Chinese Journal of Oceanology and Limnology
Vol. 27 No. 1, P. 22-30, 2009
DOI: 10.1007/s00343-009-0022-2

Spatial and temporal variations of *Synechococcus* and picoeukaryotes in the Taiwan Strait, China*

HUANG Bangqin (黄邦钦)**, LIN Xueju (林学举), HONG Huasheng (洪华生)
State Key Laboratory of Marine Environmental Science and Environmental Science Research Center, Xiamen University, Xiamen 361005, China

Received Aug. 7, 2008; revision accepted Sept. 1, 2008

Abstract The size-fractionated phytoplankton biomass, and the spatial and temporal variations in abundance of Synechococcus (SYN) and picoeukaryotes (PEUK) were measured in the Taiwan Strait during three cruises (August 1997, February-March 1998, and August 1998). The results show that picophytoplankton and nanophytoplankton dominate the phytoplankton biomass, in average of 38% and 40%, respectively. SYN and PEUK varied over time in abundance and carbon biomass, greater in summer than in winter, in range of (7.70–209.2)×10^6 and (0.75–15.4)×10^6 cells/cm^2 in the abundance, and 1.93–52.3 and 1.57–32.4 μgC/cm^2 in the carbon biomass, for SYN and PEUK, respectively. The horizontal distributions of both groups were diurnal but heterogeneous in abundance, depending on the groups and layer of depths. Temperature is the key controlling factor for picophytoplankton distribution (especially in winter) in the Strait.

Keyword: *Synechococcus*; picoeukaryotes; picophytoplankton; spatial and temporal variations; the Taiwan Strait

1 INTRODUCTION

Picophytoplankton, including cyanobacterium *Synechococcus*, picoeukaryotes, and *Prochlorococcus*, has been found ubiquitously in the tropical, subtropical, and temperate, as well as Antarctic waters (Stockner and Antia, 1986; Stockner, 1988; Ning et al., 1996; Campbell et al., 1997; Jiao et al., 2002; Tsai et al., 2008). It is a major contributor to phytoplankton biomass and productivity, accounting for up to 80% in tropical ocean (Li et al., 1983), and 60%–80% in subtropical waters (Platt et al., 1983; Takahashi and Bienfany, 1983). It has also a high turnover rate (Huang et al., 1995, Wang et al., 1997) in nutrients cycling. Therefore, it plays a critical role in carbon and nutrient cycling in an aquatic ecosystem, especially in oligotrophic waters.

The Taiwan Strait (Fig.1, 21–27°N, 116–122°E), located in southeastern coast of China connecting East China Sea and South China Sea with dynamic water exchange. Under the influence of subtropical monsoon and irregular bottom topography, upwelling well develops in coastal waters in summer, and in the Taiwan Bank, throughout the year (Hong et al., 1991; Liang, 1997), as well as several other currents such as the China Coastal Current (CCC, sometime called Zhejiang-Fujian Alongshore Current), South China Sea Warm Current (SCSWC), and intruded Kuroshio (IK) branch in this region (Hong et al., 1991; Jan et al., 2002). Several important fishing grounds are formed in the Strait such as the Central Fujian and South Fujian-Taiwan Bank Fishing Grounds (Hong et al., 1991). Recent studies on the Taiwan Strait show that phytoplankton community is highly productive and diverse (Huang et al., 1991; Li and Wang, 1991). Picophytoplankton (0.2–3 μm) dominates in the southern Taiwan Strait, while nanophytoplankton (3–20 μm) prevails in the northern Taiwan Strait (Huang et al., 1999). Chen (2006) addressed the diversity of ultraphytoplankton using small subunit ribosomal RNA. Other researchers measured the picoplankton abundance using flow cytometer during cruises between 2004-2007 (Chen et al., 1998; Jiao et al., 2002; unpublished data). Preliminary studies report that microbial loop may play an important role in carbon and nutrient cycling (Hong et al., 1997; Huang et al.,

---

*Supported by Natural Science Foundation of China (No.40730846; 40521003)

** Corresponding author: bqhuang@xmu.edu.cn

1997). The objectives of this study are to examine the spatial and temporal distribution of *Synechococcus* and picoeukaryotes in the Taiwan Strait, and to determine possible controlling environmental factors, for better understanding the microbial food web and microbial ecology in this area.

2 MATERIALS AND METHODS

2.1 Sampling

Investigations were conducted in the Taiwan Strait (21–27°N, 116–122°E) in three cruises in summer 1997 (August 1997, A1-A8), in winter 1998 (February-March 1998, B1-B10), and summer 1998 (August, 1998, T1-T15). Fig.1 shows the positions of sampling stations in the Taiwan Strait. As the sampling locations differed among the cruises, central Taiwan Strait was chosen for comparing the seasonal variation (see Table 3 for the stations in the central Strait). Physical, chemical and biological oceanographic parameters were measured simultaneously. Daily variations (48 h) of *Synechococcus* and picoeukaryotes were monitored at stations of A2 (summer time, southern Taiwan Strait, STS) and B4 (winter time, northern Taiwan Strait, NTS) at sampling time intervals of 6 and 3 h, respectively. Water samples were taken with 5 L Niskin bottles at depths of 0, 10, 20, 30, 50, and 70 m.

Temperature and salinity were recorded with General Oceanic Sea Bird SBE 19 CTD. Nutrients (phosphate, nitrate and silicate) were measured using a standard analysis method (Parsons et al., 1984).

2.2 Size-fractionated chlorophyll *a*

Phytoplankton is divided into three size categories in this study, named microphytoplankton (20–200 μm), nanophytoplankton (2–20 μm) and picophytoplankton (0.2–2 μm). Water samples were fractionated by filtering with a 20 μm mesh, 2 and 0.2 μm polycarbonate Nuclepore filters (Costar®), respectively (Wang et al., 1997). The chlorophyll *a* (Chl-*a*) content was determined by fluorescence analysis (Parsons et al., 1984), using Hitachi 850 Fluorospectrometer in excitation and emission wave length at 430 nm and 670 nm.

Contribution of each size phytoplankton was calculated from the corresponding Chl *a* divided by total Chl-*a*.

2.3 Enumeration by fluorescence microscopy

2.3.1 Preparation of slide

The samples were treated mainly according to Booth (1993), and MacIsaac and Stockner (1993). Seawater samples (18 ml) with 2 ml 2% paraformaldehyde (Sigma) (final conc. 0.2%) were kept for 1 h in dark at low temperature (<4°C). Subsamples were then filtered (5–10 ml, depending on the abundance) on polycarbonate Nuclepore filters (black) (Costar®) at vacuum pressure less than 100 mmHg (13.3 kPa). The filters were moved and placed on glass slides, and then immersed with a drop of non-fluorescent immersion oil. The slides were covered with coverglass, kept in the refrigerator (ca. 4°C) for 24–48 h, and stored in freezer (< -20°C) until analysis.

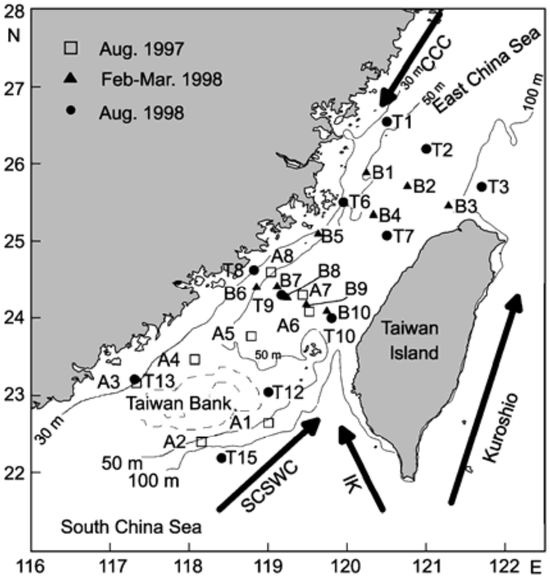

Fig.1 Sampling stations in the Taiwan Strait (CCC: China Coastal Current; SCSWC: South China Sea Warm Current; IK: Intruded Kuroshio)

Enumeration and identification of *Synechococcus* and picoeukaryotes were done according to Booth (1993) and MacIsaac and Stockner (1993), based on different colors of picophytoplankton after fluorescent excitation. In this study, we used Zeiss Aixoskop Fluorescent Microscopy equipped with 100 W mercury lamp, filters set of violet-blue (410–490 nm, OMEGA #XF18) and green (510–560 nm, Zeiss #487914). *Synechococcus* and picoeukaryotes were then identified and enumerated by switching the filter sets. Randomly 20–30 microscope fields were counted, and the sum was used to estimate the abundance.

2.3.2 Carbon biomass calculation

The biomass of *Synechococcus* and picoeukaryotes can be calculated from its abundance multiplied by its carbon conversion. The carbon conversion factors are 0.25 pg C/cell for *Synechococcus* (Kana and Gilbert, 1987), and that for picoeukaryotes is based on relationship between carbon content of non-diatom eukaryotic algae and cell volume (Strathmann, 1967):

$$\text{Log } C = 0.866 (\text{Log } V) - 0.460$$

where, C is cell carbon content (pg C/cell) and V cell volume (μm^3).

In this study, picoeukaryotes were counted within 1–3 μm. We assumed that the mean diameter is 2.5 μm (Li et al., 1992), and average volume (by quasi-sphere) is 8 μm^3. Therefore, the carbon conversion factor for picoeukaryotes was set at 2.10 pg C/cell.

2.3.3 Data analysis

One-way ANOVA was used to examine whether seasonal variation was significant or not, and check which environmental factors affected the picophytoplankton significantly. Prior to analysis, data were tested for normality and homogeneity of variation. All tests were performed using SPSS (Version 10.0, 1999). Figures were made using Surfer 8 and SigmaPlot (8.0).

3 RESULTS

3.1 Feature of hydrology

At depth of 10 m, temperature and salinity in the study area varied between 24.3–28.4°C and 32.5–33.8 in August 1997, respectively. The lower temperature (<26°C) and higher salinity (>33.5) were indicated in the southwest coast of the Strait, which was influenced by summer upwelling driven by southwesterly (SW) monsoon (Fig.2). In February-March 1998, temperature and salinity varied between 11.7–22.9°C and 29.1–35.1, respectively. The lower temperature (<15°C) and salinity (<31) were indicated in west coast of the Strait, which was influenced by the China Coastal Current in wintertime (Fig.2); higher temperature (>20–21°C) and salinity (≥35) were indicated in the east coast of the Strait, which was influenced by the intruded Kuroshio branch (Hu et al., 1999) (Fig.2). In August 1998, temperature and salinity varied from 22.0–29.2°C and 33.4–34.6, respectively. While temperature of the west coast of the Strait was lower than that of the east coast, salinity on the west coast was higher than that on the east coast (Fig.2). Waters in lower temperature and higher salinity appeared on the west coasts of the Strait, which seemed to be influenced by summer upwelling driven by southwesterly (SW) monsoon (Li et al., 2000). Therefore, the China Coastal Current, intruded Kuroshio branch, and upwelling significantly affected the hydrological features in the study area (Hong et al., 1991; Liang, 1997).

3.2 Size-fractionated phytoplankton biomass

Picophytoplankton and nanophytoplankton dominated the phytoplankton biomass in the three cruises, in average of 38% and 40%, respectively (Table 1). In the central Taiwan Strait in which seasonal comparison was made, data show that there are different variation patterns with phytoplankton fractions. For Chl-*a*, both picophytoplankton and nanophytoplankton in August 1997 are significantly lower than those in February-March 1998. However, no significant difference between those of August 1997 and 1998 was found (Fig.3). Microphytoplankton in August 1998 is significantly higher than those in August 1997 and February-March 1998, but similar between August 1997 and February-March 1998 (Fig.3). The contributions to total phytoplankton

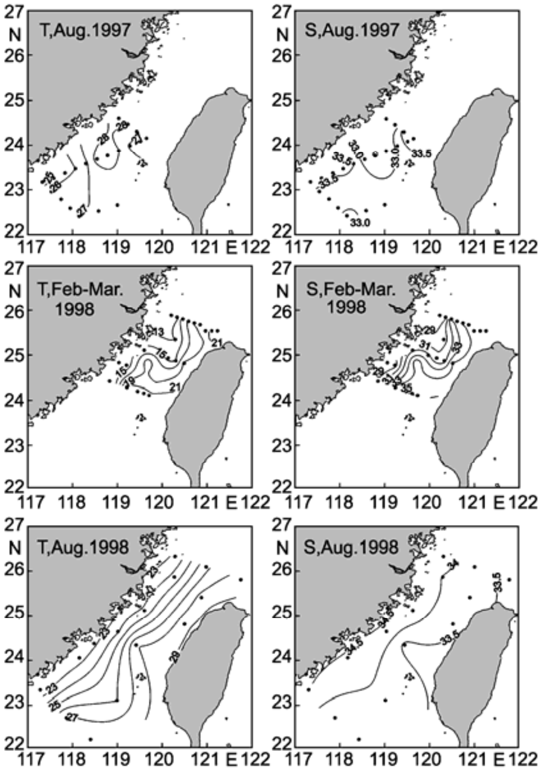

Fig.2 Horizontal distribution of temperature and salinity at 10 m depth in the Taiwan Strait (T, temperature, S, salinity)

Table 1 Variations of total phytoplankton chlorophyll *a* (Chl-*a*) **biomass and contributions of three categories of phytoplankton in the Taiwan Strait** (mean (standard deviation))

Date	Chl-*a* (mg/m^3)	PICO (%)	NANO (%)	MICRO (%)	n
Aug., 1997	0.71 (1.1)	34 (25)	47 (23)	19 (22)	144
Feb.-Mar., 1998	0.70 (0.54)	40 (25)	40 (20)	20 (21)	156
Aug., 1998	0.68 (0.69)	39 (20)	34 (21)	27 (20)	53

Note: PICO, picophytoplankton (0.2–2 μm); NANO, nanophytoplankton (2–20 μm); MICRO, microphytoplankton (20–200 μm)

Table 2 Integrated abundance (×10^6 cells/cm^2) **and carbon biomass** (μg C/cm^2) **of *Synechococcocus*** (SYN) **and picoeukaryotes** (PEUK) (mean (SD, standard deviation)) **and their contributions** (CONT, %) **in the Taiwan Strait***

Parameters	Date	SYN		PEUK		n
		Mean (SD)	CONT*	Mean (SD)	CONT*	
Abundance	Aug., 1997	51.2 (25.7)	94 (5)	2.96 (2.2)	6 (5)	162
	Feb.-Mar., 1998	7.70 (5.1)	89 (9)	0.75 (0.48)	11 (9)	149
	Aug., 1998	209 (114)	92 (4)	15.4 (8.0)	8 (4)	53
Carbon biomass	Aug., 1997	12.8 (6.4)	68 (19)	6.22 (4.6)	32 (19)	162
	Feb.-Mar., 1998	1.93 (1.3)	55 (20)	1.57 (1.0)	45 (20)	149
	Aug., 1998	52.3 (28.5)	59 (14)	32.4 (16.8)	41 (14)	53

* Contribution means both *Synechococcocus* and picoeukaryotes contributes in term of 2 picophytoplanktoners (without *Prochlorococcus*)

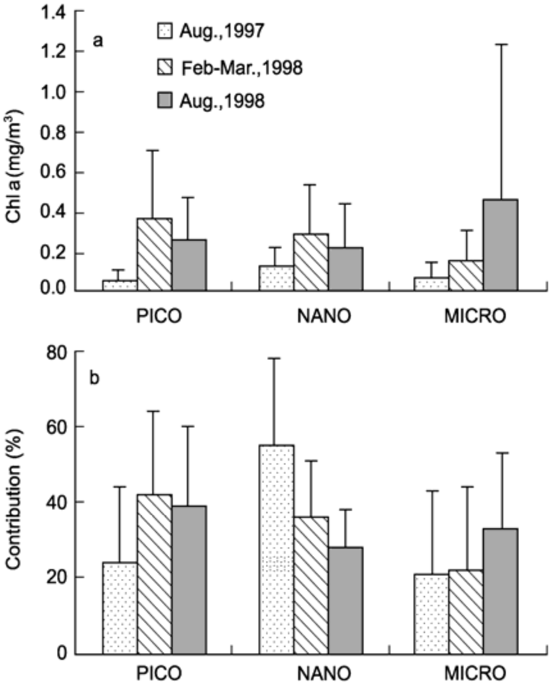

Fig.3 Seasonal variations of size-fractionated (a) **and contribution** (b) **of phytoplankton chlorophyll *a* biomass in the central Taiwan Strait**

biomass from microphytoplankton are close in results of the three cruises. Nanophytoplankton in August 1997 is significantly higher than those in February–March 1998 and August 1998; picophytoplankton in August 1997 was significantly lower than that in February–March 1998 (Fig.3).

3.3 Horizontal distribution

Synechococcus and picoeukaryotes varied over time in abundance and carbon biomass, higher in the summer and lower in winter (Table 2). The average abundance of *Synechococcus* and picoeukaryotes is (7.70–209)×10^6 and (0.75–15.4)×10^6 cells/cm^2, while that of carbon biomass, 1.93–52.3 and 1.57–32.4 μg C/cm^2, respectively. For relative contribution of the two groups of picophytoplankton, picoeukaryotes increased significantly from 6%–11% in abundance to 32%–45% in carbon biomass.

The distribution of overall abundance of *Synechococcus* and picoeukaryotes are heterogeneous for all the three cruises (Fig.4). In August 1997, high abundance of *Synechococcus* was observed in the west STS (Stn A5 and A4, (7.4–9.1)×10^7 cells/cm^2), while the densest area of picoeukaryotes was in the coast of STS (Stn A3, 6.6×10^6 cells/cm^2) (Fig.4). In February-March 1998, the highest abundance for *Synechococcus* was observed in the central Taiwan Strait (Stn B7, B8, B9, B10; (1.0–1.5)×10^7 cells/cm^2), while picoeukaryotes dominated both at the central Strait (Stn B7 and B9, (1.3–1.5)×10^6 cells/cm^2) and off the northern cape of Taiwan (Stn B3, 1.1×10^6 cells/cm^2) (Fig.4). In August 1998, the dense areas of both *Synechococcus* and picoeukaryotes were off northern Cape of Taiwan (Stn T3) and south STS (Stn T12 and T15); the abundance was 3.5×10^6 and 2.5×10^7 cells/cm^2 off northern Cape of Taiwan, and (2.8–3.0) ×10^8 and (2.1–2.4) ×10^7 cells/cm^2 at south STS (Fig.4) for *Synechococcus* and picoeukaryotes, respectively.

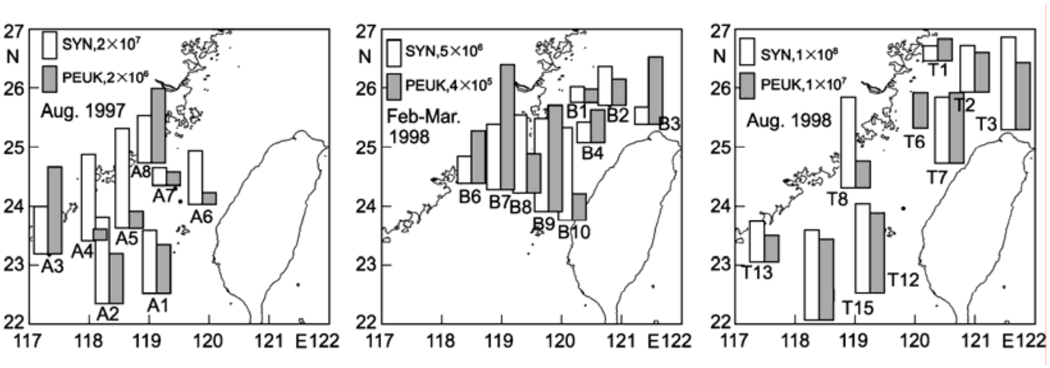

Fig.4 Distribution of integrated abundance of *Synechococcus* and picoeukaryotes in the Taiwan Strait (cells/cm^2) (SYN, *Synechocccocus*; PEUK, picoeukaryotes)

3.4 Daily variation

Both *Synechococcus* and picoeukaryotes exhibited diurnal patterns of distribution in abundance, depending on the size categories and sampling depths. For example, at Stn A2, the daily distribution varied between upper waters (0, 20 m) and deep waters (50, 66 m); the latter shows a cycle of 24 h with maximum of 12:00 and minimum of 0:00 (e.g. 66 m), while the former shows higher frequency in variation (e.g. 0 m, Fig.5). At Stn B4, *Synechococcus* generally went down at depth of 10–30 m during the investigation, while fluctuating at other depths (surface and bottom). In addition, different variation patterns between *Synechococcus* and picoeukaryotes were observed, which varied in different depths even within the same size category (Fig.6). For examples, for *Synechococcus*, there was higher variation frequency at depths of 0 and 55 m, but lower at depths of 10, 20, and 30 m. For picoeukaryotes, there was higher frequency of variation in upper waters (0, 10, 20, and 30 m) but lower at deeper water (55 m) (Fig.6).

Table 3 Seasonal variation of integrated abundance of *Synechocccocus* (SYN) **and picoeukaryotes** (PEUK) **in the central Taiwan Strait** (×10^{5}cells/cm^2) *

Date	SYN		PEUK		*n*
	Mean	SD	Mean	SD	
Aug.,1997	307	213	21	23	13
Feb.-Mar., 1998	109	43	9	4.8	64
Aug.,1998	1958	1201	129	84	7

*Stations of central Taiwan Strait: Aug., 1997: A6, A7 and A8; Feb.-Mar., 1998: B6, B7, B8, B9 and B10; Aug., 1998: T8, T9 and T10

3.5 Seasonal Variations

In the central Taiwan Strait, both *Synechococcus* and picoeukaryotes showed seasonal variations (Table 3). *Synechococcus* and picoeukaryotes in summer (August in 1997 and 1998) were significantly higher than those in the winter (February-March, 1998), and *Synechococcus* and picoeukaryotes in August 1998 were significantly higher than that in August 1997 (Table 3).

4 DISCUSSION

4.1 Factors controlling the distribution

In February-March 1998, both *Synechococcus* and picoeukaryotes showed significantly positive relationships with temperature (Fig.7, $p<0.001$). In August 1998, *Synechococcus* was positively correlated with temperature significantly ($p<0.01$), but picoeukaryotes was not. In February-March 1998, two distinct areas were recognized in environmental characteristics resulted from the China Coastal Current that flowed southward in the coastal Taiwan Strait. One was on the coastal northern Taiwan Strait (Fig.2, C-NTW, within contour of 17.0°C at depth of 10 m) of lower temperature, lower salinity, and higher nutrients. The other was on the off-coastal Taiwan Strait (O-TW, without contour of 17.0°C at depth of 10 m) that occupied by the waters of higher temperature, higher salinity, and lower nutrients (Table 4). Higher abundance of *Synechococcus* was observed in the central Strait, which can be linked to higher temperature and salinity and lower nutrient concentration. Higher abundance of picoeukaryotes was observed in the central Strait and off the north cape of Taiwan Island (Stn B3), which might be influenced by the intruded Kuroshio water with higher temperature. In August 1998, waters of higher temperatures (e.g. south STS) tend to have higher concentrations of *Synechococcus* and picoeukaryotes, although some of these data were not significant. In August 1997, the two picophytoplankton size categories were not significantly correlated with temperature and nutrients (total inorganic nitrogen and phosphate). Therefore, temperature was an important factor influencing the distribution of *Synechococcus* and picoeukaryotes in the Taiwan Strait in this study, especially in winter. This is supported by findings by Chiang et al. (2002) which suggests that temperature might be a limiting factor for *Synechococcus* during cold season (winter to late spring) in the East China Sea.

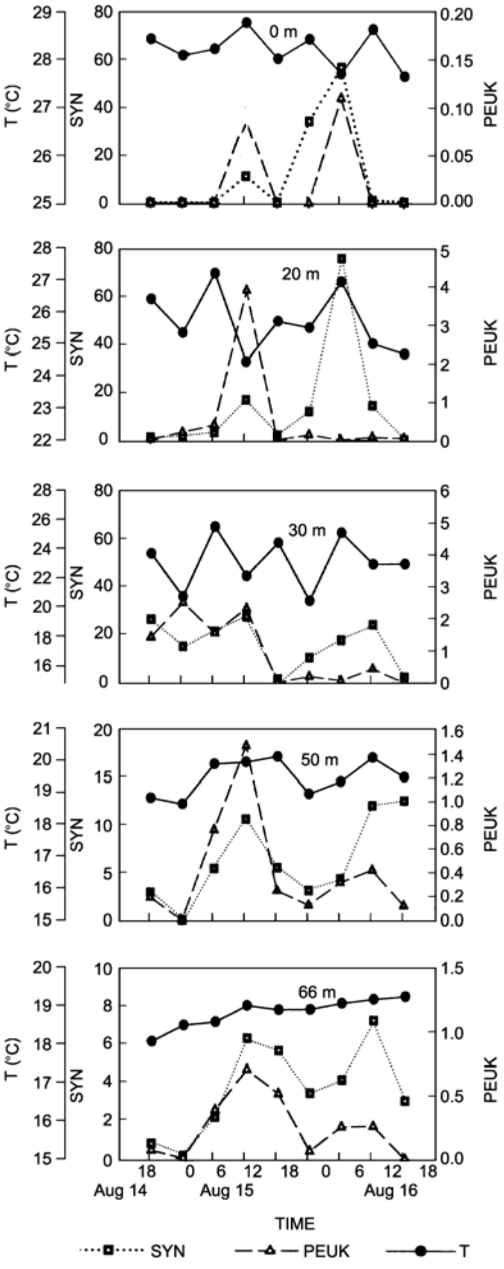

Fig.5 Daily variation of *Synechococcocus* (SYN)**, picoeukaryotes** (PEUK) **and temperature** (T, °C) **at Stn A2 in the Taiwan Strait in August, 1997** (10^3 cells/ml)

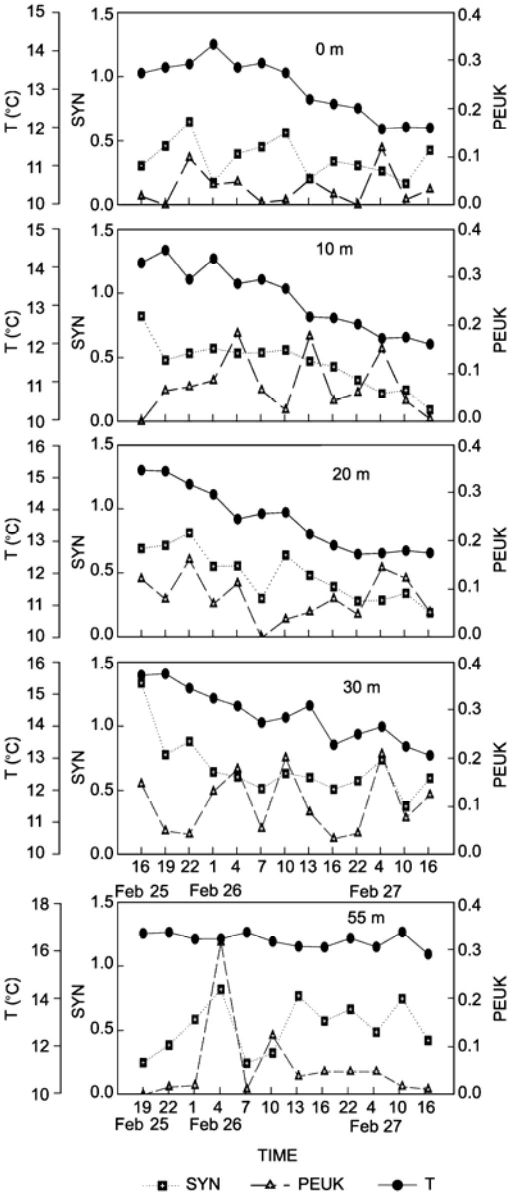

Fig.6 Daily variation of *Synechococcocus* (SYN)**, picoeukaryotes** (PEUK) **and temperature** (T, °C) **at Stn B4 in the Taiwan Strait in February-March, 1998** (10^3 cells/ml)

4.2 Daily variations

Daily variations of *Synechococcus* and picoeukaryotes indicate that different environmental factors controlled their abundance at various depths. At Stn B4, temperature affected their abundance significantly in upper waters where southward China Coastal Current (lower temperature, salinity, and *Synechococcus* abundance) dominated (Chen et al., 1998). Temperature decreased in depth of 10–40 m during the investigation (48 h), thus *Synechococcus* went down during the study period in upper layer (10–30 m). However, other environmental factors (e.g. tide in surface and other currents in bottom water) but temperature would be the controlling factors at the surface (0 m) and bottom waters (55 m). At Stn A2, temperature was not a significant factor for *Synechococcus* and picoeukaryotes, which was probably due to the rhythm of cell division based on the cycle with noon peak at 12:00 and midnight valley at 0:00. In addition, the difference between the upper (0–20 m) and the lower layers (30–66 m) may result from different currents, which were northeastward current in higher temperature and lower salinity in the upper layer (mean T=28.3°C, S=31.8), and northwestward or southwestward currents in lower temperature and higher salinity in the deeper layer (mean T=18.7°C, S=34.6) (Chen et al., 1998).

Table 4 Environmental parameters in the coastal northern Taiwan Strait (C-NTW) **and off-coastal central Taiwan Strait** (O-TW) **in February-March, 1998**

Parameter	Mean		Range	
	C-NTW	O-TW	C-NTW	O-TW
Temperature	14.03	20.42	11.76–16.77	18.81–21.97
Salinity	31.17	34.93	29.07–33.34	34.36–35.08
Nitrate	11.30	0.25	5.32–18.17	0–1.79
Phosphate	0.52	0.12	0.30–0.87	0.05–0.60
Silicate	12.04	0.80	3.15–24.23	0–5.07
n	69	50	69	50

Unit: temperature, °C; salinity, psu; nutrients (nitrate, phosphate and silicate), μmol/dm^3

The result indicates that the daily variation of *Synechococcus* and picoeukaryotes is complicated. Factors controlling the variation changed with locations and depths. At Stn B4, temperature was a key factor for the daily variation of *Synechococcus* and picoeukaryotes distribution in depth of 10, 20, and 30 m, but it was not a significant factor in the surface and bottom water (55 m). At Stn A2, the rhythm of cell division may be responsible for the variation. Similar results were reported by Charpy and Blanchot (1999). However, the rhythm of cell division (peak at noon and valley point at midnight) in the present study was opposite to other studies (peak at midnight and valley at noon) for *Synechococcus* in northwestern Mediterranean Sea and the Great Astrolabe Lagoon, Fiji (Jacquet et al., 1998; Charpy and Blanchot, 1999), the difference was probably resulted from the different ecological categories of *Synechococcus*/picoeukaryotes and environmental conditions. Besides temperature and rhythm of cell division, picophytoplankton distribution could be controlled by hydrodynamics (e.g. current), grazing pressure of mesozooplankton (e.g. protozoan), and lysis by virus (Wilson and Mann, 1997; Reckermann and Veldhuis, 1997; Jacquet et al., 1998; Raven, 1998; Christaki et al., 1999).

For the variation of *Synechococcus* and picoeukaryotes between August 1997 and August 1998, it may be tele-connected to the ENSO event occurred during 1997–1998. El Nino significantly affected the hydrological and chemical parameters, for having smaller and weaker upwelling, lower nutrients, lower dissolved oxygen and its saturation in August 1997 than those in summer of other years (Hong, 2000). The phenomenon was also found in the Hawaii waters, and Campbell et al. (1997) thought that this variation might be related to ENSO event (Campbell et al., 1997).

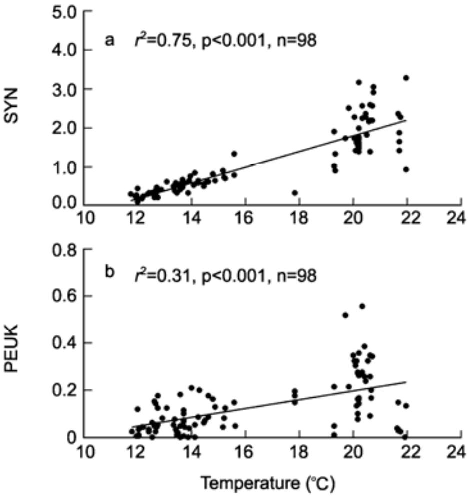

Fig.7 Relationship between picophytoplankton abundance and temperature in the Taiwan Strait in February-March, 1998 (10^3 cells/ml) **(**a. SYN, *Synechocoococus*; b. PEUK, picoeukaryotes)

5 CONCLUSION

In conclusion, picophytoplankton and nanophytoplankton dominated the phytoplankton biomass in all the three cruises, taking in average of 38% and 40%, respectively. The overall abundance by *Synechococcus* and picoeukaryotes was heterogeneous in location and season. Significant diurnal and seasonal variations were observed for both picophytoplankton categories. Our results suggest that temperature is an important factor influencing the distribution of *Synechococcus* and picoeukaryotes in the Taiwan Strait.

6 ACKNOWLEDGMENTS

The authors thank the captain and crews of *R/V Yanping No.2*, who made concerted efforts during sampling, and Dr. HU Jianyu and LIANG Hongxing for CTD data, Prof. WU Liyun for nutrient data. Many thanks to Prof. RUAN Wuqi and Prof. ZHANG Fang, Mr. ZUO Zhenghong, Dr. KE Lin for kind help in sampling and *in situ* incubation. Special thanks to Prof. T. F. George WONG of Dept of Ocean, Earth and Atmosphere Sciences, Old Dominion University (USA), Prof. W. K. W. LI of Bedford Institute of Oceanography (Canada) and Prof. Liette VASSEUR of K.C. Irving Chair in Sustainable Development, University of Moncton, Moncton (Canada) for their comments on draft manuscript.

References

Booth, B. C., 1993. Estimating cell concentration and biomass of autotrophic plankton using microscopy. *In*: Kemp, P. F., B. F. Sherr, E. B. Sherr, J. J. Cole, (eds.), Handbook of Methods in Aquatic Microbial Ecology. Lewis Publishers, Chelsea, Michigan. p. 199-205.

Campbell, L., H. B. liu, H. A. Nolla and D. Vaulot, 1997. Annual variability of phytoplankton and bacteria in the subtropical north pacific ocean at station ALOHA during the 1991-1994 ENSO event. *Deep-Sea Res*. Part I, **44**(2): 167-191.

Charpy, L. and J. Blanchot, 1999. Picophytoplankton biomass, community structure and productivity in the Great Astrolabe Lagoon, Fiji. *Coral Reefs* **18**: 155-162.

Chen, J. X., 2006. Studies on Ultraplankton Diversity in Subtropical Coastal Waters of China Seas, Ph. D Dissertation, Xiamen University, China. p.342.

Chen, Z., J. Hu, C. Zhang, X. Zhang, H. Lin, H. Liang and J. Hong, 1998. *In situ* measurement of tide and residue current in the Taiwan Strait in August, 1997. *J. Xiamen Univ. (Natural Science)* **38**(2): 268-272. (in Chinese with English abstract)

Chiang, K. P., M. C. Kuo, J. Chang, R. H. Wang and G. C. Gong, 2002. Spatial and temporal variation of the *Synechococcus* population in the East China Sea and its contribution to phytoplankton biomass. *Continental Shelf Res.* **22**(1): 3-13.

Christaki, U., S. Jacquet, J. R. Dolan, D. Vaulot and F. Rassoulzadegan, 1999. Growth and grazing on *Prochlorococcus* and *Synechococcus* by two marine ciliates. *Limnol. Oceanogr*. **44** (1): 52-61.

Hong, H. 2000, Study of biogeochemistry of carbon and nutrients in the Taiwan Strait, Project Review Report, unpublished.

Hong, H., H. Wang, B. Huang and M. El-Bakkari, 1997. The Primary Production Processes in the Taiwan Strait, IV. The preliminary study on bacteria-phytoplankton relationship and microbial loop. *In*: Hong H (ed.). Oceanography in China No. 7, China Ocean Press, Beijing. p. 38-48. (in Chinese with English abstract)

Hong, H., S. Qiu, W. Ruan and G. Hong, 1991. Review of Minnan-Taiwan bank fishing ground upwelling ecosystem study, *In*: Hong, H., S. Qiu, W. Ruan, G. Hong, (eds.), Minnan-Taiwan Bank Fishing Ground Upwelling Ecosystem Study, China Science Press, Beijing. p. 1-18. (in Chinese with English abstract)

Hu, J., H. Hong, Z. He, Z. Chen, J. Hong and H. Liang, 1999. Sectional features of temperature and salinity in the northern Taiwan Strait during February-March, 1998. *J. Xiamen Univ. (Natural Science)* **38**(2): 263-267. (in Chinese with English abstract)

Huang, B., H. Hong and H. Wang, 1997. The Primary Production Processes in the Taiwan Strait, III. Size-fractionated phytoplankron biomass and primary productivity and structure of photosynthetic product. *In*: Hong, H. (ed.) Oceanography in China No.7, China Ocean Press, Beijing. p. 31-37. (in Chinese with English abstract)

Huang, B., H. Hong and H. Wang, 1999. Size-fractionated primary productivity and the phytoplankton-bacteria relationship in the Taiwan Strait. *Mar. Ecol. Prog. Ser*. **183**: 29-38.

Huang, B., H. Hong, H. Wang and L. Hong, 1995. Size-fractionated phosphate uptake of by phytoplankton in West Xiamen Harbor. *J. Oceanogr in Taiwan Strait* **14**: 269-273. (in Chinese with English abstract)

Huang, B., S. Liu and H. Hong, 1991. Ecological studies of phytoplankton in Minnan-Taiwan bank fishing ground upwelling regions, II. Distribution of ecological groups of phytoplankton. *In*: Hong, H., S. Qiu, W. Ruan, G. Hong, (eds.). Minnan-Taiwan Bank Fishing Ground Upwelling Ecosystem Study, China Science Press, Beijing. p. 417-426.(in Chinese with English abstract)

Jacquet, S., J. F. Lennon, D. Marie and D. Vaulot, 1998. Picoplankton population dynamics in coastal waters of the northwestern Mediterranean Sea. *Limnol. Oceanogr.* **43**(8): 1 916-1 931.

Jan, S., J. Wang, C. S. Chern and S. Y. Chao, 2002. Seasonal variation of the circulation in the Taiwan Strait. *J. Mar. Syst.* **35**(3-4): 249-268.

Jiao N. Z., Y. H. Yang, H. Koshikawa and M. Watanabe, 2002. Influence of hydrographic conditions on picoplankton distribution in the East China Sea. *Aquat. Microb. Ecol*. **30**(1): 37-48.

Kana, T. M. and P. M. Gilbert, 1987. Effect of irradiances up to 2000 μmol m^{-2} s^{-1} on marine *Synechococcus* WH7803. I. Growth, pigmentation, and cell composition. *Deep-Sea Res.* **34**: 479-495.

Li, H., J. Hu, Z. Chen, X. Zhang and Z. He, 2000. Distribution of temperature and salinity field in the Taiwan Strait during summer, 1999. *Mar. Sci. Bull.* **19** (4): 8-12. (in Chinese with English abstract)

Li, W. and X. Wang, 1991. Primary productivity in the Taiwan Strait. *In*: Hong, H., S. Qiu, W. Ruan, G. Hong, (eds.). Minnan-Taiwan Bank Fishing Ground Upwelling Ecosystem Study. China Science Press, Beijing. p. 331-340. (in Chinese with English abstract)

Li, W. K. W., D. V. S. Rao, W. G. Harrison, J. C. Smith, J. J. Cullen, B. Irwin and T. Platt, 1983. Autotrophic picoplankton in the tropical ocean. *Science* **219**: 292-295.

Li, W. K. W., P. M. Dickie, B. D. Irwin and A. M. Wood, 1992. Biomass of bacteria, cyanobacteria, prochlorophytes and photosynthetic eukaryotes in the Sargasso Sea. *Deep-Sea Res*. **39**: 501-519.

Liang, H., 1997. Characteristics of hydrodynamics in the Taiwan Strait in August, 1994. *In*: Hong, H. (ed.), Oceanography in China No. 7, China Ocean Press, Beijing. p. 49-61. (in Chinese with English abstract)

Maclsaac, E. A. and J. G. Stockner, 1993. Enumeration of Phototrophic picoplankton by autofluorescence microscopy. *In*: Kemp, P. F., B. F. Sherr, E. B. Sherr, J. J. Cole, (eds). Handbook of Methods in Aquatic Microbial Ecology. Lewis Publishers, Chelsea, Michigan. p.187-197.

Ning, X., Z. Liu, G. Zhu and J. Shi, 1996. Size-fractionated biomass and productivity of phytoplankton and particulate organic carbon in the Southern Ocean. *Polar Biol.* **16**: 1-11.

Parsons, T. R., Y. Maita and C. M. Lalli, 1984. A Manual of Chemical and Biological Methods for Seawater Analysis. Pergamon Press, Oxford. p. 107-109, p. 115-122.

Platt, T., D. V. Subba-Rao and B. Erwin, 1983. Photosynthesis of picoplankton in the oligotrophic ocean. *Nature* **301**: 702-704.

Raven, J. A., 1998. The twelfth Tansley Lecture: Small is beautiful: the picophytoplankton. *Functional Ecol*. **12**(4): 503-513.

Rechermann, M. and M. J. W. Veldhuis, 1997. Trophic interactions between picophytoplankton and microzooplankton and nanozooplankton in the western Arabian sea during the NE Monsoon 1993. *Aquat. Microb.Ecol*. **12**(3): 263-273.

Stockner, J. G. and N. J. Antia, 1986. Algal picoplankton from marine and freshwater ecosystems: A multidisciplinary perspective. *Canadian J. Fish. Aquat. Sci*. **43**: 2472-2503.

Stockner, J. G., 1988. Phototrophic picoplankton: An overview from marine and freshwater ecosystems. *Limnol. Oceanogr*. **33**(4, part2): 765-775.

Strathmann, P. R., 1967. Estimating the organic carbon content of phytoplankton from cell volume or plasma volume. *Limnol. Oceanogr.* **12**(3): 411-418.

Takahashi, M. and P. K. Bienfany, 1983. Size structure of phytoplankton biomass and photosynthesis in subtropical Hawaiian waters. *Mar. Biol*. **76:** 203-211.

Tsai, A. Y., K. P. Chiang, J. Chang and G. C. Gong, 2008. Seasonal variations in trophic dynamics of nanoflagellates and picoplankton in coastal waters of the western subtropical Pacific Ocean. *Aquat. Microb. Ecol*. **51**(3): 263-274.

Wang, H., B. Huang and H. Hong, 1997. Size-fractionated productivity and nutrient dynamics of phytoplankton in subtropical coastal environments. *Hydrobiol*. **352:** 97-106.

Wilson, W. H. and N. H. Mann, 1997. Lysogenic and lytic viral production in marine microbial communities. *Aquat. Microb. Ecol*. **13**(1): 95-100.