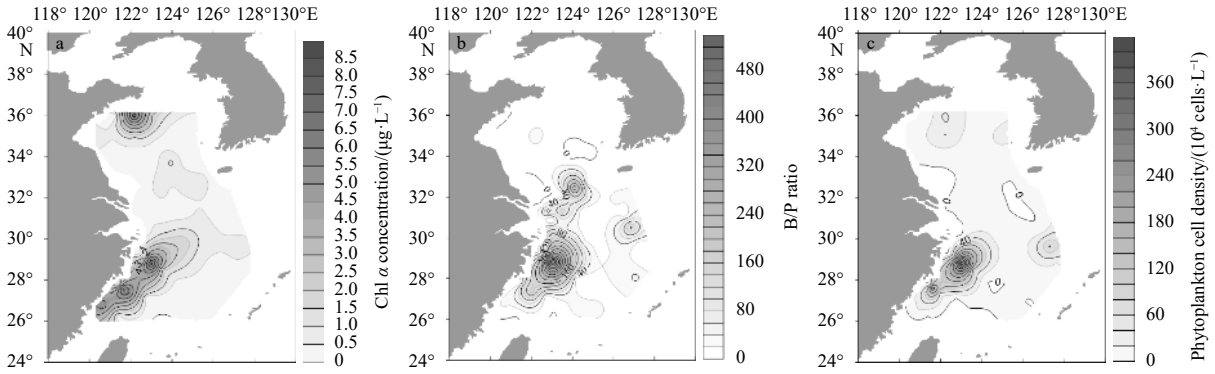

Fig. 3. Distributions of Chl *a* concentration (a), Bacillariophyta cell density/Pyrrophyta cell density (B/P) (b) and phytoplankton cell density (c) in the East China Sea and the southern Yellow Sea.

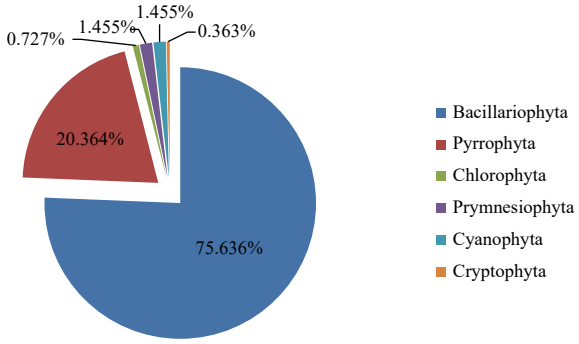

Fig. 4. Phytoplankton community structure in the investigated sea area.

to 418.73×10⁴ cells/L, with an average value of 21.46×10⁴ cell/L. The highest cell density was 418.73×10⁴ cells/L at Station E3, and the lowest cell density was 0.06 ×10⁴ cells/L at Station F3. The phytoplankton cell density in the northern SYS and offshore waters of the ECS were high (Fig. 3c). The average diatom cell density was 18.52×10⁴ cells/L, while the highest cell density was 417.96×10⁴ cells/L (Station E3), and the lowest cell density was 0.02×10⁴ cells/L (Station F3).

3.5 *Dominant species of phytoplankton*

Skeletonema dohrnii was the dominant species in spring 2017. Its average cell density was 8.05×10⁴ cells/L, which accounted for 37.51% of the total phytoplankton cell density. The maximum cell density was 262.50×10⁴ cells/L at Station E3 (Fig. 5a); *Chaetoceros vanheurckii* had an average cell density of 1.94×10⁴ cells/L, which accounted for 9.04% of the total density, and the maximum cell density was 70.50×10⁴ cells/L at Station E3 (Fig. 5b); *Prorocentrum donghaiense* had an average cell density of 0.68 ×10⁴ cells/L (3.17%) and a maximum of 6.60×10⁴ cells/L at Station B6 (Fig. 5c). The distributions of the dominant phytoplankton species during this voyage were generally consistent with the overall cell density distribution, which was mainly concentrated in the northern part of the SYS and offshore areas of the ECS. The high-value areas for *S. dohrnii* and *C. vanheurckii* were mainly distributed in the offshore areas of Zhejiang and Fujian in the ECS (Stations E3 and S2), and the high-value areas for *P. donghaiense* were distributed in the eastern part of the SYS (Figs 5a–c). The frequency and dominance of the dominant species are shown in Table 1.

3.6 *Community structure of phytoplankton*

The average Shannon-Wiener index for the phytoplankton community in spring in the SYS and ECS was 2.965, and the average Pielou's index was 0.668. The species number in the SYS ranged from 20 to 25, and the species number in the ECS coastal waters was much higher (35 to 45). In the ECS, the phytoplankton Shannon-Wiener and Pielou's indexes both showed a trend of being low in coastal areas and high in offshore areas (Fig. 6).

4 Discussion

4.1 *Distribution characteristics of Chl a*

In spring 2017, the Chl *a* concentration in the investigated sea

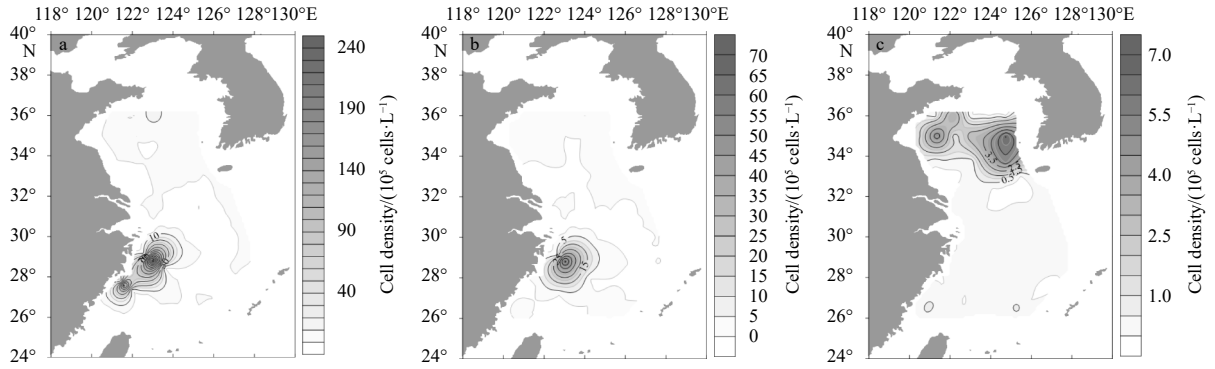

Fig. 5. Distributions of phytoplankton dominant species in the East China Sea and the southern Yellow Sea. a. *Skeletonema dohrnii*; b. *Chaetoceros vanheurckii*; and c. *Prorocentrum donghaiense.*

Table 1. Dominant species of phytoplankton in the East China Sea and the southern Yellow Sea

Dominant species	Cell density /(10^4 cells·L^{-1})	Frequency (f_i)	Dominance (Y)
Skeletonema dohrnii	8.05	0.34	0.03
Chaetoceros vanheurckii	1.94	0.38	0.14
Prorocentrum donghaiense	0.68	0.77	0.02

area was characterized by high alongshore values and low offshore values (Fig. 3a). Compared with historical data from the same season, the Chl *a* concentrations in the YS and the ECS were different (Table 2). The Chl *a* concentrations in spring 2017 were significantly higher than those in 2000–2001 (Huang et al., 2006), similar to those in 2006–2007 (Wang, 2011) and lower than those in 2011 (Wen et al., 2012). These results may be attributed to the hydrological differences among the investigated sea areas. In spring, the cold water mass of the YS has not yet formed (Li et al., 2012). Because of the mixing action, large amounts of nutrients are carried to the upper and middle seawater and phytoplankton multiply in large numbers, leading to the occurrence of areas with high Chl *a* concentrations in the SYS. This result is consistent with that of Cho et al. (1994). Due to the influence of the Kuroshio subsurface water and Taiwan Warm Current on the eastern and southern parts of the ECS (Wen et al., 2012), the concentration of Chl *a* is low in the open sea. In spring, the coastal areas of the ECS are controlled by fresh water with low transparency and high nutrient levels (Li and Luan, 1998), as well as by the influence of coastal upwelling, which forms a high-value area in the southern part of the Changjiang River Estuary near the Zhoushan Islands and Minjiang River Estuary.

4.2 *Phytoplankton community structure, interannual variations and their relationship with environmental factors*

The investigation of phytoplankton in the eastern shelf area shows that phytoplankton are mostly concentrated in the Changjiang River Estuary and adjacent sea areas (Table 3). The number of phytoplankton species in this survey area increased from 2002 to 2011. Diatoms and dinoflagellates are the most important groups in the investigated sea area. In spring, the upwelling of the ECS coast leads to increased water temperatures and nutrients, and the rapid growth of phytoplankton near the coast, which forms a high-density phytoplankton accumulation area.

The dominant species in previous surveys were mainly *Pseudo-nitzschia* sp., *Thalassiosira* sp., *Skeletonema costatum*, *Prorocentrum dentatum* and *Chaetoceros* sp. (Table 3). The dominant species of phytoplankton obtained in this survey were different from those shown in the historical data. It is suspected that, in this investigation of *P. donghaiense,* this species is the same as the *P. dentatum* mentioned in past studies because many scholars have mistakenly identified *P. donghaiense* as *P. dentatum* in the past (Chen et al., 2015; Qi and Wang, 2003). *Skeletonema dohrnii* and *C. vanheurckii* exhibit greater dominance in coastal areas and form dominant populations (Fig. 5), which may be due to the increased temperatures and nutrient levels in spring that are affected by upwelling along the Fujian (Jiang and Wang, 2018; Wang et al., 2016) and Zhejiang (Duan et al., 2014) coasts.

Correlation analyses among phytoplankton cell density, diversity index, B/P and sulfide and environmental factors in the SYS and the ECS in the spring of 2017 were performed using the R Programming Language software. There was a significant negative correlation between phytoplankton density and salinity (P<0.05), and phytoplankton density decreased with increasing salinity (Fig. 7a). There was a significant correlation between phytoplankton density and nitrite (P<0.05); generally, nutrients affect the distribution and community structure of phytoplankton (Fig. 7a). There were significant correlations between phytoplankton density and dissolved oxygen, and pH and Chl *a* concentration (P<0.001) (Fig. 7a). In this study, the correlation between phosphate, nitrate and phytoplankton density is not significant, because the nutrients in the coastal waters in spring increase and the upwelling is significant. Nutrients are not the main factor limiting the growth and reproduction of phytoplankton. When the environmental conditions are suitable, phytoplankton grow and reproduce in large quantities. The ratio of Si, N and P will affect the phytoplankton community structure. According to the historical data over the years (Luan, 2007; Tan et al., 2009; Tian et al., 2010), when the environmental conditions are suitable in spring, the growth and reproduction of diatoms will be promoted first. *Skeletonema* and *Chaetoceros* will often become the dominant species or red tide species in the sea area, which may increase the production of DMSPp.

4.3 *The relationship of DMS with the phytoplankton community structure*

In a review of previous findings, it was found that little attention has been paid to the relationship between the phytoplank-

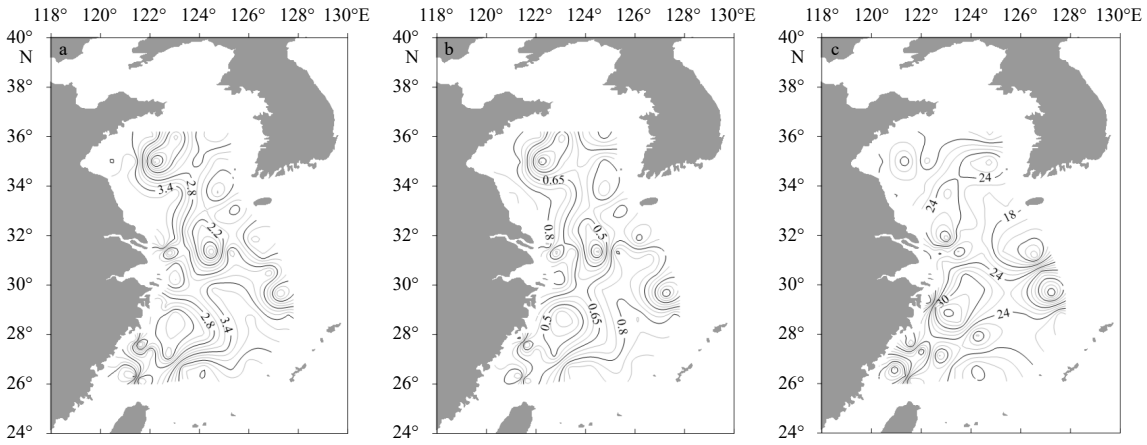

Fig. 6. Phytoplankton species diversity in the East China Sea and the southern Yellow Sea. a. Shannon-Wiener index; b. Pielou's index; and c. species number.

Table 2. Comparisons of the average Chl *a* concentration in this study and other investigations in the Yellow Sea (YS) and the East China Sea (ECS)

Investigation area	Investigation time	Average Chl *a* concentration/(μg·L^{-1})	References
SYS, ECS	2017	1.10	this study
SYS, northern of ECS	2011	1.43	Wen et al. (2012)
YS, ECS	2006–2007	1.17	Wang (2011)
SYS, ECS	2000–2001	0.75	Huang et al. (2006)

Note: SYS is the abbreviation of the South Yellow Sea.

ton community structure and DMS in the entire sea area during the same season (Yang et al., 2016; Jian et al., 2018, 2019). The relationship of DMS with the phytoplankton community structure in the investigated sea areas was analyzed in the present study. Our results showed that there was a significant correlation between phytoplankton density and DMS (P<0.05), a significant positive correlation with DMSPp and DMSOp (P<0.001), and a significant positive correlation between B/P ratio and DMS and DMSPp (P<0.05) (Fig. 7b). Pearson correlation analysis found that diatom cells density showed significant positive correlations with DMS (P<0.05) and DMSPp (P<0.01). At the same time, through Canonical correspondence analysis, we found that the dominant species of phytoplankton (*C. curvisetus*, *C. debilis, C. diadema, C. muelleri, C. vanheurckii, Leptocylindrus danicus,* and *S. dohrnii*) with high DMSP contents were positively correlated with dimethyl sulfur compounds (Fig. 8), indicating that diatoms may play an important role in DMS production in the investigated sea area. These results can be attributed to the fact that phytoplankton are the main contributors to marine DMS and that DMSPp is mainly derived from phytoplankton cells (Archer et al., 2013; Thariath et al., 2019). DMSPd is produced through natural secretion, cytolysis during virus lysis, grazing by zooplankton or cell rupture (Jian et al., 2019; Stefels et al., 2007; Wolfe et al., 2000; Zubkov et al., 2002). DMSP is decomposed by DMSP lyase or bacteria after entering seawater to produce DMS (Alcolombri et al., 2014, 2015; Caruana and Malin, 2014). According to the available references, it is known that diatom is not main DMSP producer at individual species level, compared with other phytoplankton groups such as Pyrrophyta and Haptophyta (Jian et al., 2019). In previous investigations of this area, researchers have paid more attention to the correlations between Chl *a* concentration, dinoflagellates, environmental factors and DMS (Yang et al., 2000; Wu et al., 2017; Xu et al., 2019; Qu et al., 2020), while the relationships between the phytoplankton community structure (especially diatoms) and DMSP have received little attention, which may have ignored the contribution of diatoms to dimethylsulfide in the sea area. Many studies have shown that diatoms dominate phytoplankton communities in the YS and ECS in spring (Guo, 2012; Tian et al., 2010; Xiao et al., 2013; Zhou et al., 2015). In this study, we found that the concentration of DMSPp was higher in the stations with higher diatom density, for example, the density of *S. dornii* in Station S2 accounts for 80.71% of the total density, and its DMSPp concentration is the highest in the investigated sea area; the density of *S. dornii* and *C. vanheurckii* in Station E3 accounted for 79.53% of the total density, and the DMSPp concentration in Station E3 ranking only second to in Station S2. Some stations with higher dinoflagellate density had lower DMSP concentration, for example, the concentration of DMSPp in stations (Stations B5 and FJ3) with lower B/P ratio was at lower level. This indicates that the DMSP production of some diatoms is not lower than that of dinoflagellates. It also states that diatoms can also make great contributions to the overall production of dimethylsulfide in waters when the diatom cell density is very high in seawater, and these results are consistent with those of Jiao et al. (2003).

5 Conclusions

In the spring survey of 2017, 275 species of phytoplankton were identified in the SYS and ECS, and both phytoplankton taxa and abundances were dominated by diatoms followed by dino-

Table 3. Comparison of species number, cell density and dominant species of the same survey area in this study and other studies

Sampling time	Survey area	Species number	Cell density/(10^4 cells·L^{-1})	Dominant species	References
April, 2017	26°–36°N, 120°–128°E	275	21.46	*Skeletonema dohrnii, Chaetoceros vanheurckii, Prorocentrum donghaiense*	this study
May, 2011	25°00′–33°30′N, 120°00′–127°30′E	193	6.69	*Prorocentrum dentatum, Pseudo-nitzschia delicatissim, Skeletonema* sp., *Paralia sulcata, Prorocentrum minimum, Gymnodinium lohmanni, Coscinodiscus* sp., *Chaetoceros curvisetus*	Zhao et al. (2015)
April, 2009	30°30′–32°00′N, 121°00′–123°30′E	64	58.22	*Skeletonema dohrnii, Paralia sulcata, Thalassionema nitzschioides, Pseudo-nitzschia pungens*	Sun and Tian (2011)
May, 2008	26°50′–34°07′N, 120°50′–123°59′E	155	26.63	*Prorocentrum dentatum, Skeletonema costatum, Scrippsiella trochoidea, Paralia sulcata*	Tian et al. (2010)
May, 2007	26°50′–34°00′N, 120°50′–124°00′E	144	7.89	*Pseudo-nitzschia delicatissim, Prorocentrum dentatum, Skeletonema costatum, Thalassiosira rotula*	Tan et al. (2009)
June–July, 2006	25°00′–39°00′N, 118°00′–129°00′E	136	0.84	*Thalassiosira scrotiformis, Pseudo-nitzschia pungens*	Zhou (2014); Zhou et al. (2015)
June, 2006	26°00′–34°00′N, 121°00′–126°00′E	130	14.70	*Prorocentrum dentatum, Karenia mikimotoi, Pseudo-nitzschia pungens, Pseudo-nitzschia. delicatissima*	Wang et al. (2008)
May, 2005	30°30′–32°30′N, 121°00′–123°30′E	92	36.18	*Karenia mikimotoi, Skeletonema costatum, Prorocentrum dentatum*	Luan (2007)
May, 2002–June, 2005 (Spring)	27°00′–32°00′N, 122°00′–123°30′E	162	–	*Paralia sulcate, Nitzschia* spp., *Pseudo-nitzschia* spp., *Pseudo-nitzschia delicatissima, Pseudo-nitzschia pungens, Thalassiosira* spp., *Thalassiosira rotula, Skeletonema costatum, Coscinodiscus* spp., *Chaetoceros* spp.	Xie (2007)
April, 1998	23°30′–33°00′N, 118°30′–128°00′E	–	0.002	*Chaetoceros lorenzianus, Noctiluca scintillans*	Luo et al. (2007)
1960, 1971	27°–34°N, the west of 127°E	–	–	*Rhizosolenia styliformis, Guinardia cylindrus, Climacodium biconcavum*	Chen et al. (1980)

Note: – represents no data.

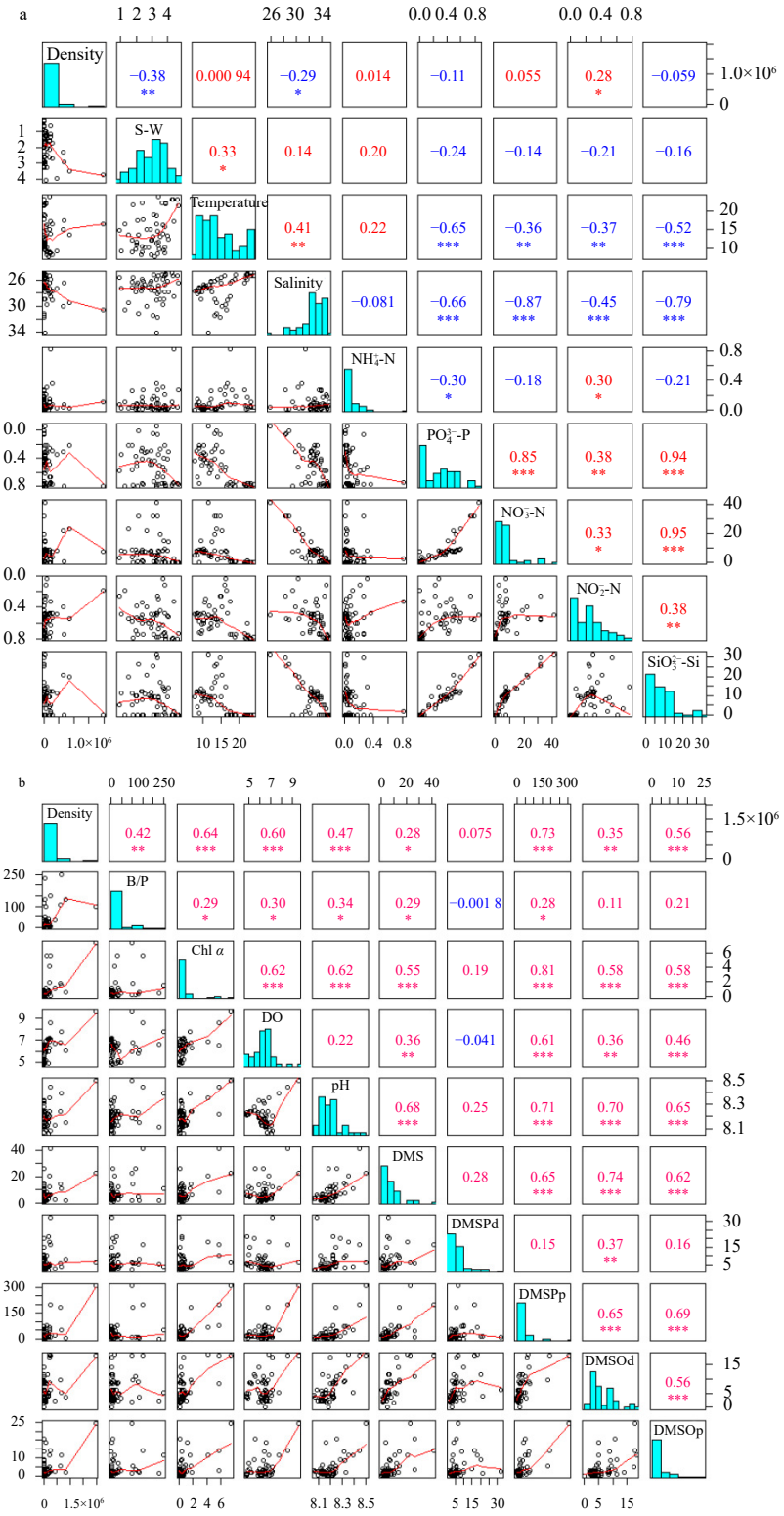

Fig. 7. Correlation analysis of phytoplankton, environmental factors and sulfide in seawater. a. Correlation analysis of phytoplankton diversity with temperature, salinity and nutrients; b. correlation analyses of phytoplankton diversity with DO, pH, Chl *a* concentration and dimethyl sulfide concentration. Density represents phytoplankton density; S-W, Shannon-Wiener diversity index; NH_4^+-N, ammonium nitrogen; NO_2^--N: nitrate nitrogen; PO_4^{3-}-N, phosphate phosphorus; SiO_3^{2-}-Si, silicate silicon; B/P, Bacillariophyta cell density/Pyrrophyta cell density; DO, dissolved oxygen; Chl *a*: Chlorophyll *a* concentration; pH, potential of hydrogen; DMS, dimethylsulfide; DMSPd, dissolved dimethylsulfoniopropionate; DMSPp, particle dimethylsulfoniopropionate; DMSOd, dissolved dimethyl sulfoxide; DMSOp, particle dimethyl sulfoxide. Blue numbers indicate negative correlations; red numbers, positive correlations. * denotes $P<0.05$; **, $P<0.01$; and ***, $P<0.001$. The coordinate axis value in the figure indicates the parameters of the diagonal.

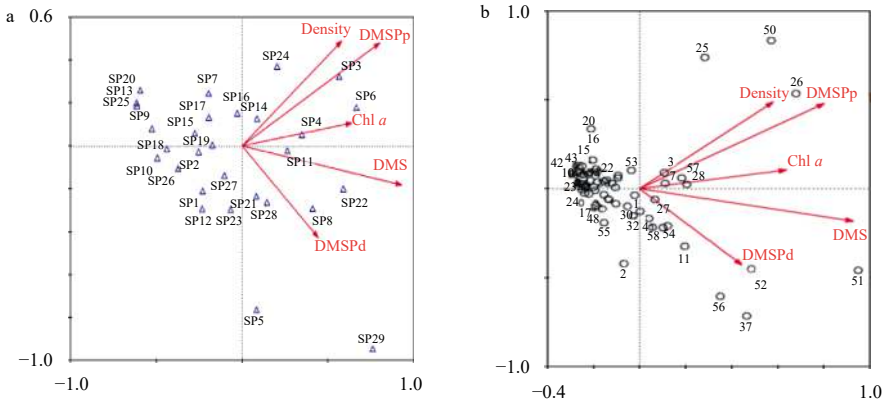

Fig. 8. Biplot of the canonical correspondence analysis results for dominant phytoplankton cell density (a), sampling stations (b) and environmental variables (→). Numbers with letters represent the relevant species: SP1, *Bacteriastrum hyalinum*; SP2, *Chaetoceros castracanei*; SP3, *C. curvisetus*; SP4, *C. debilis*; SP5, *C. densus*; SP6, *C. diadema*; SP7, *C. lorenzianus*; SP8, *C. muelleri*; SP9, *C. pelagicus*; SP10, *C. pseudocurvisetus*; SP11, *C. vanheurckii*; SP12, *Cyclotella striata*; SP13, *Frustulia interposita* var. *chinensis*; SP14, *Leptocylindrus danicus*; SP15, *Melosira moniliformis*; SP16, *Nitzschia closterium*; SP17, *N. longissima*; SP18, *Paralia sulcata*; SP19, *P. donghaiense*; SP20, *P. micans*; SP21, *P. minimun*; SP22, *Pseudo-nitzschia delicatissima*; SP23, *Skeletonema costatum*; SP24, *S. dohrnii*; SP25, *S. marinol*; SP26, *S. munzelii*; SP27, *Thalassiosira rotula*; SP28, *Thalassiosira* sp.; and SP29, *Trichodesmium hildebrandtii*. Chl *a* represents Chlorophyll *a* concentration; Density, sampling station phytoplankton density.

flagellates. The high phytoplankton abundances were mainly present in the coastal waters of Fujian and Zhejiang, which were affected by upwelling of Fujian and Zhejiang coastal waters and were rich in nutrients.

Phytoplankton play an important role in DMS production and are the main source of dimethylsulfide compounds in the ocean. In particular, the correlations between the cell density and dominant species of diatom and dimethylsulfide species were significantly positive (P<0.05). Although some studies have shown that the DMS yield from diatom cells is not high, the contribution to DMS by diatoms cannot be ignored under the high cell density conditions of the sea. Our results demonstrated that diatoms play a greater role in the production of dimethylsulfide in the ESC and SYS.

Acknowledgements

We thank the captain and crew of the R/V *Dongfanghong 2* for their help and cooperation during the cruises. We would like to express our sincere thanks to Guipeng Yang of China Ocean University for providing DMS, DMSP and other related data, and to Yu Xin for providing nutrition data. We also thank the laboratory staff who helped collect samples during the expedition.

References

Alcolombri U, Ben-Dor S, Feldmesser E, et al. 2015. Identification of the algal dimethyl sulfide-releasing enzyme: a missing link in the marine sulfur cycle. Science, 348(6242): 1466–1469, doi: 10.1126/science.aab1586

Alcolombri U, Laurino P, Lara-Astiaso P, et al. 2014. DddD is a CoA-Transferase/Lyase producing dimethyl sulfide in the marine environment. Biochemistry, 53(34): 5473–5475, doi: 10.1021/bi500853s

Anderson D M, Glibert P M, Burkholder J M. 2002. Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. Estuaries, 25(4): 704–726, doi: 10.1007/BF02804901

Andreae M O, Crutzen P J. 1997. Atmospheric aerosols: biogeochemical sources and role in atmospheric chemistry. Science, 276(5315): 1052–1058, doi: 10.1126/science.276.5315.1052

Archer S D, Kimmance S A, Stephens J A, et al. 2013. Contrasting responses of DMS and DMSP to ocean acidification in Arctic waters. Biogeosciences, 10(3): 1893–1908, doi: 10.5194/bg-10-1893-2013

Aubry F B, Cossarini G, Acri F, et al. 2012. Plankton communities in the northern Adriatic Sea: patterns and changes over the last 30 years. Estuarine, Coastal and Shelf Science, 115: 125–137, doi: 10.1016/j.ecss.2012.03.011

Caruana A M N, Malin G. 2014. The variability in DMSP content and DMSP lyase activity in marine dinoflagellates. Progress in Oceanography, 120: 410–424, doi: 10.1016/j.pocean.2013.10.014

Charlson R J, Lovelock J E, Andreae M O, et al. 1987. Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. Nature, 326(6114): 655–661, doi: 10.1038/326655a0

Chen-Tung Arthur Chen. 2009. Chemical and physical fronts in the Bohai, Yellow and East China seas. Journal of Marine Systems, 78(3): 394–410, doi: 10.1016/j.jmarsys.2008.11.016

Chen Yanghang. 2017. Ecological characteristics of phytoplankton and physiological mechanism of interspecies relationship between the key phytoplankton species in a scallop culture sea area of Bohai Bay (in Chinese)[dissertation]. Xiamen: Xiamen University

Chen Qingchao, Chen Yaqu, Hu Yazhu. 1980. Preliminary study on the plankton communities in the southern Yellow Sea and the East China Sea. Haiyang Xuebao (in Chinese), 2(2): 149–157

Chen Peng, Pan Delu, Mao Zhihua. 2015. Application of a laser fluorometer for discriminating phytoplankton species. Optics & Laser Technology, 67: 50–56, doi: 10.1016/j.optlastec.2014.09.013

Chen Baohong, Xu Zhuhua, Zhou Qiulin, et al. 2010. Long-term changes of phytoplankton community in Xiagu waters of Xiamen, China. Acta Oceanologica Sinica, 29(6): 104–114, doi: 10.1007/s13131-010-0081-4

Cheng Zhaodi, Gao Yahui, Liu Shicheng, et al. 2013a. *Flora Algarum Marinarum Sinicarum*. Tomus V. Bacillariophyta, No. III. Pennatae II. Naviculales, Naviculaceae, Cymbellaceae, Auriculaceae, Gomphonemaceae (in Chinese). Beijing: Science Press

Cheng Zhaodi, Gao Yahui, Liu Shicheng, et al. 2013b. Flora Algarum Marinarum Sinicarum, Tomus V. Bacillariophyta, No. II. Pennatae I. Diatomales, Achnanthales, Phaeodactylales, Eunotiales (in Chinese). Beijing: Science Press

Chiang Kuo-Ping, Chen Ying-Tun, Gong Gwo-Ching. 1999. Spring distribution of diatom assemblages in the East China Sea. Marine Ecology Progress Series, 186: 75–86, doi: 10.3354/meps186075

Chiang Kuo-Ping, Chou Yu-Hsuan, Chang Jeng, et al. 2004. Winter

distribution of diatom assemblages in the East China Sea. Journal of Oceanography, 60(6): 1053–1062, doi: 10.1007/s10872-005-0013-7

Chinese Society of Oceanography. 2015. History of Oceanography in China (in Chinese). Beijing: China Science and Technology Press

Cho B C, Choi J K, Chung C S, et al. 1994. Uncoupling of bacteria and phytoplankton during a spring diatom bloom in the mouth of the Yellow Sea. Marine Ecology Progress Series, 115(1): 181–190, doi: 10.3354/meps115181

Dacey J W H, Blough N V. 1987. Hydroxide decomposition of dimethylsulfoniopropionate to form dimethylsulfide. Geophysical Research Letters, 14(12): 1246–1249, doi: 10.1029/GL014i012p01246

Deng Xuwei, Chen Juan, Hansson L A, et al. 2021. Eco-chemical mechanisms govern phytoplankton emissions of dimethylsulfide in global surface waters. National Science Review, 8(2): nwaa140, doi: 10.1093/nsr/nwaa140

do Rosario Gomes H, Xu Qian, Ishizaka J, et al. 2018. The influence of riverine nutrients in niche partitioning of phytoplankton communities—A contrast between the Amazon River plume and the Changjiang (Yangtze) River diluted water of the East China Sea. Frontiers in Marine Science, 5: 343, doi: 10.3389/fmars.2018.00343

Du Xiaoming, Liu Houtian, Liu Ruoan, et al. 1998. The flux of oceanic dimethyl sulfide from coastal area in Xiamen to the atmosphere. Research of Environmental Sciences, 11(2): 34–36

Duan Shanshan, Xing Lei, Zhang Hailong, et al. 2014. Upwelling and anthropogenic forcing on phytoplankton productivity and community structure changes in the Zhejiang coastal area over the last 100 years. Acta Oceanologica Sinica, 33(10): 1–9, doi: 10.1007/s13131-014-0535-1

Falkowski P G, Woodhead A D, Vivirito K. 1992. Primary Productivity and Biogeochemical Cycles in the Sea. New York: Plenum Press

Findlay D L, Kasian S E M, Turner M T, et al. 1999. Responses of phytoplankton and epilithon during acidification and early recovery of a lake. Freshwater Biology, 42(1): 159–175, doi: 10.1046/j.1365-2427.1999.00458.x

Furuya K, Kurita K, Odate T. 1996. Distribution of phytoplankton in the East China Sea in the winter of 1993. Journal of Oceanography, 52(3): 323–333, doi: 10.1007/BF02235927

General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration. 2008. GB/T 12763.6–2007 Specifications for Oceanographic Survey—Part 6: Marine Biological Survey. Beijing: Standards Press of China, 159

Guan Bingxian. 1984. Major features of the shallow water hydrography in the East China Sea and Huanghai Sea. Elsevier Oceanography Series, 39: 1–13, doi: 10.1016/S0422-9894(08)70288-5

Guan Bingxian. 1994. Patterns and structures of the currents in Bohai, Huanghai and East China Seas. In: Zhou Di, Liang Yuanbo, Zeng Chengkui, eds. Oceanology of China Seas. Dordrecht: Springer, 17–26, doi: 10.1007/978-94-011-0862-1_3

Guo Yujie. 1963. The nature of *Chaetoceros* flora of the Yellow Sea. Oceanologia et Limnologia Sinica, 6(4): 322–332

Guo Shujin. 2012. Study on phytoplankton assemblage in the East China Sea (in Chinese)[dissertation]. Qingdao: Ocean University of China

Guo Yujie, Qian Shuben. 2003. Flora Algarum Marinarum Sinicarum, Tomus Ⅴ. Bacillariophyta No. I. Centricae (in Chinese). Beijing: Science Press

Guo Shujin, Tian Wei, Dai Minhan, et al. 2011. Phytoplankton assemblages in the East China Sea in summer 2009. Advances in Marine Science, 29(4): 474–486, doi: 10.3969/j.issn.1671-6647.2011.04.007

Hays G C, Richardson A J, Robinson C. 2005. Climate change and marine plankton. Trends in Ecology & Evolution, 20(6): 337–344, doi: 10.1016/j.tree.2005.03.004

Hoegh-Guldberg O, Jacob D, Taylor M, et al. 2018. Impacts of 1.5°C global warming on natural and human systems. In: Masson-Delmotte V, Zhai P, Pörtner H O, et al, eds. Global Warming of 1.5°C. https://unfccc.int/topics/science/workstreams/cooperation-with-the-ipcc/ipcc-special-report-on-global-warming-of-15-degc[2020-03-12]

Hu Min, Tang Xiaoyan, Li Jinlong. 1995. Measurement of dimethyl sulfide in the Bo Sea and Gulf of Jiaozhou. Pure and Applied Chemistry, 67(8–9): 1481–1486

Hu Min, Tang Xiaoyan, Li Jinlong, et al. 1997. Dimethylsulfide in sea water in the Gulf of Jiaozhou. Acta Scientiae Circumstantiae, 17(1): 110–115

Huang Zongguo, Lin Mao. 2012. The Living Species and Their Illustrations in China's Seas (Part Ⅱ), an Illustrated Guide to Species in China's Seas Vol. 1 (in Chinese). Beijing: China Ocean Press

Huang Bangqin, Liu Yuan, Chen Jixin, et al. 2006. Temporal and spatial distribution of size-fractionized phytoplankton biomass in East China Sea and Huanghai Sea. Haiyang Xuebao (in Chinese), 28(2): 156–164, doi: 10.3321/j.issn:0253-4193.2006.02.021

Huang Wenxiang, Sheng Liangfu, Zhu Lin. 1984. Phytoplankton in the Yellow Sea. Marine Environmental Science, 3: 19–28

Jia Haibo, Shao Junbo, Hu Haoyan, et al. 2014. Changes and reason analysis of phytoplankton community structure in the Yangtze Estuary and adjacent sea before and after the impoundment of the Three Gorges Dam. Marine Science Bulletin, 33(3): 305–314, doi: 10.11840/j.issn.1001-6392.2014.03.009

Jian Shan, Zhang Honghai, Yang Guipeng, et al. 2019. Variation of biogenic dimethylated sulfur compounds in the Changjiang River Estuary and the coastal East China Sea during spring and summer. Journal of Marine Systems, 199: 103222, doi: 10.1016/j.jmarsys.2019.103222

Jian Shan, Zhang Honghai, Zhang Jing, et al. 2018. Spatiotemporal distribution characteristics and environmental control factors of biogenic dimethylated sulfur compounds in the East China Sea during spring and autumn. Limnology and Oceanography, 63(S1): S280–S298, doi: 10.1002/lno.10737

Jiang Rui, Wang Youshao. 2018. Modeling the ecosystem response to summer coastal upwelling in the northern South China Sea. Oceanologia, 60(1): 32–51, doi: 10.1016/j.oceano.2017.05.004

Jiao Nianzhi, Liu Chengzheng, Hong Huasheng, et al. 2003. Dynamics of dimethylsulfide and dimethylsulfoniopropionate produced by phytoplankton in the Chinese seas—Distribution patterns and affecting factors. Acta Botanica Sinica, 45(7): 774–786

Jin Xiaoying, Yuan Dongxing, Chen Meng, et al. 2004. Distribution of dimethylsulfide of Xiamen sea surface water in spring. Marine Environmental Science, 23(2): 12–15

Karsten U, Kirst G O, Wiencke C. 1992. Dimethylsulphoniopropionate (DMSP) accumulation in green macioalgae from polar to temperate regions: interactive effects of light versus salinity and light versus temperature. Polar Biology, 12(6): 603–607, doi: 10.1007/BF00236983

Karsten U, Kück K, Vogt C, et al. 1996. Dimethylsulfoniopropionate production in phototrophic organisms and its physiological functions as a cryoprotectant. In: Kiene R P, Visscher P T, Keller M D, et al, eds. Biological and Environmental Chemistry of DMSP and Related Sulfonium Compounds. Boston: Springer, 143–153

Kiene R P, Gerard G. 1994. Determination of trace levels of dimethylsulfoxide (DMSO) in seawater and rainwater. Marine Chemistry, 47(1): 1–12, doi: 10.1016/0304-4203(94)90009-4

Kiene R P, Slezak D. 2006. Low dissolved DMSP concentrations in seawater revealed by small-volume gravity filtration and dialysis sampling. Limnology and Oceanography: Methods, 4(4): 80–95, doi: 10.4319/lom.2006.4.80

Kirst G O. 1990. Salinity tolerance of eukaryotic marine algae. Annual Review of Plant Physiology and Plant Molecular Biology, 41: 21–53, doi: 10.1146/annurev.pp.41.060190.000321

Koblentz-Mishke O J, Volvovinsky V V, Kabanova J G. 1970. Plankton primary production of the world ocean. In: Wooster W S, ed. Scientific Exploration of the South Pacific. Washington: National Academy of Sciences, 183–193

Lammers J M, van Soelen E E, Donders T H, et al. 2013. Natural environmental changes versus human impact in a Florida estuary (Rookery Bay, USA). Estuaries and Coasts, 36(1): 149–157, doi: 10.1007/s12237-012-9552-5

Lampitt R S, Wishner K F, Turley C M, et al. 1993. Marine snow studies in the Northeast Atlantic Ocean: distribution, composition and role as a food source for migrating plankton. Marine Biology, 116(4): 689–702, doi: 10.1007/BF00355486

Leira M, Sabater S. 2005. Diatom assemblages distribution in catalan rivers, NE Spain, in relation to chemical and physiographical factors. Water Research, 39(1): 73–82, doi: 10.1016/j.watres.2004.08.034

Li Chaolun, Luan Fenghe. 1998. A proliminary study on the distribution of size-fractionated chlorophyll-*a* in the euphotic zone of the East China Sea in spring. Marine Sciences, (4): 59–62

Li Wei, Wang Yuheng, Wang Jianing, et al. 2012. Distributions of water masses and hydrographic structures in the Yellow Sea and East China Sea in spring and summer 2011. Oceanologia et Limnologia Sinica, 43(3): 615–623

Liu Chao, Kang Jiancheng, Wang Guodong, et al. 2012. Monthly change of nutrients impact on phytoplankton in Kuroshio of East China Sea. Energy Procedia, 16: 1193–1198, doi: 10.1016/j.egypro.2012.01.190

Liu Yue, Liu Chunying, Yang Guipeng, et al. 2016. Biogeochemistry of dimethylsulfoniopropionate, dimethylsulfide and acrylic acid in the Yellow Sea and the Bohai Sea during autumn. Environmental Chemistry, 13(1): 127–139, doi: 10.1071/EN15025

Liu Ruiyu, Xu Fengshan. 1963. Preliminary studies on the benthic fauna of the Yellow Sea and the East China Sea. Oceanologia et Limnologia Sinica, 5(4): 306–321

Lu Douding, Goebel J. 2001. Five red tide species in genus *Prorocentrum* including the description of *Prorocentrum donghaiense* Lu SP. nov. from the East China Sea. Chinese Journal of Oceanology and Limnology, 19(4): 337–344, doi: 10.1007/BF02850738

Luan Qingshan. 2007. Ecological study on phytoplankton assemblage in Changjiang River Estuary and its adjacent waters (in Chinese)[dissertation]. Qingdao: Ocean University of China

Luo Minbo, Lu Jianjian, Wang Yunlong, et al. 2007. Horizontal distribution and dominant species of phytoplankton in the East China Sea. Acta Ecologica Sinica, 27(12): 5076–5085, doi: 10.3321/j.issn:1000-0933.2007.12.016

Ma Qiju. 2004. The emission of dimethyl sulfur and its contribution to sulfate in China offshore (in Chinese)[dissertation]. Beijing: Peking University

Ma Sha. 2018. Studies on responses of phytoplankton and community structure to ocean acidification (in Chinese)[dissertation]. Shanghai: Shanghai Ocean University

Ma Qiju, Hu Min, Tian Xudong, et al. 2004. Dimethylsulfide emission in Qingdao near-shore waters and atmospheric dimethylsulfide concentration variation. Environmental Science, 25(1): 20–24

Najjar R G, Pyke C R, Adams M B, et al. 2010. Potential climate-change impacts on the Chesapeake Bay. Estuarine, Coastal and Shelf Science, 86(1): 1–20, doi: 10.1016/j.ecss.2009.09.026

Najjar R G, Walker H A, Anderson P J, et al. 2000. The potential impacts of climate change on the mid-Atlantic coastal region. Climate Research, 14(3): 219–233

Nick F M, Vieli A, Andersen M L, et al. 2013. Future sea-level rise from Greenland's main outlet glaciers in a warming climate. Nature, 497(7448): 235–238, doi: 10.1038/nature12068

Nishiguchi M K, Somero G N. 1992. Temperature- and concentration-dependence of compatibility of the organic osmolyte β-dimethylsulfoniopropionate. Cryobiology, 29(1): 118–124, doi: 10.1016/0011-2240(92)90011-P

Noman M A, Sun Jun, Gang Qian, et al. 2019. Factors regulating the phytoplankton and tintinnid microzooplankton communities in the East China Sea. Continental Shelf Research, 181: 14–24, doi: 10.1016/j.csr.2019.05.007

Norse E A. 1993. Global Marine Biological Diversity: A Strategy for Building Conservation into Decision Making. Washington: Island Press

Parsons T R, Maita Y, Lalli C M. 1984. A Manual of Chemical and Biological Methods for Seawater Analysis. Oxford: Pergamon Press

Pielou E C. 1969. An Introduction to Mathematical Ecology. New York: Wiley-Interscience

Qi Yuzao, Wang Yan. 2003. What the *Prorocentrum* species should be? —A review on identification of a *Prorocentrum* species from the East China Sea. Chinese Journal of Applied Ecology, 14(7): 1188–1190

Qu Bo, Yang Guipeng, Guo Liyan, et al. 2020. The satellite derived environmental factors and their relationships with dimethylsulfide in the east marginal seas of China. Journal of Marine Systems, 204: 103305, doi: 10.1016/j.jmarsys.2020.103305

Reynolds C S. 1984. Phytoplankton periodicity: the interactions of form, function and environmental variability. Freshwater Biology, 14(2): 111–142, doi: 10.1111/j.1365-2427.1984.tb00027.x

Round F, Crawford R M, Mann D G. 1990. The Diatoms, Biology and Morphology of the Genera. Cambridge: Cambridge University Press

Sarmiento J L, Toggweiler J R, Najjar R. 1988. Ocean carbon-cycle dynamics and atmospheric Pco_2. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 325(1583): 3–21, doi: 10.1098/rsta.1988.0039

Schaffer G, Leth O, Ulloa O, et al. 2000. Warming and circulation change in the eastern South Pacific Ocean. Geophysical Research Letters, 27(9): 1247–1250, doi: 10.1029/1999GL010952

Sekerc Y, Ozarslan R. 2020. Oxygen-plankton model under the effect of global warming with nonsingular fractional order. Chaos, Solitons & Fractals, 132: 109532, doi: 10.1016/j.chaos.2019.109532

Shannon C E. 1948. A mathematical theory of communication. The Bell System Technical Journal, 27(4): 623–656, doi: 10.1002/j.1538-7305.1948.tb00917.x

Shannon C E, Weaver W. 1949. The Mathematical Theory of Communication. Urbana, IL: University of Illinois Press

Simó R. 2001. Production of atmospheric sulfur by oceanic plankton: biogeochemical, ecological and evolutionary links. Trends in Ecology Evolution, 16(6): 287–294, doi: 10.1016/S0169-5347(01)02152-8

Song Shuqun. 2010. Phytoplankton functional groups in the Yellow Sea and the East China Sea (in Chinese)[dissertation]. Beijing: Chinese Academy of Sciences

Song Shuqun, Li Zhao, Li Caiwen, et al. 2017. The response of spring phytoplankton assemblage to diluted water and upwelling in the eutrophic Changjiang (Yangtze River) Estuary. Acta Oceanologica Sinica, 36(12): 101–110, doi: 10.1007/s13131-017-1094-z

Spiese C E, Kieber D J, Nomura C T, et al. 2009. Reduction of dimethylsulfoxide to dimethylsulfide by marine phytoplankton. Limnology and Oceanography, 54(2): 560–570, doi: 10.4319/lo.2009.54.2.0560

Stefels J. 2000. Physiological aspects of the production and conversion of DMSP in marine algae and higher plants. Journal of Sea Research, 43(3–4): 183–197, doi: 10.1016/S1385-1101(00)00030-7

Stefels J, Steinke M, Turner S, et al. 2007. Environmental constraints on the production and removal of the climatically active gas dimethylsulphide (DMS) and implications for ecosystem modelling. In: van Leeuwe M A, Stefels J, Belviso B, eds. Phaeocystis, Major Link in the Biogeochemical Cycling of Climate-Relevant Elements. Dordrecht: Springer, 245–275, doi: 10.1007/978-1-4020-6214-8_18

Stefels J, van Leeuwe M A. 1998. Effects of iron and light stress on the biochemical composition of Antarctic *Phaeocystis* sp. (Prymnesiophyceae). Ⅰ. Intracellular DMSP concentrations. Journal of Phycology, 34(3): 486–495, doi: 10.1046/j.1529-8817.1998.340486.x

Sun Jun. 2011. Marine phytoplankton and biological carbon sink. Acta Ecologica Sinica, 31(18): 5372–5378

Sun Jun, Tian Wei. 2011. Phytoplankton in Yangtze River Estuary and its adjacent waters in spring in 2009: species composition and size-fractionated chlorophyll *a*. Chinese Journal of Applied Ecology, 22(1): 235–242

Tan Shujie, Gong Xiangzhong, Sun Jun, et al. 2009. The phytoplankton community in spawning ground of the East China Sea and its adjacent waters in spring. Marine Sciences, 33(8): 5–10

Taylor J C, Prygiel J, Vosloo A, et al. 2007. Can diatom-based pollution indices be used for biomonitoring in South Africa? A case study of the Crocodile West and Marico water management area. Hydrobiologia, 592(1): 455–464, doi: 10.1007/s10750-007-0788-1

Thariath D V, Divakaran D, Chenicherry S. 2019. Influence of salinity on the dimethylsulphoniopropionate production from *Prymnesium simplex*. Sustainable Environment Research, 29: 17, doi: 10.1186/s42834-019-0017-4

Tian Wei, Sun Jun, Fan Xiaopeng, et al. 2010. Phytoplankton community in coastal waters of the East China Sea in spring 2008. Advances in Marine Science, 28(2): 170–178, doi: 10.3969/j.issn.1671-6647.2010.02.006

Torrisi M, Dell'Uomo A. 2006. Biological monitoring of some Apennine rivers (central Italy) using the diatom-based Eutrophication/Pollution Index (EPI-D) compared to other European diatom indices. Diatom Research, 21(1): 159–174, doi: 10.1080/0269249X.2006.9705657

Van Meerssche E, Pinckney J L. 2017. The influence of salinity in the domoic acid effect on estuarine phytoplankton communities. Harmful Algae, 69: 65–74, doi: 10.1016/j.hal.2017.10.003

Wang Chunsheng. 2011. Research Report on Offshore Marine Life and Ecology in China. Hangzhou: Second Institute of Oceanography, 93–94

Wang Dan, Huang Bangqin, Liu Xin, et al. 2014. Seasonal variations of phytoplankton phosphorus stress in the Yellow Sea Cold Water Mass. Acta Oceanologica Sinica, 33(10): 124–135, doi: 10.1007/s13131-014-0547-x

Wang Yu, Kang Jianhua, Ye Youyin, et al. 2016. Phytoplankton community and environmental correlates in a coastal upwelling zone along western Taiwan Strait. Journal of Marine Systems, 154: 252–263, doi: 10.1016/j.jmarsys.2015.10.015

Wang Dan, Sun Jun, Zhou Feng, et al. 2008. Phytoplankton of Changjiang (Yangtze River) Estuary hypoxia area and the adjacent East China Sea in June 2006. Oceanologia et Limnologia Sinica, 39(6): 619–627

Wen Fei, Sun Xiaoxia, Zheng Shan, et al. 2012. Spatial and seasonal variations of chlorophyll *a* and primary productivity in spring and summer in the Yellow Sea and East China Sea. Oceanologia et Limnologia Sinica, 43(3): 438–444

Wolfe G V, Levasseur M, Cantin G, et al. 2000. DMSP and DMS dynamics and microzooplankton grazing in the Labrador Sea: application of the dilution technique. Deep–Sea Research Part I: Oceanographic Research Papers, 47(12): 2243–2264, doi: 10.1016/S0967-0637(00)00028-5

Wolfe G V, Steinke M. 1996. Grazing-activated production of dimethyl sulfide (DMS) by two clones of *Emiliania huxleyi*. Limnology and Oceanography, 41(6): 1151–1160, doi: 10.4319/lo.1996.41.6.1151

Wu Jiunn-Tzong, Kow Lai-Tsu. 2002. Applicability of a generic index for diatom assemblages to monitor pollution in the tropical River Tsanwun, Taiwan. Journal of Applied Phycology, 14(1): 63–69, doi: 10.1023/A:1015277013102

Wu Xi, Li Peifeng, Liu Chunying, et al. 2017. Biogeochemistry of dimethylsulfide, dimethylsulfoniopropionate, and acrylic acid in the Changjiang Estuary and the East China Sea. Journal of Geophysical Research: Oceans, 122(12): 10245–10261, doi: 10.1002/2017JC013265

Xiao Wupeng, Liu Xin, Huang Bangqin. 2013. Phytoplankton community structure and its environmental controlling in the nearshore surface water of the East China Sea in spring. Journal of Marine Sciences, 31(3): 76–82

Xie Wenling. 2007. Community structure and dynamics of planktonic diatoms in typical areas of East China Sea (in Chinese)[dissertation]. Xiamen: Xiamen University

Xu Feng, Jin Na, Ma Zhun, et al. 2019. Distribution, occurrence, and fate of biogenic dimethylated sulfur compounds in the Yellow Sea and Bohai Sea during spring. Journal of Geophysical Research: Oceans, 124(8): 5787–5800, doi: 10.1029/2019JC015085

Yang Shimin, Li Ruixiang, Dong Shugang. 2016a. Dinoflagellates in the China's Seas Ⅰ (Prorocentrales, Dinophysiales) (in Chinese). Beijing: China Ocean Press

Yang Shimin, Li Ruixiang, Dong Shugang. 2016b. Dinoflagellates in the China's Seas Ⅱ (Gonyaulacales) (in Chinese). Beijing: China Ocean Press

Yang Jian, Yang Guipeng, Zhang Honghai, et al. 2015a. Spatial distribution of dimethylsulfide and dimethylsulfoniopropionate in the Yellow Sea and Bohai Sea during summer. Chinese Journal of Oceanology and Limnology, 33(4): 1020–1038, doi: 10.1007/s00343-015-4188-5

Yang Jian, Yang Guipeng, Zhang Honghai, et al. 2016c. Temporal variations of dimethylsulfide and dimethylsulfoniopropionate in the southern Yellow Sea in spring and autumn. Acta Oceanologica Sinica, 35(2): 76–87, doi: 10.1007/s13131-015-0780-y

Yang Guipeng, Zhang Jianwu, Li Li, et al. 2000. Dimethylsulfide in the surface water of the East China Sea. Continental Shelf Research, 20(1): 69–82, doi: 10.1016/S0278-4343(99)00039-4

Yang Guipeng, Zhang Shenghui, Zhang Honghai, et al. 2015b. Distribution of biogenic sulfur in the Bohai Sea and northern Yellow Sea and its contribution to atmospheric sulfate aerosol in the late fall. Marine Chemistry, 169: 23–32, doi: 10.1016/j.marchem.2014.12.008

Yang Guipeng, Zhang Honghai, Zhou Limin, et al. 2011. Temporal and spatial variations of dimethylsulfide (DMS) and dimethylsulfoniopropionate (DMSP) in the East China Sea and the Yellow Sea. Continental Shelf Research, 31(13): 1325–1335, doi: 10.1016/j.csr.2011.05.001

Yu Peiran, Guo Tianfeng, Zhu Yujiao, et al. 2017. Concentration and size distribution of amines in marine atmospheric particles over Yellow Sea, East China Sea and Northwest Pacific Ocean. Periodical of Ocean University of China, 47(5): 19–26

Zeebe R E. 2012. History of seawater carbonate chemistry, atmospheric CO_2, and ocean acidification. Annual Review of Earth and Planetary Sciences, 40: 141–165, doi: 10.1146/annurev-earth-042711-105521

Zhang Qilong, Weng Xuechuan, Yang Yuling. 1996. Analysis of water masses in the south Yellow Sea in spring. Oceanologia et Limnologia Sinica, 27(4): 421–428

Zhang Shenghui, Yang Guipeng, Zhang Honghai, et al. 2014. Spatial variation of biogenic sulfur in the South Yellow Sea and the East China Sea during summer and its contribution to atmospheric sulfate aerosol. Science of the Total Environment, 488–489, 157–167, doi: 10.1016/j.scitotenv.2014.04.074

Zhao Qibiao, Sun Jun, Li Dan, et al. 2015. Seasonal changes of the phytoplankton along hypoxia area and adjacent waters in the East China Sea. Acta Ecologica Sinica, 35(7): 2366–2379, doi: 10.5846/stxb201306021273

Zhao Yuyin, Sun Jun, Wei Yuqiu. 2020. Research progress in the effects of ocean acidification on phytoplankton physiology. Marine Sciences, 44(10): 121–132, doi: 10.11759/hykx20200203001

Zhao Yue, Yu Rencheng, Kong Fanzhou, et al. 2019a. Features of phytoplankton communities and their controlling factors in the Yellow Sea and the East China Sea in summer time. Oceanologia et Limnologia Sinica, 50(4): 838–850

Zhao Yue, Yu Rencheng, Kong Fanzhou, et al. 2019b. Distribution patterns of picosized and nanosized phytoplankton assemblages in the East China Sea and the Yellow Sea: implications on the impacts of Kuroshio intrusion. Journal of Geophysical Research: Oceans, 124(2): 1262–1276, doi: 10.1029/2018JC014681

Zhao Li, Zhao Yanchu, Dong Yi, et al. 2018. Influence of the northern Yellow Sea Cold Water Mass on picoplankton distribution around the Zhangzi Island, northern Yellow Sea. Acta Oceanologica Sinica, 37(5): 96–106, doi: 10.1007/s13131-018-1149-9

Zhou Qianqian. 2014. Studies on community structure and biodiversity of phytoplankton in eastern marginal seas of China and Beibu Gulf (in Chinese) [dissertation]. Xiamen: Xiamen University

Zhou Qianqian, Chen Changping, Liang Junrong, et al. 2015. Species

composition and seasonal variation of netz-phytoplankton in the eastern marginal China seas. Biodiversity Science, 23(1): 23–32, doi: 10.17520/biods.2014103

Zhou Mingjiang, Shen Zhiliang, Yu Rencheng. 2008. Responses of a coastal phytoplankton community to increased nutrient input from the Changjiang (Yangtze) River. Continental Shelf Research, 28(12): 1483–1489, doi: 10.1016/j.csr.2007.02.009

Zhu Shuping, Guo Yujie. 1959. A decade of marine phytoplankton research in China. Oceanologia et Limnologia Sinica, 2(4): 223–229

Zubkov M V, Fuchs B M, Archer S D, et al. 2002. Rapid turnover of dissolved DMS and DMSP by defined bacterioplankton communities in the stratified euphotic zone of the North Sea. Deep–Sea Research Part II: Topical Studies in Oceanography, 49(15): 3017–3038, doi: 10.1016/S0967-0645(02)00069-3