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Monsoon-driven dynamics of environmental factors and phytoplankton in tropical Sanya Bay, South China Sea

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Key words: Environmental factors; Monsoon-driven dynamics; phytoplankton; bacterioplankton; Sanya Bay

Abstract

In this work, we analyze environmental (physical and chemical) and biological (phytoplankton) data obtained in Sanya Bay during four cruises, carried out in January, April, August, and October. The main objective of this study was to identify the key environmental factors affecting phytoplankton structure and bacterioplankton in the bay. Results suggest that spatial variations in the phytoplankton community and bacterioplankton biomass are the result of nutrients. Temporal variation in the abundance of bacterioplankton and phytoplankton are affected by a combination of physical and biological factors, such as temperature and nutrients. The silicate, phosphate, and nitrogen phytoplankton require for growth may be co-limited. Monsoon winds (a southwestern monsoon during summer and a northeastern monsoon during winter) play important roles in controlling the phytoplankton community and bacterioplankton abundance in Sanya Bay, northern South China Sea.

INTRODUCTION

Phytoplankton are the main primary producers in coastal ecosystems. A number of factors define phytoplankton abundance and community structure in coastal ecosystems, including salinity, temperature, light (influenced by turbidity), nutrients, and water dynamics (Brogueira et al. 2007). In addition, phytoplankton composition influences various processes such as nutrient recycling, grazing, particle sinking, and food webs (Cetinic et al. 2006).

Previous studies of Sanya Bay concerning phytoplankton composition identified distinct temporal and spatial distributions (Zhou et al. 2009, Yang et al. 2007). Zhou et al. (2009) found the spatial distribution patterns of phytoplankton and bacterioplankton biomass were very similar. The highest biomass was found in the Sanya River estuary and decreased seaward, primarily due to terrestrial input from the Sanya River and an influx of oceanic water. Yang et al. (2007) found that the annual variations in phytoplankton abundance in Sanya Bay showed an obvious two-peak cycle, with peaks of cell abundance in spring and autumn separated by the lowest abundance in summer. Abundance decreased towards the outer sea. However, there is no explanation for the influence of the hydrographic conditions on the composition and seasonality of the phytoplankton in Sanya Bay. The influence of environmental factors driven by southwest (SW) and northeast (NE) monsoons on variations in the phytoplankton standing stock has been demonstrated in the South China Sea (SCS) (Ning et al. 2004), but

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little is known about the environmental factors that regulate the community structure of phytoplankton in Sanya Bay, in particular.

The main objectives of this paper are to describe the phytoplankton species diversity and evenness, the spatial distribution and temporal variability in abundance, and to characterize the main environmental factors that control the distribution pattern of phytoplankton in Sanya Bay.

MATERIALS AND METHODS

Study area

Sanya Bay is situated south of Hainan Island (from 109°20' to 109°30'E, 18°11' to 18°18'N), with a water area of 120 km^2 and an average depth of 16 m. It is a typical tropical, permanently open bay. With rapid urbanization and development of the tourism industry, Sanya Bay has experienced increasing anthropogenic influences. It receives rainwater and the agricultural, domestic, and industrial sewage from the Sanya River, as well as nutrient enrichment and toxins from cage aquaculture (Huang et al. 2003). Dongmao Island, Ximao Island, and Luhuitou, located in the bay mouth, possess mostly coastal coral reefs. The Sanya River is located in the eastern part of the bay (length 31.3 km, drainage area 337 km^2, and annual flow of 2.11 × 10^9 m^3) (Huang et al. 2003). The warm, wet, southwest monsoon prevails in the wet season from April to September, bringing humid air from low latitudes, resulting in gentle monsoonal rainfall in spring and heavy rainfall in summer. In contrast, a cold, dry, northeast monsoon predominates in the dry season from October to March.

In order to evaluate the anthropogenic and natural influences in this area, 10 monitoring stations were located in Sanya Bay (Fig. 1).

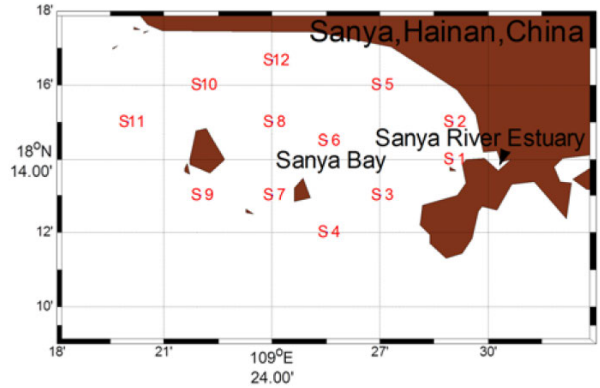

Fig. 1. Monitoring stations in Sanya Bay.

Sampling and chemical analyses

Water samples were taken at the surface and bottom layers of all stations at quarterly intervals in 2008. A Quanta® Water Quality Monitoring System (Hydrolab Corporation, USA) was employed to collect the data for temperature (T/°C), pH, and salinity (S/PSU) in the surface and bottom layers. Seawater samples for analysis of nutrients, chlorophyll *a* (Chl *a*), chemical oxygen demand (COD), and 5-day biochemical oxygen demand (BOD_5) were taken using 5-l GO FLO bottles at the surface and bottom layers. Additional samples from the surface and bottom layers were also collected according to the methods and sampling tools of "The specialties for oceanography survey" (GB12763-91, China). Water samples from the surface and bottom layers were analyzed for nitrate (NO_3-N/μmol l^{-1}), nitrite (NO_2-N/μmol l^{-1}), and silicate (SiO_3-Si/μmol l^{-1}) with a SKALAR auto-analyzer (Skalar Analytical B.V. SanPlus, Holland). Ammonium (NH_4-N/μmol l^{-1}) was analyzed using the hypobromite oxidation method. Phosphorus (PO_4-P/μmol l^{-1}) was analyzed using the molybdophosphoric blue oxidation method. For total nitrogen (TN/μmol l^{-1}) and total phosphorus (TP/μmol l^{-1}) measurements, samples were first digested with potassium persulfate and heated in an autoclave for 30 minutes before analysis. Dissolved inorganic nitrogen (DIN/μmol l^{-1}) was the sum of nitrate, nitrite, and ammonia. Dissolved oxygen (DO/mg l^{-1}) was determined using the Winkler titration method. The saturation dissolved oxygen (Sat DO) was calculated based on DO content. Phytoplankton were sampled with a standard Shallow III Microplankton Net (diameter 37 cm, mesh fiber JF62, mesh size 0.077 mm) that was hauled vertically from the bottom to the surface layer, strictly following the standard method (China State Bureau of Technical Supervision). Samples were mixed with buffered formaldehyde to obtain a final concentration of 2.5%. Enumeration and identification of phytoplankton were performed using an Olympus BX51 Inverted Microscope (Olympus, Japan). Bacteria were counted using the 4',6-diamidino-2-phenylindole (DAPI)-staining with DNA intercalating dye technique (DAPI). For details refer to (Zhou et al. 2009). The water quality parameters, their units, and analytical methods are summarized in Table 1.

Table 1

Water quality parameters, their units, and analytical methods.

Parameter	Unit	Surface				Bottom			
		min	max	mean	SD	min	max	mean	SD
Bacterioplankton Abundance (BA)	$\times 10^6$ cell ml^{-1}	0.3738	3.2102	0.9375	0.5596	0.3251	3.1539	0.8629	0.5352
Bacterioplankton Biomass (BB)	μg C l^{-1}	7.4752	64.2050	18.7498	11.1923	6.5024	63.0780	17.2576	10.7046
DO	mg l^{-1}	6.0200	7.2800	6.8135	0.2671	5.9100	7.4000	6.7448	0.3076
Chl *a*	μg l^{-1}	0.2788	3.8540	1.2152	0.8553	0.2698	3.1314	1.4942	0.7259
Temperature	°C	23.5200	29.6300	26.8894	1.8861	23.4500	28.3700	25.7373	1.7020
Salinity	PSU	32.8000	34.7800	34.2492	0.3525	33.4000	34.7500	34.2779	0.3025
Suspended Particulate Matter	mg l^{-1}	4.3000	22.8000	10.2458	5.1518	3.9000	32.2000	13.0000	7.2181
pH		7.9800	8.2500	8.1650	0.0444	7.9800	8.2700	8.1573	0.0436
SiO_3-Si	μmol l^{-1}	2.0895	8.6786	3.1123	1.0856	2.0895	4.3654	2.8449	0.4794
PO_4-P	μmol l^{-1}	0.0103	0.4658	0.1481	0.1102	0.0103	0.6665	0.1602	0.1227
NO_2-N	μmol l^{-1}	0.0328	1.8634	0.2007	0.2956	0.0328	1.1071	0.2011	0.2190
NH_4-N	μmol l^{-1}	0.2775	7.9514	1.3163	1.4495	0.3819	4.1129	1.0094	0.6821
COD	mg l^{-1}	0.3500	8.9200	1.3150	1.2702	0.1800	8.7600	1.2471	1.3050
BOD_5	mg l^{-1}	0.0200	1.0700	0.4110	0.2686	0.0100	1.0300	0.3702	0.2533
TP	μmol l^{-1}	0.0445	0.5662	0.2691	0.1246	0.0787	0.7334	0.2730	0.1372
TN	μmol l^{-1}	22.3362	630.5938	77.2542	95.0840	23.4518	249.3521	62.0024	42.1370

Data analysis

Multivariate methods were applied to analyze the data. A logarithmic transformation (log (x+1)) was used on the phytoplankton density and bacterioplankton abundance to obtain the normal distribution. Canonical Correspondence Analysis (CCA) was used to display relationships between the environment and phytoplankton.

All mathematical and statistical computations were performed using MATLAB 6.5 (Mathworks Inc., USA).

RESULTS

Physical parameters

The water temperature ranged between 23.45°C and 29.63°C during the study period. The mean water temperature of the surface and bottom layers was 26.89°C and 25.74°C, respectively. The surface temperature exhibited a clear seasonal variation in the bay (Fig. 2), with the lowest temperatures (23.52°C) in winter and the highest (29.63°C) in summer. The horizontal distributions of the surface and bottom temperatures were similar during the study periods, decreasing from the northern and eastern parts of the bay to the south. The differences between the surface and bottom temperatures were insignificant in winter (mean 0.15°C), spring (mean 1.58°C), and autumn (mean 0.08°C). The mean difference between the surface and bottom temperature was 2.81°C in summer.

Stratification in summer was well developed due to the temperature and salinity differences between the surface and the bottom waters (Fig. 2c). As reported by others (Huang et al. 2003), we also found that the bay was affected by cold water upwelling during summer. In contrast, strong vertical mixing occurred in the bay in winter and autumn (Figs 2a and d). The salinity varied slightly from 32.80 to 34.78 PSU.

Nutrients

The concentrations of both PO_4-P and SiO_3-Si were low (0.15 μmol l^{-1} and 2.98 μmol l^{-1}) in the bay (Table 1). The horizontal distribution of NH_4-N concentration at the surface revealed that the NH_4-N concentration decreased from inshore to offshore waters, and was lowest in spring (Fig. 3). In general, NH_4-N concentrations were low (1.27 μmol l^{-1}). Both PO_4-P and SiO_3-Si decrease in concentration from inshore to offshore waters (not shown), diminishing with increasing distance from land and the freshwater discharges of the Sanya River.

Phytoplankton

Chlorophyll a (chl *a*) in Sanya Bay ranged from 0.27 to 3.85 mg l^{-1} and averaged 1.35 mg l^{-1}. The means of chl *a* in winter, spring, summer, and

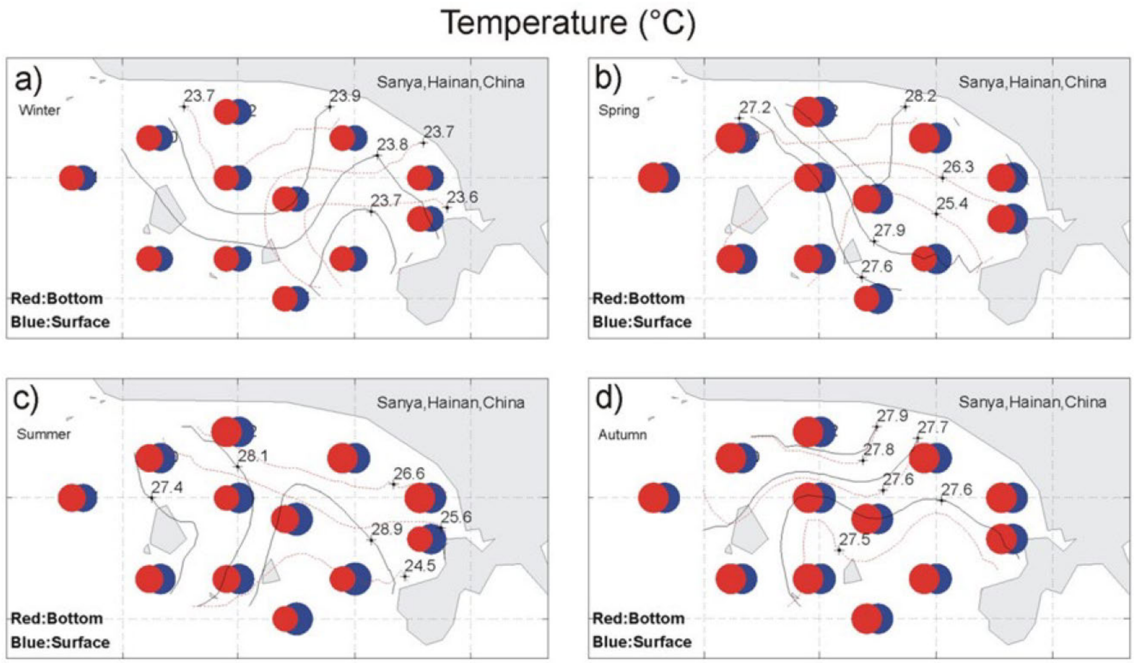

Fig. 2. The spatial distribution of surface and bottom temperatures in four seasons.

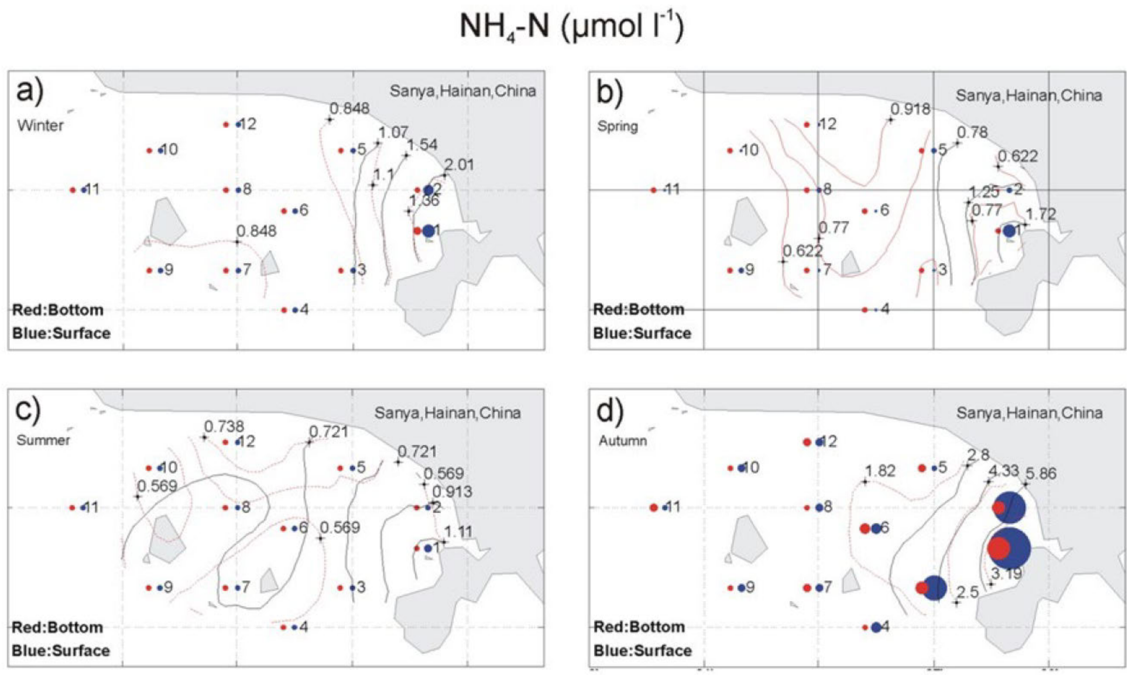

Fig. 3. The spatial distribution of surface and bottom NH_4-N concentrations in four seasons.

autumn were 1.35, 1.08, 1.19, and 1.79 μg l^{-1}, respectively. Chl *a* was highest in the Sanya River estuary, and decreased offshore (Fig. 4). Chl *a* was more prevalent in the surface layer than in the bottom layer, except in summer (Fig. 4c).

Bacterioplankton

The annual mean Bacterioplankton Abundance (BA) and bacterioplankton biomass (BB) were 9.00 $\times 10^5$ cells ml^{-1}, and 18.00 μg C l^{-1}, respectively, and the surface layer was higher than the bottom layer.

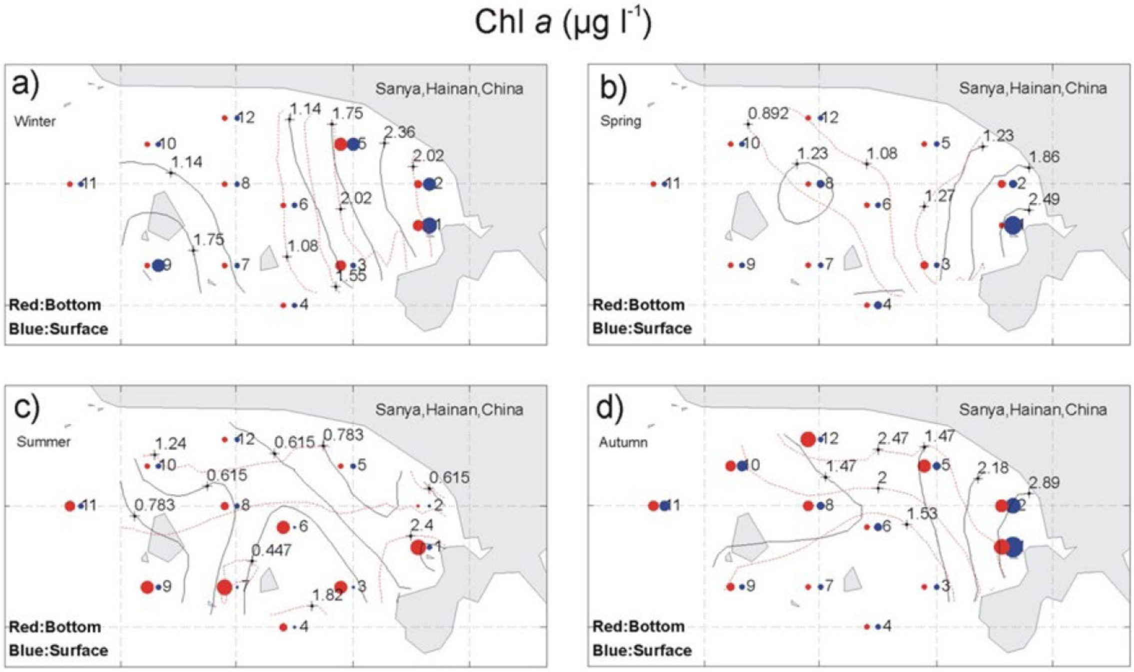

Fig. 4. The spatial distribution of surface and bottom Chl *a* concentration in four seasons.

The means of BA in winter, spring, summer, and autumn were 1.33 $\times 10^5$, 1.33 $\times 10^5$, 1.45 $\times 10^5$, and 3.09 $\times 10^5$ cells ml^{-1}, respectively. The means of BA and BB at monitoring station S1 were 1.86 $\times 10^6$ cells ml^{-1}, and 37.32 μg C l^{-1}, respectively.

The seasonal horizontal distribution pattern of bacterioplankton abundance and biomass was similar to that of chl *a* (Fig. 5 and Fig. 6). The highest abundance appeared near the river mouth (S1), with decreasing concentrations from the eastern to the western part of the bay.

Canonical correspondence analysis

Canonical correspondence analysis (CCA) was used to find relationships between the phytoplankton community, bacterioplankton biomass, and environmental factors. Eigenvalues (indicating strength of the model) for the first two multivariate axes were 0.367 (CCA1) and 0.297 (CCA2). The sum of all canonical eigenvalues was 0.72. The first two CCA axes account for 45% of the total variance with the first axis alone explaining 25%, indicating a strong gradient in the data set. Each variable is represented by an arrow, which determines an axis (Fig. 7a).

The parameter lines were obtained from the factor loadings of the original variables. They stand for the contribution (significance) of the parameters to the samples. The closer two parameter lines lie together, the stronger the mutual correlation is. COD, NO_3-N and PO_4-P are positively correlated with cyanobacteria and diatoms. Temperature was mostly negatively correlated with cyanobacteria and diatoms. The temporal variations of the samples in the bay are clearly evident. A cluster of the samples in winter is characterized by high PO_4-P and SiO_3-Si (Fig. 7b). A cluster of the samples in autumn is characterized by high BA (Fig. 7a, b). The average scores of the samples are shown in Fig. 7c. The monitoring station (S1) is characterized by TN and TP in CCA1, and high NH_4-N, PO_4-P and SiO_3-Si in CCA2, respectively (Fig. 7). As mentioned before, external pollution from land sources is introduced into the bay by river, runoff, and rain.

Discussion

Spatial variability

Sanya Bay is a typical, tropical, permanently open bay, with no major rivers but two minor ones (Sanya River and Shaoqi River). The salinity of the bay varied slightly from 32.80 to 34.78 PSU. The annual salinity at stations S1 and S12 was insignificantly different from that at other monitoring stations by one-way analysis of variance ($p>0.05$). To a certain extent, fresh water from the Shaoqi and Sanya Rivers

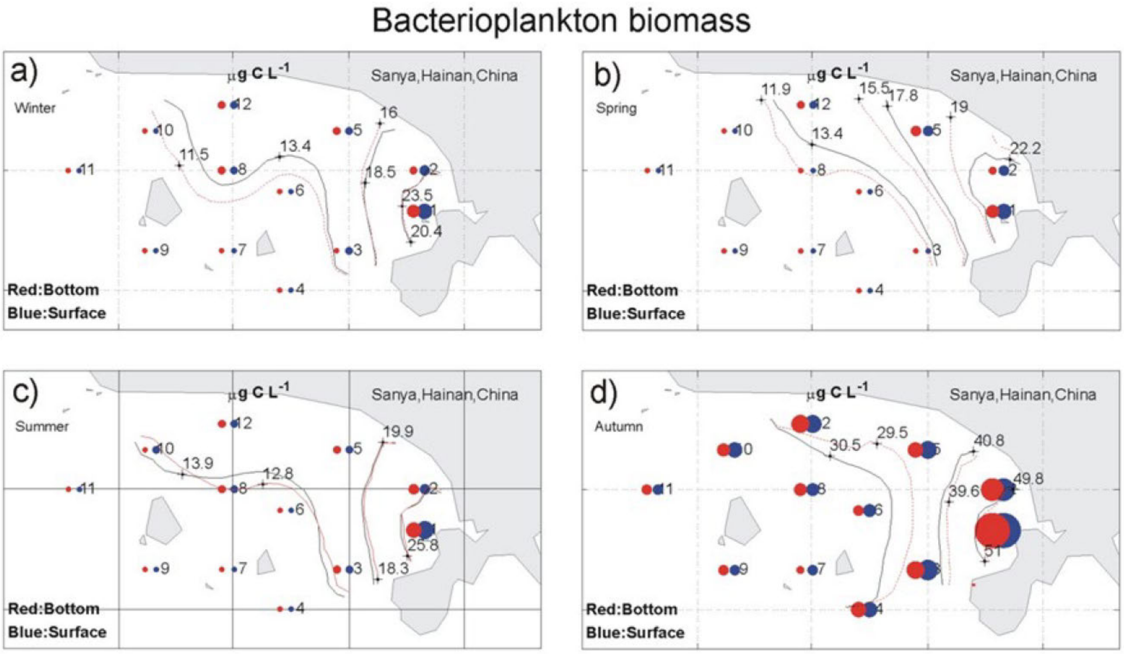

Fig. 5. The spatial distribution of bacterioplankton biomass in four seasons.

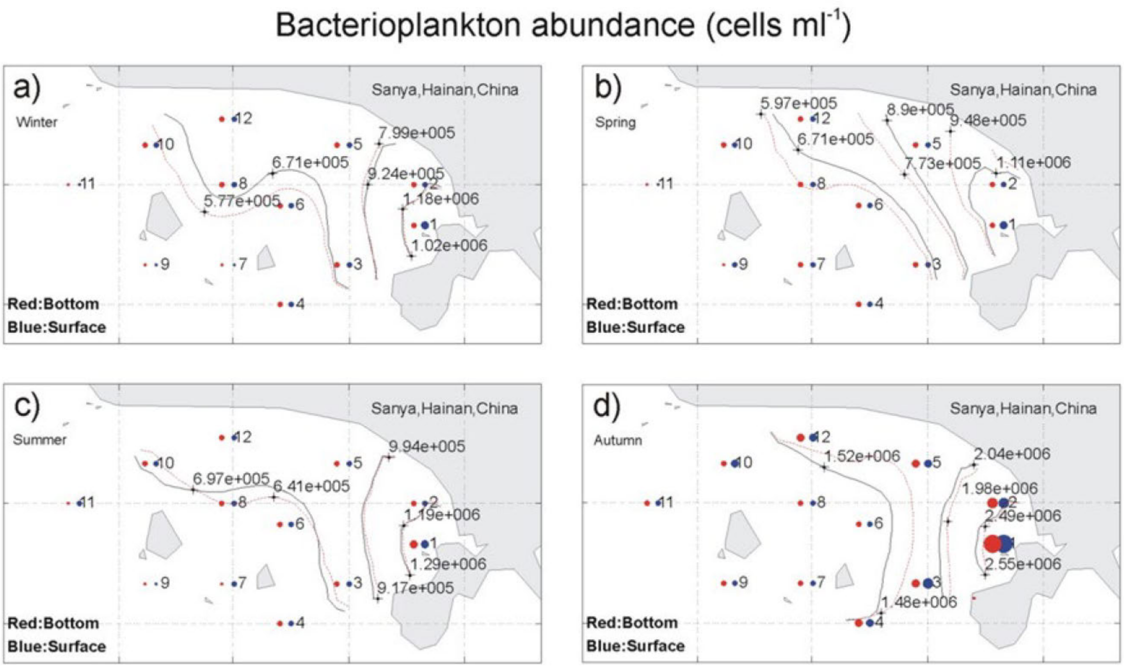

Fig. 6. The spatial distribution of bacterioplankton abundance in four seasons.

diminishes the surface salinity in the waters adjacent to their mouths. Sanya Bay and the South China Sea mainly exchange waters with each other. Therefore, the water in South China Sea is an important influence on Sanya Bay.

The average concentrations of nutrients show similar spatial variations, decreasing from the eastern and northern to the southern and western parts of the bay (Fig. 3). Domestic and industrial wastewater discharge enters the Sanya River, and then the bay. Station S1 was clearly influenced by the domestic wastewater and freshwater runoff from Sanya River (Dong et al. 2010). Both PO_4-P and SiO_3-Si concentrations decrease from east to west, probably as a result of the effects of land sources and the Sanya River (Huang et al. 2003). Nutrient

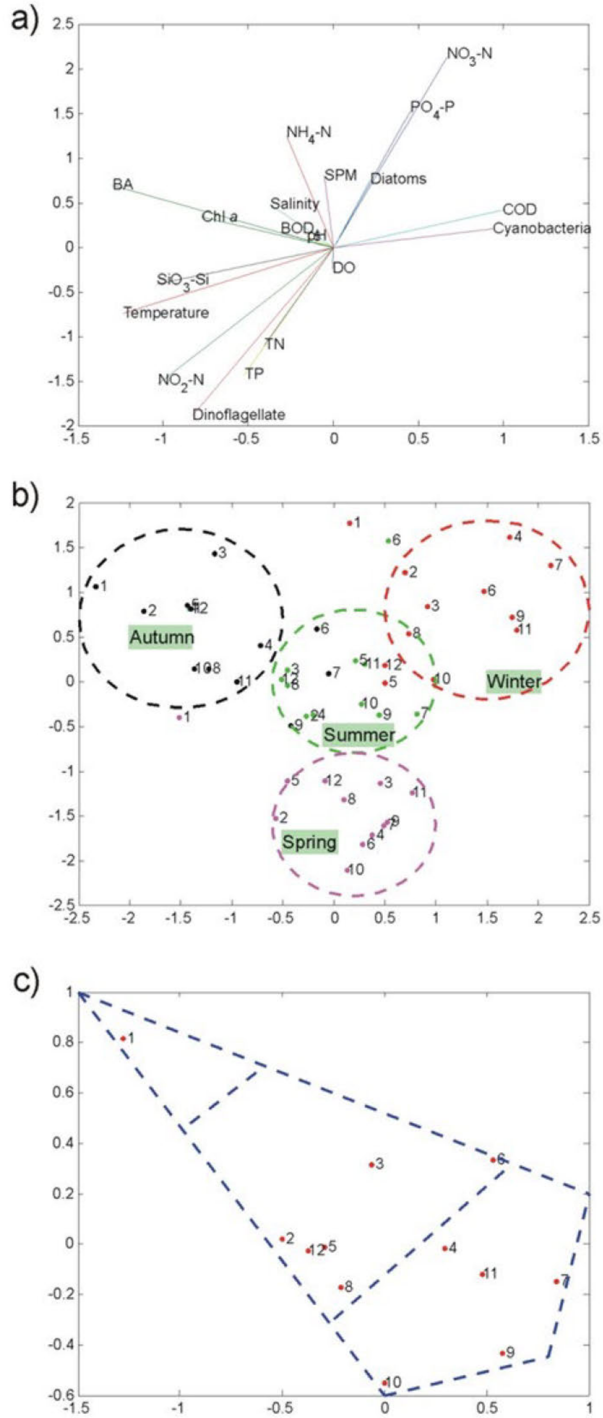

Fig. 7. Ordination diagram displaying first and second axis of CCA. (a) the environmental variables are displayed as arrows; (b) temporal pattern of samples, depending on the cluster analysis affiliation; (c) spatial pattern of samples, depending on the cluster analysis affiliation.

concentrations increased shoreward and clearly demonstrated the impact from the terrestrial input and the Sanya River (Zhou et al. 2009). These results showed that human activities have an important effect on water quality in the bay. In addition, the concentrations of both PO_4-P and SiO_3-Si decrease from the mouth of Sanya River to offshore waters, probably because the nutrient concentration (pollution) from the Sanya River becomes more diluted as one moves farther from the mouth of the river.

Nutrients are considered one of the major factors controlling the composition and abundance of the phytoplankton community. It has been generally thought that DIN and SiO_3-Si play important roles in the population dynamics of phytoplankton.

The distribution of bacterioplankton and phytoplankton biomass gradually decreased from the mouth of the Sanya River to the open coastal waters. The main terrestrial nutrient source for the bay was the Sanya River, which directly controls the distribution of bacterioplankton and phytoplankton biomass. This significantly demonstrated the fact that the influence of land-based nutrient sources to the biomass distribution pattern was diluted by seawater. SiO_3-Si and PO_4-P had a highly significant correlation with bacterioplankton biomass ($p<0.05$). Nutrient concentration correlated significantly with bacterioplankton biomass (Zhou et al. 2009).

Results from CCA also showed the spatial characters of ecological and environmental factors (Fig. 7). Station S1 was quite different from the other station in terms of higher concentrations of nutrients, probably due to the proximity of anthropogenic activity. Station S1, located at the mouth of the Sanya River estuary, received the most domestic and industrial sewage. In this case, anthropogenic pollution is mainly estimated by a high concentration of nutrients, compared with the outer bay. The inner bay stations (S2, S3, S5, S6, S8 and S12) are close to the center of Sanya City. Thus, human activities and the Sanya River may also have an important influence on these stations, due to the sea current. The concentrations of nutrients were comparatively lower than those at S1 and higher than at outer bay stations (S4, S7, S9, S10 and S11).

Results from CCA also showed that bacterioplankton biomass positively correlated with TN, SiO_3-Si, and NO_2-N. Dinoflagellates were negatively related to PO_4-P and NO_3-N in CCA1, and positively to SiO_3-Si in Fig. 7.

The CCA extracted a typical seasonal pattern for environmental factors, bacterioplankton, and phytoplankton abundance. Dinoflagellates are positively influenced by TN, TP, SiO_3-Si and NO_2-N concentrations and negatively influenced by PO_4-P and NO_3-N concentrations.

Cyanobacteria species *Trichodesmium erythraeum* and *Trichodesmium thiebautii* were predominant in winter and spring. *Trichodesmium,* a planktonic, nitrogen-fixing cyanobacterium, is particularly abundant and occurs in tropical and sub-tropical seas where it contributes a major fraction of the new nitrogen input to the oligotrophic surface waters (Capone et al. 1997). A significant positive correlation was seen between *Trichodesmium* biomass and water temperature in the coastal waters of Tanzania (Lugomela et al. 2002). However, no relationship with seawater temperature could be established for the outer bay in Sanya Bay (Dong et al. 2008). Generally, monsoons play a significant role in the distribution of *Trichodesmium* in Sanya Bay (Dong et al. 2008). *Trichodesmium* was the predominant species in spring and summer, and comprised 16% and 10% of the total cells, respectively (Zhou et al. 2009). The results confirmed that the surface water temperature played little or no role in limiting *Trichodesmium* growth when it was above 25°C in the South China Sea (Chen et al. 2003). In this study, a significant negative correlation was seen between *Trichodesmium* biomass and water temperature in Sanya Bay. Thus, temperature may not be the limiting factor for *Trichodesmium* growth in Sanya Bay.

In laboratory studies, *Trichodesmium* spp. can utilize low levels (Carpenter and McCarthy 1975) and sometimes high levels (Saino and Hattori 1978) of nitrogenous compounds such as NO_3-N, NH_4-N, and organic N in culture mediums. Nitrate was not the limiting factor for the growth of *Trichodesmium thiebautii* and *T. erythraeum* (Ohki et al. 1986).

Trichodesmium is capable of hydrolyzing dissolved organic P (DOP) compounds and the inorganic products from hydrolysis may provide an additional source of P for growth. DOP may represent an important P source for *Trichodesmium* growth (Mulholland et al. 2002).

Temporal variability

In this region, the Southeast Asian monsoons, northeasterly from October to April and southwesterly from May to September, have important effects on biogeochemical cycles in South China Sea waters (Chen et al. 2006).

The average sea surface temperature was higher in spring (27.85°C), summer (28.22°C), and autumn (27.66°C) than in winter (23.82°C), with significant difference by one-way analysis of variance ($p<0.01$). The inverse relationship between temperature and DO is a natural process because warm water easily becomes saturated with oxygen, and thus, can hold less DO.

The average salinity at the surface was 34.51, 34.23, 34.16 and 34.10 PSU in winter, spring, summer, and autumn, respectively. The lowest salinity appeared in autumn and the highest appeared in winter (Zhou et al. 2009). Salinity was high in the bay all year, with an annual average of 34.26. The salinity varies from 33.0 to 34.5 PSU in the South China Sea (Han 1998). The salinity in the bay waters lies in this range. Sanya Bay waters are refreshed by an influx of water from the South China Sea.

The seasonal variation in chl *a* was in the following order from the highest to the lowest: autumn, winter, summer, and spring with averages of 1.79, 1.35, 1.18, and 1.08 mg l^{-1}, respectively. The chl *a* concentration in Sanya Bay waters appears to be related to seasonal exchange.

The chl *a* concentration in the surface layer was lower than in the bottom layer in summer (Fig. 4). The stable water in summer can help release nutrients from the sediment to the overlying water, supplying algal growth in the bottom layer (Wang et al. 2003). In addition, the bay is also affected by cold-water upwelling June through August (Huang et al. 2003, Dong et al. 2002).

Sanya Bay is a shallow water bay with an average depth of 16 m. Transparency could reach the depth of 6.1 and 7.0 m. There was sufficient sunlight for phytoplankton in the bottom layer to carry out photosynthesis because sunlight could pass through the whole water column. Light was not the limiting factor for phytoplankton growth.

Temperature played a major role in regulative functions and became the main regulating factor for phytoplankton and bacterioplankton growth. Results from CCA showed that bacterioplankton biomass and dinoflagellates were positively correlated with temperature. Diatoms and cyanobacteria were negatively correlated with temperature (Fig. 7).

NH_4-N concentration was lower in summer than in any other month. It had a strong influence on the biology. Cold, high-salinity waters permeated the bottom of the bay, forming a thermocline. It hampered the exchange of nutrients between the surface and bottom (Dong et al. 2002).

The concentrations of PO_4-P, SiO_3-Si, NO_3-N, NO_2-N and NH_4-N in the surface layer in the South China Sea were 0-0.4, 0-5, 0-0.5, 0-0.1, and 0-0.9 μmol l^{-1}, respectively (Han 1998). Average concentration ranges of total dissolved inorganic nitrogen, PO_4-P and SiO_3-Si in Sanya Bay were 3.038-4.907, 0.140-0.195 and 18.57-31.25 μmol l^{-1} during 1999-2002, respectively (Wang et al. 2006). Thus, Sanya Bay is an oligotrophic body of water. Therefore, the water in the northern South China Sea very clearly influences Sanya Bay.

The atomic Si:N:P ratio of marine diatoms is about 16:16:1 when nutrient levels are sufficient (Brzezinski 1985, Redfield et al. 1963). Deviations from this ratio either in nutrients taken up, or available in the water column in a dissolved form, indicate potential for N, P, or Si limitation of phytoplankton growth (Hecky and Kilham 1988, Dortch and Whitledge 1992). The concentrations of dissolved Si = 2.0 μM, DIN = 1.0 μM and dissolved P (reactive P) = 0.1 μM were selected as threshold values.

The silicate, phosphate, and nitrogen for the growth of phytoplankton may be co-limited (Fig. 8). Phosphate was a limiting factor in the growth of phytoplankton during the wet season, and nitrogen was a limiting factor during the dry season (Wang et al. 2002). Phytoplankton growth was significantly controlled by environmental factors, such as temperature and nutrients.

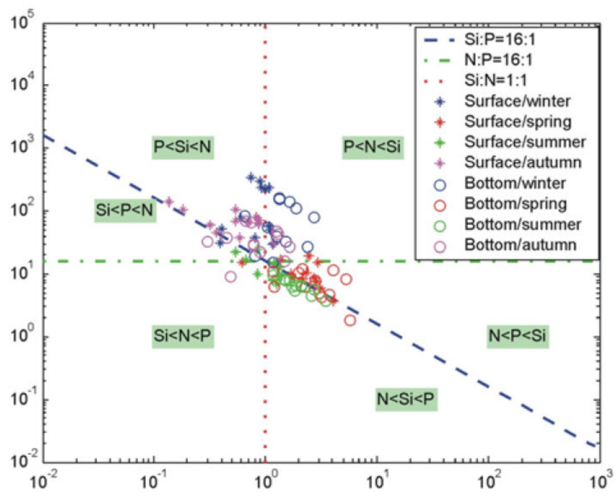

Fig. 8. Scatter diagrams of the Si:N:P atomic nutrient ratios in the water column in four seasons. Molar quotients between the concentrations of potentially limiting nutrients are delimited in this logarithmic plot (log Si:N vs. log N:P) by the Si:N=1, N:P=16, and Si:P=16 lines, which define six different areas within the plot, with each one characterized by the potentially limiting nutrients in order of priority. In this case, N denotes DIN, P denotes PO_4-P, and Si denotes SiO_3-Si.

CONCLUSION

Results suggest that spatial variations in the phytoplankton community and bacterioplankton biomass are the result of nutrients, while temporal variation in the abundance of bacterioplankton and phytoplankton are affected by a combination of physical and biological factors, such as temperature and nutrients. Silicate, phosphate, and nitrogen may co-limit phytoplankton growth. In conclusion, monsoon winds were shown to play important roles in controlling the phytoplankton community and bacterioplankton abundance in Sanya Bay, northern South China Sea.

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