Acta Oceanol. Sin., 2016, Vol. 35, No. 2, P. 46–55
DOI: 10.1007/s13131-016-0811-3
http://www.hyxb.org.cn
E-mail: hyxbe@263.net

Spatiotemporal heterogeneity of phytoplankton diversity and its relation to water environmental factors in the southern waters of Miaodao Archipelago, China

ZHENG Wei[1*], LI Fen[1, 2], SHI Honghua[1], HUO Yuanzi[1], LI Yan[1], CHI Yuan[1], GUO Zhen[1], WANG Yuanyuan[1, 3], SHEN Chengcheng[1, 4], LIU Jian[4], QIAO Mingyang[1, 2]

[1] First Institute of Oceanography, State Oceanic Administration, Qingdao 266061, China

[2] Research Center of Applied Mathematics, Ocean University of China, Qingdao 266100, China

[3] College of Environmental and Municipal Engineering, Qingdao Technology University, Qingdao 266033, China

[4] College of Environment Science and Engineering, Ocean University of China, Qingdao 266100, China

Received 20 July 2015; accepted 21 September 2015

Abstract

To study the water quality influenced by the anthropogenic activities and its impact on the phytoplankton diversity in the surface waters of Miaodao Archipelago, the spatiotemporal variations in phytoplankton communities and the environmental properties of the surface waters surrounding the Five Southern Islands of Miaodao Archipelago were investigated, based on seasonal field survey conducted from November 2012 to August 2013. During the survey, a total of 109 phytoplankton species from 3 groups were identified in the southern waters of Miaodao Archipelago, of which 77 were diatoms, 29 were dinoflagellates, and 3 were chrysophytes. Species number was higher in winter (73), moderate in autumn (70), but lower in summer (31) and spring (27). The species richness index in autumn (5.92) and winter (4.28) was higher than that in summer (2.83) and spring (1.41). The Shannon-Wiener diversity index was high in autumn (2.82), followed by winter (1.99) and summer (1.92), and low in spring (0.07). The species evenness index in autumn (0.46) and summer (0.39) was higher than that in winter (0.32) and spring (0.02). On the basis of principal component analysis (PCA) and redundancy analysis (RDA), we found that dissolved inorganic nitrogen (DIN) and chemical oxygen demand (COD) in spring, COD in summer, pH in autumn, and salinity and oil pollutant in winter, respectively, showed the strongest association with the distribution of phytoplankton diversity. The spatial heterogeneity of the southern waters of Miaodao Archipelago was quite obvious, and three zones, i.e., northeastern, southwestern and inter-island water area, were identified by cluster analysis (CA) based on key environmental variables.

Key words: Miaodao Archipelago, environmental factors, spatial distribution, phytoplankton, statistical analysis

Citation: Zheng Wei, Li Fen, Shi Honghua, Huo Yuanzi, Li Yan, Chi Yuan, Guo Zhen, Wang Yuanyuan, Shen Chengcheng, Liu Jian, Qiao Mingyang. 2016. Spatiotemporal heterogeneity of phytoplankton diversity and its relation to water environmental factors in the southern waters of Miaodao Archipelago, China. Acta Oceanologica Sinica, 35(2): 46–55, doi: 10.1007/s13131-016-0811-3

1 Introduction

Phytoplankton plays a vital role in the energy flow, nutrient cycling, and information transfer in marine ecosystem, manifested mainly by their biomass and diversity (Rolland et al., 2009). The diversity of marine phytoplankton not only affects the health and stability of marine ecosystem, but also influences the marine carbon sink function (Yamamoto and Hatta, 2004; De La Rocha and Passow, 2007). The diversity of phytoplankton is under the influence of a variety of environmental factors, such as hydrological, physicochemical, and biological factors. Environmental factors (e.g., surface seawater temperature, pH, salinity, nutrients) are often heterogenous in both space and time. Besides the tide turbulence, the nutrients or contaminations from the islands also have significant impacts on the waters surrounding islands (Xu et al., 2008). In addition, the existence of islands results in the poor water exchange, which means that eutrophication can be more frequently induced in inter-island waters (Blain et al., 2001; Gilmartin and Revelante, 1974).

The island ecosystem has the features of both terrestrial and aquatic ecosystems. The aquatic environmental factors manifest significant spatial heterogeneity due to the barrier effect of the islands and the disturbance of human activities (Blain et al., 2001; Gilmartin and Revelante, 1974). This drew our attention to study the spatial heterogeneity of phytoplankton in the waters around islands.

The islands in the southern Miaodao Archipelago are centrally distributed, located between the two waterways named Dengzhou and Changshan, consisting of five islands with human habitation and several uninhabited islands. This area is the traditional breeding area and mariculture zone of fishery and is subject to more frequent and intensive human activities as in Miaodao Archipelago. In the last two decades, there were some sporadic data for the small-scale monitoring of environmental impact by marine engineering projects, but no systematic reports on the marine ecosystem in this area.

To study the water quality status and its impact on the phyto-

Foundation item: The Special Project of Science and Technology Fundamental Work from the Ministry of Science and Technology of China under contract No. 2012FY112500; the National Natural Science Foundation of China under contract Nos 41206111 and 41206112.
*Corresponding author, E-mail: zhengwei@fio.org.cn

plankton diversity, this study reported the main results of an annual survey on the phytoplankton and water environment in the surface waters of southern Miaodao Archipelago in four seasons of 2012–2013. The key environmental factors exhibiting the strongest association with the heterogeneity of phytoplankton diversity were determined in order to better understand the spatial distribution of coastal phytoplankton diversity.

2 Materials and methods

2.1 *Field survey*

Twenty-one sampling stations (Fig. 1) were distributed in the southern waters of Miaodao Archipelago surrounding the five islands with human habitation. Four cruises were conducted in autumn (November 2012), winter (February 2013), spring (May 2013), and summer (August 2013). Water samples were collected from surface water at each station to determine the concentrations of nutrients and phytoplankton biomass as well as phytoplankton species composition.

2.2 *Analysis methods of phytoplankton and environment*

Surface seawater temperature (SST) was measured *in situ*. Water samples were analyzed within 24 h (10 h for oil pollutant) of sampling to measure chemical oxygen demand (COD), nitrate nitrogen (NO_3-N), nitrite (NO_2-N), ammonium (NH_4-N), dissolved inorganic phosphorus (PO_4-P), silicate (SiO_3-Si), volatile phenol (VP), pH, salinity (Sal), suspended solids (SS), dissolved oxygen (DO) and oil pollutant (Oil) based on National Standard of the People's Republic of China on Specifications for oceanographic survey (GB/T 12763–2007). NO_3-N, NO_2-N and NH_4-N were integrated as dissolved inorganic nitrogen (DIN). Inverted microscopy and Utermöhl (1958) methods were used to identify and count the phytoplankton, and the abundance of phytoplankton was shown in cells/m^3.

2.3 *Statistical analysis*

Margalef species richness index (Margalef, 1968): $D=(S-1)/\log_2 N$, Shannon-Wiener diversity index: $H'=-\sum_{i=1}^{S} P_i \log_2 P_i$, Pielou evenness index (Pielou, 1966): $J=H'/\log_2 S$ and dominance index: $C=(N_1+N_2)/N$ were adopted to represent the phytoplankton biodiversity. Dominant species was determined by the dominance factor, $y = f_i \times p_i$, where f_i is the appearance frequency of species i in the sampling sites of one season; p_i is the abundance ratio of species i among all species of one season; and y>0.02 indicated dominant species (Lampitt et al., 1993).

SST, SS, pH, DO, Sal, COD, DIN, DIP, Oil, SiO_3 and VP were adopted as the explanatory variables, namely environmental factors. The differences in the environmental factors and phytoplankton diversity indices among seasons and among sampling stations were tested using the one-way ANOVA. Ordination analysis was used to determine the relationship between environmental factors and phytoplankton diversity conducted with multivariate statistical analysis methods using the CANOCO for Windows version 4.5. Before the analysis, the data on phytoplankton were all log(x+1) transformed. The phytoplankton data first went through detrended correspondence analysis (DCA), to determine whether they have a unimodal or linear distribution. The DCA result of the dominant phytoplankton species indicated that the maximum gradient lengths of the axes was 0.683, less than 3; the DCA result of phytoplankton diversity indicated that the maximum gradient length of the axes of the four seasons were 1.25, 1.61, 1.84, and 1.13, respectively, all less than 3. Therefore, principle component analysis (PCA) and redundancy analysis (RDA) were used (Leps and Smilauer, 2003). PCA was used to determine the distributions of the biomass of the dominant phytoplankton species and the phytoplankton diversity, whereas RDA was used to determine the key environmental factors having the strongest association with the spatial heterogeneity of phytoplankton diversity. The significance of correlation in RDA was tested by Monte Carlo simulation. To eliminate the possibility of a relatively high correlation between environmental factors, those factors with partial correlation coefficient greater than 0.8 and variation of volatility index greater than 20 were excluded from the RDA (Tang et al., 2006).

To study the spatial distribution characteristics of phytoplankton diversity as well as environmental factors, the experimental sites were grouped by cluster analysis (CA) based on the three sets of data as follows respectively: (1) data of environmental factors (excluding the water depth and temperature) for all seasons; (2) data of the main environmental factors having the strongest association with the distribution of phytoplankton diversity for all seasons; (3) data of the phytoplankton diversity in-

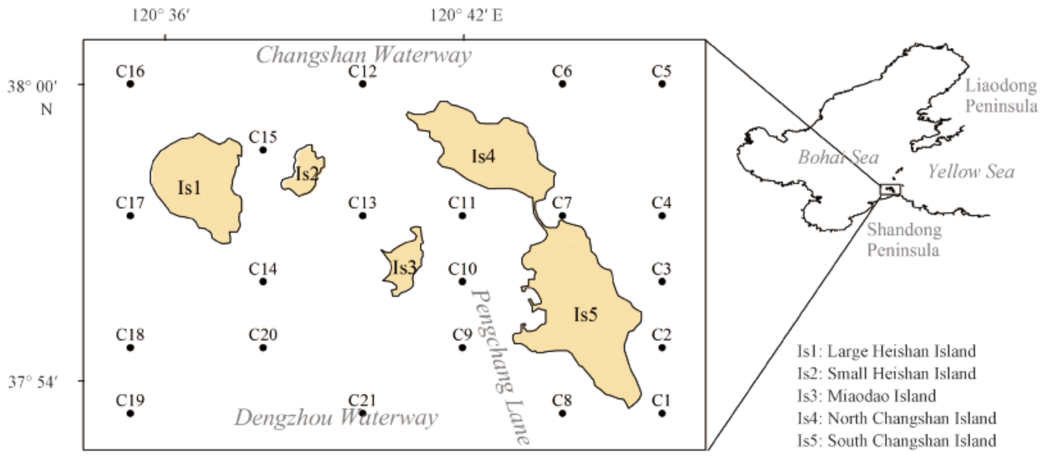

Fig. 1. Location of study area namely the southern waters of Miaodao Archipelago and distribution of 21 sampling stations labeled as C1–C21.

dices for all seasons. Both the CA and one-way ANOVA were used by the software of SPSS 19.

3 Results

3.1 *Environmental characteristics*

Environmental factors of the surface water area of southern Miaodao Archipelago varied significantly between seasons (p<0.01, Table 1). SST was higher in summer and autumn and lower in winter and spring. SS, pH, nutrients, and Oil were higher in summer but lower in other seasons, while Sal, DO, and COD were higher in spring. In spring, DIN peaked at 0.14 mg/L at Site C19, whereas that was all less than 0.05 mg/L at Sites C2, C12, and C14, and DIN ranged from 0.05 to 0.1 mg/L at the other Sites. COD reached its minimum of 3.07 mg/L at Site C18, and was less than 3 mg/L at all other Sites. In summer, COD peaked at 2.38 mg/L at Sites C12 and C16. In winter, Oil reached its maximum of 0.02 mg/L at Site C19, while Sal reached its maximum of 31.10 at Site C3.

3.2 *Structure of phytoplankton community*

During the survey, a total of 109 phytoplankton species from 3 groups were identified in the southern waters of Miaodao Archipelago, of which there were 77 diatoms, 29 dinoflagellates, and 3 chrysophytes. Species number was higher in winter (73), moderate in autumn (70), but lower in summer (31) and spring (27).

The abundance of phytoplankton varied between seasons which was higher in spring (35.85×10^7cells/m^3) and winter (20.33×10^7cells/m^3) but significantly lower in autumn (0.64×10^7 cells/m^3) and summer (0.21×10^7 cells/m^3). Meanwhile, the phytoplankton abundance also showed obvious spatial differences, which was higher in the northeast waters than that in the southwest waters in spring. While the abundance of phytoplankton in the open waters outside the islands was higher than that in the inter-island waters in summer and autumn, the phytoplankton abundance in the central and southern waters was higher than that in other areas in winter (Fig. 2).

The seasonally dominant phytoplankton amounted to thirteen species and only two were dominant in more than one season (Table 2). *Guinardia delicatula* (*spe*1), *Gymnodinium* (*spe*2), *Paralia sulcata* (*spe*3) and *Thalassiosira pacifica* (*spe*10), with dominance all greater than 0.20, were most dominant in spring, summer, autumn, and winter, respectively. The PCA results showed that the cumulative contribution of the first 2 eigenvalues on the ranking axis accounted for 55.8%, well reflecting the characteristics of dominant phytoplankton species (Fig. 3). Stations along the positive PC2 axis mainly laid in the southwest of the study area (e.g., Stations C17–C20). Only *Paralia sulcate* (*spe*3) in spring and *Thalassiosira rotula* (*spe*10) in winter were shown here to be dominant species, while the other dominant species were distributed in the other side of the study area (Fig. 3). Although *Paralia sulcate* was a dominant species in summer, autumn, and winter and *Coscinodiscus* (*spe*5) was dominant in both summer and autumn, they presented different spatial distribution of biomass in different seasons (Fig. 3).

3.3 *Distribution of phytoplankton diversity*

The spatiotemporal variations of the diversity indices of phytoplankton in the southern waters of Miaodao Archipelago were statistically significant (p<0.01). The species richness index in autumn (5.92) and winter (4.28) as higher than those in summer (2.83) and spring (1.41). The diversity index was higher in autumn (2.82), followed by winter (1.99) and summer (1.92), with spring (0.07) showing the lowest diversity. The species evenness index in autumn (0.46) and summer (0.39) as higher than those in winter (0.32) and spring (0.02) (Fig. 4).

The results of PCA, used to characterize the distribution of phytoplankton diversity, showed that the cumulative contribution of the first two eigenvalues on the ranking axis of each season accounted for 81.5%, 88.3%, 82.4%, and 82.5%, respectively (Fig. 5). In spring, the evenness and diversity indices were higher in the southwest and center of the study area, but lower in the east. The species number and the species richness index showed the opposite distribution. In summer, the evenness index was lower in the southwestern area, the species number was lower in the western and southern water area, and the richness and diversity indices were lower in the southeastern water area and the middle part of the western water area. The four indices were all lower at Site C11. In autumn, the four indices were all lower in the inter-island water area. In winter, the species number and the richness index were higher in the southern water area, and the evenness index was lower in the southwestern water area. The diversity index was slightly higher in the northwest area and lower in the southwest area.

3.4 *Relationship between phytoplankton diversity and environmental factors*

The results of RDA indicated that the ranking axes of all seasons all reached significant level under Monte Carlo permutation test (p<0.001). The selected environmental factors explained 85.1%, 98.1%, 97.4%, and 85.3% of the diversity change information in spring through winter, respectively. The first two axes explained cumulatively 37.7%, 73.4%, 68%, and 29.7% of the diversity change information in spring through winter, respectively,

Table 1. Means and standard errors of environmental parameters

Environmental parameters	Spring		Summer		Autumn		Winter	
	Mean	Standard error	Mean	Standard error	Mean	Standard error	Mean	Standard error
SST /°C	10.830	1.250	26.520	0.660	14.330	0.310	3.010	0.250
SS/mg·L^{-1}	13.560	4.380	45.960	5.310	19.870	6.900	8.030	0.040
pH	8.110	0.200	8.540	0.070	8.010	0.070	8.030	0.040
Sal	30.660	0.310	27.000	0.460	29.430	0.240	30.580	0.320
DO/mg·L^{-1}	10.130	0.520	6.700	0.040	7.860	0.180	8.920	0.190
COD/mg·L^{-1}	2.300	0.450	2.040	0.220	1.240	0.300	1.550	0.180
DIP/mg·L^{-1}	0.002	0.001	0.012	0.008	0.006	0.002	0.006	0.003
DIN/mg·L^{-1}	0.060	0.030	0.130	0.030	0.180	0.060	0.170	0.050
SiO_3/mg·L^{-1}	0.088	0.036	0.561	0.211	0.174	0.074	0.149	0.040
Oil/mg·L^{-1}	0.007	0.012	0.033	0.008	0.030	0.037	0.016	0.004

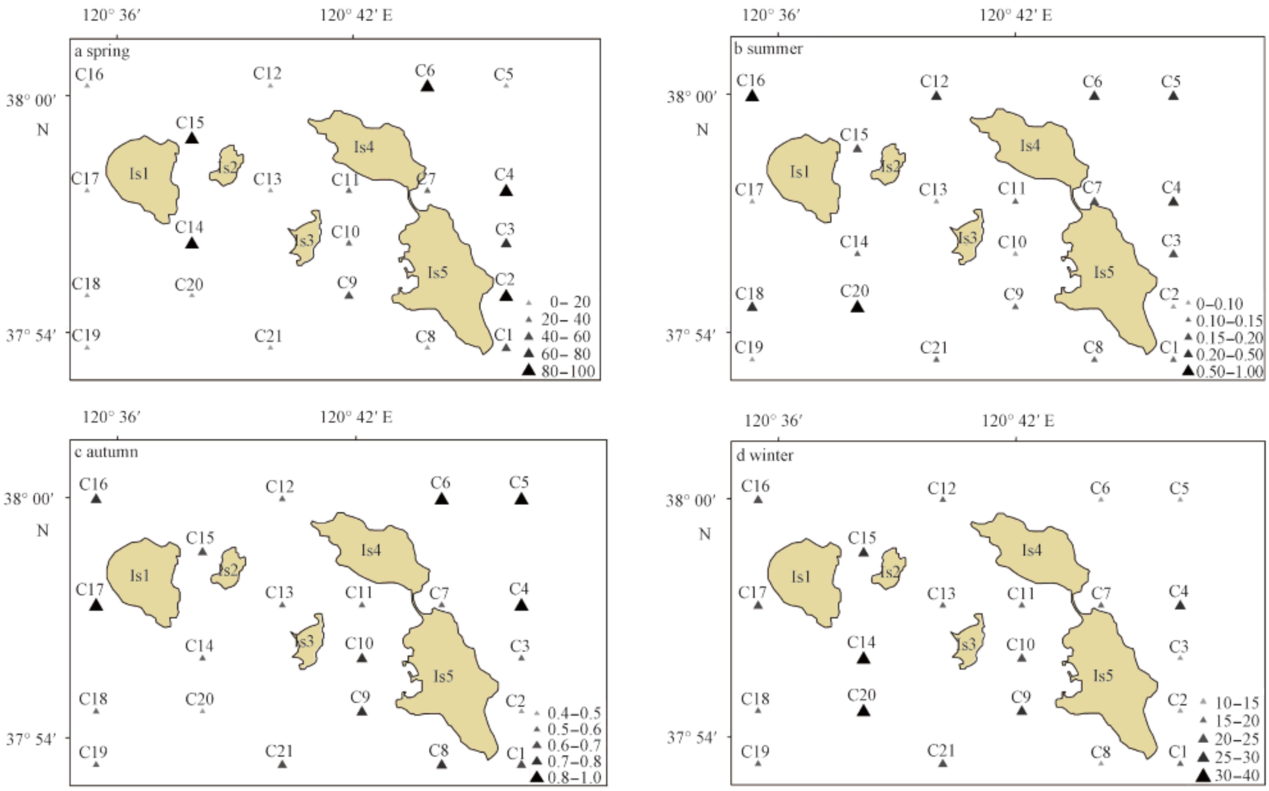

Fig. 2. Distribution maps of phytoplankton abundance (10^7 cells/m^3) in southern waters surrounding Miaodao Archipelago.

Table 2. The codes and dominance factor values of the seasonal phytoplankton dominant species in the southern waters of Miaodao Archipelago, 2012–2013

Code	Species	Taxonomic group	Spring	Summer	Autumn	Winter
*Spe*1	*Guinardia delicatula*	*Bacillariophyceae*	0.993	–	–	–
*Spe*2	*Gymnodinium* sp.	*Dinophyceae*	–	0.219	–	–
*Spe*3	*Paralia sulcata*	*Bacillariophyceae*	–	0.142	0.504	0.230
*Spe*4	*Prorocentrum dentatum*	*Dinophyceae*	–	0.033	–	–
*Spe*5	*Coscinodiscus* sp.	*Bacillariophyceae*	–	0.025	0.021	–
*Spe*6	*Ceratium tripos*	*Bacillariophyceae*	–	–	0.123	–
*Spe*7	*Pseudo-nitzschia delicatissima*	*Bacillariophyceae*	–	–	0.042	–
*Spe*8	*Ceratium fusus*	*Bacillariophyceae*	–	–	0.030	–
*Spe*9	*Dictyocha fibula*	*Chrysophyceae*	–	–	0.024	–
*Spe*10	*Thalassiosira pacifica*	*Bacillariophyceae*	–	–	–	0.541
*Spe*11	*Asteroplanus karianus*	*Bacillariophyceae*	–	–	–	0.104
*Spe*12	*Thalassiosira eccentrica*	*Bacillariophyceae*	–	–	–	0.040
*Spe*13	*Thalassiosira rotula*	*Bacillariophyceae*	–	–	–	0.028

Note: – represents that the species was not dominant in the corresponding season.

and 100% of the information regarding the changes of environment-diversity relationship for all seasons (Table 3).

Forward selection methods were used in this study to further screen the environmental factors stepwise. Monte Carlo permutation test indicated that the factors exerting the highest effects on the distribution of phytoplankton diversity in the southern waters of Miaodao Archipelago were as follows: DIN (f=5.55, p=0.003) and COD (f=4.36, p=0.005) in spring, COD (f=3.29, p=0.030) in summer, pH (f=4.40, p=0.020) in autumn, and salinity (f=4.14, p=0.007) and oil pollutant (f=3.03, p=0.025) in winter, while the influence of other environmental factors was not significant (p>0.05). It suggested that DIN and COD in spring, COD in summer, pH in autumn, and salinity and oil pollutant in winter, respectively, were the key environmental factors that have the strongest association with the distribution of phytoplankton diversity in this study.

The relationship between phytoplankton diversity and environmental factors in the southern waters of Miaodao Archipelago was well demonstrated by the RDA ordination diagram in Fig. 6. In spring, the first axis was positively correlated with COD (r=0.64) and DIN (r=0.83) respectively, while the second axis was negatively correlated with COD (r=–0.77) but positively correlated with DIN (r=0.56), representing the characteristic changes of DIN and COD. The first axis was negatively correlated with COD

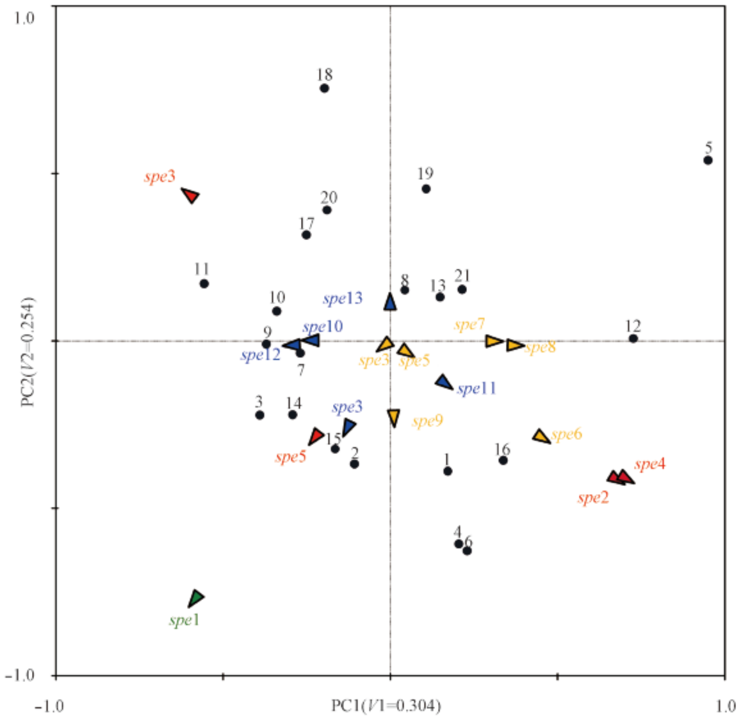

Fig. 3. Location in ordination space (PCA) of the first and second axis of sample sites and dominant phytoplankton species. The numbers with black dots represent the sampling stations and the letters with color triangles represent the dominant species (species codes correspondent to those in Table 2) in different seasons of which the green mean spring, the red mean summer, the yellow mean autumn, and the blue mean winter.

(r=–1.00) in summer, showing the changes in COD. In autumn, the first axis was negatively correlated with pH (r=–1.00), indicating the changes of pH. In winter, the first axis was negatively correlated with salinity (r=–0.79) but positively correlated with oil pollutant (r=0.57), while the second axis was negatively correlated with both salinity (r=–0.61) and oil pollutant (r=–0.82).

3.5 *Clustering results of phytoplankton diversity and environmental factors*

The southern waters of Miaodao Archipelago were spatially divided into three water areas based on all water environmental factors: east, northwest and southwest water area (Fig. 7a); three areas based on the key environmental factors having the strongest association with the distribution of phytoplankton diversity: northeastern, southwestern and inter-island water area (Fig. 7b); three areas based on the phytoplankton diversity: northern, central eastern and southwestern water area (Fig. 7c).

4 Discussion

4.1 *Characteristics of phytoplankton community structure*

Our survey revealed that among the 109 phytoplankton species identified in the southern waters of Miaodao Archipelago, 77 were diatoms, indicating that diatoms were the main species group in these waters. Studies have shown that diatoms are hypothermophilous, with most suitable growth temperature of below 18 (da Silva et al., 2005; Wasmund et al., 2011). Among the four seasons in this study, spring and winter had a relatively lower surface seawater temperature (Table 1), and were thus suitable for the growth and reproduction of diatoms. Although the growth of phytoplankton is influenced by many environmental factors, especially the dissolved nutrients and seawater temperature, it is generally believed that in the tropical region, dissolved nutrients are the key factor having the strongest association with the seasonal changes of phytoplankton, whereas the role of seawater temperature is not evident; however, in temperate regions, seawater temperature becomes the most important environmental factor affecting the seasonal changes of phytoplankton (Xiao et al., 2011; Huang et al., 2013). Accordingly, in this study, surface seawater temperature was the key factor having the strongest association with the growth changes of phytoplankton in Miaodao Archipelago, i.e., the low surface seawater temperature in winter and spring was suitable for the growth of diatoms, resulting in a significantly higher abundance of phytoplankton in these two seasons compared to the other two seasons, which is consistent with the results of the studies on phytoplankton in the Bohai Bay (Sun et al., 2004b; Liu et al., 2007; Zhou et al., 2013).

In this study, diatom species were dominant in both number and abundance in all the seasons, which is also in line with the previous studies on phytoplankton in the Bohai Sea (Sun et al., 2004a, b; Guo et al., 2014), suggesting that in the past two decades, there was no major changes in the diatoms-dominated community structure of phytoplankton in the Bohai sea. However, the dominant species of phytoplankton in the surface waters in the South of Miaodao Archipelago varied significantly with seasons (Table 2), with different dominant species appearing in different seasons, forming a distinct seasonal succession of phytoplankton community. In this study, *Paralia sulcata* was a dominant species in summer, autumn, and winter, and its abundance in winter was 10 times more than that in either summer or autumn, which is because that the main habitats of this

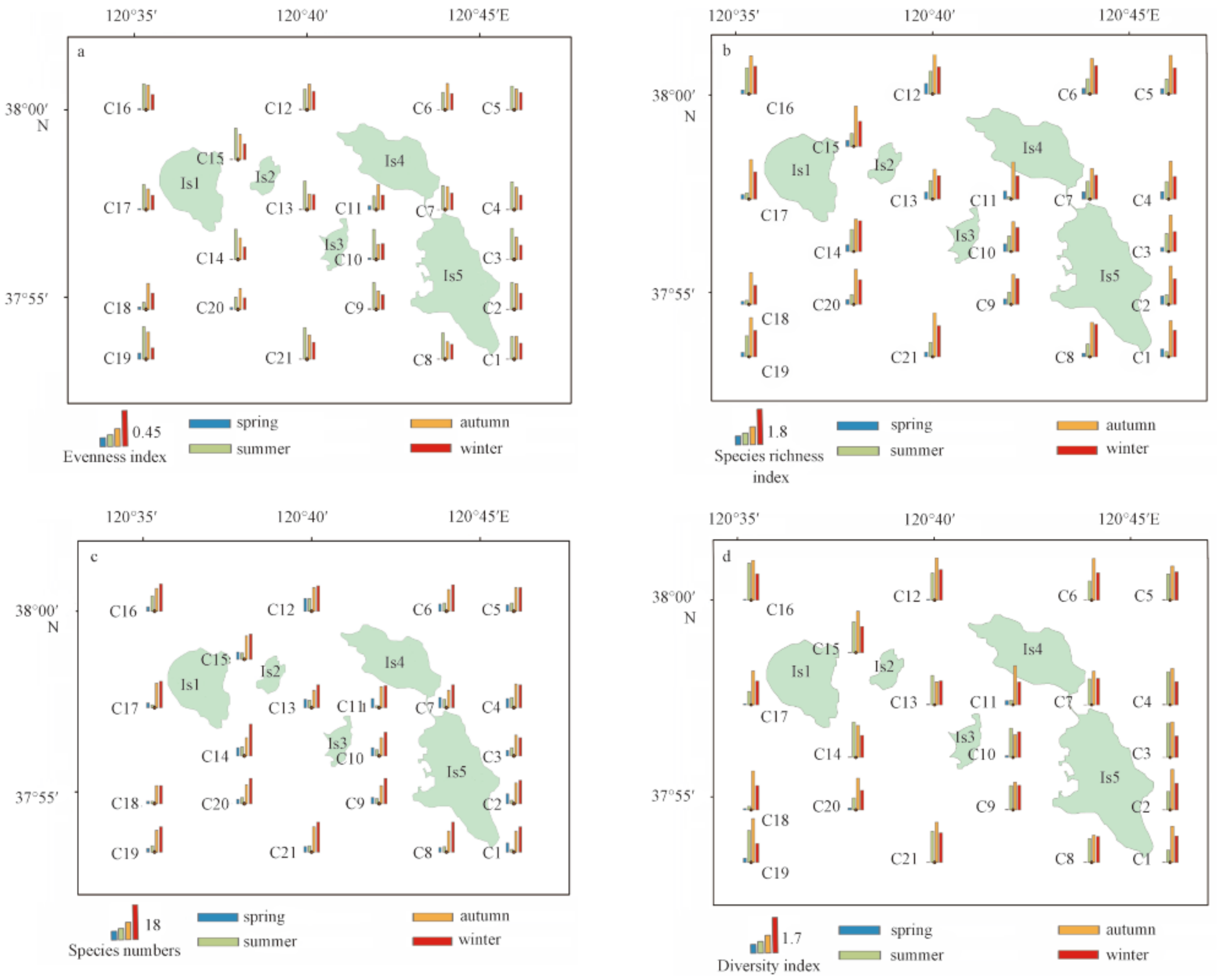

Fig. 4. Distribution maps of phytoplankton diversity indices in the southern waters of Miaodao Archipelago. The number in the lower-left corner identifies the corresponding maximum value of all seasons in each figure.

species are surface and bottom waters (McQuoid and Nordberg, 2003); the frequent and strong wind in the Bohai Sea in winter caused a vertical mixing of the seawater, which transported phytoplankton to the surface water, resulting in a significantly higher abundance of diatoms in the surface water. In spring, *Guinardia delicatula* with a dominance of 0.993 became the absolutely dominant species, which was also significantly dominant in the Bohai Bay in the spring of 2012 (Yin et al., 2013). Since it is a kind of the red-tide species, *Guinardia delicatula* should be monitored as an important species. *Gymnodinium* with the highest dominance was the dominant phytoplankton species in summer (Table 2), which was related with its adaptation to the high temperature and the resulted extensive growth and reproduction (Adam et al., 2011). Only second to *Paralia sulcata*, *Ceratium tripos* was another important species dominant in autumn, with dominance of 0.123 (Table 2). Escaravage et al. (1996) and Yung et al. (1997) demonstrated that a lower nitrogen/phosphorus (N/P) ratio helps dinoflagellates dominate the species competition. Therefore, the change of dominance from diatoms to dinoflagellates in this study might be related with the relatively low N/P ratio in summer and autumn (the seasonal N/P ratios from spring through winter were 72, 27, 20, and 120, respectively). *Thalassiosira pacifica* and *Asteroplanus karianus* were the major dominant species in winter (both with dominance larger than 0.10; Table 2). Especially the *Thalassiosira pacifica* with a dominance of 0.541 became the most dominant species in winter, which was related to the hypothermophilous property of diatoms (Wasmund et al., 2011). Similar results were also observed in the study on phytoplankton in Oregon waters of the United States (Du and Peterson, 2014).

4.2 *Effect of environmental factors on the distribution of phytoplankton diversity*

The spatial distribution of phytoplankton diversity in the southern waters of Miaodao Archipelago was affected by different environmental factors in different seasons (Fig. 6). In spring, the key environmental factors having the strongest association with the distribution of phytoplankton diversity were DIN and COD. RDA ordination diagram (Fig. 6) indicated that the diversity and evenness indices were very close to the vector DIN, suggesting that an increase in DIN in spring would lead to a more stable phytoplankton community structure. Although there was no appearance of nitrogen limitation in a traditional sense (i.e., N/P ratio <10 and Si/N ratio >1; Justić et al., 1995) in the southern waters of Miaodao Archipelago, the DIN concentration in spring was at least 50% lower than that in other seasons (Table 1).

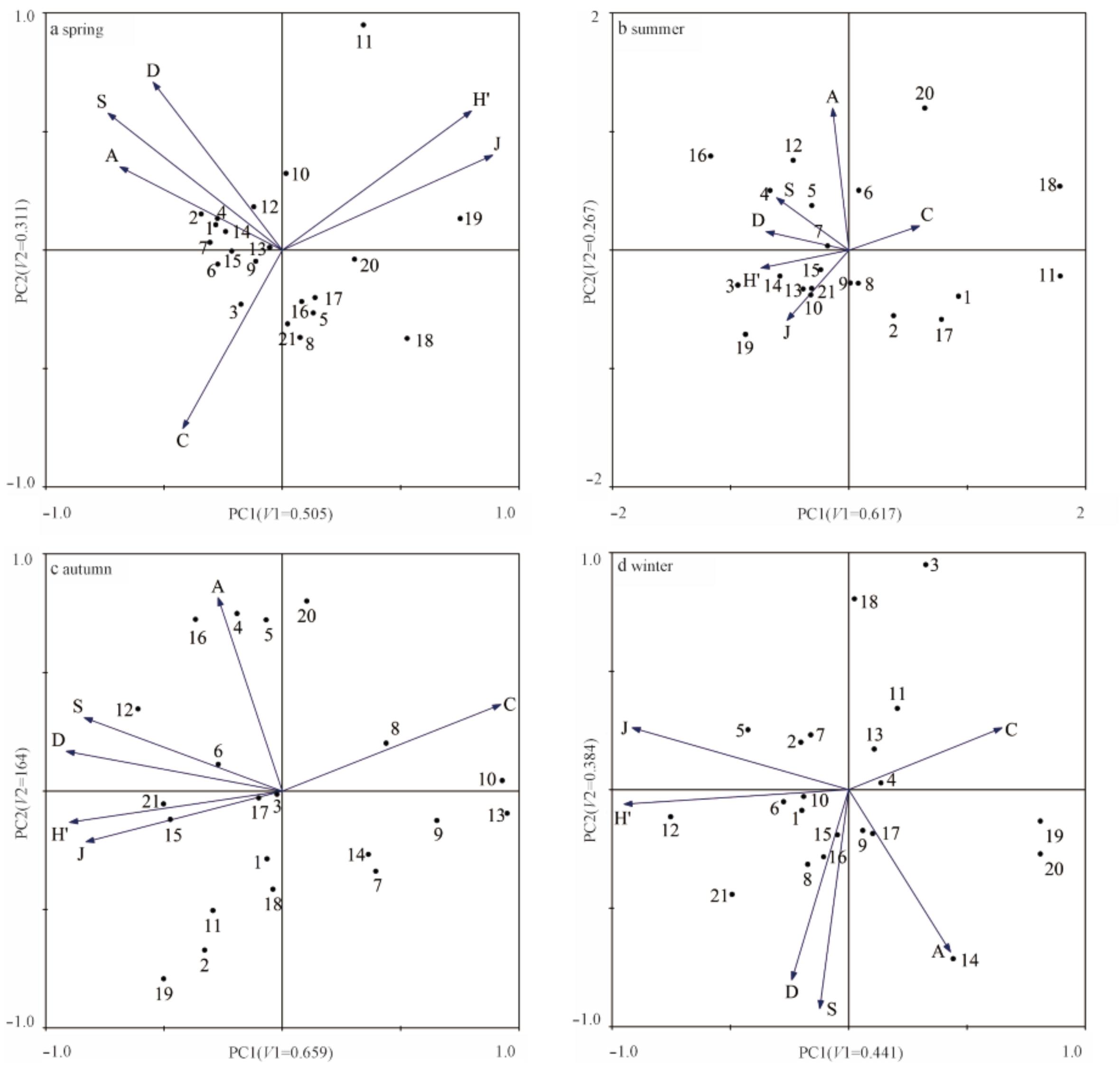

Fig. 5. Location in ordination space (PCA) of the first and second axis of samples and phytoplankton diversity. The numbers with black dots represent the sampling stations and the letters with blue arrows represent the species diversity indices of which J means Pielou evenness index, H' means diversity index, D means species richness index, S means species numbers, A means species abundance, and C means dominance index.

COD was the key environmental factor in summer. RDA ordination diagram showd a positive correlation between phytoplankton average abundance and COD, which is in agreement with the results of Wang et al. (2007). The key environmental factor in autumn was pH, and the mean phytoplankton abundance was positively correlated with pH. The pH in the southern waters of Miaodao Archipelago in autumn was between 7.85 and 8.08, within the range of promoting phytoplankton growth (McQuoid and Nordberg, 2003), and the phytoplankton biomass decreased with the decrease in pH. In winter, salinity and oil pollutant were the key factors controlling the distribution of phytoplankton diversity, while the abundance, species number, and species richness displayed a significantly negative correlation with the salinity; the dominance index was significantly positively correlated with the oil pollutant. The relevant study has already shown the negative correlation between phytoplankton biomass and salinity (Le and Ning, 2006). In winter, diatoms were the main phytoplankton in the southern waters of Miaodao Archipelago, and most of them adapted to wide temperature but low salt; high salinity was hence unfavorable to their growth and reproduction. Therefore, the phytoplankton biomass was negatively correlated with salinity. The water-soluble fraction (WSF) of oil pollutant exerted a toxic effect on marine organisms as “promoting at low content but inhibiting when high” (Pérez et al., 2010; Wang et al., 2011). The oil pollutant concentration in the southern waters of Miaodao Archipelago in winter was 0.008–0.023 mg/L, lower than 0.21 mg/L, thus promoting the growth of phytoplankton (Huang et al., 2011). The sensitivity of different phytoplankton species to oil pollutant pollution varied (Wang et al., 2011). In the waters polluted by oil pollutant, opportunistic species usually replace balanced species to become a local dominant species (Stepanyan and Voskoboinikov, 2006). *Thalassiosira pacifica*, *Thalassiosira eccentrica*, *Thalassiosira rotula*, and *Asteroplanus karianus* became the dominant species in winter, which belong to the pollution-tolerant species. Therefore, the dominance indices of

Table 3. Redundancy analysis results of phytoplankton diversity and environmental factors

Season	Axis	Eigenvalue	Diversity-environment correlations	Cumulative percentage variance		Sum of all canonical eigenvalues
				Diversity	Diversity-environment relation	
Spring	Axis 1	0.286	0.762	28.6	76.0	
	Axis 2	0.091	0.547	37.7	100.0	0.851
	Axis 3	0.242	0.000	61.9	0.0	
	Axis 4	0.222	0.000	84.0	0.0	
Summer	Axis 1	0.148	0.648	14.8	100.0	
	Axis 2	0.586	0.000	73.4	0.0	0.981
	Axis 3	0.171	0.000	90.5	0.0	
	Axis 4	0.073	0.000	97.8	0.0	
Autumn	Axis 1	0.188	0.551	18.8	100.0	
	Axis 2	0.492	0.000	68.0	0.0	0.974
	Axis 3	0.161	0.000	84.1	0.0	
	Axis 4	0.130	0.000	97.1	0.0	
Winter	Axis 1	0.269	0.795	26.9	90.4	
	Axis 2	0.029	0.323	29.7	100.0	0.853
	Axis 3	0.387	0.000	68.5	0.0	
	Axis 4	0.156	0.000	84.1	0.0	

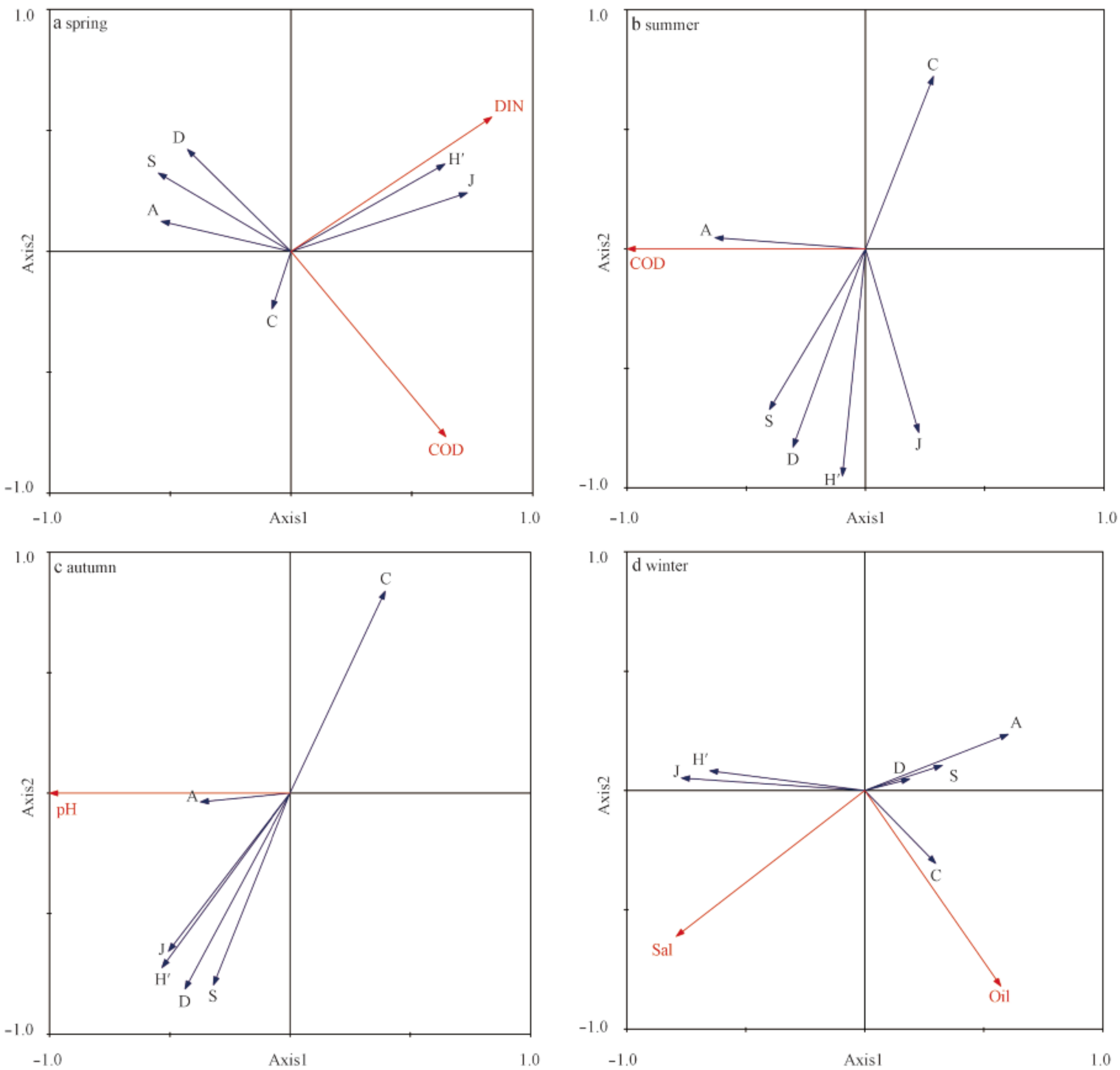

Fig. 6. Plots of the redundancy analysis (RDA) on the relationship between the environmental factors (indicated by red arrows) and phytoplankton diversity (indicated by black arrows, diversity indices correspond to those in Fig. 5).

them were positively correlated with oil pollutant content.

4.3 *Spatial heterogeneity of phytoplankton diversity and environmental factors*

Hydrodynamic conditions in the adjacent sea area surrounding islands displayed great difference due to the natural isolation by the islands. In the meantime, human activities at various locations on the island exhibited different disturbances to the adjacent water area, and different regions of sea area had different uses. All these features lead to the spatial heterogeneity of environmental factors.

Water area on the west and east sides of the line of North Changshan Island-South Changshan Island showed distinct natural geographical feature due to the isolation by the islands. The open water on the east side was deep, while the western water was shallow. At the same time, the intensity of the development and utilization of the waters on the west and east side were different. First of all, the mariculture and marine traffic on the western waters were denser than those on the east waters. Furthermore, the population of the island group was mainly distributed in the west side of South Changshan Island and in the southwest and northwest side of North Changshan Island. Therefore, the pollutants generated by human had major impact on the western waters. Clustering analysis based on all the environmental factors also clearly separated the west and east water area (Fig. 7a); meanwhile, clustering analysis based on major environmental factors demonstrated that the study area exhibited obvious spatial heterogeneity in water environment (Fig. 7b). In particular, the Changshanwei area is located in the south end of the South Changshan Island. The two sampling sites (C1 and C8) located on the opposite side of this boundary displayed significant heterogeneity in terms of environmental factors and phytoplankton diversity. Our results also showed that in spring, the diversity and evenness indices of phytoplankton in the eastern waters (A) were significantly lower than the west (B, C).

Compared to the open waters, inter-island water area showed lower connectivity and different intensities of human disturbance, clustering analysis based on major environmental factors also clearly differentiated these two sides of sea waters (Fig. 7b).

The southern waters locating close to the Shandong Peninsula (Fig. 1) were affected by the pollution from mainland and by the additional influences from the North-South Pengchang Waterway and the transmeridional Dengzhou Waterway, i.e., under more complex human disturbances, resulting in a more complicated distribution of phytoplankton diversity compared with the northern waters. In the meantime, the northern waters were affected not only by the Changshan Waterway, but also by a relatively balanced interference from human activities, resulting in a similar characteristic of phytoplankton diversity within (Fig. 7c). Above all, clustering analysis based on major environmental factors separated the northeastern and southwestern water areas, which reflects, to a certain extent, the different characteristics between the northern and southern waters (Fig. 7b).

Therefore, obvious differences were observed between the east and the west, the north and the south, as well as the inter- and off-island regions of the study water area, and were clearly reflected by the clustering based on major environmental factors as well.

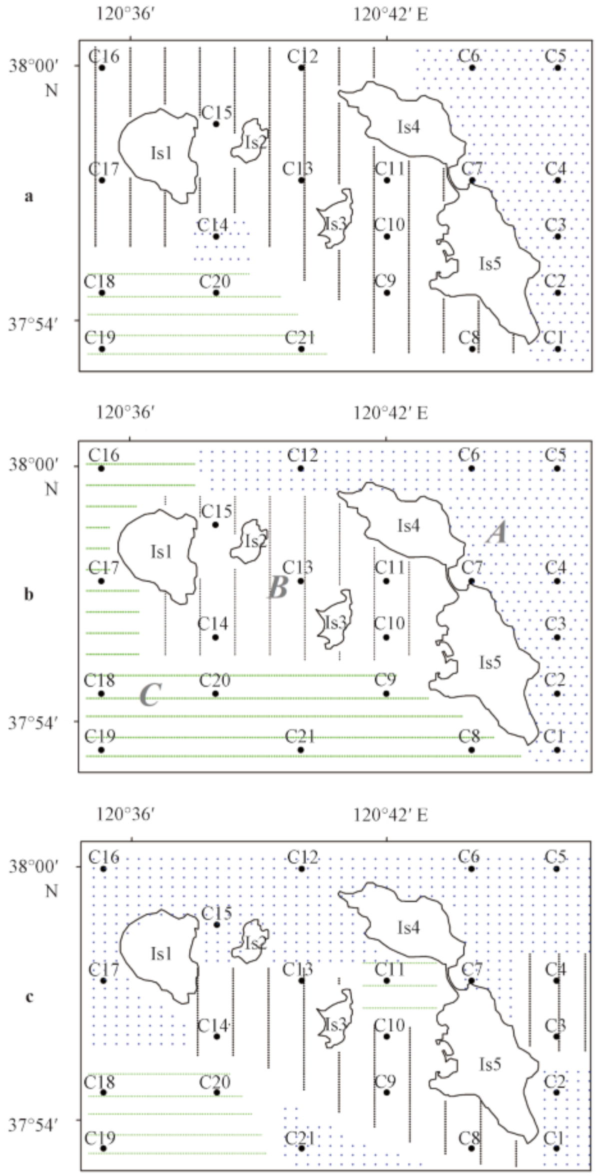

Fig. 7. Zonation based on cluster analysis according to environmental variables or phytoplankton diversity: a. All the environmental factors measured in this study were taken into account, including SS, pH, salinity, DO, COD, DIP, DIN, SiO_3, Oil pollutant, volatile phenol, TN, TP; b. the dominant environmental factors including DIN, COD, pH, salinity, Oil pollutant were taken into account; and c. species diversity indices of phytoplankton.

5 Conclusions

The spatial distribution of phytoplankton diversity in the southern waters of Miaodao Archipelago in different seasons was affected by different environmental factors. DIN and COD were the key factors in spring, while the key factor in summer was COD, pH was in autumn, and the salinity and oil pollutant were in winter. There was significant spatial heterogeneity in the southern waters of Miaodao Archipelago. On the basis of major environmental factors having the strongest association with the distribution of phytoplankton diversity, this area was separated into northeastern, southwestern and inter-island water area.

Acknowledgements

This study is partially supported by China-Korea Joint Ocean

Research Center. The authors would like to thank several national institutions in Changdao County, including Marine and Environment Monitoring Center, Management Office of Demonstration Zone for National Sustainable Development and Marine and Fishery Administration, for their supporting in data collection, and several experts who offer constructive comments in this study.

References

Adam A, Mohammad-Noor N, Anton A, et al. 2011. Temporal and spatial distribution of harmful algal bloom (HAB) species in coastal waters of Kota Kinabalu, Sabah, Malaysia. Harmful Algae, 10(5): 495–502

Blain S, Tréguer P, Belviso S, et al. 2001. A biogeochemical study of the island mass effect in the context of the iron hypothesis: Kerguelen Islands, Southern Ocean. Deep Sea Research Part I: Oceanographic Research Papers, 48(1): 163–187

da Silva C A, Train S, Rodrigues L C. 2005. Phytoplankton assemblages in a Brazilian subtropical cascading reservoir system. Hydrobiologia, 537(1–3): 99–109

De La Rocha C L, Passow U. 2007. Factors influencing the sinking of POC and the efficiency of the biological carbon pump. Deep Sea Research Part II–Topical Studies in Oceanography, 54(5–7): 639–658

Du Xiuning, Peterson W T. 2014. Seasonal cycle of phytoplankton community composition in the coastal upwelling system off central Oregon in 2009. Estuaries and Coasts, 37(2): 299–311

Escaravage V, Prins T C, Smaal A C, et al. 1996. The response of phytoplankton communities to phosphorus input reduction in mesocosm experiments. Journal of Experimental Marine Biology and Ecology, 198(1): 55–79

Gilmartin M, Revelante N. 1974. The “island mass” effect on the phytoplankton and primary production of the Hawaiian Islands. Journal of Experimental Marine Biology and Ecology, 16(2): 181–204

Guo Shujin, Li Yanqiao, Zhang Cuixia, et al. 2014. Phytoplankton community in the Bohai Sea and its relationship with environmental factors. Marine Science Bulletin (in Chinese), 33(1): 95–105

Huang Xianghui, Hu Ren, Lei Lamei, et al. 2013. Seasonal succession of phytoplankton functional groups in typical small and medium-sized reservoirs in southern China. Ecology and Environmental Sciences (in Chinese), 22(2): 311–318

Huang Yijun, Chen Quanzhen, Zeng Jiangning, et al. 2011. The impact of oil pollution on marine phytoplankton community growth change. Acta Ecologica Sinica (in Chinese), 31(2): 513–521

Justić D, Rabalais N N, Turner R E, et al. 1995. Changes in nutrient structure of river-dominated coastal waters: stoichiometric nutrient balance and its consequences. Estuarine, Coastal and Shelf Science, 40(3): 339–356

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

Le Fengfeng, Ning Xiuren. 2006. Variations of the phytoplankton biomass in the northern South China Sea. Journal of Marine Sciences (in Chinese), 24(2): 60–69

Leps J, Smilauer P. 2003. Multivariate analysis of ecological data using CANOCO. Cambridge: Cambridge University Press

Liu Sujuan, Tao Jianhua, Zhao Haiping. 2007. Diversity analyse of phytoplankton in the Bohai Bay. Journal of Hebei University of Engineering (Natural Science Edition) (in Chinese), 24(1): 74–77

Margalef R. 1968. Perspectives in Ecological Theory. Chicago: University of Chicago Press, 111

McQuoid M R, Nordberg K. 2003. The diatom *Paralia sulcata* as an environmental indicator species in coastal sediments. Estuarine, Coastal and Shelf Science, 56(2): 339–354

Pérez P, Fernández E, Beiras R. 2010. Fuel toxicity on Isochrysis galbana and a coastal phytoplankton assemblage: Growth rate vs. variable fluorescence. Ecotoxicology and Environmental Safety, 73(3): 254–261

Pielou E C. 1966. Species-diversity and pattern-diversity in the study of ecological succession. Journal of Theoretical Biology, 10(2): 370–383

Rolland A, Bertrand F, Maumy M, et al. 2009. Assessing phytoplankton structure and spatio-temporal dynamics in a freshwater ecosystem using a powerful multiway statistical analysis. Water Research, 43(13): 3155–3168

Stepanyan O V, Voskoboinikov G M. 2006. Effect of oil and oil products on morphofunctional parameters of marine macrophytes. Russian Journal of Marine Biology, 32(1): S32–S39

Sun Jun, Liu Dongyan, Wang Wei, et al. 2004a. The netz-phytoplankton community of the central Bohai Sea and its adjacent waters in autumn, 1998. Acta Ecologica Sinica (in Chinese), 24(8): 1643–1655

Sun Jun, Liu Dongyan, Xu Jun, et al. 2004b. The netz-phytoplankton community of the Central Bohai Sea and its adjacent waters in spring 1999. Acta Ecologica Sinica (in Chinese), 24(9): 2003–2016

Tang Tao, Cai Qinghua, Liu Jiankang. 2006. Using epilithic diatom communities to assess ecological condition of Xiangxi River system. Environmental Monitoring and Assessment, 112(1–3): 347–361

Utermöhl H. 1958. Zur Vervollkommnung der quantitativen Phytoplankton-Methodik. Mitteilungen-Internationale Vereiningung fur Limnologie, 9: 1–38

Wang Junli, Liu Chunguang, Feng Jianfeng, et al. 2011. Literature review of the effects of petroleum hydrocarbons on marine phytoplankton. Environmental Pollution and Control (in Chinese), 33(4): 81–86

Wang Xiaolong, Lu Yonglong, He Guizhen, et al. 2007. Exploration of relationships between phytoplankton biomass and related environmental variables using multivariate statistic analysis in a eutrophic shallow lake: A 5-year study. Journal of Environmental Sciences, 19(8): 920–927

Wasmund N, Tuimala J, Suikkanen S, et al. 2011. Long-term trends in phytoplankton composition in the western and central Baltic Sea. Journal of Marine Systems, 87(2): 145–159

Xiao Lijuan, Wang Tian, Hu Ren, et al. 2011. Succession of phytoplankton functional groups regulated by monsoonal hydrology in a large canyon-shaped reservoir. Water Research, 45(16): 5099–5109

Xu Henglong, Song Weibo, Warren A, et al. 2008. Planktonic protist communities in a semi-enclosed mariculture pond: structural variation and correlation with environmental conditions. Journal of the Marine Biological Association of the UK, 88(7): 1353–1362

Yamamoto T, Hatta G. 2004. Pulsed nutrient supply as a factor inducing phytoplankton diversity. Ecological Modelling, 171(3): 247–270

Yin Cuiling, Zhang Qiufeng, Cao Chunhui, et al. 2013. Net-phytoplankton community in the Tianjin nearshore waters of Bohai Bay in spring of 2012. Journal of Marine Sciences (in Chinese), 31(4): 80–89

Yung Y K, Wong C K, Broom M J, et al. 1997. Long-term changes in hydrography, nutrients and phytoplankton in Tolo Harbour, Hong Kong. Hydrobiologia, 352(1–3): 107–115

Zhou Ran, Peng Shitao, Qin Xuebo, et al. 2013. Phytoplankton assemblages and their relation to environmental factors by multivariate statistic analysis in Bohai Bay. Environmental Science (in Chinese), 34(3): 864–873