Phytoplankton community structure and environmental parameters in aquaculture areas of Daya Bay, South China Sea

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Abstract

Environmental characteristics and phytoplankton community structure were investigated in two aquaculture areas in Dapeng Cove of Daya Bay, South China Sea, between April 2005 and June 2006. Phytoplankton abundance ranged between 5.0 and 8877.5 cells/mL, with an average of 751.8 cells/mL. The seasonal cycle of phytoplankton were demonstrated by frequent oscillations, with recurrent high abundances from late spring to autumn and a peak stage in late winter. Diatoms were the predominant phytoplankton group, accounting for 93.21% of the total abundance. The next most abundant group was the dinoflagellates, which made up only 1.24% of total abundance. High concentrations of *Alexandrium tamarense* (Lebour) Balech with a maximum of 603.0 cells/mL were firstly recorded in this area known for high rates of paralytic shellfish poisoning (PSP) contamination. Temperatures and salinities were within the suitable values for the growth of phytoplankton, and were important in phytoplankton seasonal fluctuations. The operation of the Daya Bay Nuclear Power Station (DNPS) exerts influences on the phytoplankton community and resulted in the high abundances of toxic dinoflagellate species during the winter months. Dissolved inorganic nitrogen (DIN) and dissolved silicate (DSi) were sufficient, and rarely limited for the growth of phytoplankton. Dissolved inorganic phosphorus (DIP) was the most necessary element for phytoplankton growth. The enriched environments accelerated the growth of small diatoms, and made for the shift in predominant species from large diatom *Rhizosolenia* spp. to chain-forming diatoms such as *Skeletonema costatum*, *Pseudo-nitzschia* spp. and *Thalassiosira subtilis*.

Key words: phytoplankton; environmental factor; South China Sea; aquaculture; nuclear power station

DOI: 10.1016/S1001-0742(08)62414-6

Introduction

The increase of anthropogenic nutrient inputs in many coastal areas has resulted in severe eutrophication problems, which brought on increases in both phytoplankton populations and harmful algal blooms (López-Flores *et al.*, 2006). The phytoplankton composition and structure have greatly changed due to the enrichment of nutrients and alteration of nutrient element ratios (Spatharis *et al.*, 2007; Glé *et al.*, 2008).

Daya Bay is located in the northeast part of the South China Sea, which is an important cultural area in southern China. This bay is strongly affected by eutrophication due to the increase nutrient loadings since 1990s caused by the rapidly expanding mariculture and human population. Inorganic nitrogen content has increased by four- to five-fold during the past decade, and N:P ratio increased about 40-fold (Qiu, 2001; Wang *et al.*, 2004, 2008). Daya Bay is also the location of the Daya Bay Nuclear Power Station (DNPS), the first nuclear power station in China. DNPS has operated since February 1994, and it discharges heated

water at the rate of 2.9×10^7 m^3/year (Liu *et al.*, 2006). The changes in nutrient structure and the operation of DNPS have intensely modified the phytoplankton community structure in this area. The phytoplankton biomass had increased dramatically, and harmful species have become more prevalent in the last few years (Zhong *et al.*, 2002; Xiao *et al.*, 2003; Li *et al.*, 2005). Episodes of paralytic shellfish poisoning (PSP) occurred frequently (Lin *et al.*, 1994, 1999; Anderson *et al.*, 1996).

Previous studies have investigated the phytoplankton community structure and its interactions with environmental variations in aquaculture areas of Dapeng Cove (Wei *et al.*, 2003, 2004; Wang *et al.*, 2004; Li *et al.*, 2005; Liu *et al.*, 2006; Sun *et al.*, 2006; Wang *et al.*, 2006). However, most of these reports presented data obtained from routine seasonal surveys (Zhou *et al.*, 1998; Wang *et al.*, 2004; Li *et al.*, 2005; Liu *et al.*, 2006; Su *et al.*, 2006; Wang *et al.*, 2006) or continual observation over a short period (Wei *et al.*, 2003, 2004). The phytoplankton communities are composed of multispecies dynamic, characterized by high diversity. These communities respond to environmental fluctuations immediately and undergo rapid shifts in species composition (Brogueira *et al.*, 2007). Seasonal

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surveys could not provide enough information on phytoplankton variability and the influences of human activities on phytoplankton communities. Indeed, PSP causative species such as *Alexandrium* spp. and *Gymnodinium catenatum* Graham were seldom observed in routine surveys, though PSP events occur frequently in this area.

In this article, the seasonal variability of phytoplankton community composition and abundance, as well as physical and chemical environmental parameters, were investigated in two aquaculture areas of Dapeng Cove between April 2005 and June 2006. The objectives of this study were to evaluate phytoplankton dynamics and the environmental variability using a high frequency sampling strategy, and to demonstrate the effects of human activities on phytoplankton community structure.

1 Materials and methods

1.1 Study area and sampling

Daya Bay is located in the southeast part of the South China Sea (22°30′–22°50′N, 114°30′–114°50′E). It is a semi-enclosed shallow embayment with depth ranging between 6 and 15 m. It covers an area of 650 km^2 at flood tide and is separated into several small sub-basins. Dapeng Cove is a sub-basin in the southwest portion of the bay, and DNPS is situated on the north shore of the cove. Daya Bay is characterized by a mild subtropical climate with an annual mean air temperature of 22°C. The coldest months are January and February, which have a monthly mean air temperature of about 15°C. The hottest months are July and August, when the monthly mean air temperature is about 28°C. Salinity is usually between 22 and 33.

Dapeng Cove has been introduced to fish culture since 1985. Aquaculture increased dramatically in the late 1990s, and aquaculture areas increased from 540 m^2 in 1994 to 1300 m^2 in 1998 (Huang *et al.*, 2005). The cultural area is currently approximately 30 hm^2, and the annual fish production is about 4.5×10^5 kg (Huang *et al.*, 2005). Sampling stations (Fig. 1) were located in two aquaculture areas of the cove. Station 1 (St.1) was located at a shellfishery area. Station 2 (St.2) was at a fish cage
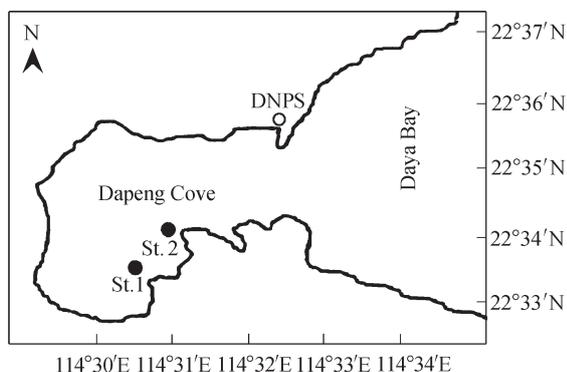
Fig. 1 Sampling stations in two cultural areas in Dapeng Cove of Daya Bay, the South China Sea. DNPS: Daya Bay Nuclear Power Station. St.1 is located at shellfish cultural area, and St.2 is at fish cage area close to a residential area.

area close to the shore and to a residential town.

Surface water samples (0.5 m below the surface) were collected with a Niskin bottle from April 10, 2005, to June 10, 2006, and analyzed for nutrient content (DIN, dissolved inorganic nitrogen, the sum of ammonium, nitrites and nitrates; DIP, dissolved inorganic phosphorus, orthophosphates; DSi, dissolved silicate), phytoplankton composition and abundance. The four seasonal periods of the survey were defined as: spring (March to May), summer (June to August), autumn (September to November), and winter (December to February).

1.2 Measurements

Surface water temperature (SWT), salinity (S) and dissolved oxygen content (DO) were determined *in situ* with an YSI meter (YSI 85, YSI Incorporated, USA). Transparency was measured with a Secchi disk. Water samples to be used for nutrient analysis were immediately filtered through glass fibre filters (Whatman GF/F, porosity = 0.7 μm), placed in a freezer, and analyzed within 24 hours according to the standard methods of State Oceanic China (SOC, 1991).

One liter water samples were collected for phytoplankton analysis, fixed in 4% neutralized formalin, and then concentrated to 20 mL by sedimentation. Phytoplankton species were identified and counted by microscopic examination under an inverted microscope (Leica DMIRB) at magnifications of 100–600 ×.

SWT, S and DO measurements and phytoplankton observations were conducted once every three days, and other parameters were determined two times per month during the study period.

1.3 Data analysis

Bravais Pearson's correlation analysis was applied to discrete correlations between environmental and phytoplankton variables using SPSS 13.0 software.

2 Results

2.1 Environmental parameters

2.1.1 Surface water temperature and salinity

The surface water temperature and salinity were relatively consistent between two stations; therefore, seasonal variations in average temperature and salinity of two stations are described in Fig. 2a. SWT followed the classical seasonal evolution of southern China sea areas, characterized by a minimum of 14.0°C (January 8, 2006) and a maximum of 32.8°C (July 16, 2005). SWT was over 25°C during most portions of the year, declining rapidly to less than 20°C at the end of November, then remaining between 14 and 20°C until the end of March. There was a marked increase in water temperature during March, which increased from 18°C at the beginning of March to 23.5°C in late March. Salinity ranged from 17.5 (August 20, 2005) to 33.5 (December 15, 2005) and was generally greater than 25, except from April to May (spring rainy season) and from June to September (typhoon storm
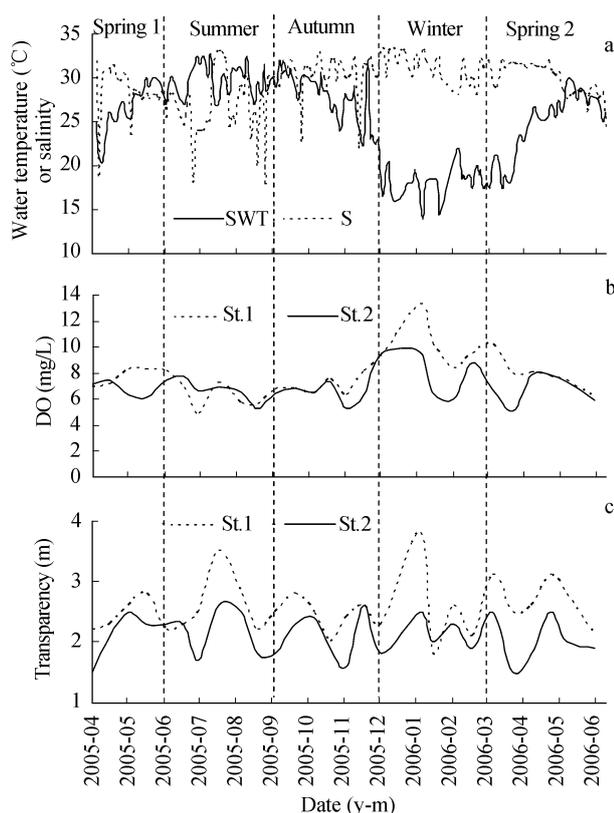
Fig. 2 Seasonal variations of surface water temperature (SWT), salinity (S), dissolved oxygen (DO) and transparency in Dapeng Cove of Daya Bay.

Fig. 3 Seasonal variations of DIN (dissolved inorganic nitrogen), DIP (dissolved inorganic phosphorus) and DSi (dissolved silicate) in Dapeng Cove of Daya Bay.
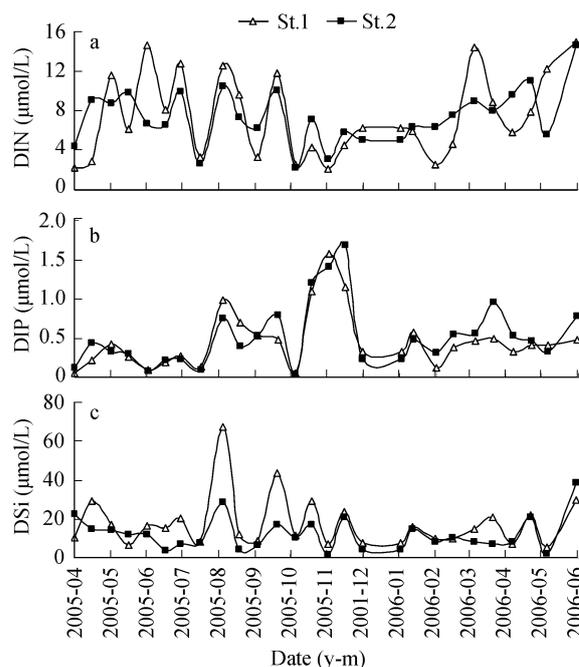
season).

2.1.2 Dissolved oxygen and transparency

The DO annual cycles showed greater values in winter and ranged from 4.91 to 13.26 mg/L (Fig. 2b). DO values were, on average, higher in St.1 (mean 7.77 mg/L) than in St.2 (mean 6.97 mg/L).

Transparency fluctuated considerably, and was generally higher in St.1 (Fig. 2c). Transparencies ranged from 1.5 m (April 11, 2005, St.2) to 3.8 m (January 13, 2006, St.1) with a mean value of 2.56 m in St.1 and 2.11 m in St.2.

2.1.3 Nutrients

DIN concentration ranged from 2.04 to 14.94 μmol/L, showing an annual cycle characterized by higher values in spring and summer and lower values during late autumn and winter (Fig. 3a). The annual mean values were 6.96 μmol/L at St.1 and 6.85 μmol/L at St.2. DIP concentration remained consistently low (Fig. 3b) and ranged from 0.04 to 1.67 μmol/L. DIP levels were slightly higher in St.2, with the annual means of 0.46 μmol/L in St.1 and 0.52 μmol/L in St.2. The seasonal variations in DIP concentration showed similar patterns at the two stations, including a notable peak in November and a low point in August. DIP varied widely and suddenly, reaching the lowest concentration of 0.04 μmol/L in mid October and increasing rapidly to the highest concentration of 1.67 μmol/L in early November (Fig. 3b). DSi was high, ranging from 1.77 to 67.12 μmol/L. DSi level was predictably higher in St.1 than in St.2 (Fig. 3c), with mean concentrations of 17.77 and

12.22 μmol/L, respectively. The seasonal variations in DSi concentration were characterized by high values during the period of high freshwater input from August to November and by low values during dry season between December and April.

For all the nutrient data obtained from both stations, DIN and DSi showed a significant inverse correlation with salinity by Bravais Pearson's correlation analysis ($r =$ –0.681, $p < 0.01$ for NO_3^--N; $r = $ –0.396, $p < 0.05$ for NO_2^--N; $r = $ –0.520, $p < 0.01$ for DIN, and $r = $ –0.46, $p < 0.01$ for DSi, d$f = 54$). However, NH_4^+-N and DIP showed no significant relationship with salinity ($r = $ –0.169 and –0.087, $p > 0.1$).

2.1.4 Nutrient ratios

The ratio of N:P was generally less than 40, and the annual mean ratio of Si:N:P was 55:24:1. Seasonal variations of Si:N were similar to those of DSi, characterized by high values during the rainy season and fluctuating with some low values. The Si:N ratio was markedly higher in St.1 (range 0.47–10.25, mean 2.95) than that in St.2 (range 0.40–5.19, mean 1.77) due to the high DSi levels in St.1. Ratios of Si:P did not show clear seasonal variation, and were higher in St.1 (from 4.83 to 195.39, mean 60.67) than those in St.2 (from 1.25 to 231.24, mean 43.19).

In order to better explain the potential limiting nutrient in these environments, nutrient ratios were compared with Redfield ratios (Si:N:P = 16:16:1; Fig. 4). At both stations, Si was the least limited element, and only one sample from St.1 and five samples from St.2 were Si limited. N was the second most abundant nutrient and only a few samples showed a limited concentration of N. P was the most deficient nutrient, and about 60% of all samples were deficient in P.
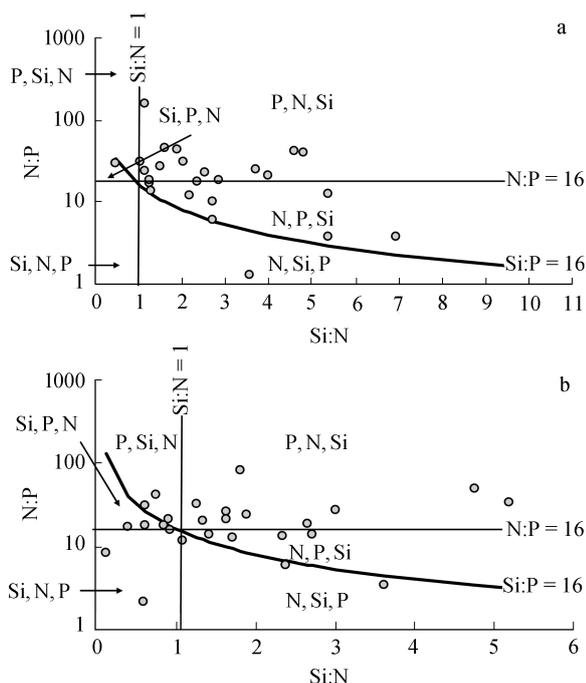
Fig. 4 Synthetic graph of Si:N:P ratios of all samples from two cultural areas in Dapeng Cove of Daya Bay during the survey period from April 2005 to June 2006. The horizontal line (N:P = 16), the vertical line (Si:N = 1) and the curve (Si:P = 16) separated all samples into six areas. In each area, delimited Redfield ratios (Si:N:P = 16:16:1) and potential limited nutrients are described in the order of priority. (a) St.1; (b) St.2.

2.2 Phytoplankton community structure

2.2.1 Composition

A total of 183 phytoplankton species were identified during this survey. Diatom represented the most diverse group, and 112 diatom species were identified, representing 70.44% of the total species described. Dinoflagellate was the second most diverse group, with 38 species representing 23.90% of the total taxa. Species in other groups, including chlorophyta, cyanobacteria, chrysophyta, cryptophyta, and euglenophyta, were recorded more sporadically.

Diatom was the most abundant phytoplankton group, accounting for 93.21% of the total abundance. Most of the common diatoms were species typical of warm brackish or eurythermal euryhaline conditions. The species *Skeletonema costatum* (Greville) Cleve and *Pseudo-nitzschia* spp. were the most dominant taxa, representing 34.89% and 27.15% of the total abundance, respectively.

The phytoplankton composition and predominant species changed between seasons. *S. costatum* was abundant throughout the year. During the spring, some eurythermal species such as *Leptocylindrus danicus* Cleve, *Pseudo-nitzschia* spp., and *Thalassiosira subtilis* (Ostenfeld) Gran occurred at high frequency. The filamentous cyanobacterium, *Romeria* sp., was abundant in spring and early summer. Euryhaline species such as *Asterionella japonica* Cleve in Cleve *et* Moller, *Chaetoceros* spp. and *Rhizosolenia* spp. dominated the phytoplankton community during the summer. As water temperature decreased and salinity increased at autumn months, *Pseudo-nitzschia* spp. and

Thalassionema nitzschioides (Grunow) Mereschkowsky became the dominant. In winter, when the water temperature dropped to 15–20°C, dinoflagellates increased, even though phytoplankton communities remained dominated by diatoms. During this period, the common dinoflagellates included *Prorocentrum* spp., *Alexandrium tamarense* (Lebour) Balech, *Scrippsiella trochoidea* (Stein) Loeblich III, *Karenia* spp., *Protoperidinium* spp., and *Peridinium quinquecorne* Abé.
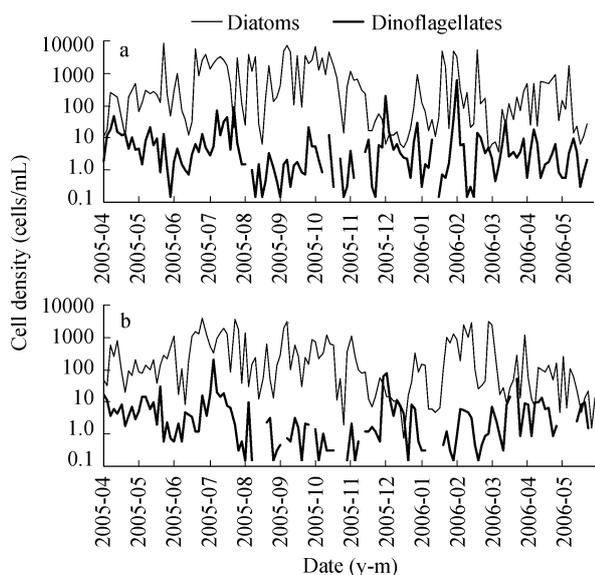
2.2.2 Abundance

The inter-annual variation of phytoplankton abundance ranged between three orders of magnitude, from the minimum of 5.0 cells/mL (January 23, 2006, in St.2) to the maximum of 8877.5 cells/mL (May 31, 2006, in St.1). Phytoplankton abundance was generally high, with an annual mean of 751.8 cells/mL. The abundances oscillated frequently (Fig. 5) but showed a regular annual pattern similar in both stations, with relatively low abundance in spring, peaks during late spring-autumn (from late May to October), progressively decreasing abundance during late autumn-early winter until the yearly minimum in January, followed by the second peak stage between late February and early March.

The phytoplankton assemblages were characterized by a great abundance of diatoms. The seasonal dynamics of diatoms (Fig. 6) were consistent with the dynamics of the total phytoplankton community, except for a peak contributed by *Romeria* sp. (cyanobacteria) in June 2006 at St.2 (Fig. 5). The diatom peaks were caused by the nanoplanktonic taxa (*Pseudo-nitzschia* spp., *S. costatum*, *T. subtilis*, *Chaetoceros* spp. etc.), and they dominated the phytoplankton community simultaneously or in an alternating manner.

Dinoflagellates generally occurred in low numbers, representing only 1.24% of total abundance. *P. quinquecorne* and *Gyrodinium spirale* (Bergh) Kofoid *et* Swezy were the two main species contributing to the abundance at St.2 in mid July, while *Prorocentrum* spp., such as *Prorocentrum micans* Ehrenberg and *Prorocentrum triestinum* Schiller, were abundant in December in both stations. The highest
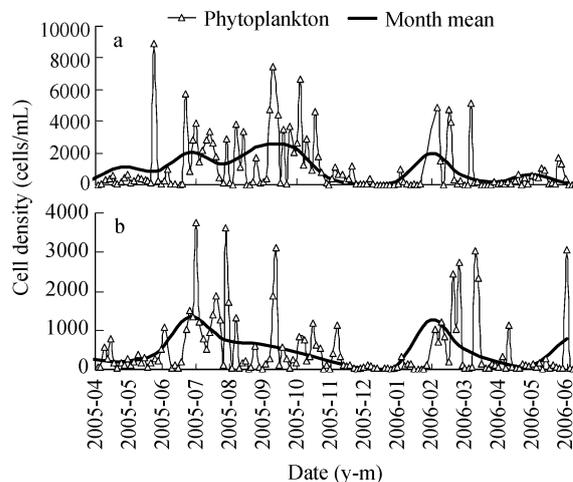
Fig. 5 Seasonal variations of phytoplankton abundance in Dapeng Cove of Daya Bay. (a) St.1; (b) St.2.

Fig. 6 Seasonal variations of abundance of diatoms and dinoflagellates in Dapeng Cove of Daya Bay. (a) St.1; (b) St.2.

concentration of dinoflagellates (611.4 cells/mL) was observed on February 19, 2006, at St.1 (Fig. 6a), which was dominated by the toxic species *A. tamarense*. This toxic species was found near bloom concentration up to 603.0 cells/mL and contributed 98.30% of the total dinoflagellate abundance.

Other groups of phytoplankton, including species of cyanobacteria, chlorophyta and raphidophyceae, generally occurred at a low abundance, with a mean abundance of 41.9 cells/mL and a mean proportion of 5.53% of total abundance. However, the filament nano-cyanobacteria *Romeria* sp. was extremely abundant, and it peaked in abundance during early June with a maximum of 3045.0

cells/mL, contributing 99.23% of total phytoplankton abundance.

2.3 Relationship of phytoplankton community with environmental parameters

2.3.1 Surface water temperature and salinity

Figures 7a and 7b illustrate a scatter plot of abundance of diatoms and dinoflagellates vs. surface water temperature in this survey. The greater densities of diatoms occurred at temperatures between 17.5 and 32.5°C. Greater abundance of dinoflagellates was observed in the range of 17.5–29°C, indicating their low ability to thrive at higher temperatures. The relationships of diatoms and dinoflagellates to temperature mirrored the seasonal dynamics of phytoplankton. Diatoms peaked in two temperature zones, during winter at about 20°C and during summer to autumn at 30°C. Dinoflagellates, peaked at water temperatures about 18 and 28°C dominated by *A. tamarense* and *Prorocentrum* spp., respectively.

Figures 7c and 7d show the relationships between abundances of diatoms and dinoflagellates and salinity. High abundances of diatoms were distributed in three salinity zones (Fig. 7c): (1) abundances between 1000 and 2000 cells/mL occurred in salinities of about 18, during which the dominant species were *S. costatum*, *C. subtilis* and *T. subtilis*; (2) peak values between 2000 and 4000 cells/mL occurred in salinities of 23–36, dominated by *Pseuodo-nitzschia* spp., *T. subtilis*, and *T. nitzschioides*; (3) peak abundances occurred in salinity between 28 and 33, including the maximum density of 8863.4 cells/mL. The dominant diatoms in this zone were *T. subtilis*, *Pseuodo-nitzschia* spp., *S. costatum*, and *L. danicus*. Dinoflagellates showed less tolerance to high salinity (Fig. 7d). *S. tro-choidea* and *P. quinquecorne* dominated in salinity of 25,
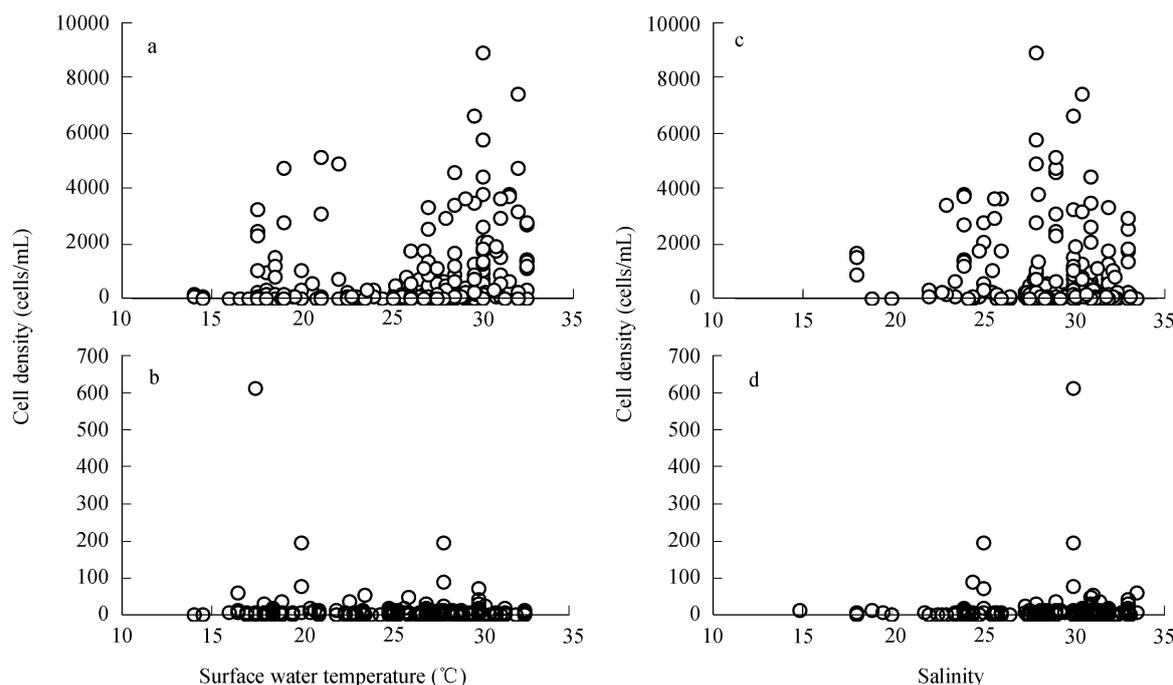
Fig. 7 Surface water temperature (SWT) and salinity (S) plotted against abundance of diatoms and dinoflagllates. (a) diatoms vs. SWT; (b) dinoflagllates vs. SWT; (c) diatoms vs. S; (d) dinoflagllates vs. S.

and *A. tamarense* peaked in abundance at 30.

2.3.2 Nutrients

In general, inverse relationships were observed between phytoplankton (total phytoplankton, diatoms, dinoflagellates and some dominant diatom species) and nutrients (N, P and Si; Table 1). This was caused by the substantial uptake of nutrients by phytoplankton during periods of great phytoplankton abundance. Dinoflagellates showed significantly negative relationships with all three macronutrients ($p < 0.05$, Bravais Pearson's correlation), whereas neither phytoplankton nor diatom abundance displayed any significant relationships with nutrient levels. Cyanobacteria correlated positively with DIP and showed no significant correlations with other nutrients (Table 1).

3 Discussion

3.1 Characteristics of phytoplankton community and environmental parameters

The phytoplankton community in Dapeng Cove was characterized by high abundance and was dominated by small diatoms, particularly chain-forming diatoms such as *S. costatum*, *Pseudo-nitzschia* spp. and *T. subtilis*. These diatoms dominated the community simultaneously or in an alternating manner, and attained peak abundances throughout the year, resulting in a great abundance of total phytoplankton. *S. costatum* and *Pseudo-nitzschia* spp. were the two most prevalent species, contributing 34.89% and 27.15% of the total abundance, respectively. *S. costatum* has been reported as a predominant phytoplankton species in other Chinese cultural areas, including Jiaozhou Bay (Li *et al*., 2005), Changjiang estuary (Liu *et al*., 2007), and Zhelin Bay (Zhou *et al*., 2004).

The water temperatures and salinities in Dapeng Cove ranged within a threshold suitable for phytoplankton growth. Temperature and salinity were two important parameters influencing phytoplankton community composition and abundance. The eurythermal and euryhaline diatoms occurred abundantly throughout the year, while other species reached the greatest abundance only within optimal temperature and salinity ranges. *A. tamarense*, for example, peaked at temperatures near 18°C and salinity around 30.

The phytoplankton structure was closely correlated to nutrient levels and ratios. As a cultural coastal area, DIN and DSi in Dapeng Cove appeared to be plentiful and

unlikely to limit phytoplankton growth. Conversely, DIP levels remained low throughout the study period, with most samples showing limited P. However, phosphates recovered rapidly from sediment efflux (Qiu, 2001). Therefore, phytoplankton is being able to grow and maintain high abundance during the temporary P depleted conditions. There were different relationships of diatoms and dinoflagellates with nutrient levels (Table 1), which indicated that the two main phytoplankton groups each possessed independent nutrient niches, resulting in their alternating dominance of the phytoplankton community and the high abundance of phytoplankton.

One characteristic of phytoplankton structure observed in this study is an increase in abundance of cyanobacteria, a typical indication in high trophic state ecosystem (Moncheva *et al*., 2001). Cyanobacteria abundance showed a significant positive relationship with DIP, though species being able to fix atmospheric N were not observed. The abundance and contribution of cyanobacteria are increasing in this area, especially in surface microlayer during our continuing observation (unpublished data).

3.2 Effects of aquacultures on phytoplankton structure

The anthropogenic pressures have caused significant changes in hydrological and chemical states in Dapeng Cove, and they have probably influenced the biological communities in several ways. Mariculture was thought to be the important source of nitrogen in this area (Wang *et al*., 2004; Huang *et al*., 2005). Wang *et al*. (2003) calculated the nitrogen and phosphorus loadings of fish culture in this area, and their results showed that breeding 1000 kg of fish introduced 156 kg N and 32.3 kg P into environment. In addition, the domestic discharges due to increasing population and marine activities including sightseeing also contributed to nutrient enrichment in this area (He *et al*., 2005). The rapid expansion of mariculture and population resulted in a notable increase of DIN from 1.53 μmol/L in 1985 to 4.08 μmol/L in 1997 (Wang *et al*., 2008). Great changes in nutrient structure occurred as well, N:P ratios increased about 40-fold during the same time (Wang *et al*., 2004, 2008). It is known that small diatoms are more competitive at the high nutrient condition due to their high propagation rate (Riegman, 1995). As a result of eutrophication, the predominant species in Daya Bay switched from the large diatom genus *Rhizosolenia* (Zhou *et al*., 1998) to small chain-forming diatoms such as *Skeletonema*, *Pseudo-nitzschia*, *Chaetoceros* and *Thalassiosira* in this study.

Table 1 Bravais Pearson's correlation coefficients between phytoplankton and nutrients (df = 54)

	DIN	DIP	DSi	N:P	Si:N	Si:P
Phytoplankton	−0.075	−0.125	0.013	0.070	0.027	0.090
Diatoms	−0.076	−0.126	0.016	0.071	0.024	0.090
Dinoflagellates	−0.334*	−0.338*	−0.256*	0.061	0.030	0.072
Cyanobacteria	0.025	0.163*	0.046	−0.068	0.151	−0.072
Chaetoceros spp.	0.133	0.000	0.253*	−0.010	0.085	0.121
Pseudo-nitzschia spp.	−0.142	0.005	−0.121	−0.098	−0.023	−0.120
Skeletonema costatum	−0.057	−0.135	−0.082	0.052	−0.026	0.064
Thalassiosira subtilis	−0.018	−0.127	−0.042	0.322**	−0.051	0.215*

* $p < 0.05$, ** $p < 0.01$. DIN, DIP, DS are refered to Fig. 3.

The seasonal patterns and composition in phytoplankton were generally similar at the two stations. However, the abundances were much higher in St.1, a shellfishery area, than those in St.2, a fish cage area. As the predator to phytoplankton, shellfish produce predatory pressure (top-down effects) on the growth of phytoplankton and lead to the miniaturization of phytoplankton cells (Nakamura and Kerciku, 2000). Indeed, shellfish excrete organic sedimentary matters to bottom sediments and reduce the nutrient levels in water column, which decontaminate cultural environments to some extent (Gerritsen *et al.*, 1994). However, these sedimentary nutrients also provide a vital nutrient pool for phytoplankton growth. Although the DIN levels were slightly lower in St.1, DIP concentrations were higher, and DSi levels were much higher than those in St.2. The sufficient DSi concentrations in St.1 facilitated the growth of diatoms, causing the higher contributions of diatoms in the station. On the contrary, low transparency and large amounts of suspended matter in St.2 inhibited the growth of phytoplankton.

3.3 Nuclear Power Station and phytoplankton structure

The DNPS discharges large amounts of cooling water into the environments, resulting in an obvious increase in surface water temperature (SWT) of the surrounding area. The yearly mean SWT increased by 0.4–1.1°C after DNPS operation in 1994 (Tang *et al.*, 2003). The changes in SWT were more evident in winter months, increasing about 2°C from 16.04 to 18.03°C (Wang *et al.*, 2004).

The increasing of SWT together with the remarkable changes in nutrient composition exerted strong influences on the phytoplankton community structure. Previous data showed that the phytoplankton abundances were higher in spring and summer and lower in autumn and winter during the early 1990s (Zhou *et al.*, 1998). Increasing winter abundance has been observed since late 1990s (Liu *et al.*, 2006). In the present study, high and frequent population peaks occurred in winter months. Furthermore, species richness and diversity decreased after the introduction of DNPS (Wang *et al.*, 2003), and predominant species shifted from large *Rhizosolenia* to small *Skeletonema*, and flagellate species occurred more frequently (Wang *et al.*, 2004; Liu *et al.*, 2006).

High concentrations of *A. tamarense*, the primary cause of PSP, were observed in this study, with a maximum number of 603.0 cells/mL. To our knowledge, it was the first observation of such high concentration of *A. tamarense* in this area. Dapeng Cove has one of the highest PSP contents and experiences regular PSP episodes (Lin *et al.*, 1994, 1999), and *Alexandrium* cysts distributed widely and abundantly in the surface sediments from this area (Wang *et al.*, 2004). In previous phytoplankton studies, vegetative cells of *Alexandrium* were seldom observed in the water column through seasonal routine observation due to the long duration of sampling (Wei *et al.*, 2003, 2004; Li *et al.*, 2005; Liu *et al.*, 2006). However, peak abundance of *Alexandrium* was captured in this survey using a frequent sampling strategy. *A. tamarense* has a narrow tolerance

for growth temperature (ca. 15–25°C, with optimal growth at 17–22°C) (Yan *et al.*, 2002). After the operation of DNPS, winter temperatures have increased to favor the growth of *Alexandrium* (ca. 18–20°C). In addition, the winter dry season experiences low nutrient levels. The massive growth of diatoms exhausts nutrients not initially sufficient, particularly DSi. *Alexandrium* is competitively excluded by diatoms during nutrient depletion condition due to its higher nutrient affinities and capability to utilize organic nutrients (Collos *et al.*, 2007). The high abundance of *A. tamarense* indicated that the operation of DNPS exerts influences on the phytoplankton community and that it is partially responsible for the frequent occurrence of harmful species and high level of PSP toxins in the nearby area.

4 Conclusions

The phytoplankton community in Dapeng Cove was characterized by high species richness and abundance, and was dominated by small diatoms. While other non-siliceous groups such as dinoflagellate and cyanobacteria occurred more frequently and abundantly.

DIN was enriched greatly due to high loadings of mariculture and other human activities. DSi were sufficient and rarely limited for the growth of diatoms. However, DIP was deficient and was the most necessary element for phytoplankton growth.

The water temperatures and salinities in Dapeng Cove ranged within a threshold suitable for phytoplankton growth. And the eurythermal and euryhaline diatoms occurred abundantly throughout the year; however, other species reached the greatest abundance only within optimal temperature and salinity ranges.

The increasing of winter water temperature after the operation of the Daya Bay Nuclear Power Station together with the remarkable changes in nutrient composition resulted in the high production of phytoplankton and high abundance of toxic *A. tamarense* during the winter month.

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