Journal of the Marine Biological Association of the United Kingdom, 2016, 96(3), 715–723.
doi:10.1017/S0025315415000673

Seasonal shift in community pattern of planktonic diatoms and environmental drivers in Jiaozhou Bay, northern China

HONGLI QI[1,2†], YUPING XU[1†], XIAOZHONG HU[1], HONGGANG MA[1] AND HENGLONG XU[1]

[1]Institute of Evolution and Marine Biodiversity, Ocean University of China, Qingdao 266003, China, [2]College of Fisheries Science, Tianjin Agricultural University, Tianjin 300384, China

*Diatoms are a primary producer and play an important role in the functioning of microbial food webs. Temporal variations in community patterns of planktonic diatom assemblages were studied during a 1-year cycle (June 2007–May 2008) in Jiaozhou Bay, northern China. Samples were collected biweekly at a depth of 1 m from five sampling stations. A total of 75 diatom species representing 40 genera, 28 family, 19 orders and three classes were recorded. Of these species, 11 distributed in all four seasons, while 27, 35, 56 and 28 forms occurred only in spring, summer, autumn and winter season, respectively. The species number and total abundance peaked in autumn, with minimum values in May. All three species biodiversity measures (Shannon diversity, Pielou's evenness and Marglef's richness) peaked in spring and autumn. There was a significant difference in diatom community patterns among seasons, except the pair of spring and winter. The environmental variables, especially temperature and the nutrients, could significantly drive the seasonal variation in diatom community patterns. Of 11 dominant species, four (*Paralia sulcata, Skeletonema costatum, Guinardia delicatula *and* Nitzschia lorenziana*) were significantly related with temperature, pH and/or nutrients. These findings suggest that the seasonal shift in community pattern of planktonic diatoms was driven by both temperature and nutrients in this eutrophic basin ecosystem.*

Keywords: Seasonal shift, planktonic diatom, environmental driver, bioassessment, Jiaozhou Bay

Submitted 22 January 2015; accepted 16 April 2015; first published online 20 May 2015

INTRODUCTION

As a primary producer, diatoms play an important role in the functioning of microbial food webs and geo-chemical cycles of silica and carbon in aquatic ecosystems (Round *et al.*, 1990; Berger & Wefer, 1991; Finkelstein & Davis, 2006; Smucker & Vis, 2011a, b; Di *et al.*, 2013; Liu *et al.*, 2013, 2014). With their short cycle development, high species diversity, a wide range of occurrence, and sensitivity to environmental changes, they are particularly useful to indicate the intensity of anthropogenic impact and climate change in most aquatic ecosystems compared with the other living organisms (e.g. macroinvertebrates, molluscs, fish) (Round *et al.*, 1990; Zielinski & Gersonde, 1997; Wan Mazahn & Mansor, 2002; Duong *et al.*, 2006; Berthon *et al.*, 2011; Stenger-Kovács *et al.*, 2013; Chen *et al.*, 2014).

Jiaozhou Bay is a large eutrophic basin, covering an area of about 390 km^2 with an average depth of about 7 m. It is connected to the Yellow Sea via a narrow mouth about 2.5 km in width, surrounded by Qingdao, northern China (Shen, 2001; Liu *et al.*, 2004; Xu *et al.*, 2011). So far, Jiaozhou Bay has been stressed by human activities and is thus subject to eutrophication events (Jiang *et al.*, 2011, 2013, 2014). Although several studies have been conducted on community research of plankton in Jiaozhou Bay (Nuccio *et al.*, 2003; Liu *et al.*, 2005, 2008, 2014), the annual cycle of planktonic diatoms has yet to be investigated.

In this study, a 1-year baseline survey on annual dynamics in community patterns of planktonic diatoms was performed during the period of June 2007–May 2008 in Jiaozhou Bay. Our aims of this study were: (1) to investigate the temporal variations in species composition, distribution and community patterns of planktonic diatoms; and (2) to determine the environmental drivers for seasonal shift in the diatom community structure in the marine ecosystem.

MATERIALS AND METHODS

Sampling stations and data collection

Five sampling sites (A–E) were selected in Jiaozhou Bay (35°55′–36°18′N 120°04′–120°23′E), surrounded by Qingdao, northern China (Figure 1). A total of 24 cruises were performed biweekly over a 1-year period from June 2007 to May 2008.

Water samples were collected at a depth of about 1 m. Both for quantitative measures and for species identification of diatoms, 1000 mL of seawater was fixed with acid Lugol's iodine solution (2% final concentration, volume/volume) (Jiang *et al.*, 2011).

Water temperature (T), pH, salinity (Sal) were measured *in situ*, using a multi-parameter kit (MS5, HACH). Soluble reactive phosphate (SRP), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N) and nitrite nitrogen (NO_2-N) were

---

† Co-first author

Corresponding author:
H. Xu
Email: henglongxu@126.com

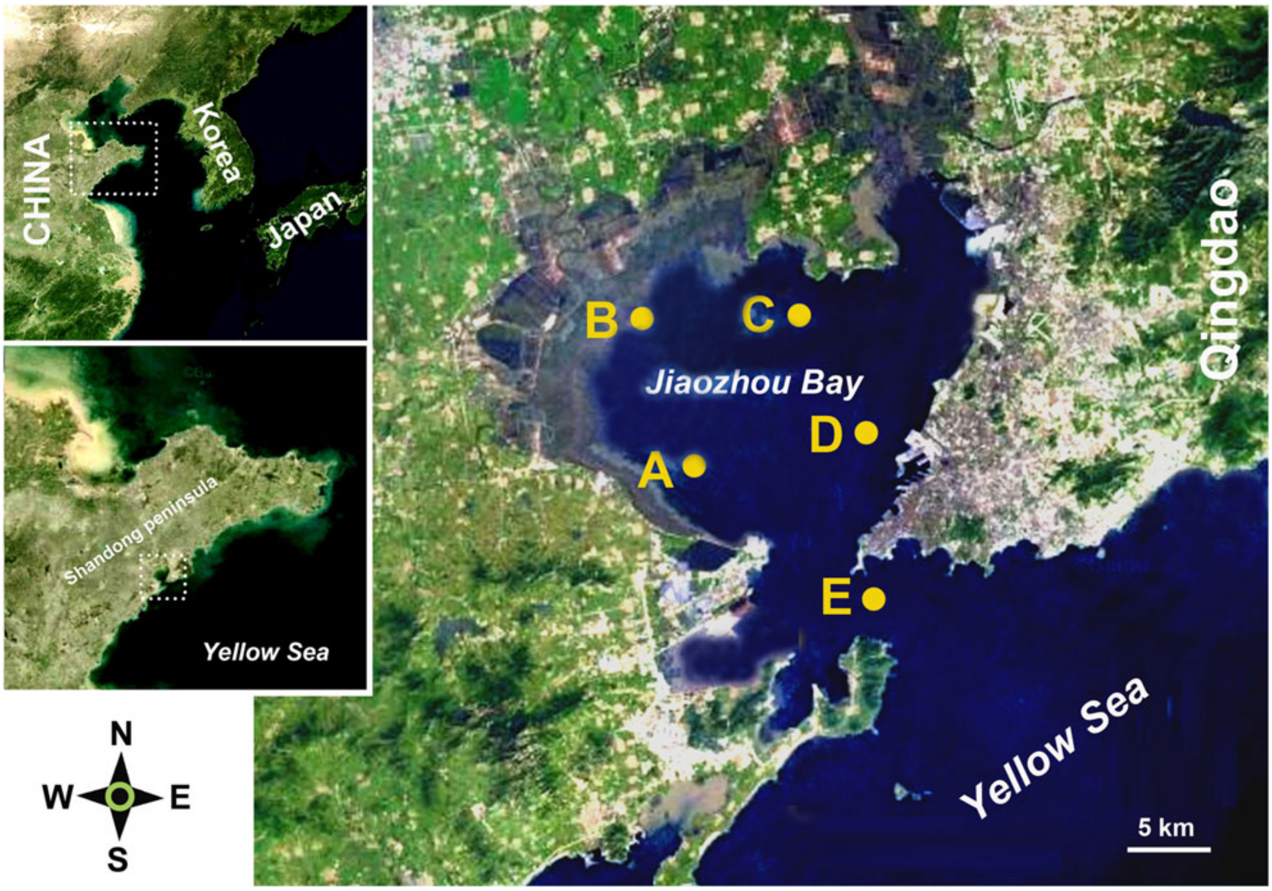

Fig. 1. Sampling stations of planktonic ciliates in Jiaozhou Bay.

determined using a UV-visible spectrophotometer (DR-5000, HACH) according to the 'Standard Methods for the Examination of Water and Wastewater' (APHA, 1992).

Identification and enumeration

For purposes of identification and enumeration, 1000 mL of Lugol's-fixed seawater was settled for 48 h resulting in 30 mL of concentrated sediment (Utermöhl, 1958). A 0.1 mL aliquot of each concentrated sample was placed in a Perspex chamber and the diatoms were counted under a light microscope at magnification 400× (Xu *et al*., 2008). Five aliquots from each sample were counted and yielded a standard error (SE) of <8% of the mean values of counts (Xu *et al*., 2008). Diatom identification and enumeration were carried out following the methods outlined by Round *et al.* (1990). The taxonomic classification of diatoms was based on the published references to keys and guides such as Hasle & Syvertsen (1997). The taxonomic scheme used was according to Round *et al.* (1990).

Table 1. Average values of environmental variables monitored within each month in Jiaozhou Bay during the 1-year cycle of June 2007–May 2008.

Month	*T*	pH	Sal	NH3-N	NO3-N	NO2-N	SRP
Jan	3.00 ± 2.78	8.46 ± 0.14	31.84 ± 1.05	0.28 ± 0.57	0.27 ± 0.22	0.02 ± 0.01	0.19 ± 0.21
Feb	2.31 ± 1.46	8.11 ± 0.38	31.06 ± 0.39	0.16 ± 0.13	0.15 ± 0.08	0.03 ± 0.04	0.09 ± 0.05
Mar	6.24 ± 1.41	8.07 ± 0.15	30.77 ± 1.06	0.18 ± 0.29	0.31 ± 0.12	0.01 ± 0.01	0.17 ± 0.17
Apr	9.76 ± 1.60	8.02 ± 0.10	30.72 ± 0.93	0.29 ± 0.31	0.24 ± 0.12	0.01 ± 0.01	0.08 ± 0.06
May	12.90 ± 4.89	7.10 ± 2.5	28.02 ± 9.85	0.28 ± 0.28	0.29 ± 0.13	0.02 ± 0.02	0.19 ± 0.11
Jun	19.59 ± 7.17	7.19 ± 2.53	28.86 ± 10.14	0.21 ± 0.19	0.67 ± 0.49	0.02 ± 0.03	0.16 ± 0.11
Jul	24.39 ± 1.27	8.18 ± 0.10	31.41 ± 0.54	0.27 ± 0.12	0.70 ± 0.09	0.08 ± 0.17	0.12 ± 0.06
Aug	26.86 ± 1.13	8.35 ± 0.30	26.16 ± 7.17	0.28 ± 0.21	0.63 ± 0.43	0.09 ± 0.10	0.28 ± 0.21
Sep	24.68 ± 1.64	8.18 ± 0.21	23.72 ± 7.32	0.76 ± 1.06	0.83 ± 0.44	0.11 ± 0.05	0.30 ± 0.12
Oct	20.72 ± 2.13	8.25 ± 0.11	29.90 ± 0.93	0.39 ± 0.43	0.41 ± 0.33	0.09 ± 0.03	0.18 ± 0.07
Nov	14.19 ± 2.08	8.35 ± 0.08	31.16 ± 0.54	0.21 ± 0.23	0.32 ± 0.32	0.04 ± 0.02	0.19 ± 0.09
Dec	8.21 ± 2.46	8.36 ± 0.29	31.64 ± 0.71	0.32 ± 0.41	0.51 ± 0.21	0.03 ± 0.02	0.15 ± 0.13

Sal: salinity; NH_4-N: ammonium nitrogen; NO_3-N: nitrate nitrogen; NO_2-N: nitrite nitrogen; SRP: soluble active phosphate.

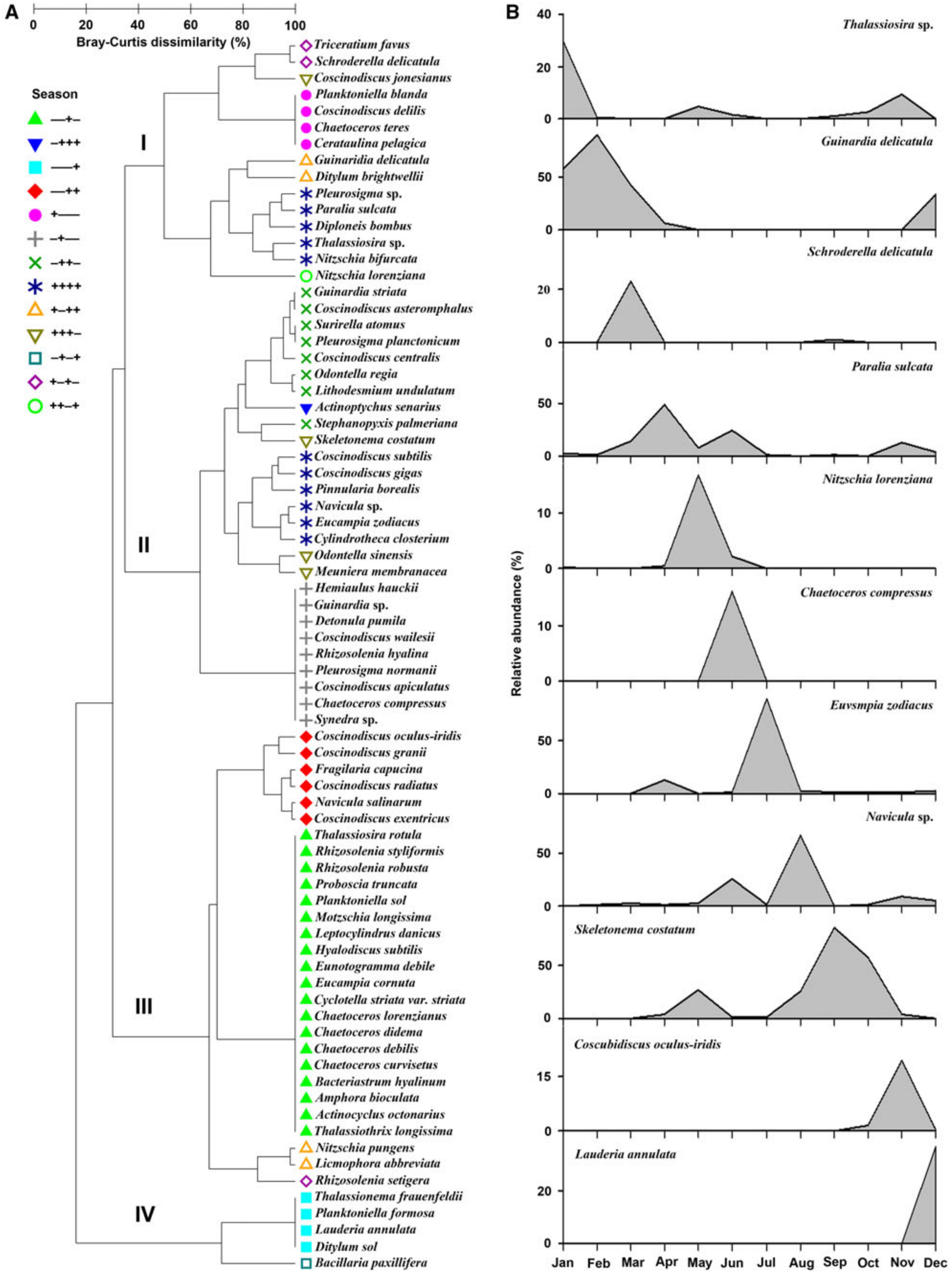

Fig. 2. Seasonal variation in species composition of planktonic diatoms (A), and the temporal succession of 11 dominant species during a 1-year cycle (B). I–IV = group I–IV.

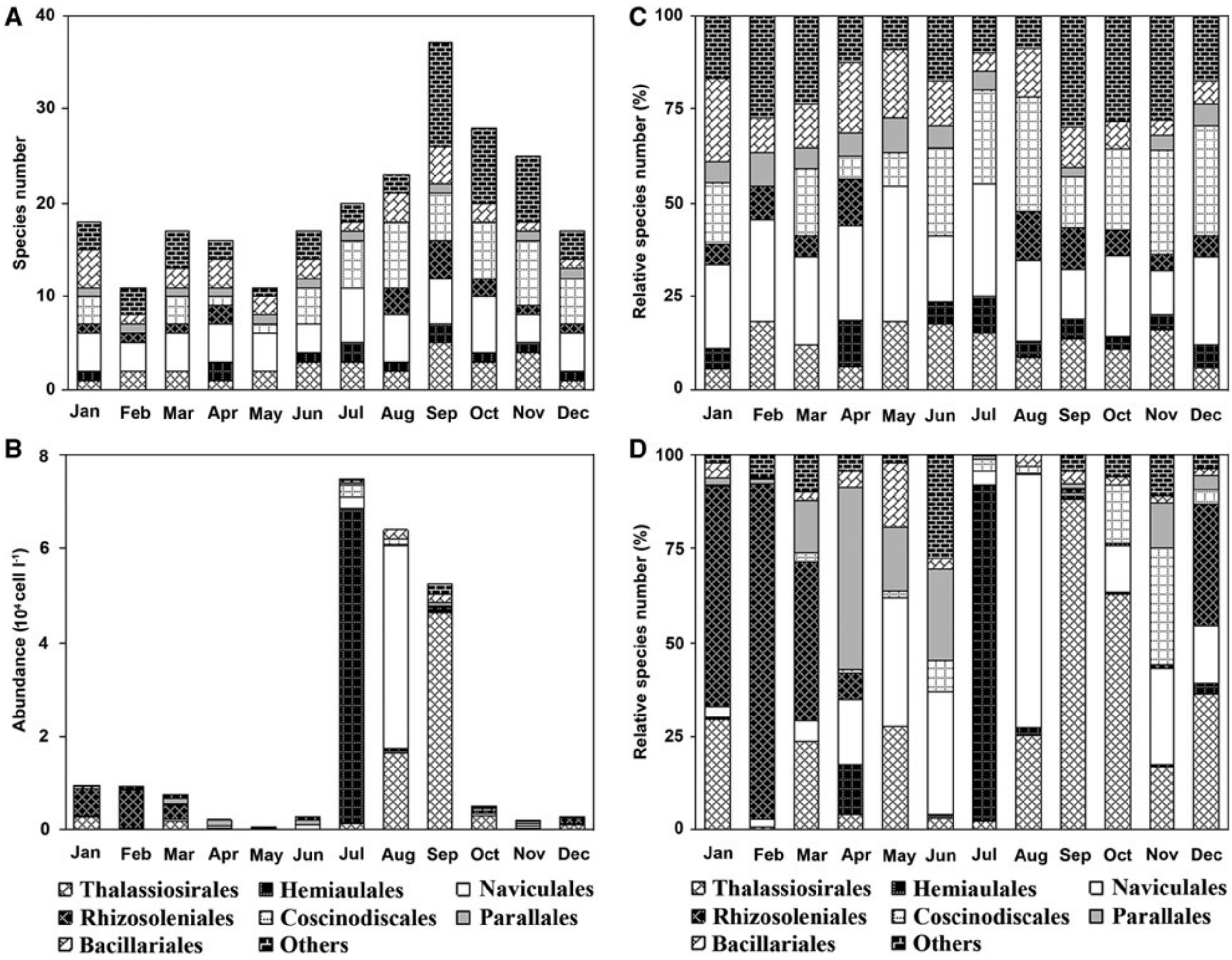

Fig. 3. Annual variations in species number (A), abundance (B, cells L^{-1}), relative species number (C) and relative abundance (D) of the diatoms in Jiaozhou Bay during the study period. Others = sum of Chaetocerotales, Lithodesmiales, Triceratiales, Anaulales, Licmophorales, Thalassionematales, Fragilariales, Surireliales, Thalassiophysales and Melosirales.

Data analyses

Species diversity (Shannon diversity) (H'), evenness (Pielou's evenness) (J') and richness (Margalef's richness) (D) of samplings were calculated as follows:

$$H' = \sum_{i=1}^{S} Pi(\ln Pi)$$

$$J' = H'/\ln(S)$$

$$D = (S - 1)/\ln(N)$$

where Pi = proportion of the total count arising from the ith species; S = total number of species; and N = total number of individuals (Xu *et al.*, 2008).

Multivariate analyses of temporal variations in planktonic diatom communities were performed using the PRIMER v6.1.16 package (Clarke & Gorley, 2006) and the PERMANOVA+ for PRIMER (Anderson *et al.*, 2008). The seasonal species distributions of the diatoms were summarized using clustering submodule, while the seasonal shift in community patterns was summarized using canonical analysis of principal coordinates (CAP). Differences in species distribution patterns among groups were signified by the submodule ANOSIM, while those in community pattern between seasons of samples were tested by the submodule PERMANOVA (Anderson *et al.*, 2008). The significance of biota-environment correlations was tested using Mental (RELATE) analysis, while the top 10 significant correlations between biotic and abiotic matrices were explored using the submodule BIOENV (biota-environment) (Clarke & Gorley, 2006). Bray–Curtis similarity matrix for biotic data was computed from square root transformed species-abundance data, while Euclidean distance matrix for abiotic data was calculated from log-transformed environmental variable data (Xu *et al.*, 2011). It should be noted that, to obtain the similarity matrix for clustering analysis of species distributions, the species abundance data were standardized before data transformation (Xu *et al.*, 2008).

Univariate analyses of correlations were carried out using the statistical program SPSS v16.0. Data were log-transformed before analyses (Xu *et al.*, 2008).

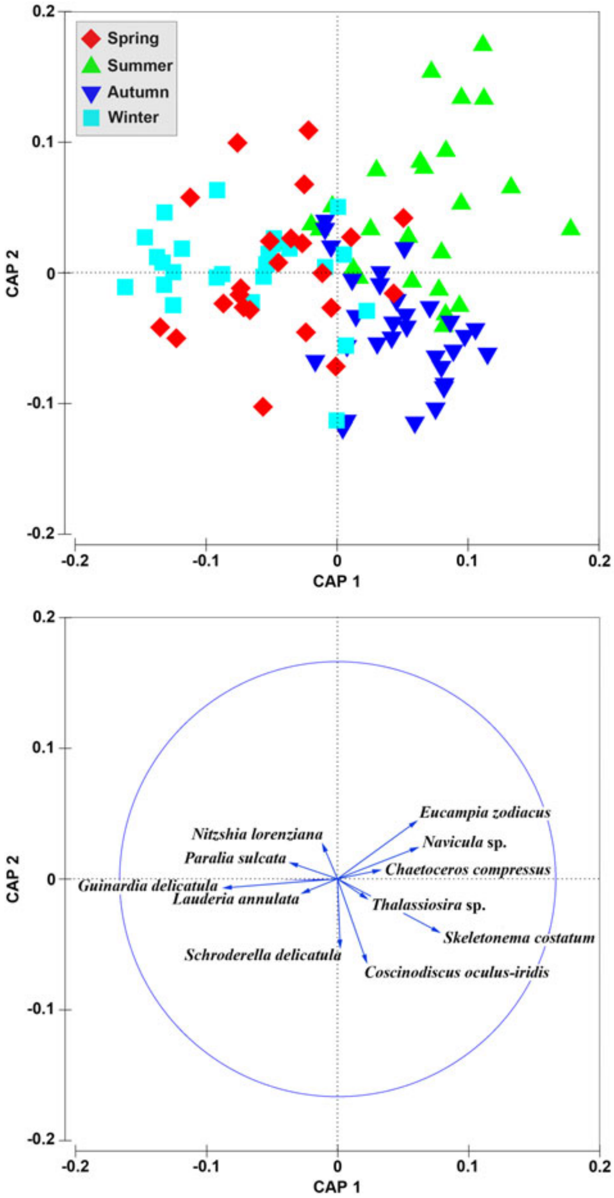

Fig. 4. Canonical analysis of principal coordinates (CAP) on seasonal scale for 120 data points of the diatom communities in Jiaozhou Bay during the study period (top), and correlations of 11 dominant species with the two CAP axes (below).

RESULTS

Environmental parameters

The mean values of 11 environmental variables for each month are summarized in Table 1. Water temperature followed a clear seasonal pattern, ranging from 1.4 to 27.5°C (mean 14.7°C). Salinity was around 30.0 psu and levelled at a stable level over the 1-year cycle, except sharp drops in late August (21.3 psu) and in late September (20.4 psu). The pH values ranged from 7.8 to 8.6, averaging 8.2. SRP ranged from 0.1 to 0.4 mg L^{-1} (mean value of 0.2 mg L^{-1}) with a minor peak in early August. The mean concentration of NH_4-N and NO_3-N peaked in late September, whereas low concentrations of NO_2-N were maintained throughout the year apart from a minor increase between July and September.

Species composition and seasonal distribution

The species composition of diatom communities recorded during the study period is summarized in Table S1. A total of 75 diatom species, representing 40 genera, 28 families, 19 orders and three classes, were identified during the 1-year survey. Of these species, 11 forms were distributed in all seasons, while 27, 35, 56 and 28 taxa only occurred in spring, summer, autumn and winter, respectively.

The clustering analysis resulted in 75 diatom species falling into four groups with a similar distribution pattern for each at a 49% similarity level (Figure 2a). For example, group I comprised 15 species, mainly dominated in late winter and early spring (Figure 2a: I); group II comprised 27 species which predominated in late spring and early summer (Figure 2a: II); group III comprised 28 taxa, which mainly dominated in late summer and early autumn (Figure 2a: III); and group IV included only five species with high occurrence in late autumn and early winter (Figure 2a: IV). Analysis of similarities (ANOSIM) signified the differences among the four groups (Global $R = 0.894$, $P < 0.001$), and between each pair of the groups ($P < 0.001$).

A total of 11 dominant species were identified, with a contribution of more than 15% of the total diatom abundance in a month for each (Figure 2b). Five of these species (*Paralia sulcata, Nitzschia lorenziana, Schroderella delicaula, Guinarlia delicatula* and *Thalassiosira* sp.) peaked mainly in the late winter and early spring season, four (*Chaetoceros compressus, Euvsmpia zodiacus, Skeletonema costatum* and *Navicula* sp.) dominated the samples in late summer and early autumn, and the other two (*Coscubidiscus oculus-iridis* and *Lauderia annuluata*) occurred in late autumn and early winter (Figure 2b).

Annual variation in species number, abundance and biomass

The annual variations in species number showed a unimodal distribution peaking in September (Figure 3a). Parallales, Naviculales, Hemiaulales, Coscinodicales, Rhizosoleniales and Thalassiosirales were primarily responsible for taxonomic composition.

The diatom abundances also peaked in unimodal model with maximum value (7.46×10^4 cells L^{-1}) in autumn (Figure 3b). Hemiaulales, Naviculales and Thalassiosirales were the primary contributors to the communities (Figure 3b).

Seasonal variation in community pattern

Although the orders Parallales, Naviculales, Hemiaulales, Coscinodicales, Rhizosoleniales and Thalassiosirales occurred in almost all months, the community patterns showed a clear seasonal variation, especially in the relative abundances (Figure 3c, d). For example, Rhizosoleniales, Parallales and Naviculales dominated the samples in spring (March to May), followed by dominant taxa Hemiaulales and Niviculales in summer (June to August); and Thalassiosirales and Coscinodiscales predominated the samples in autumn (September to November), followed by the dominant Rhizosoleniales in winter (December to February) (Figure 3d).

By canonical analysis of principal coordinates (CAP), the 120 data points showed a clear seasonal shift: the first axis (CAP 1) separated the samples in summer and autumn (on

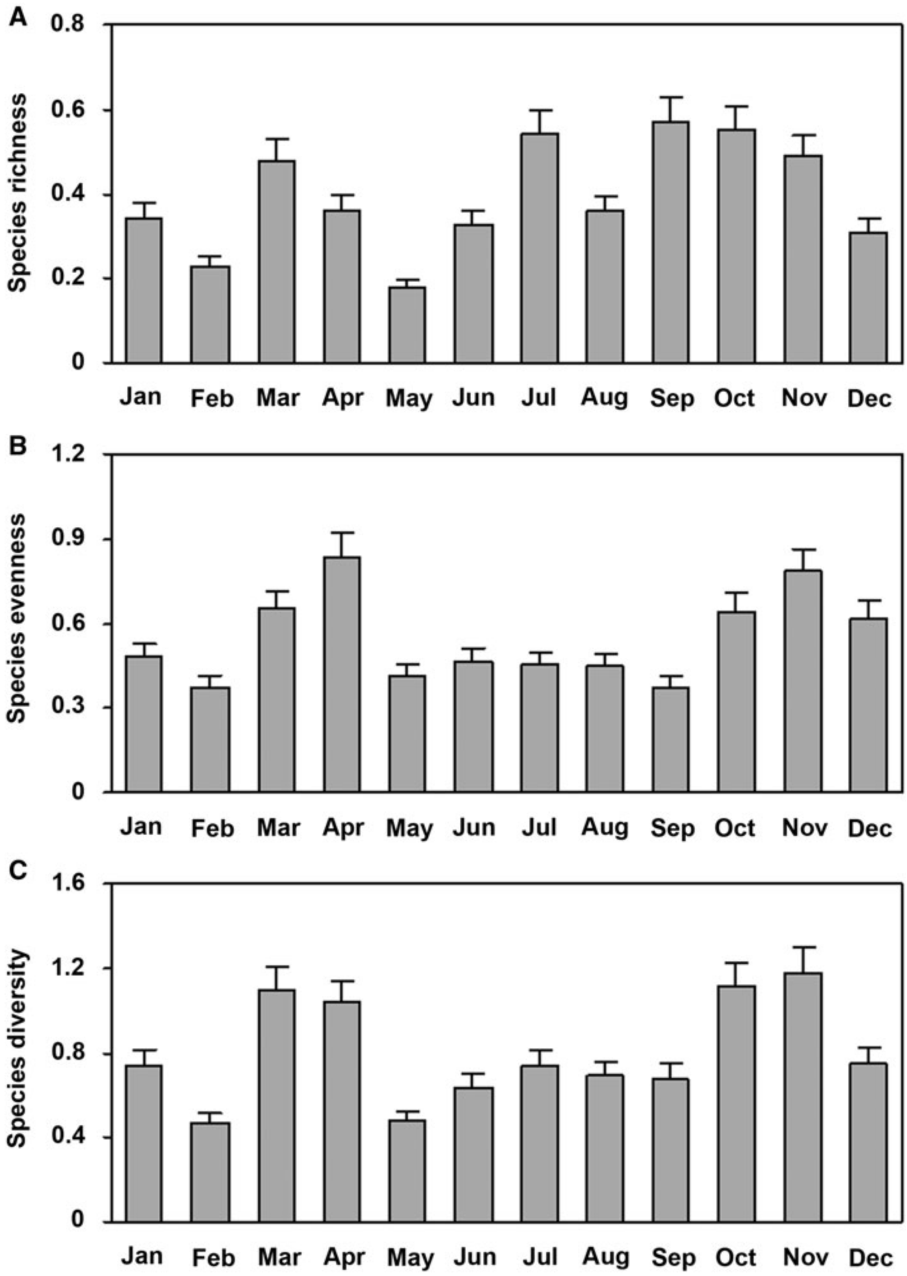

Fig. 5. Annual variations in species richness (a), evenness (b) and diversity (c) of the diatom communities in Jiaozhou Bay during the study period.

the right) from those in winter and spring (on the left), while data points in summer (upper) and those in autumn (lower) were discriminated by the second axis (CAP 2) (Figure 4a). PERMANOVA test revealed a significant difference between each pair of seasonal group ($P < 0.05$), except the pair of spring and winter ($P = 0.06$).

Vector overlay of Pearson correlations of the 11 dominant species with the canonical analysis of principal coordinates (CAP) axes was also shown in Figure 4b. Of these, three species (*Eucampia zodiacus, Chaetoceros compressus* and *Navicula* sp.) pointed toward the sample cloud of (upper right), three (*Skeletonema costutum, Coscinodiscus oculus-iridis* and *Thalassiosira* sp.) toward that of autumn (lower right), and the other five (e.g. *Nitzshia lorenziana, Guinardia delicatula* and *Paralia sulcata*) toward the data points in spring and winter (Figure 4b).

Annual variation in diversity measures

The annual variation in species diversity (H'), evenness (J') and richness (D) indices in 12 months is shown in Figure 5. All three community parameters showed a similar temporal variation with two peaks in spring and autumn, respectively (Figure 5).

Interaction between biotic data and environmental variables

Canonical analysis of principal coordinates (CAP) showed that the environmental conditions represented a clear seasonal shift (Figure 6). Mental analysis revealed a significant correlation between annual variation in community pattern and changes of environmental variables ($R = 0.157$; $P < 0.05$).

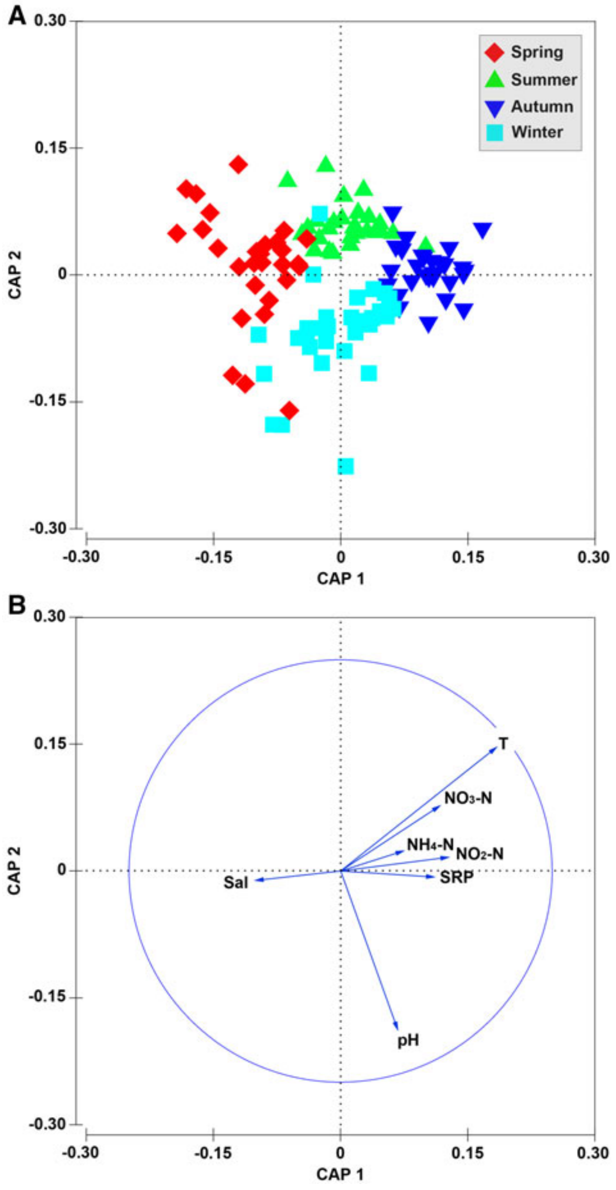

Fig. 6. Canonical analysis of principal coordinates (CAP) on seasonal scale for 120 data points of the environmental variables in Jiaozhou Bay during the study period (A), and correlations of environmental variables with the two CAP axes (B).

Table 2. Summary of results from biota-environment (BIOENV) analysis showing the 10 best matches of environmental variables with temporal variation in community patterns in coastal waters of the Yellow Sea during the study period.

Rank	*ρ* value	Environmental variables	*P* value
1	0.729	T, Sal, NO_2-N	<0.05
2	0.714	T, Sal, NO_3-N, NO_2-N	<0.05
3	0.696	T, NO_2-N	<0.05
4	0.673	T, pH, Sal, NO_3-N, NO_2-N	<0.05
5	0.672	T, NO_3-N, SRP	<0.05
6	0.667	T, NO_3-N, NO_2-N	<0.05
7	0.664	T, Sal, NO_3-N, NO_2-N, SRP	<0.05
8	0.663	T, Sal	<0.05
9	0.662	T, NO_3-N, NO_2-N, SRP	<0.05
10	0.655	T, pH, Sal, NO_2-N	<0.05

ρ = Spearman correlation coefficient. Sal = salinity; SRP = soluble active phosphate; NO_3-N: nitrate nitrogen; NO_2-N: nitrite nitrogen.

Biota-environment (BIOENV) analysis showed that the seasonal shift in community pattern was shaped by environmental drivers, especially temperature, pH, salinity and nutrients (NO_3-N, NO_2-N, SRP), alone or in combination (Table 2).

Of 11 dominant species, four (*Paralia sulcata, Skeletonema costatum, Guinardia delicatula* and *Nitzschia lorenziana*) were significantly related with temperature, pH and/or nutrients (Table 3).

DISCUSSION

In this study, a total of 75 diatom species were identified during one annual cycle in Jiaozhou Bay. The annual variations in both species number and abundance showed a similar pattern, i.e. peaked during the period of July–September. Compared with the Liu et al. (2003a, b) reports in summer (August), using a trawling method, the species number and abundance in the same month were low (21 *vs* 34; 6.4×10^4 *vs* 1.07×10^5 cells L^{-1}).

So far, although there have been a few reports on community research of diatoms, little information could be reported on the annual variation or seasonal shift in planktonic diatom community structure and their environmental drivers in Jiaozhou Bay (Liu *et al*., 2003a, b, 2008). Our data revealed that planktonic diatom assemblages represented a clear annual/seasonal variation in terms of community structure. For example, of 75 diatom species, 27, 35, 56 and 28 occurred in spring, summer, autumn and winter, with 11 dominant species predominating the samples in different seasons. Furthermore, canonical analysis of principal coordinates (CAP) and PERMANOVA test demonstrated a significant seasonal shift in the community pattern, each of which had its own most contributive species.

Mental (RELATE) analysis revealed that the temporal variation in the diatom community structure was significantly correlated with changes of environmental variables, especially the combination of water temperature, pH and nutrients. Pearson correlation analysis demonstrated that a total of four dominant/common species were significantly correlated with temperature, pH and/or nutrient variables. These results imply that the seasonal shift in planktonic diatom community structure is significantly shaped by environmental drivers, especially the water temperature and nutrients.

In addition, the biodiversity measures (i.e. species diversity, evenness and richness indices) represented a similar seasonal variation, generally peaking in spring and autumn seasons in our study. However, it should be noted that these biological indices failed to show significant correlations with environmental parameters. This is consistent with the previous report (e.g. Xu *et al*., 2008).

In summary, the diatom assemblages showed a clear seasonal shift in both species distribution and community structure, and the water temperature, pH and nutrients were the main environmental drivers in the eutrophic basin ecosystem. Further studies, however, are necessary in a range of seas and over long-term periods in order to verify these conclusions.

Table 3. Summary of results from correlation analyses between 11 four dominant diatom species and environmental variables in coastal waters of the Yellow Sea during the study period.

Species	*T*	pH	Sal	NH$_4$-N	NO$_3$-N	NO$_2$-N	SRP
Paralia sulcata	−0.100	−0.485	0.429	−0.277	−0.214	−0.761*	−0.312
Skeletonema costatum	0.688*	−0.143	−0.719*	0.712*	0.361	0.681*	0.654*
Guinardia delicatula	−0.934*	0.179	0355	−0.363	−0.617*	−0.574	−0.480
Nitzschia lorenziana	0.152	−0.656*	0.217	0.006	−0.046	−0.338	0.146

Sal = salinity; SRP = soluble active phosphate; NO$_3$-N: nitrate nitrogen; NO$_2$-N: nitrite nitrogen. *Significant difference at $P < 0.05$.

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S0025315415000673.

ACKNOWLEDGEMENTS

Our special thanks are due to: Dr Xinpeng Fan, Dr Jiamei Jiang and Dr Xumiao Chen, Laboratory of Protozoology, Institute of Evolution and Marine Biodiversity, Ocean University of China, China, for their help in sampling and enumeration.

FINANCIAL SUPPORT

This work was supported by the Darwin Initiative Programme (Project No. 14-015) which is funded by the UK Department for Environment, food and Rural Affairs.

REFERENCES

Anderson M.J., Gorley R.N. and Clarke K.R. (2008) *PERMANOVA+ for PRIMER guide to software and statistical methods.* Plymouth: PRIMER-E.

APHA (1992) *Standard methods for examination of water and waste water.* 18th edition. Washington, DC: American Public Health Association.

Berger W.H. and Wefer G. (1991) Productivity of the glacial ocean: discussion of the iron hypothesis. *Limnology and Oceanography* 36, 1899–1918.

Berthon V., Bouchez A. and Rimet F. (2011) Using diatom life-forms and ecological guilds to assess organic pollution and trophic level in rivers: a case study of rivers in south-eastern France. *Hydrobiologica* 673, 259–271.

Chen X., Qin Y., Stevenson M.A. and McGowan S. (2014) Diatom communities along pH and hydrological gradients in three montane mires, central China. *Ecological Indicators* 45, 123–129.

Clarke K.R. and Gorley R.N. (2006) *PRIMER 6 user manual/tutorial.* Plymouth: PRIMER-E.

Di B., Liu D., Wang Y., Dong Z., Li X. and Shi Y. (2013) Diatom and silicoflagellate in modern surface sediments associated with human activities: a case study in Sishili Bay, China. *Ecological Indicators* 24, 23–30.

Duong T.T., Coste M., Feurtet-Mazel A., Dang D.K., Gold C., Park Y.S. and Boudou A. (2006) Impact of urban pollution from the Hanoi area on benthic diatom communities collected from the red, Nhu and Tolich rivers (Vietnam). *Hydrobiologia* 563, 201–216.

Finkelstein S.A. and Davis A.M. (2006) Paleoenvironmental records of water level and climatic changes from the middle to late Holocene at a Lake Erie coastal wetland, Ontario, Canada. *Quaternary Research* 65, 33–43.

Hasle G.R. and Syvertsen E.E. (1997) *Marine diatoms.* In Tomas C.R. (ed.) *Identifying marine phytoplankton.* San Diego, CA: Academic Press, pp. 5–385.

Jiang Y., Xu H., Hu X., Zhu M., Al-Rasheid K.A.S. and Warren A. (2011) An approach to analyzing spatial patterns of planktionc ciliate communities for monitoring water quality in Jiaozhou Bay, northern China. *Marine Pollution Bulletin* 62, 227–235.

Jiang Y., Xu H. and Warren A. (2014) Insights into discriminating environmental quality status using taxonomic distinctness based on a small species pool of ciliated protozoa in marine ecosystems. *Science of the Total Environment* 468–469, 663–670.

Jiang Y., Zhu M., Zhang W., Al-Rasheid K.A.S. and Xu H. (2013) Influence of sample sizes on analyzing community parameters of periphytic diatoms for bioassessment using an artificial substrate in coastal waters. *Water Environmental Research* 85, 2228–2234.

Liu D., Sun J., Chen H. and Zhang L. (2003a) The phytoplankton community in summer 2001 in Jiaozhou Bay, China. *Journal of Ocean University of Qingdao* 33, 366–374. [in Chinese, with English abstract]

Liu D., Sun J., Zhang J. and Liu G. (2008) Response of the diatom flora in Jiaozhou Bay, China to environmental changes during the last century. *Marine Micropaleontology* 66, 279–290.

Liu D., Sun J. and Zhang L. (2003b) Structural characteristics of phytoplankton community during harmful alage bloom in Jiaozhou Bay. *Chinese Journal of Applied Ecology* 14, 1963–1966. [in Chinese, with English abstract]

Liu S., Zhang J., Chen H. and Zhang G. (2005) Factors influencing nutrient dynamics in the eutrophic Jiaozhou Bay, North China. *Progress in Oceanography* 66, 66–85.

Liu Y., Zhang W. and Xu H. (2013) Influence of enumeration time periods on detecting community parameters of periphytic diatoms using an artificial substratum in coastal waters. *Journal of the Marine Biological Association of the United Kingdom* 93, 2067–2073.

Liu Y., Zhang W. and Xu H. (2014) Colonization dynamics of periphytic diatoms in coastal waters of the Yellow Sea, northern China. *Acta Oceanologica Sinica* 33, 160–165.

Liu Z., Wei H., Liu G. and Zhang J. (2004) Simulation of water exchange in Jiaozhou Bay by average residence time approach. *Estuarine Coastal and Shelf Science* 61, 25–35.

Nuccio C., Melillo C., Massi L. and Innamorati M. (2003) Phytoplankton abundance, community structure and diversity in the eutrophicated Orbetello lagoon (Tuscany) from 1995 to 2001. *Oceanologica Acta* 26, 15–25.

Round F.E., Crawford R.M. and Mann D.G. (1990) *The diatoms.* New York: Cambridge University Press.

Shen Z. (2001) Historical changes in nutrient structure and its influences on phytoplankton composition in Jiaozhou Bay. *Estuarine Coastal and Shelf Science* 52, 211–224.

Smucker N.J. and Vis M.L. (2011a) Diatom biomonitoring of streams: reliability of reference sites and the response of metrics to environmental variations across temporal scales. *Ecological Indicators* 11, 1647–1657.

Smucker N.J. and Vis M.L. (2011b) Spatial factors contribute to benthic diatom structure in stream across spatial scales: considerations for biomonitoring. *Ecological Indicators* 11, 1191–1203.

Stenger-Kovács C., Lengyel E., Crossetti L.O., Üveges V. and Padisák J. (2013) Diatom ecological guilds as indicators of temporally changing stressors and disturbances in the small Torna-stream, Hungary. *Ecological Indicators* 24, 138–147.

Utermöhl H. (1958) Zurvervolkommungder quantitativen phytoplankton Methodik. Mitteilungen der Internationale Vereinigung für Theoretische und Angewandte. *Limnologie* 9, 1–38.

Wan Mazanh W.O. and Mansor M. (2002). Aquatic pollution assessment based on attached diatom communities in the Pinang river Basin, Malaysia. *Hydrobiologia* 478, 229–241.

Xu H., Jiang Y., Al-Rasheid K.A.S., Al-Farraj S.A. and Song W. (2011) Application of an indicator based on taxonomic relatedness of ciliated protozoan assemblages for marine environmental assessment. *Environmental Science and Pollution Research* 18, 1213–1221.

Xu H., Song W., Warren A., Al-Rasheid K.A.S., Al-Farraj S.A., Gong J. and Hu X. (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 United Kingdom* 88, 1353–1362.

and

Zielinski U. and Gersonde R. (1997) Diatom distribution in Southern Ocean surface sediments (Atlantic sector): implications for paleoenvironmental reconstructions, *Palaeogeography, Palaeoclimatology, Palaeoecology* 129, 213–250.

Correspondence should be addressed to:

H. Xu
Institute of Evolution and Marine Biodiversity, Ocean University of China, Qingdao 266003, China
email: henglongxu@126.com