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Seasonal Dynamics of Phytoplankton and Environmental Factors around the Chagwi-do off the West Coast of Jeju Island, Korea

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Abstract – The dynamics of phytoplankton abundance with seasonal variation in physicochemical conditions were investigated monthly at 10 stations around the Chagwi-do off the west coast of Jeju Island, Korea, including inshore, middle shore, and offshore in the marine ranching area from September 2004 to November 2005. Water temperature varied from 12.1 to 28.9°C (average 18.8°C), and salinity from 28.9 to 34.9 psu (average 33.7 psu). The chlorophyll *a* concentration was 0.02–2.05 $\mu g\ L^{-1}$ (average 0.70 $\mu g\ L^{-1}$), and the maximum concentration occurred in the bottom layer in April. A total of 294 phytoplankton species belonging to 10 families was identified: 182 Bacillariophyceae, 52 Dinophyceae, 9 Chlorophyceae, 12 Cryptophyceae, 6 Chrysophyceae, 4 Dictyophyceae, 13 Euglenophyceae, 6 Prymnesiophyceae, 5 Prasinophyceae, and 5 Raphidophyceae. The standing crop was $2.21–48.69 \times 10^4$ cells L^{-1} (average 9.23×10^4 cells L^{-1}), and the maximum occurred in the bottom layer in April. Diatoms were most abundant throughout the year, followed by dinoflagellates and phytoflagellates. A phytoplankton bloom occurred twice: once in spring, peaking in April, and once in autumn, peaking in November. The spring bloom was represented by four *Chaetoceros* species and *Skeletonema costatum*; each contributed 10–20% of the total phytoplankton abundance. The autumn bloom comprised dinoflagellates, diatoms, and phytoflagellates, of which dinoflagellates were predominant. *Gymnodinium conicum, Prorocentrum micans*, and *P. triestinum* each contributed over 10% of the total phytoplankton abundance.

Key words – environmental factor, Jeju Island, marine ranching, phytoplankton, seasonal dynamics

1. Introduction

Marine algae contribute a major portion of primary production; they are responsible for 46% of global productivity (Field *et al.* 1998) and support food webs in waters ranging from ponds to oceans. Temporal variability in the structure and function of the phytoplankton community is of fundamental importance to aquatic environments, which are subject to high temporal variability due to interactions among physical, chemical, and biological variables, resulting in frequent reorganization of the relative abundance and species composition of phytoplankton (Reynolds *et al.* 2000). The seasonal dynamics and succession of phytoplankton populations are often associated with water temperature, salinity, and nutrient concentrations. Water temperature is an important factor controlling the algal growth in natural environments (Lund 1949; Talling 1955), and growth responses to water temperature may be essential in regulating the predominance of phytoplankton species (Harris 1986). Wide ranges of salinity and water temperature may be important in the frequent appearance of phytoplankton species throughout the year in the oceans (Hoshiai *et al.* 2003).

Growing evidence indicates that human activities are altering the distribution and movements of nutrient elements, resulting in increasing nutrient loads to receiving waters. Changes in nutrient availability can alter the species composition of primary producers (Reolke *et al.*

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1999), and a pulsed supply of nutrients, for example, increases phytoplankton diversity to levels far greater than those under limited nutrients (Grover 1989). Laboratory experiments and field studies show that episodic flushing and nutrient loading can result in enhanced phytoplankton species diversity (Padisak 1993; Hambright and Zohary 2000; Lovejoy *et al.* 2002). Experimental studies of temporal changes in nutrient supply provide evidence that the effect on phytoplankton species diversity is most evident when the nutrient supply fluctuates at intervals of 3 to 7 days, corresponding to two to four generations (Sommer 1995; Sommer and Floder 1999). The competitive abilities of phytoplankton species vary as a function of the physicochemical environment. Environmental factors and population densities fluctuate in time and space (Litchman and Klausmeyer 2001), and because of the close coupling of physical forcing and biota, environmental fluctuations are expected to significantly affect communities in aquatic systems (Steele 1985).

Jeju Island is located off the southern coast of the Republic of Korea (Fig. 1) and is characterized by volcanic rocky intertidal and subtidal zones that are subjected to strong wave action. The west coast of Jeju Island is influenced by the Yellow Sea Warm Current, a branch of the Tsushima Warm Current, from winter to spring, and by huge freshwater runoff from the Changjiang River during summer (Pang *et al.* 1996; Hyun *et al.* 1997). In summer, overflow from the Changjiang River sometimes results in devastating effects on fisheries by causing mass mortality of fish and shellfish due to the considerable dilution of seawater off the west coast of Jeju Island (Suh *et al.* 1998; Lee *et al.* 1999). Currently, reports of the seasonal changes and structure of the phytoplankton community along the west coast of Jeju Island are scarce. Affan and Lee (2004) monitored phytoplankton dynamics at a single site off the west coast of Jeju Island and reported 101 phytoplankton species belonging to different taxonomic groups. Among these species, benthic diatoms were the most dominant, but the authors did not examine the mechanics of changes in phytoplankton assemblages with seasonal changes and environmental conditions. Thus, to facilitate the proper management of aquatic resources in this area, we attempted to determine the spatial and temporal variation in the phytoplankton assemblage in relation to environmental factors as a part of the marine ranching program.

2. Materials and Methods

Study area and sampling

The study was conducted off the west coast of Jeju Island, Korea, where the marine ranching program has

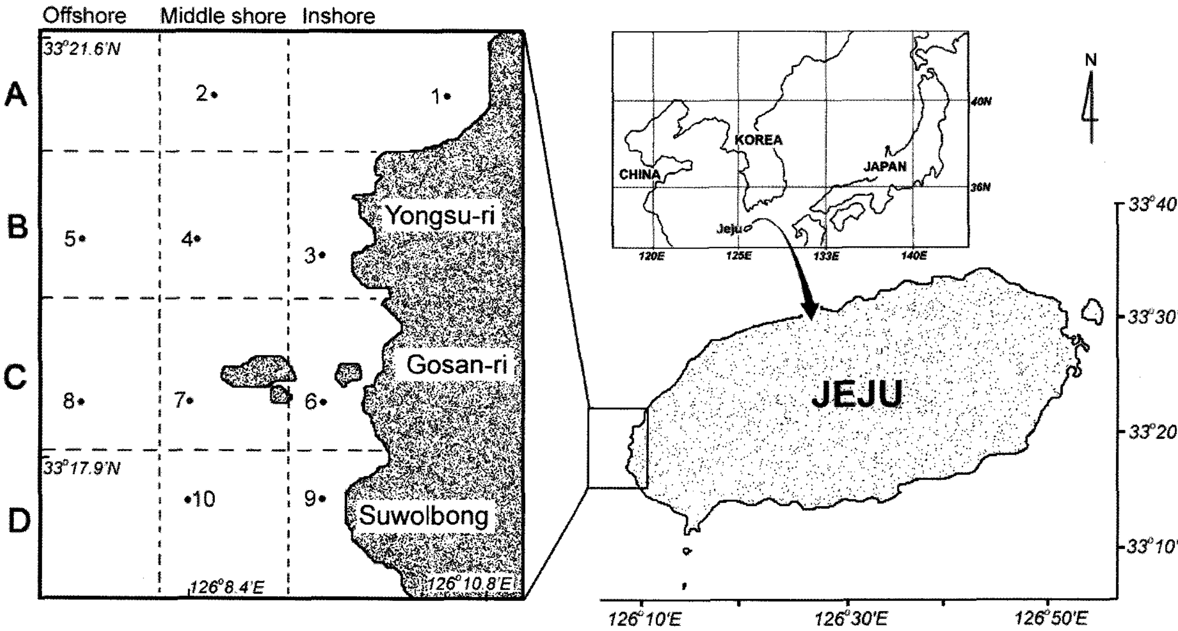

Fig. 1. Map of the Chagwi-do area off the west coast of Jeju Island, Korea, and location of the sampling transects A–D and stations 1–10.

been ongoing since 2004. In total, 10 sampling stations were designated along four transects (A–D) belonging to inshore, middle shore, and offshore areas of the coast (Fig. 1). Water samples were collected monthly at the surface and above the bottom from September 2004 to November 2005 using a water sampler. Each sample was divided into two bottles: one was used for the analysis of chlorophyll *a* and chemical factors such as nutrient concentrations; the other was used for quantitative and qualitative analyses of phytoplankton.

Phytoplankton analysis

Water samples were fixed with Lugol's iodine solution at a final concentration of 2%, and the fixed sample was transferred to a 1-L graduated cylinder with a siphon at the bottom 60 mL. The sample was left for 2 to 3 days and the supernatant was removed. For quantitative study, the concentrated sample was mixed, a 1-mL sample was taken, and the number of phytoplankton was counted on a Sedgwick-Rafter (S-R) counter chamber under a light microscope. The counts were summarized as the number of cells per liter. For species identification, the sample was observed under a phase-contrast microscope (Zeiss Axioplan, Germany) at 400 magnification. We then calculated the Shannon's species diversity index (H) (Shannon and Weaver 1984).

Chlorophyll *a* analysis

Each water sample was filtered through a glass fiber filter (Whatman GF/C 47 mm, UK), which was then placed in a 15-mL test tube with 90% acetone and refrigerated overnight. The test tube was centrifuged at 3500 rpm for 15 min, and the supernatant was used for chlorophyll *a* analysis using a spectrophotometer (Shimadzu UV-1201, Japan). The chlorophyll *a* concentration was calculated according to the methods of Parsons *et al.* (1984).

Analysis of environmental factors

A conductivity–temperature–depth (CTD) unit (Sea-Bird Electronics SBE 16, USA) was used to measure water temperature and salinity. The concentrations of NO_3-N, NO_2 -N, NH_4-N, and PO_4-P were determined using a spectrophotometer (Shimadzu UV-1201, Japan) according to the methods of Parsons *et al.* (1984). Values were averaged at the surface and bottom layers for inshore, middle shore, and offshore areas.

3. Results

Dynamics of hydrological factors

Water temperature

The water temperature of the surface layer followed a seasonal cycle characterized by a minimum of 14.2°C in March and a maximum of 28.9°C in August, with an average of 20.1°C (Fig. 2A); no significant variation occurred among stations. In the bottom layer, the water temperature varied from 12.1 to 27.0°C, with an average of 20.3°C; the minimum and maximum occurred in August and September 2005, respectively (Fig. 2B). From November to May, the bottom water temperature did not vary significantly among stations, but did vary significantly from June to September. The temperature was much lower at the middle shore and offshore than at the inshore areas (Fig. 2B). The bottom water temperature inshore was higher from June to September than that offshore and

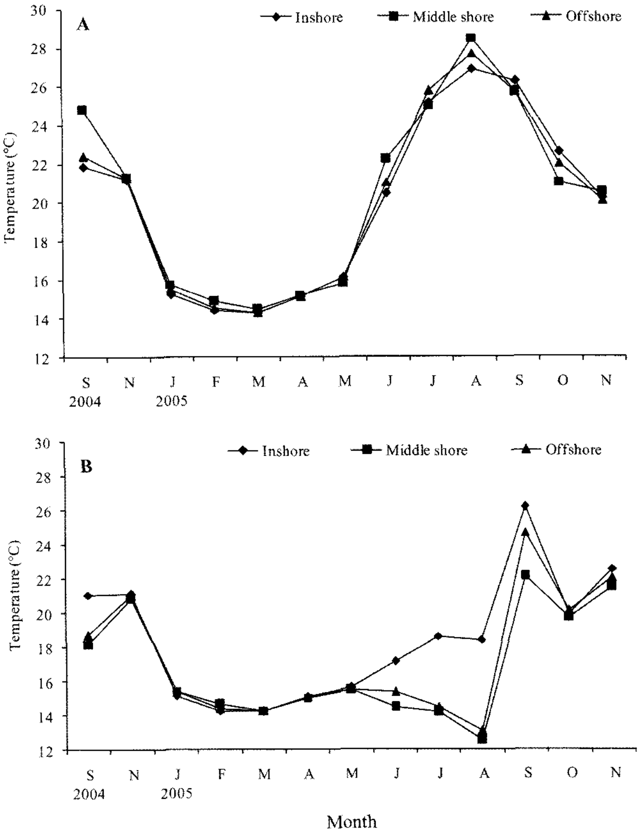

Fig. 2. Variation in the water temperature of the (A) surface layer and (B) bottom layer at inshore, middle shore, and offshore areas around the Chagwi-do off the west coast of Jeju Island from September 2004 to November 2005.

at middle shore areas (Fig. 2B). The water temperature did not differ between the surface and bottom layer from winter to spring (Fig. 2A and B).

Salinity

Salinity varied from 29.8 to 35.0 psu, with an average of 33.8 psu. The lowest salinity was recorded in the surface layer inshore in July, whereas the highest salinity occurred in the bottom layer offshore in November 2005 (Fig. 3A and B). The average salinity of the surface and bottom layers was 33.0 and 34.0 psu, respectively (Fig. 2A). The salinity of the surface layer was significantly lower than that of the bottom layer from June to September 2005. The salinity of the surface layer did not differ significantly among stations throughout the study period (Fig. 3A). The salinity of the bottom layer also did not differ significantly among stations from November 2004 to May 2005. However, the salinity inshore was much lower than that at the middle shore and offshore areas from June to October 2005 (Fig. 3B).

In the surface layer, salinity and water temperature were strongly and significantly negatively correlated at inshore (r = −0.79), middle shore (r = −0.80), and offshore (r = −0.82) areas. However, no significant correlation was detected between these two factors in the bottom layer.

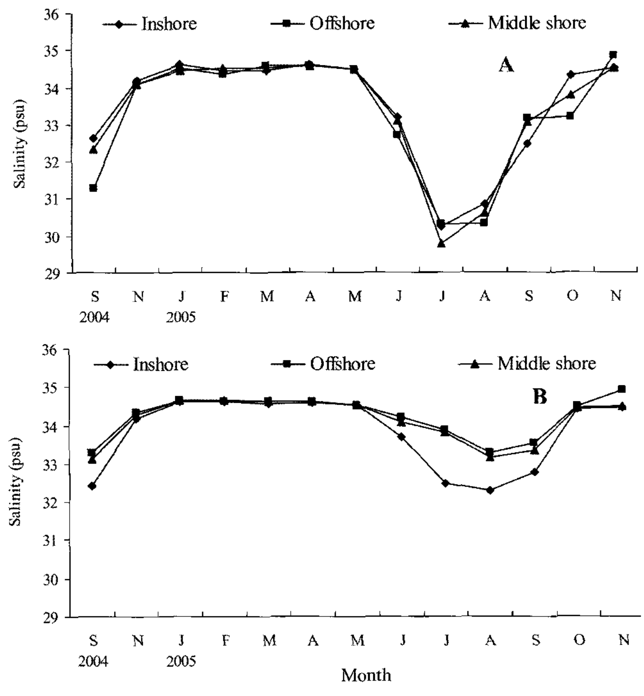

Fig. 3. Variation in the salinity of the (A) surface layer and (B) bottom layer at inshore, middle shore, and offshore areas around the Chagwi-do off the west coast of Jeju Island from September 2004 to November 2005.

Nutrient dynamics

The NH_4-N concentration varied from 0.08 to 5.85 μg-at L^{-1}, with an average of 1.63 μg-at L^{-1}; the lowest and highest concentrations occurred in the surface layer offshore in November 2004 and February 2005, respectively. In February, NH_4-N was higher in both the surface and bottom layers at the offshore than at the middle shore, followed by the inshore area. Among the stations, the highest average NH_4-N concentration was 2.24 μg-at L^{-1} in the surface layer at the middle shore and the lowest was 0.86 μg-at L^{-1} in the bottom layer inshore (Table 1).

The NO_3-N concentration fluctuated from 0.09 to 9.95 μg-at L^{-1}, with an average of 3.93 μg-at L^{-1}. The highest and lowest concentrations occurred in the bottom layer of the middle shore in August and November, respectively. The highest average NO_3-N concentration was 4.35 μg-at L^{-1} in the surface layer inshore (Table 1).

The NO_2-N concentration varied from 0.09 to 8.68 μg-at L^{-1}. The lowest concentration occurred in the surface layer inshore in November 2005 and the highest concentration occurred in the bottom layer of the middle shore at the same time. The lowest mean NO_2-N concentration was 0.14 μg-at L^{-1} in the surface layer inshore, whereas the highest mean concentration was 1.92 μg-at L^{-1} in the bottom layer of the middle shore (Table 1).

The PO_4-P concentration varied from 0.06 to 0.66 μg-at L^{-1}, with an average of 0.26 μg-at L^{-1}. The lowest concentration occurred in the surface and bottom layers at the inshore and middle shore areas in May 2005, whereas the highest concentration occurred in the bottom layer offshore in November 2005 (Table 1).

NH_4-N and water temperature were negatively correlated at the middle shore (r = −0.51) and offshore (r = −0.79) areas in the surface layer, whereas NH_4-N and salinity were negatively correlated in the bottom layer inshore (r = −0.65). NO_3-N was highly positively correlated with water temperature in the surface layer of the inshore (r = 0.89) and middle shore (r = 0.81) areas, and negatively correlated with salinity in the surface layer of the inshore (r = −0.73) and middle shore (r = −0.81) areas, and in the bottom layer of the inshore (r = −0.88), middle shore (r = −0.95), and offshore (r = −0.96) areas. NO_2-N was strongly positively correlated with standing crop production in the

Table 1. Seasonal dynamics of NH_4-N, NO_3-N, NO_2-N, and PO_4-P concentrations (μg-at L^{-1}) in the surface and bottom layers at inshore, middle shore, and offshore areas around the Chagwi-do off the west coast of Jeju Island.

	Surface layer											
Month	Inshore				Middle shore				Offshore			
	NH_4-N	NO_3-N	NO_2-N	PO_4-P	NH_4-N	NO_3-N	NO_2-N	PO_4-P	NH_4-N	NO_3-N	NO_2-N	PO_4-P
Nov 2004	0.63±0.27	4.53±0.63	0.32±1.81	0.45±0.09	0.13±0.06	3.58±0.07	0.26±0.61	0.47±0.04	0.08±0.12	4.07±0.02	0.26±1.15	0.25±0.03
Feb 2005	1.68±0.03	3.33±0.39	0.11±0.84	0.21±0.03	5.56±0.09	3.66±0.63	0.11±1.02	0.34±0.01	5.85±0.01	3.96±0.19	0.12±1.71	0.23±0.03
May 2005	0.67±0.05	1.94±0.36	0.17±1.22	0.07±0.17	1.00±0.03	1.53±0.26	0.20±1.25	0.06±0.14	2.65±0.02	0.51±0.05	0.02±0.43	0.08±0.01
Aug 2005	2.28±0.05	6.65±0.10	0.18±0.59	0.15±0.10	1.44±0.20	6.57±0.85	0.18±1.23	0.19±0.08	0.53±0.08	5.37±0.37	0.15±0.58	0.11±0.01
Nov 2005	1.89±0.18	5.32±1.12	0.09±1.58	0.24±0.03	1.52±0.05	3.99±0.99	0.16±1.18	0.13±0.01	2.10±0.04	4.51±1.92	0.10±0.49	0.13±0.01
Mean	1.43±0.05	4.35±0.79	0.17±0.05	0.22±0.05	2.24±1.43	3.68±0.04	0.18±0.02	0.16±0.04	1.93±2.05	3.87±0.88	0.14±0.01	0.24±0.06
	Bottom layer											
Month	Inshore				Middle shore				Offshore			
	NH_4-N	NO_3-N	NO_2-N	PO_4-P	NH_4-N	NO_3-N	NO_2-N	PO_4-P	NH_4-N	NO_3-N	NO_2-N	PO_4-P
Nov 2004	0.45±0.71	4.29±1.27	0.29±0.09	0.47±0.25	0.11±0.11	4.29±0.68	0.26±0.03	0.60±0.13	0.39±0.41	5.05±1.00	0.31±0.05	0.66±0.01
Feb 2005	0.41±0.32	3.44±0.41	0.16±0.05	0.23±0.01	3.54±4.04	2.89±0.44	0.17±0.03	0.30±0.13	4.89±0.42	3.08±0.01	0.15±0.07	0.31±0.04
May 2005	0.67±0.69	2.50±0.10	0.18±0.04	0.06±0.09	1.34±0.25	2.65±2.24	0.25±0.06	0.13±0.05	1.86±0.34	2.86±0.18	0.23±0.01	0.18±0.02
Aug 2005	1.83±1.38	8.01±2.04	0.18±0.03	0.13±0.17	0.79±0.54	9.95±2.33	0.14±0.02	0.37±0.10	0.44±0.06	9.17±0.15	0.17±0.01	0.37±0.08
Nov 2005	0.97±0.90	0.12±0.04	6.75±0.95	0.23±0.01	2.11±1.22	0.09±0.03	8.27±2.13	0.29±0.05	1.03±0.30	0.13±0.04	8.68±2.17	0.30±0.01
Mean	0.86±0.57	3.67±0.42	1.52±0.20	0.22±0.07	1.72±1.36	4.06±1.07	1.92±0.57	0.27±0.02	1.58±0.94	3.97±0.99	1.82±0.43	0.34±0.04

bottom layer of the inshore (r = 0.94), middle shore (r = 0.96), and offshore (r = 0.95) areas. PO_4-P and water temperature were positively correlated in the bottom layer inshore (r = 0.57); PO_4-P and salinity were negatively correlated in the bottom layer of the middle shore area (r = –0.51).

Phytoplankton dynamics

Species composition and diversity

We identified a total of 294 phytoplankton species belonging to 10 families: 182 Bacillariophyceae, 52 Dinophyceae, 9 Chlorophyceae, 12 Cryptophyceae, 6 Chrysophyceae, 4 Dictyophyceae, 13 Euglenophyceae, 6 Prymnesiophyceae, 5 Prasinophyceae, and 5 Raphidophyceae. The species diversity index (H) ranged from 1.88 to 3.18, with an average of 2.50. The lowest and highest diversity occurred in the surface layer of the middle shore area in April and November 2005, respectively (Fig. 4A and B).

Standing crops

Phytoplankton abundance fluctuated from 2.21 × 10^4 to 48.69 × 10^4 cells L^{-1}, with an average of 9.23 × 10^4 cells L^{-1} among the stations throughout the study period. The lowest abundance occurred in the surface layer offshore in February and the highest abundance was observed in the bottom layer inshore in April 2005 (Fig. 5A and B).

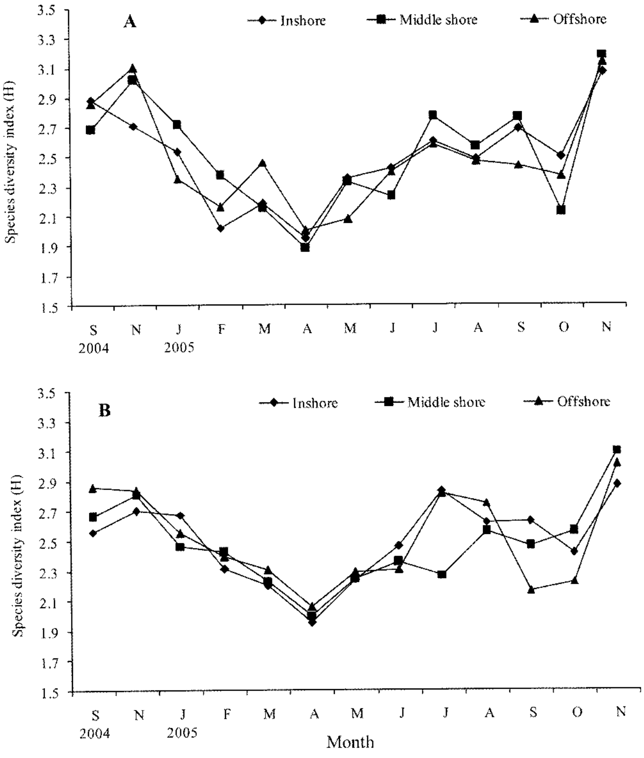

Fig. 4. Variation in the species diversity index (H) of phytoplankton in the (A) surface layer and (B) bottom layer at inshore, middle shore, and offshore areas around the Chagwi-do off the west coast of Jeju Island from September 2004 to November 2005.

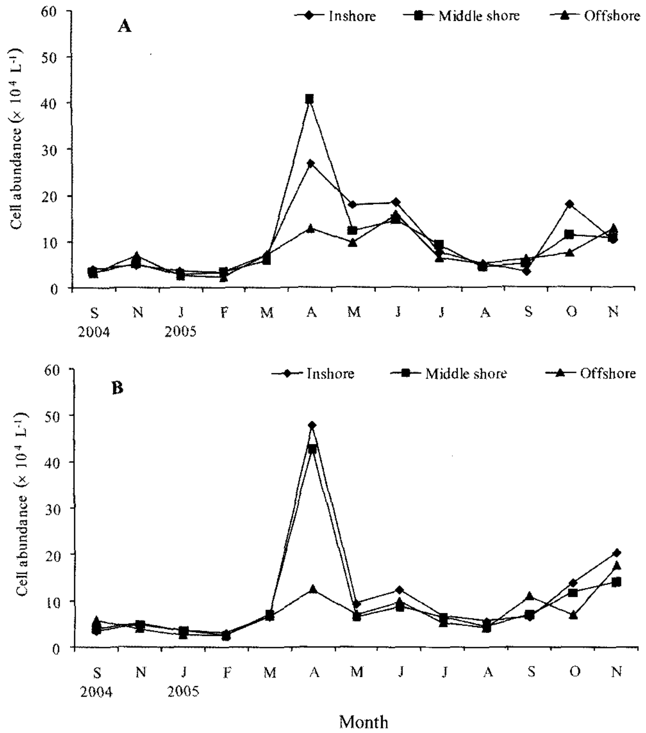

Fig. 5. Dynamics of phytoplankton cell abundance in the (A) surface layer and (B) bottom layer at inshore, middle shore, and offshore areas around the Chagwi-do off the west coast of Jeju Island from September 2004 to November 2005.

Phytoplankton abundance was significantly high in the bottom layer inshore, followed by that in the surface layer inshore and in the surface and bottom layers of the middle shore area. Two phytoplankton blooms occurred during the study period: one in spring (March to May), peaking in April; the other in autumn (October to November), peaking in November 2005 (Fig. 5A and B). Diatoms were dominant in the phytoplankton communities, with the exception of November 2005, at which time dinoflagellates were dominant (Fig. 6A–C). Dinoflagellates were also high in abundance at all stations in July 2005. The contribution of dinoflagellates to total phytoplankton abundance varied from 32.2 to 48.1%, and the highest contribution was in offshore areas (Fig. 6C). Phytoflagellates other than dinoflagellates had maximal abundances at all stations in September 2004 and ranged from 18.4 to 31.8%, with an average of 9.7%. Their highest abundance as a percentage of total phytoplankton abundance was 25.9, 18.3, and 31.3% in inshore, middle shore, and offshore areas, respectively (Fig. 6A–C).

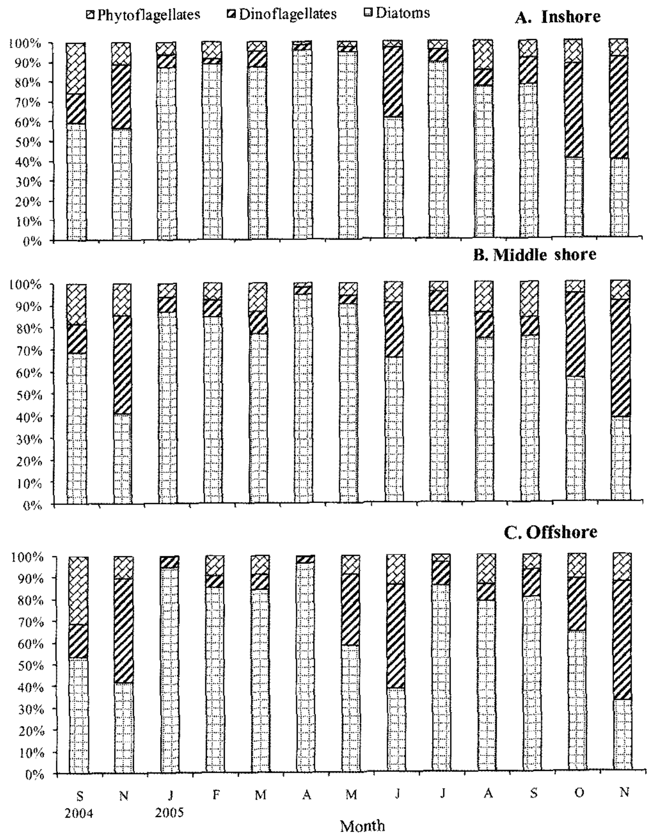

Fig. 6. Percent abundance composition of diatoms, dinoflagellates, and phytoflagellates at (A) inshore, (B) middle shore, and (C) offshore areas around the Chagwi-do off the west coast of Jeju Island from September 2004 to November 2005.

Chlorophyll a

The chlorophyll *a* concentration varied from 0.06 to 1.81 μg L^{-1}, with an average of 0.60 μg L^{-1}. The chlorophyll *a* concentration was highest in April at all stations. The highest chlorophyll *a* concentration occurred in the bottom layer of the inshore area (Fig. 7A and B).

Phytoplankton blooms

The spring bloom was mainly composed of diatoms, whereas the autumn bloom comprised dinoflagellates, diatoms, and phytoflagellates. During the spring bloom, the highest abundance of diatoms was 47.50 × 10^4 cells L^{-1} and occurred in the bottom layer inshore (Fig. 8A). The contribution of diatoms to the phytoplankton varied from 93.5 to 97.6% with the highest abundance in the bottom layer inshore (Fig. 8B). The most abundant species of diatoms were *Chaetoceros lorenzianus*, *C. pseudocrinitus*, *C. socialis*, *Skeletonema costatum*, and the most abundant

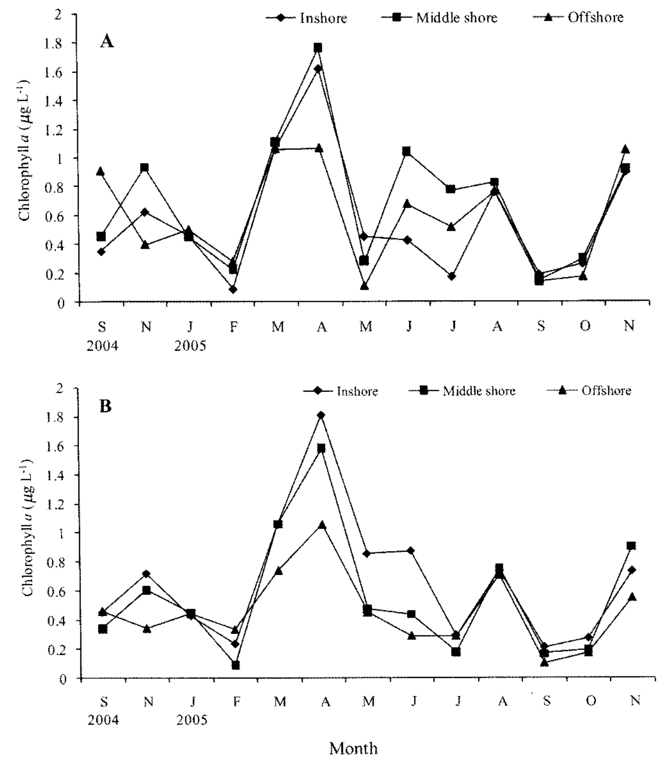

Fig. 7. Variation in the chlorophyll *a* concentration in the (A) surface layer and (B) bottom layer at inshore, middle shore, and offshore areas around the Chagwi-do off the west coast of Jeju Island from September 2004 to November 2005.

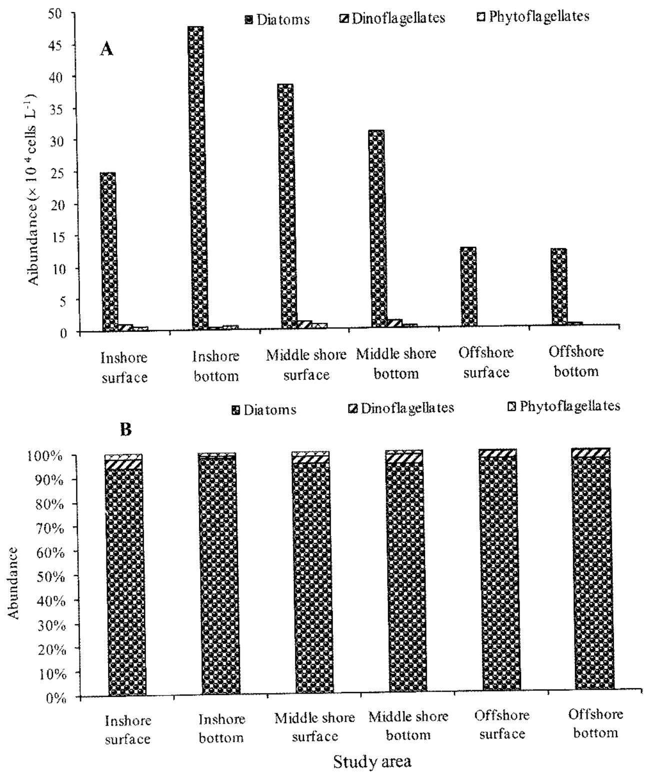

Fig. 8. (A) Cell abundance and (B) percent abundance composition of diatoms, dinoflagellates, and phytoflagellates during the peak of the 2005 spring bloom around Chagwi -do off the west coast of Jeju Island.

species of phytoflagellates was *Hillea* sp. *Chaetoceros socialis* and *S. costatum* were important in the spring bloom, with the highest abundance. The percent abundance of *C. socialis* varied from 19.7 to 31.5%, with an average of 24.6%, and from 29.7 to 43.3%, with an average of 35.8%, in the surface and bottom layers, respectively (Table 2). The percent abundance of *S. costatum* varied from 12.5 to 28.1%, with an average of 18.5%, and from 10.0 to 30.4%, with an average of 19.0%, in the surface and bottom layers, respectively (Table 2).

During the autumn bloom, the abundance ranges of diatoms, dinoflagellates, and phytoflagellates were 4.04–8.02$\times 10^4$ cells L^{-1}, 5.63–9.83$\times 10^4$ cells L^{-1}, and 1.04–2.27 $\times 10^4$ cells L^{-1}, respectively (Fig. 9A). In the surface layer, 16 species of phytoplankton had over 10% abundance relative to the total phytoplankton abundance, of which 10 species belonged to Bacillariophyceae, 3 to Dinophyceae, 1 to Chlorophyceae, 1 to Cryptophyceae, and 1 to Euglenophyceae. In the bottom layer, 14 species were dominant, including 9 species of Bacillariophyceae, 3 of Dinophyceae, 1 of Cryptophyceae, and 1 of Dictyophyceae (Table 3). The contribution of dinoflagellates varied from 46.9 to 58.4%, with an average of 51.2%, and the highest abundance occurred in the bottom layer offshore (Fig. 9B). The most dominant dinoflagellate species in the surface and bottom layers were *Gymnodinium conicum*, *Prorocentrum micans*, and *Prorocentrum triestinum*; their respective average contributions were 10.4, 11.3, and 10.5% in the surface layer, and 11.1, 12.2, and 11.8% in the bottom layer (Table 3). The dominant phytoflagellate species were *Hillea fusiformis* (13.1%), *Dunaliella martimum* (11.9%), and *Eutreptia viridis* (12.1%) in the surface layer, and *H. fusiformis* (11.6%) and *Pesudopedinella pyriforme* (10.7%) in the bottom layer (Table 3).

4. Discussion

Dynamics of environmental factors

The physical characteristics, especially the changing patterns of water temperature, were stable from the beginning of winter (January) to the end of spring (May) and did not differ among stations. This may have been

Table 2. List of dominant phytoplankton species (>10% of total abundance) and percent abundance during the spring bloom around the Chagwi-do off the west coast of Jeju Island

Species name	Surface layer									Average
	Inshore			Middle shore			Offshore			
	March	April	May	March	April	May	March	April	May	
Diatoms										
Chaetoceros lorenzianus		11.33			10.11			10.04	10.85	10.58
Chaetoceros pseudocrinitus		16.66			15.01			13.35		15.01
Chaetoceros socialis	19.95	22.59		26.16	19.70	15.95	16.58	31.45	12.42	20.60
Skeletonema costatum	11.03	10.85	22.91	14.61	15.34	18.81	16.78	12.46	17.85	15.63
Phytoflagellates										
Hillea sp.							10.33			10.33

Species name	Surface layer									Average
	Inshore			Middle shore			Offshore			
	March	April	May	March	April	May	March	April	May	
Diatoms										
Chaetoceros lorenzianus		11.05			13.34			10.38		11.59
Chaetoceros pseudocrinitus		14.08	12.52		11.50	11.54		12.90	17.65	13.37
Chaetoceros socialis	15.40	29.69	25.66	22.64	43.26	17.51	16.26	34.53	19.85	24.98
Skeletonema costatum	30.39	12.98	22.60	10.12	15.23	16.87	18.67	16.57	14.71	17.57

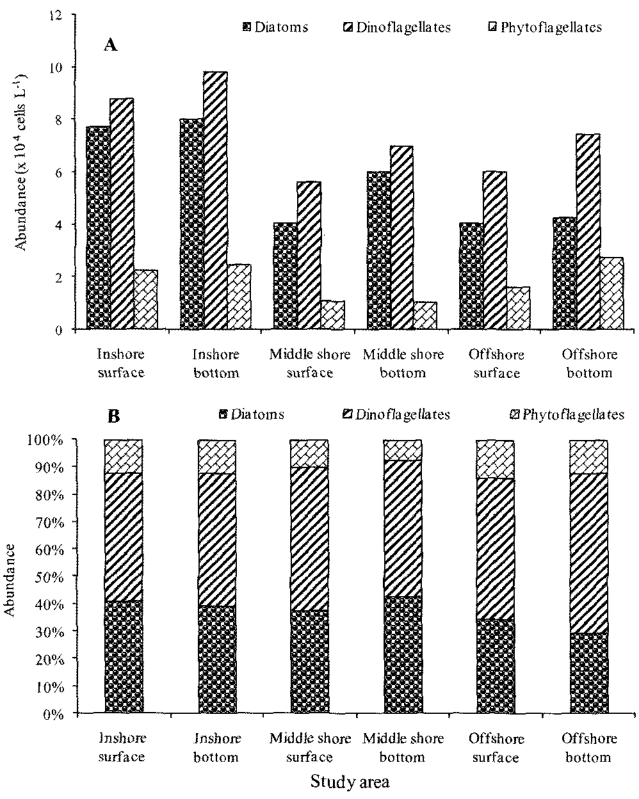

Fig. 9. (A) Cell abundance and (B) percent abundance composition of diatoms, dinoflagellates, and phytoflagellates during the peak of the 2005 autumn bloon around Chagwi–do off the west coast of Jeju Island.

attributable to the effective vertical mixing of surface and bottom water. The water temperature of the surface layer was high from the beginning of summer (June) to the end of autumn (November), and no significant difference was observed among stations. The water temperature of the bottom layer of the offshore and middle shore areas was much lower than that of the inshore areas. This indicates that a distinct thermocline may develop in summer as a result of weak vertical mixing, as well as the Yellow Sea Cold Water, which flows southward below the thermocline (Park 1986; Mask and O'Brien 1998).

Like water temperature, the salinity from winter to spring was similar in the surface and bottom layers due to effective vertical mixing, whereas the salinity in summer was higher in the bottom than in the surface layer. Heavy flows of freshwater from the Changjiang River in summer decrease the surface water salinity through dilution. Low salinity in summer is frequently observed off the west coast of Jeju Island and sometimes causes severe damage to fishery industries such as fish and gastropod aquaculture (Suh *et al.* 1998). Inshore salinity was lower than that of the middle shore and offshore areas during summer in both the surface and bottom layers. The huge surface runoff from adjacent mainland China due to heavy rainfall during summer may the possible cause of this phenomenon.

Table 3. List of dominant phytoplankton species (>10% of total abundance) and percent abundance during the autumn bloom around the Chagwi-do off the west coast of Jeju Island

Species name	Surface layer						Average
	Inshore		Middle shore		Offshore		
	October	November	October	November	October	November	
Diatoms							
Achnanthes longipes			10.29				10.29
Chaetoceros convolutus		11.89		10.02			10.96
Chaetoceros costatus		12.03				10.16	10.11
Chaetoceros lorenzianus				11.21		18.28	14.15
Chaetoceros pseudocrinitus		14.74				11.00	12.87
Leptocylindrus danicus			11.86				11.86
Licmophora paradoxa	10.00						10.00
Nitzschia sigma	12.00						12.00
Paralia sulcata			21.50				21.50
Skeletonema costatum			13.24		11.94		12.59
Dinoflagellates							
Gymnodinium conicum	11.03	10.21	10.05	10.16	10.01	12.02	10.41
Prorocentrum micans	11.67	10.00	11.29	10.45	11.04	11.60	11.34
Prorocentrum triestinum		10.42		10.14		11.01	10.52
Phytoflagellates							
Hillea fusiformis	10.34				11.84		11.09
Dunaliella martimum					10.08		10.08
Eutreptia viridis	12.07						12.07

Species name	Bottom layer						Average
	Inshore		Middle shore		Offshore		
	October	November	October	November	October	November	
Diatoms							
Chaetoceros convolutes		17.85	10.36	11.00		10.20	12.35
Chaetoceros costatus		16.74		12.01		11.03	13.26
Chaetoceros pseudocrinitus				10.39			10.39
Leptocylindurs danicus	10.10		18.16		11.58		13.28
Nitzschia longissima		10.75					10.75
Skeletonema costatum			11.11		11.43		11.27
Nitzschia sigma	11.65		12.12		10.98		11.58
Paralia sulcata	14.38						14.38
Stauroneis membranacea	10.10						10.10
Dinoflagellates							
Gymnodinium conicum	10.01	10.25	12.13	10.02	13.00	10.26	11.12
Prorocentrum micans	13.65	13.00	15.79	12.50	10.02	10.00	12.16
Prorocentrum triestinum		11.52		13.67		10.11	11.77
Phytoflagellates							
Hillea fusiformis	11.67				11.43		11.55
Pseudopedinella pyriforme			10.71				10.71

Phytoplankton dynamics in relation to environmental factors

The abundance and species composition of phytoplankton varied strongly with season. Spring and autumn phytoplankton blooms occurred, which were confirmed by the higher chlorophyll *a* concentrations at these times. The species diversity index was lowest during the spring bloom. Phytoplankton abundance was higher during the spring bloom than the autumn bloom. The increasing water temperature, irradiance, day length, and nutrient availability from the bottom layer may have promoted the growth of the dominant species during the spring bloom. Additionally, the concentration of NH_4-N, which is the nitrogen form most preferred by phytoplankton, may increase in winter and become available for the spring bloom.

Centric diatoms were the most abundant species during the spring bloom. The smaller chain-forming diatoms such as *C. socialis*, *C. lorenzianus*, *C. pseudocrinitus*, and *S. costatum*, as well as the phytoflagellate *Hillea* sp. mainly composed the spring bloom. These small-sized phytoplankton may be the most efficient at using the available nutrients for growth. Chisholm (1992) found that smaller phytoplankton had minimal sinking velocities and high surface area to volume ratios, thereby optimizing light and nutrient absorption efficiencies. Diatoms may also have an advantage because of their high fucoxanthin content. In coastal waters, where particulate and dissolved organic matter occur in high concentrations, blue light is rapidly attenuated, with preferential transmission of green to yellow wavelengths (Gin *et al.* 2003). Fucoxanthin is the most efficient photosynthetic carotenoid that absorbs light in the green wavelengths (Ondrusek *et al.* 1991).

During the autumn bloom, dinoflagellates, rather than diatoms, were most abundant in the bottom layer at all stations, with the highest abundance (51.2%) offshore. The high NO_2-N concentration and moderate temperature may have contributed to the rapid growth of the dominant dinoflagellates in autumn. Dinoflagellates were also abundant in midsummer (July), and *P. triestinum* was the most abundant species, with 30.1 and 15.3% abundance in the surface and bottom layers, respectively. Low salinity, high water temperature, and adequate nutrient availability likely contributed to the increase in abundance. Low salinity and nutrient inputs may be caused by high water flow from the Changjiang River in summer. Hyun and Pang (1998) reported that the massive water output of the Changjiang River frequently reaches the west coast of Jeju Island in summer.

In conclusion, the dynamics of the water temperature of the surface layer were similar to those of the atmospheric temperature, whereas low water temperature occurred in the bottom layer, especially in summer. Diatoms were dominant in spring, whereas dinoflagellates and phytoflagellates were dominant in autumn. The most important factors underlying the dynamics of the phytoplankton blooms were temperature and nutrients, especially the form of nitrogen available.

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