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The profound influence of Kuroshio intrusion on microphytoplankton community in the northeastern South China Sea

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Abstract

To further understand the effect of Kuroshio intrusion on phytoplankton community structure in the northeastern South China Sea (NSCS, 14°–23°N, 114°–124°E), one targeted cruise was carried out from July to August, 2017. A total of 79 genera and 287 species were identified, mainly including Bacillariophyta (129 species), Pyrrophyta (150 species), Cyanophyta (4 species), Chrysophyta (3 species) and Haptophyta (1 species). The average abundance of phytoplankton was 2.14×10^3 cells/L, and *Cyanobacterium* was dominant species accounting for 86.84% of total phytoplankton abundance. The abundance and distribution of dominant *Cyanobacterium* were obviously various along the flow of the Kuroshio, indicating the *Cyanobacterium* was profoundly influenced by the physical process of the Kuroshio. Therefore, *Cyanobacterium* could be used to indicate the influence of Kuroshio intrusion. In addition, the key controlling factors of the phytoplankton community were nitrogen, silicate, phosphate and temperature, according to Canonical Correspondence Analysis. However, the variability of these chemical parameters in the study water was similarly induced by the physical process of circulations. Based on the cluster analysis, the similarity of phytoplankton community is surprisingly divided by the regional influence of the Kuroshio intrusion, which indicated Kuroshio intrusion regulates phytoplankton community in the NSCS.

Key words: phytoplankton, community, Kuroshio, South China Sea

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1 Introduction

Phytoplankton contributes approximately 50%–60% of the primary production in the ocean, and plays an important role in maintaining the stability of different marine ecosystems (Sun, 2011). Due to its high diversity and typical sensitivity to human activities and climate change, phytoplankton is also a key initiator for the variation in marine environment (Tang et al., 2017). Phytoplankton species composition or dominant species distribution can reflect the physical and chemical environment, such as nutrients, temperature and light in water. Phytoplankton community sustainability can reflect the impact of human activities on the marine ecological environment (Vila and Masó, 2005), as well as climate change. Phytoplanktons have been used as indicator species to analyze Kuroshio water masses (Fujioka, 1990) and there are more investigations of phytoplankton community to be done because of its crucial role in the marine ecosystem.

As one of the largest marginal sea in the world, the South China Sea (SCS) has apparently received influence from the coastal upwelling and freshwater input, especially in its northeastern part effected by the Zhujiang River (Pearl River) (Yin et al., 2001; Xie et al., 2003). The northeastern South China Sea (NSCS), as a crossroad between the SCS and West Pacific Ocean (WPO), is profoundly affected by adjacent physical processes, such as circulations and mesoscale eddies which are very differences in structural and functional components. Thus, the ecological environment in the NSCS is not only affected by the coastal upwelling and runoff characterized by low salinity and high nutrients, but also controlled by the circulations and mesoscale eddies with relatively high salinity and low nutrients (Centurioni et al., 2004; Caruso et al., 2006). In particular, among the circulations and water masses, the Kuroshio Current has significant influence on the structural and functional components of the NSCS (Sun et al., 2006). Previous studies have shown that the Kuroshio Current frequently intruded into the NSCS during winter (Zhou et al., 2009). However, Chen et al. (2011) recently revealed that the Kuroshio Current can extend westward to 117°E in the September 2008. Sun et al. (2006) also reported that the Kuroshio Current has to some extent influence on the SCS during fall. These exchanges between the SCS and WPO, especially the Kuroshio intrusion, will crucially influence the phytoplankton

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abundance, distribution and composition (Chen, 2005).

The Kuroshio invasion is all year round. There have been studies of phytoplankton communities on the Kuroshio frontal surface. There is no research on the process of phytoplankton responses as the Kuroshio invaded and weakened from the Luzon Strait. In order to understand the impact of Kuroshio invasion on phytoplankton in summer and comparison with other seasons, we took samples in this area. In addition, we have adopted an improved method to identify more species with concentrated samples.

2 Materials and methods

2.1 *Sampling area*

A comprehensive investigation on biology and environment was carried out in the NSCS (14°–23°N, 114°–124°E) from 12 July to 11 August 2017. A total of 56 water samples from eight stations were collected as shown in Fig. 1.

2.2 *Sampling and analysis methods*

The seawater samples (7–10 L) for phytoplankton analysis were collected from depths of 5 m, 25 m, 50 m, deep chlorophyll maximum (DCM), 100 m, 150 m and 200 m using the Seabird CTD (Conductivity, Temperature and Depth; SBE 19 Plus) sampler on a rosette system. Physicochemical parameters such as temperature, salinity and depth were obtained by CTD at the same time. Thereafter, seawater samples were filtered through 20 μm mesh. Finally, phytoplankton was eluted by seawater filtered with GFF and stored in formalin. The final volume was 100 mL and the final concentration of formalin was 3%. Laboratory analysis were performed by a modified Utermöhl method (Utermöhl type) under a solution inverted microscope (Motic AE 2000) (Sun et al., 2002). The phytoplankton species were identified according to Jin (1965), Isamu (1962) and Sun and Liu (2002).

Water samples for nutrients were pre-filtered through 0.45 μm cellulose acetate membrane filters and then refrigerated at 4°C for further analysis. Nutrient concentrations including ammonium, phosphate, nitrate and silicate were examined by Technicon AA3 Auto-Analyzer (Bran+Luebbe). The nitrate and ammonium concentrations were analyzed using the copper-cadmium column reduction method and the indophenol blue spectrophotometric method, respectively. Dissolved inorganic silica (DSi) and phosphorus (DIP) were measured using spectrophotometric methods (Pai et al., 2001; Dai et al., 2008; Guo et al., 2014).

2.3 *Data analysis and statistical methods*

Dominance index (Y) was calculated to describe the species dominance in the phytoplankton community. The calculation equation was as follows (Sun, 1987):

$$Y = \frac{n_i}{N} f_i. \tag{1}$$

The Shannon-Wiener diversity index (H') was used to calculate the species diversity index. The calculation equation was as follows (Shannon and Weaver, 1949):

$$H' = -\sum_{i=1}^{S} P_i \log_2 P_i. \tag{2}$$

The Pielou J index was used to calculate the species evenness index (J). The calculation equation was as follows (Pielou, 1969):

$$J = \frac{H'}{\log_2 S}, \tag{3}$$

where n_i is the number of cells of species i, N is the total number of individuals in the collected samples, the number of total species of phytoplankton in the samples collected is S, the probability of cell abundance of species i in the samples is P_i, and f_i is the frequency of occurrence of species i in each sample.

The Jaccard similarity index (P) was calculated using the following formula (Jaccard, 1908):

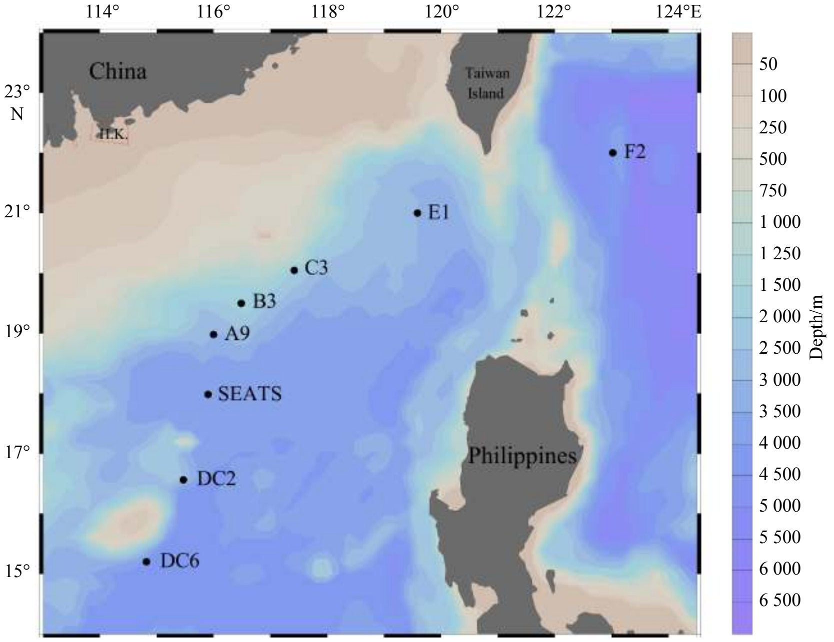

Fig. 1. Sampling stations in the survey area.

$$P = \frac{c}{a+b-c}, \tag{4}$$

where a and b are the numbers of species in two stations, and c is the number of the common species in the two stations.

The abundance of phytoplankton cells in water column is calculated by trapezoidal integral method (Tan et al., 2013):

$$P = \left\{ \sum_{i=1}^{n-1} \frac{P_{i+1} + P_i}{2} \left(D_{i+1} - D_i \right) \right\} / D, \tag{5}$$

were P is the average of phytoplankton abundance in water column, P_i is the abundance value of phytoplankton in layer i, D is the maximum sampling depth, D_i is the depth of layer i, and N is the sampling level.

The relationship between phytoplankton and environmental factors was analyzed by the Canonical Correspondence Analysis (CCA; Canoco 4.5), and the influence of circulations or water masses on the different regional distribution of phytoplankton communities was analyzed by the cluster analysis (Primer 6.0). Figures depicting horizontal and vertical distributions of phytoplankton were constructed using Ocean Data View 4.10, Sigmaplot 10.0.

3 Results

3.1 *Environmental parameters*

The transect distributions of temperature and salinity in the NSCS area are shown in Fig. 2. The temperature ranged from 13.8°C to 30.9°C, and the salinity ranged from 33.4 to 35.1. In general, temperature decreased with depth while salinity increased with depth. The stratification was obvious in the survey region. From Fig. 2a, we observed a significant difference in the thermocline between Stations DC6–C3 and Stations E1–E3. In addition, we observed a significant hypersaline intrusion under 100 m of Stations E1–F2. In brief, all the hydrologic results suggested that Kuroshio resulted in profound influence on the study area. Water temperature and salinity data were analyzed to draw T-S (temperature and salinity) scatter diagram as shown in Fig. 2c. The survey area is divided into two distinct areas, KC and SCS.

3.2 *Species composition*

A total of 287 species (79 genera and 5 phyla) of phytoplankton were identified in the NSCS. Among all the species, Bacillariophyta (129 species) and Pyrrophyta (150 species) were the most abundant, accounting for 44.94% and 52.26% of the total species, respectively. However, Cyanophyta, Chrysophyta and Haptophyta were recorded sporadically, and they only accounted for about 2.8% of the total species. Among Bacillariophyta, *Chaetoceros* (32 species) and *Rhizosolenia* (13 species) had the maximum species numbers, which accounted for 24.80% and 10.07% of the total diatom species. The most common species of Pyrrhophyta was *Ceratium* (26 species) *Propolydina* (23 species), accounting for 32.91% and 29.11% of the total Pyrrophyta species respectively. In this investigation, cyanobacteria belong to 2 genera and 4 species. *Trichodesmium* is mainly *Trichodesmium thiebautii*, *Trichodesmium erythraeum* and *Trichodesmium hildebrandtii*. *Trichodesmium thiebautii* is the most dominant species. Additionally, *Richelia intracellularis* appeared in two lifestyles, i.e., free living and *extracellular endosymbiosis* with *Rhizosolenia styliformis*.

3.3 *Section distribution of phytoplankton*

Phytoplankton abundance in the NSCS ranged from 50×10^4 to 2.04×10^4 cells/L, with an average of 2.14×10^3 cells/L. Cyanobacteria had the largest abundance of 2.02×10^4 cells/L, with an average of 1.85×10^3 cells/L, accounting for 86.84% of the total phytoplankton abundance. Diatom abundance varied between 0.04×10^3 and 1.41×10^3 cells/L, with an average of 0.22×10^3 cells/L. Compared with Cyanobacteria and Diatom, Dinoflagellates presented to low abundance, with an average of 0.03×10^3 cells/L. Overall, Cyanobacteria accounted for a large proportion of phytoplankton abundance, indicating the phytoplankton abundance was dominated by Cyanobacteria. Cyanobacteria abundance decreased gradually from Station F2 to Station DC6, however, the number of species did not change dramatically.

The transect distributions of phytoplankton, Cyanobacteria are shown in Fig. 3. The transect distribution of phytoplankton varies greatly, especially Cyanobacteria. The distribution of phytoplankton was mainly determined by Cyanobacteria, and *Trichodesmium thiebaultii* were dominant species in Cyanobacteria. The diatom was the second dominate species in phytoplankton community. The maximum cell abundance (2.56×10^3 cells/L) appeared at 75 m depth of Station DC6, which may be mainly affected by the topography of seamounts. The maximum cell abundance of Dinoflagellate (0.20×10^3 cells/L) was found at 25 m depth of Station F2. The vertical variation of total phytoplankton was similar to that of Cyanobacteria, showing the maximum abundance at the subsurface (0–50 m). Cyanobacteria

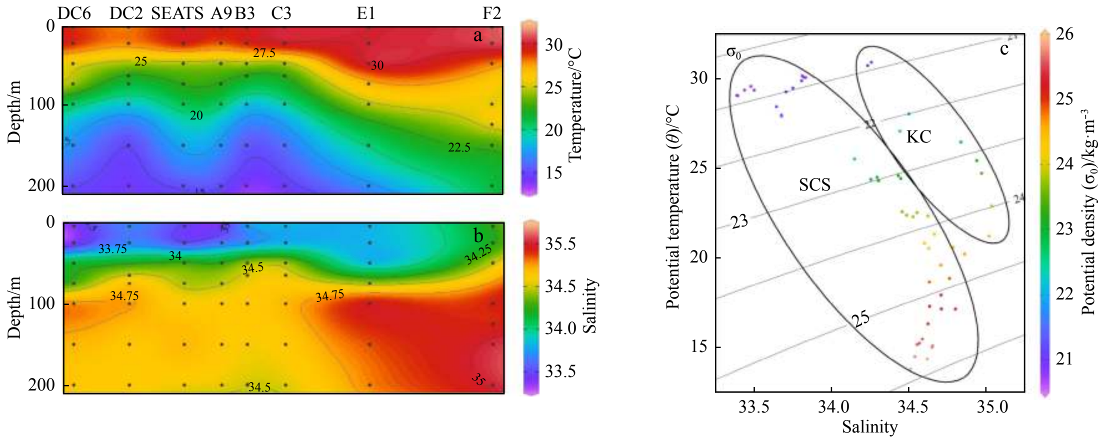

Fig. 2. Distribution of temperature and salinity. a. Temperature, b. salinity, and c. temperature and salinity (T-S) scatter diagram.

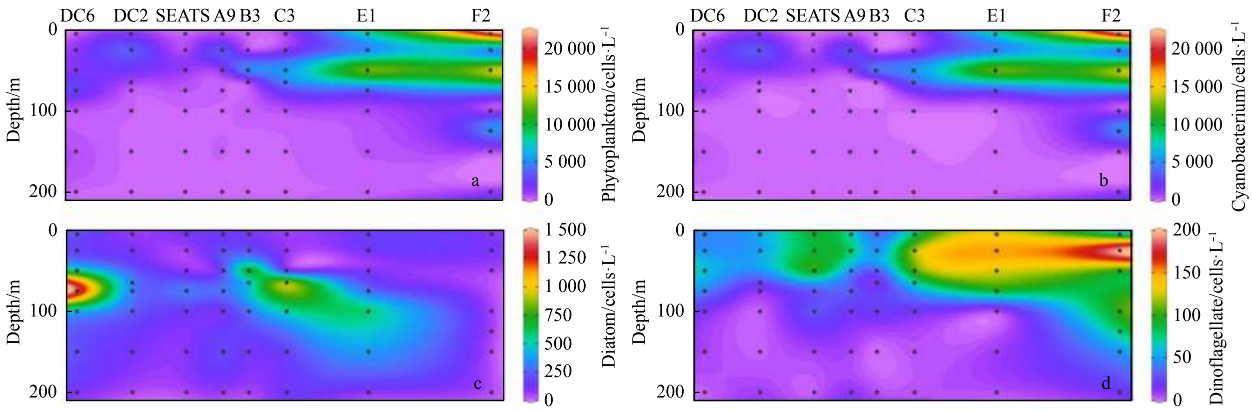

Fig. 3. The transect distribution of phytoplankton. a. Phytoplankton, b. Cyanobacterium, c. Diatom, and d. Dinoflagellate.

abundance was mainly determined by *Trichodesmium thiebautii* in this survey (Fig. 3). Diatom was not homogeneous distributed in the water column, with the maximum abundance near the DCM layer (~75 m). Dinoflagellates were mainly distributed in the upper layer (0–75 m).

3.4 *Dominant species*

The first 16 most dominant species were belonged to Bacillariophyta (11 species), Pyrrophyta (2 species), Cyanophyta (2 species), and Chrysophyceae (1 species) (Table 1). *Trichodesmium thiebautii* was the dominant species during the period of investigation. It is mainly distributed in the water layer above 50 m. The cell abundance of *Trichodesmium thiebautii* was between not detected (ND) and 19.88×10^3 cells/L with an average cell abundance at 1.82×10^3 cells/L. The maximum cell abundance of *Trichodesmium thiebautii* were observed in 5 m depth at Station F2.

The main ecological types of phytoplankton species are tropical coastal species and alongshore warm-water species, which are consistent with the characteristics of subtropical climate in this sea area. The distribution of dominant species is shown in Fig. 4. *Hemiaulus hauckii* (5.63 cells/L in average), *Leptocylindrus mediterraneus* (34.78 cells/L in average) and *Pseudosolenia calcar-avis* (3.89 cells/L in average) were the main representative species of warm water species. *Rhizosolenia styliformis* (5.83 cells/L in average), *Thalassionema nitzschiides* (31.01 cells/L in average), *Chaetoceros pelagicus* (12.09 cells/L in average) were the main representative species of the eurythermal species and wide-distribution types. *Scrippsiella trochoidea* (8.08 cells/L in average) and *Prorocentrum compressum* (5.16 cells/L in average) were dominated in Dinoflagellates, and they presented to highest abundance at Stations F2 and E1 where the temperature and salinity were optimal for the Dinoflagellate growth. *Synedra* spp. (9.67 cells/L in average), *Coscinodiscus subtilis* (6.08 cells/L in average), *Dictyocha fibula* (10.06 cells/L in average), *Eucampia Zodiacus* (6.49 cells/L in average), *Richelia intracellularis* (12.88 cells/L in average) and *Navicula* spp. (3.81 cells/L in average) were all commonly detected in the study area. The distribution of *Richelia intracellularis* in Cyanophyta is similar to that of its symbiont *Rhizosolenia styliformis*.

3.5 *Phytoplankton diversity index*

Diversity indexes are important tools to measure the stability of community structure (Sun and Liu, 2005), but it is easy to cause deviation by using only one diversity index to illustrate the diversity of the whole phytoplankton community. Therefore, Shannon-Wiener (S-W) diversity index and Pielou evenness index (J) were used in the present study to conduct a comprehensive analysis of community species diversity. From Fig. 5, the distribution trend of S-W diversity index was similar to Pielou even-

Table 1. Dominant species

Dominant species	Abundance ratio/%	Frequency (f_i)	Dominance index (Y)
Trichodesmium thiebautii	85.11	0.607	0.516 75
Leptocylindrus mediterraneus	1.62	0.714	0.011 60
Thalassionema nitzschioides	1.45	0.589	0.008 53
Synedra spp.	0.45	0.786	0.003 55
Scrippsiella trochoidea	0.38	0.643	0.002 43
Chaetoceros pelagicus	0.56	0.429	0.002 42
Coscinodiscus subtilis	0.28	0.804	0.002 28
Rhizosolenia styliformis	0.27	0.768	0.002 09
Dictyocha fibula	0.47	0.357	0.001 68
Prorocentrum compressum	0.24	0.625	0.001 51
Hemiaulus hauckii	0.26	0.571	0.001 50
Eucampia zodiacus	0.30	0.482	0.001 46
Richelia intracellularis	0.60	0.232	0.001 40
Navicula spp.	0.18	0.643	0.001 14
Chaetoceros messanense	0.23	0.500	0.001 13
Pseudosolenia calcar-avis	0.18	0.536	0.000 97

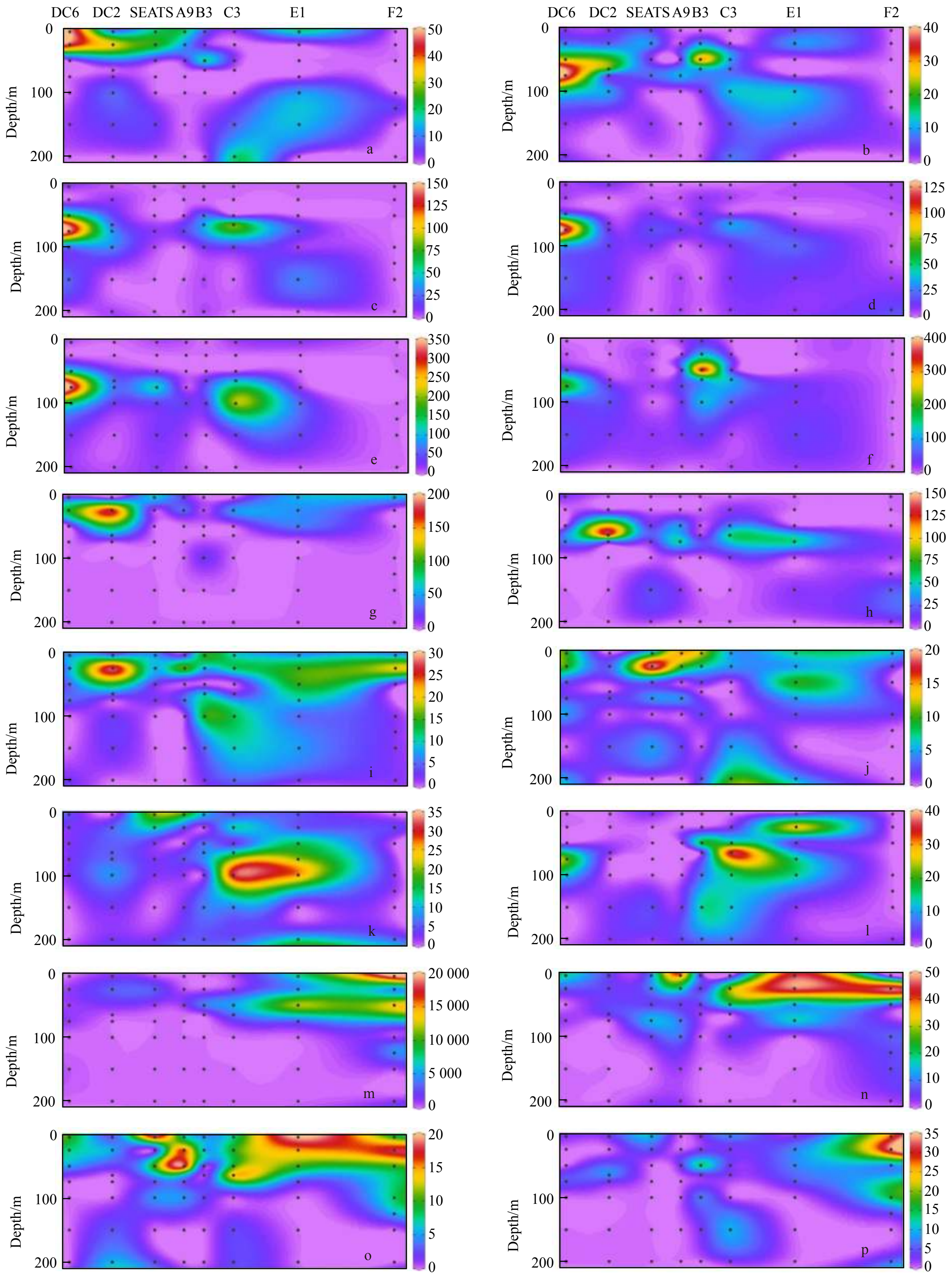

Fig. 4. Distribution of the dominant species. a. *Eucampia zodiacus*, b. *Hemiaulus hauckii*, c. *Chaetoceros pelagicus*, d. *Synedra* spp., e. *Thalassionema nitzschioides*, f. *Leptocylindrus mediterraneus*, g. *Richelia intracellularis*, h. *Dictyocha fibula*, i. *Rhizosolenia styliformis*, j. *Navicula* spp, k. *Coscinodiscus subtilis*, l. *Chaetoceros messanense*, m. *Trichodesmium thiebautii*, n. *Scrippsiella trochoidea*, o. *Prorocentrum compressum*, and p. *Pseudosolenia calcar-avis*. Unit: cells/L.

ness index. The S-W diversity index of phytoplankton ranged from 0.14 to 4.68 (mean=2.65±1.40) and the highest value was found in 100 m depth at Station E1. Pielou evenness index ranged from 0.03 to 0.97 (mean=0.56±0.31). The distribution pattern of

Pielou evenness index of phytoplankton was consistent with that of the S-W diversity index, presenting lower values in the upper layer of Stations F2 and E1.

Cluster analysis was carried out on account of the cell abundance value and species number of each station (Fig. 6). According to Bray-Curtis similarity, eight stations were divided into two groups. Stations F2 and E1 were divided into the first group (KC), and the other six stations (C3, B3, A9, SEATS, DC2 and DC6) were divided into the second group (SCS).

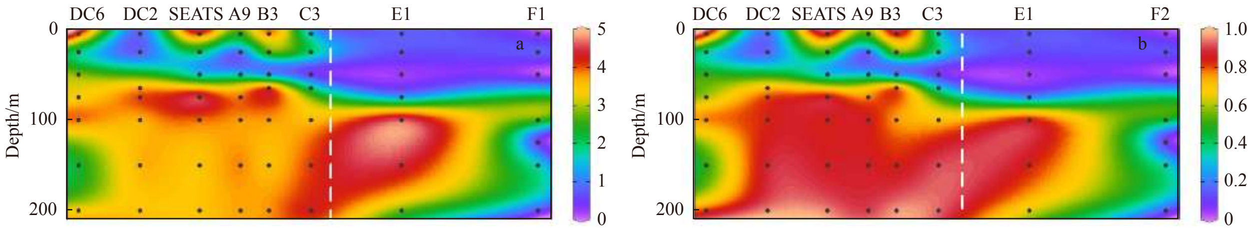

Fig. 5. The transect distribution of S-W diversity index (a) and Pielou evenness index (b).

In order to further study phytoplankton community structure, we divided these stations into two groups according to cluster analysis. The dominant species of each group were calculated separately, and four of the top ten dominant species of the two groups were the same (Table 2).

3.6 *CCA ordination of dominant species in KC and SCS with environmental variables*

In the present study, CCA was used to analyze the relationship between environmental parameters and dominant species. According to the results of 999 times Monte Carlo permutations, temperature (p<0.01) and salinity (p<0.01) contributed significantly to the total variance in the survey area (Fig. 7), species in the survey area are mainly divided into three groups in the two region, i.e., groups suitable for living at high temperature, groups with high salinity tolerance, and groups with wide temperature distribution. *Scrippsiella trochoidea*, *Trichodesmium erythraeum* and *Prorocentrum compressum* showed a significant positive correlation with temperature. Nutrient is a key factor affecting phytoplankton community structure in the South China Sea (Fig. 7). *Leptocylindrus mediterraneus*, *Thalassionema nitzschioides*, *Synedra* spp., *Chaetoceros pelagicus*, *Coscinodiscus subtilis*, and *Hemiaulus hauckii* were positively correlated with silicate, nitrate, phosphate and nitrate levels.

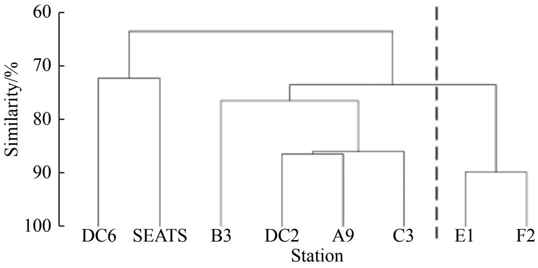

Fig. 6. Cluster analysis of phytoplankton community structure.

4 Discussion

4.1 *Comparison with historical data*

Compared with the historical data of phytoplankton community in water sample of similar regions and same season (Table 3), the survey area of this study included the outer Luzon Strait, where the total and *Trichodesmium* cell abundance were higher than those of other stations in SCS. The higher cell abundance may be related to high temperature and salinity and low nutrient contents (Ding, 2009). In Tan et al.'s (2013) study in 2008, the research area was mainly concentrated in the Luzon Strait. There are more species of Diatoms and Dinoflagellates and lower the cell abundance in this survey compared with that in Tan's study. This may be due to different investigation methods. In the present study, we filtered the water sample by 20 μm mesh, in which only the phytoplankton with diameter larger than 20 μm would be retained. However, more rare species would be found in larger volumes of seawater.

4.2 *Indicator species of KC and SCS*

Previous studies revealed that the composition of phytoplankton community was closely related to the variable circulations and water masses (Liu et al., 2004). Yang et al. (2011) declared that the Kuroshio branches were significant drivers of the biogeochemical cycles in the East China Sea and South China Sea. The T–S diagram analysis suggested that the relatively high temperature and salinity appeared in the KC. The results of cluster analysis divide the survey area into two parts. Somewarm-

Table 2. Dominant species of Kuroshio and South China Sea

Dominant species of Kuroshio	Dominance index (Y)	Dominant species of South China Sea	Dominance index (Y)
Trichodesmium thiebautii	0.874 82	*Trichodesmium thiebautii*	0.327 14
Scrippsiella trochoidea	0.001 85	*Leptocylindrus mediterraneus*	0.036 76
Trichodesmium erythraeum	0.001 17	*Thalassionema nitzschioides*	0.025 15
Rhizosolenia styliformis	0.001 18	*Synedra* spp.	0.007 84
Pseudosolenia calcar-avis	0.001 09	*Chaetoceros pelagicus*	0.007 31
Synedra spp.	0.000 93	*Coscinodiscus subtilis*	0.004 75
Prorocentrum compressum	0.000 83	*Hemiaulus hauckii*	0.004 22
Richelia intracellularis	0.000 72	*Eucampia zodiacus*	0.004 04
Coscinodiscus subtilis	0.000 72	*Dictyocha fibula*	0.003 82
Ceratium teres	0.000 70	*Scrippsiella trochoidea*	0.003 68

water species such as *Leptocylindrus mediterraneus*, *Rhizosolenia styliformis*, *Thalassionema nitzschiides*, and temperate coastal species such as *Thalassionema nitzschiides* are abundant in the first group. Some eurythermal species and coastal species occur mainly at the site of the second group, such as *Chaetoceros pelagicus* and *Coscinodiscus subtilis*. In the second group, the cell abundance of *Trichodesmium* in the first subgroup was much higher than that in the second subgroup. Three species of Dinoflagellates (*Scrippsiella trochoidea*, *Prorocentrum compressum* and *Ceratium teres*) were found with high dominance in Kuroshio area. This may be caused by higher ecological adaptability of Dinoflagellates than that of Diatoms under the conditions of high temperature and low nutrients (Li et al., 2003; Wang et al., 2006).

The dominant species in the two regions were analyzed, and there was a significant correlation between the distribution of dominant species and the water mass. For example, the distributions of *Trichodesmium thiebautii*, *Scrippsiella trochoidea*, *Prorocentrum compressum and Pseudosolenia calcar-avis* are determined by their different tolerance to temperature and salinity (Figs 4m–p) (Sun et al., 2001). Diatoms, such as *Eucampia doracus*, *Hemiaulus hauckii*, *Chaetoceros pelagicus*, *Synedra* spp., *Thalassionema nitzschioides* and *Richelia intracellularis*, were dominant in the SCS (Figs 4a–e, g), which further demonstrated the response of phytoplankton to the environment. Given the above discussion, we believe that Cyanobacteria (*Trichodesmium thiebautii*) and Diatom (*Thalassionema nitzschioides*) can be the indicator species in the KC and the SCS, respectively.

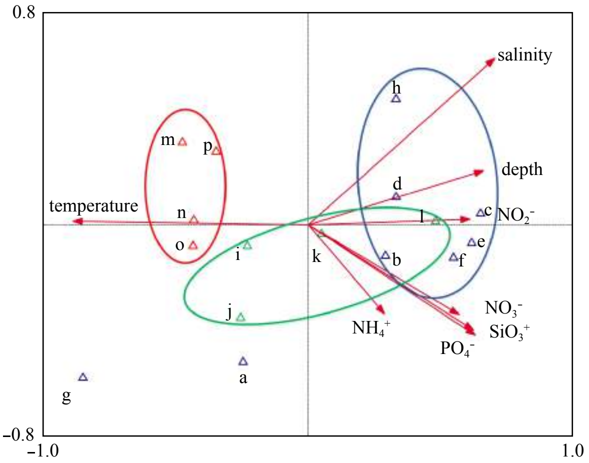

Fig. 7. CCA ordination of dominant species. a. *Eucampia zodiacus*, b. *Hemiaulus hauckii*, c. *Chaetoceros pelagicus*, d. *Synedra* spp., e. *Thalassionema nitzschioides*, f. *Leptocylindrus mediterraneus*, g. *Richelia intracellularis*, h. *Dictyocha fibula*, i. *Rhizosolenia styliformis*, j. *Navicula* spp., k. *Coscinodiscus subtilis*, l. *Chaetoceros messanense*, m. *Trichodesmium thiebautii*, n. *Scrippsiella trochoidea*, o. *Prorocentrum compressum*, and p. *Pseudosolenia calcar-avis*.

4.3 *Changes in species and cell abundance from KC to SCS*

The ratio of Diatom and Dinoflagellate is a fundamental factor to measure the stability of community structure in the ocean. In general, the higher proportion of Dinoflagellate may lead to the occurrence of harmful algal bloom which is toxic to water mass (Sun and Liu, 2005). In Station F2 the proportion of diatom species number was 31.97% and cell abundance was 41.30%. Overall, the proportion of diatom from Station F2 to Station DC6 was gradually increasing and reached more than 50% in SCS (Fig. 8) because Dinoflagellates have higher ecological adaptability than Diatoms under the conditions of high temperature and low nutrients (Li et al., 2003; Wang et al., 2006)

The Kuroshio had very high species richness (nearly 500 species) and phytoplankton diversity (Sun et al., 2001). When the Kuroshio invades the South China Sea, phytoplankton may also move with the water mass. There are 23 common species in the survey area, including 15 Diatoms, 6 Dinoflagellates and 2 Cyanobacteria. Comparing species at Station F2 with those at other stations, there were great differences in phytoplankton species in the investigated area. Each station was compared with Station F2 with Jaccard similarity (Table 4). The similarity in Station E1 and Station C3 was higher (0.414 and 0.368) while the similarity at other stations was lower and the difference was not significant. The main group of Station F2 is Dinoflagellates, which is related to the fact that Dinoflagellates prefer higher water temperature.

4.4 *The key environmental factors controlling phytoplankton community in SCS and KC*

The physical factors (temperature, salinity), chemical factors (nutrients) and biological factors (competition among phytoplankton) were the main variables affecting the phytoplankton community distribution (Sun et al., 2007). The relative positions of Diatom and Dinoflagellate in CCA biplot reflected the dependence of the species on environmental factors. CCA was used to analyze dominant species in the Kuroshio and South China Sea areas (Fig. 7). Combined with temperature and salinity distribution and transect distribution of phytoplankton community structure, we found that the Kuroshio area was greatly affected by temperature. There were three species of Cyanobacteria and three species of Dinoflagellates in the top ten dominant species. The reason may be that Cyanobacteria and Dinoflagellates were more tolerant to temperature (Fig. 7), and the distribution of Diatoms in the two regions was mainly affected by nutrients. The salinity of the sea area near the Luzon Strait was high due to the Kuroshio intrusion. The inshore diatoms decreased in the phytoplankton composition. The species and cell abundance of Dinoflagellates and Cyanobacteria increased obviously (Tan et al., 2013). Due to the higher water temperature in the area affected by the Kuroshio, Diatoms were rare, but warm-water Dinoflagellates and Cyanobacteria predominated. Higher water temperat-

Table 3. Comparing with the historical data

Time	Research area	Depth	Number of species	Cell abundance/10^3 cells·L^{-1}	References
Jul.–Aug. 2017	14°–22°N, 114°–124°E	0–200	287	2.141	this study
Aug. 2014	18°–22°N, 114°-116°E	0–200	229	14.653	Xue et al. (2016)
Jul.–Aug. 2009	18°–23.5°N, 109°–120°E	0–200	150	26.490	Ma and Sun (2014)
Aug. 2009	18°–22°N, 110°–117°E	0–200	109	8.197	Li et al. (2012)
Aug.–Sep. 2008	18°–23°N, 120°–122.5°E	0–200	169	1.448	Tan et al. (2013)
Aug. 2007	18°–23°N, 110°–120°E	0–200	216	11.220	Ke et al. (2011)
Aug. 2004	18°–22°N, 110°–117°E	0–200	159	115.050	Le et al. (2006)

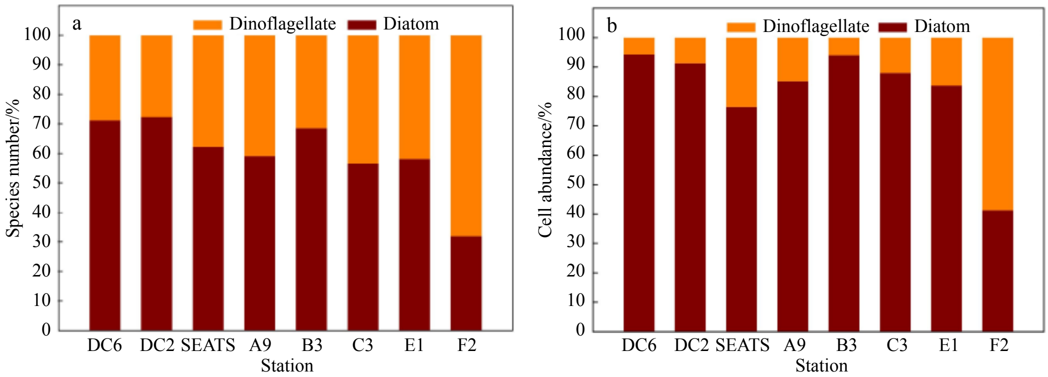

Fig. 8. The histogram of ratio of Diatom and Dinoflagellate species number and cell abundance. a. The histogram of ratio of species number and b. the histogram of ratio of cell abundance.

Table 4. The Jaccard similarity index

Station	DC6	DC2	SEATS	A9	B3	C3	E1	F2
Same species with F2	59	40	52	55	50	74	87	154
Similarity index value	0.289	0.206	0.275	0.286	0.255	0.368	0.414	1.000

ures (>30°C) will limit the phytoplankton growth. The surface layer was affected by tropical high temperature and strong radiation, what was more, the nutrient concentration was low and could not meet the needs of phytoplankton growth (Zhu et al., 2003). It indicated that temperature had the greatest influence on the phytoplankton community structure during the Kuroshio invasion to the SCS.

5 Conclusions

Our preliminary investigation of phytoplankton community structure showed that the distribution of phytoplankton was mainly determined by Cyanobacteria. Because of the abundance and distribution of *Trichodesmium* showed apparent heterogeneity along the flow of the Kuroshio, *Trichodesmium* can be used as an excellent indicator of Kuroshio intrusion. In addition, diatoms gradually dominated the phytoplankton community from Station F2 to Station DC6, due to the diminishing influence of the Kuroshio. The study area was obviously affected by the invasion of Kuroshio water, which has a remarkable characteristic of high temperature, high salinity and low nutrients. Dinoflagellates had better ecological adaptability than diatoms under high temperature and low nutrient conditions and therefore dominated in Station F2. Cluster analysis and hydrological data demonstrated that the phytoplankton community structure in the study area could be divided into three types, the South China Sea water masses, the mixed water and Kuroshio.

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References

Caruso M J, Gawarkiewicz G G, Beardsley R C. 2006. Interannual variability of the Kuroshio intrusion in the South China Sea. Journal of Oceanography, 62(4): 559–575, doi: 10.1007/s10872-006-0076-0

Centurioni L R, Niiler P P, Lee D K. 2004. Observations of inflow of Philippine Sea surface water into the South China Sea through the Luzon Strait. Journal of Physical Oceanography, 34: 113–121, doi: 10.1175/1520-0485(2004)034<0113:OOIOPS>2.0.CO;2

Chen Y F L. 2005. Spatial and seasonal variations of nitrate-based new production and primary production in the South China Sea. Deep-Sea Research Part I: Oceanographic Research Papers, 52(2): 319–340, doi: 10.1016/j.dsr.2004.11.001

Chen Gengxin, Hu Po, Hou Yijun, et al. 2011. Intrusion of the Kuroshio into the South China Sea, in September 2008. Journal of Oceanography, 67(4): 439–448, doi: 10.1007/s10872-011-0047-y

Dai Minghan, Wang Lei, Guo Xianghui, et al. 2008. Nitrification and inorganic nitrogen distribution in a large perturbed river/estuarine system: the Pearl River Estuary, China. Biogeosciences, 5: 1227–1244, doi: 10.5194/bg-5-1227-2008

Ding Changling. 2009. The abundance, the spatial and temporal distributions of cyanobacteria in the Yellow Sea, the East China Sea and the South China Sea (in Chinese) [dissertation]. Qingdao: Ocean University of China

Fujioka S. 1990. Illustrations of the plankton of the Kuroshio-waters. Plankton in Amami-oshima Island Coastal Waters. Nagasaki, Japan: Nagasaki-ken Culture Publishing Union

Guo Shujing, Feng Yuanyuan, Wang Lei, et al. 2014. Seasonal variation in the phytoplankton community of a continental-shelf sea: The East China Sea. Marine Ecology Progress, 516: 103–126, doi: 10.3354/meps10952

Isamu Y. 1962. Illustrations of the Marine Plankton of Japan. Tokyo: Hoikusha Publishing

Jaccard P. 1908. Nouvelles recherches sur la distribution florale. Bulletin de la Societe Vaudoise des Sciences Naturelles, 44: 223–270

Jin Dexiang. 1965. Chinese Marine Planktonic Diatoms (in Chinese). Shanghai: Shanghai Scientific and Technical Publishers

Ke Zhixin, Huang Liangmin, Tan Yehui, et al. 2011. Species composition and abundance of phytoplankton in the northern South China Sea in summer 2007. Journal of Tropical Oceanography (in Chinese), 30(1): 131–143

Le Fengfeng, Sun Jun, Ning Xiuren, et al. 2006. Phytoplankton in the northern South China Sea in summer 2004. Oceanologia et Limnologia Sinica (in Chinese), 37(3): 238–248

Li Xin, Sun Jun, Tian Wei, et al. 2012. Phytoplankton community in the northern area of South China Sea in summer of 2009. Marine Sciences (in Chinese), 36(10): 33–39

Li Ruixiang, Zhu Mingyuan, Wang Zongling, et al. 2003. Mesocosm experiment on competition between two HAB species in East China Sea. Chinese Journal of Applied Ecology (in Chinese), 14(7): 1049–1054

Liu Dongyan, Sun Jun, Liu Zhe, et al. 2004. The effects of spring-neap tide on the phytoplankton community development in the Jiaozhou Bay, China. Acta Oceanologica Sinica, 23(4): 687–697

Ma Wei, Sun Jun. 2014. Characteristics of phytoplankton community in the northern South China Sea in summer and winter. Acta Ecologica Sinica (in Chinese), 34(3): 621–632

Pai Sucheng, Tsau Y J, Yang T I. 2001. pH and buffering capacity problems involved in the determination of ammonia in saline water using the indophenol blue spectrophotometric method. Analytica Chimica Acta, 434(2): 209–216, doi: 10.1016/S0003-2670(01)00851-0

Pielou E C. 1969. An introduction to mathematical ecology. New York: Wiley Interscience

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

Sun Ruyong. 1987. The Principle of Animal Ecology (in Chinese). Beijing: Beijing Normal University Press

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

Sun Jian, Hou Lipei, Xie Julun. 2006. Preliminary analysis of seasonal variation of Kuroshio in Luzon Strait. Marine Forecasts (in Chinese), 23(S1): 60–63

Sun Jun, Liu Dongyan. 2002. The preliminary notion on nomenclature of common phytoplankton in China Seas waters. Oceanologia et Limnologia Sinica (in Chinese), 33(3): 271–286

Sun Jun, Liu Dongyan. 2005. Net phytoplankton community of the Bohai Sea in the autumn of 2000. Haiyang Xuebao (in Chinese), 27(3): 124–132

Sun Jun, Liu Dongyan, Qian Shuben. 2002. A quantative research and analysis method for marine phytoplankton: an introduction to Utermöhl method and its modification. Journal of Oceanography of Huanghai & Bohai Seas (in Chinese), 20(2): 105–112

Sun Jun, Liu Dongyan, Wei Hao, et al. 2001. Fuzzy evaluation on the marine phytoplankton diversity of Ryükyü-Guntö and its adjacent waters. Oceanologia et Limnologia Sinica (in Chinese), 32(4): 445–453

Sun Jun, Song Shuqun, Le Fengfeng, et al. 2007. Phytoplankton in northern South China Sea in the winter of 2004. Haiyang Xuebao (in Chinese), 29(5): 132–145

Tan Jiyang, Huang Liangmin, Tan Yehui, et al. 2013. The influences of water-mass on phytoplankton community structure in the Luzon Strait. Haiyang Xuebao (in Chinese), 35(6): 178–189

Tang Senming, Cai Rongshuo, Guo Haixia, et al. 2017. Response of phytoplankton in offshore China seas to climate change. Journal of Applied Oceanography (in Chinese), 36(4): 455–465

Vila M, Masó M. 2005. Phytoplankton functional groups and harmful algae species in anthropogenically impacted waters of the NW Mediterranean Sea. Scientia Marina, 69(1): 31–45, doi: 10.3989/scimar.2005.69n131

Wang Zongling, Li Ruixiang, Zhu Mingyuan, et al. 2006. Study on population growth processes and interspecific competition of *Prorocentrum donghaiense* and *Skeletonema costatum* in semi-continuous dilution experiments. Advances in Marine Science (in Chinese), 24(4): 495–503

Xie Shangping, Xie Qiang, Wang Dongxiao, et al. 2003. Summer upwelling in the South China Sea and its role in regional climate variations. Journal of Geophysical Research, 108(C8): 3261, doi: 10.1029/2003JC001867

Xue Bing, Sun Jun, Li Tingting. 2016. Phytoplankton community structure of northern South China Sea in summer of 2014. Haiyang Xuebao (in Chinese), 38(4): 54–65

Yang Dezhou, Yin Baoshu, Liu Zhiliang, et al. 2011. Numerical study of the ocean circulation on the East China Sea shelf and a Kuroshio bottom branch northeast of Taiwan in summer. Journal of Geophysical Research: Oceans, 116(C5): C05015

Yin Kedong, Qian Peiyuan, Wu M C S, et al. 2001. Shift from P to N limitation of phytoplankton growth across the Pearl River estuarine plume during summer. Marine Ecology Progress Series, 221: 17–28, doi: 10.3354/meps221017

Zhou Hui, Nan Feng, Shi Maochong, et al. 2009. Characteristics of water exchange in the Luzon Strait during September 2006. Chinese Journal of Oceanology and Limnology, 27(3): 650–657, doi: 10.1007/s00343-009-9175-2

Zhu Genhai, Ning Xiuren, Cai Yuming, et al. 2003. Studies on species composition and abundance distribution of phytoplankton in the South China Sea. Haiyang Xuebao (in Chinese), 25(S2): 8–23