Article

Temporal Variation of Phytoplankton Community Related to Water Column Structure in the Korea Strait

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Abstract : Photosynthetic pigments, nutrients, and hydrographic variables were examined in order to elucidate the spatio-temporal variation of water column structure and its effect on phytoplankton community structure in the western channel of the Korea Strait in fall 2006 and spring 2007. High phytoplankton biomass in the spring was associated with high salinity, implying that nutrients were not supplied by coastal waters or the Yangtze-River Diluted water (YRDW) with low salinity. Expansion of the Korea Strait Bottom Cold Water (KSBCW) and a cold eddy observed during the spring season might enhance the nutrient supply from the subsurface layer to the euphotic zone. Chemotaxonomic examination showed that diatoms accounted for 60-70% of total biomass, followed by dinoflagellates. Nutrient supply by physical phenomena such as the expansion of the KSBCW and the occurrence of a cold eddy appears to be the controlling factors of phytoplankton community composition in the Korea Strait. Further study is needed to elucidate the mechanisms by which the KSBCW is expanded, and its role in phytoplankton dynamics.

Key words : phytoplankton, nutrients, Korea Strait, Korea Strait Bottom Cold Water, eddy

1. Introduction

Phytoplankton community structure in the ocean may have an effect on biological productivity, food web structure in pelagic and benthic ecosystems, and carbon export to the deep ocean (Azam et al. 1983; Karl 1999; Karl et al. 2001). Phytoplankton community composition and biomass are controlled by various physical and chemical factors including nutrient and light conditions, seawater acidification, and hydrographic features such as water column structure, eddies, and upwelling (Schofield et al. 1993; Ruud et al. 1997; Moline 1998; Lee et al. 2009).

The Korea Strait is located between the Korean

peninsula and the Japanese islands. It is similar to a sill separating the East China Sea (ECS) and the East/Japan Sea (EJS). The Tsushima Warm Current (TWC), a branch of the Kuroshio Warm Current (KWC), is the principal surface current flowing northeastward from the ECS into the EJS through the Korea Strait. It plays an important role in transporting nutrients and various materials, originating from Yangtze-River discharge, to the southern region of the EJS and the Korea Strait (Yanagi 2002; Onitsuka et al. 2007; Morimoto et al. 2009).

The Korea Strait is a dynamic environment because of topography, river discharge (e.g. Yangtze River), and current transport. Having the largest flux of freshwater and various materials into the ECS, annual discharge from the Yangtze River was reported to be approximately $9.25 \times 10^{11} \text{ m}^3 \text{ yr}^{-1}$ (Tian et al. 1993). Freshwater discharge

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control by the recent construction of the Three Gorges Dam on the Yangtze River (Jiao et al. 2007) was suggested to influence physical and chemical environments as well as biological response in the ECS, Korea Strait, and potentially EJS (Liu et al. 2003; Gong et al. 2006; Onitsuka et al. 2007; Jiao et al. 2007). Yang et al. (2000) suggested that initiation of the harmful algal bloom occurring along the southern coast of Korea during summer season is related to the intrusion of the Yangtze-River Diluted water (YRDW) containing high nutrients. Volume transport of the TWC through the Korea Strait exhibits a seasonal variation, typically high in the summer and low in the winter (Lyu et al. 2002; Takikawa et al. 2005). Counterclockwise eddies, affecting phytoplankton biomass in the euphotic zone, have been observed frequently in the eastern channel of the Korea Strait (Morimoto et al. 2009).

It is important to understand the relationship between phytoplankton community structure and the hydrological and chemical variables in a complex system like the Korea Strait (Onitsuka et al. 2009). However, few studies have been conducted to understand temporal variation of phytoplankton community structure and biomass, and the relationship to short- and long-term variability in water mass properties in the Korea Strait.

To understand the biological change (phytoplankton community structure) related to temporal variation of physical and chemical environments in the Korea Strait, this study investigated 1) the spatial and temporal variation of water mass properties, including nutrient

dynamics, and 2) the response of phytoplankton biomass and community structure to water mass variations in a northwest-southeast transect across the Korea Strait using HPLC pigment analysis and CHEMTAX analysis of pigment signatures, which have been used as powerful tools for studying phytoplankton community (Mackey et al. 1996; Hassen et al. 2008).

2. Materials and methods

Study area and seawater sampling

The Korea Strait is divided by Tsushima Island into eastern and western channels. This study was mainly conducted in the western channel of the Korea Strait. Hydrographic observation and seawater sampling were conducted on 9 October, 26 October, and 13 November in 2006 as well as 28 May in 2007 along a transect located in the western channel of Tsushima Island (St. NK1-NK6 in Fig. 1). In May 2007, the cruise was extended to the eastern channel of the Korea Strait (St. NK1-NK10). Hydrographic properties (temperature and salinity) were measured with a CTD profiler (Seabird Electronics 911).

Nutrient and photosynthetic pigment analyses

Water samples for nutrient and pigment analyses were taken at depth intervals of 10 m in the upper layer above 150 m at each station in the transect, with the exception of some stations. To determine nutrient concentration, approximately 500 ml of each seawater sample was filtered through GF/F filters (25 mm in diameter) and

Fig. 1. Sampling locations in the Korea Strait.

stored in a freezer at -20°C . Concentrations of NO_3^- , NO_2^- , PO_4^{3-} , and $\text{Si}(\text{OH})_4$ were analyzed with an Auto-Analyzer (Futura plus II, Alliance Co.). NO_x is defined as the sum of NO_3^- and NO_2^- , DIP as PO_4^{3-} , and DSI as $\text{Si}(\text{OH})_4$.

To analyze photosynthetic pigments, seawater samples (~ 2 l) were filtered immediately after sampling using GF/F filters (47 mm in diameter) onboard the ship. Each filter was wrapped in aluminum foil and stored in a freezer (-20°C). Upon arrival at the land-based laboratory, the samples were stored at -80°C in a deep freezer until analysis. The samples were extracted with 100% acetone (5 ml) for 24 hrs in the dark (-20°C) after sonication for 5 minutes to enhance cell disruption. The extracted solution was centrifuged at 2500 rpm for 10 min to remove particulate materials. Supernatant (1 ml) was well-mixed with 300 μl of deionized water. Then 100 μl of this mixture was analyzed by reverse-phase high-performance liquid chromatograph (Shimadzu Co. system) equipped with a Rexchrom-S5-100-ODS column (Regis, USA, 250×4.6 mm, particle size: 5 μm), following a modified method described by Wright et al. (1991). Canthaxanthin was used as an internal standard. Standard pigments were quantified by a spectrophotometer using a published extinction coefficient (Jeffrey 1997). Pure standard pigments, obtained from Sigma Chemical and DHI, were used to identify pigment peaks and calibrate pigment concentrations based on the peak areas.

On the basis of measured pigment signatures, phytoplankton community composition was determined using the CHEMTAX program (Mackey et al. 1996). In this study, the diagnostic biomarker pigments are chlorophyll *a*, fucoxanthin, 19'-hexanoyloxy-fucoxanthin, 19'-butanoyloxy-fucoxanthin, peridinin, chlorophyll *b*, prasinoxanthin, lutein, violaxanthin, alloxanthin, and zeaxanthin. Modified from the values in Mackey et al. (1996), class-specific pigment

ratios were used as the input pigment ratios of the CHEMTAX program (Table 1). The initial ratios of marker pigments to chlorophyll *a* for chlorophytes, dinoflagellates, diatoms, and cyanobacteria were obtained from phytoplankton species isolated from offshore seawaters of the Korean peninsula by the Korea Marine Microalgae Culture Center (KMMCC).

3. Results and discussion

Distributions of temperature, salinity, and nutrients

Various factors, such as light intensity, stability of the water column, temperature, and nutrient concentrations, may influence biomass and community composition of phytoplankton (Reid et al. 1990; Lee et al. 2009). During the study periods, seawater temperature and salinity ranged from 5 to 25°C and from 32 to 35, respectively. Temperature in May 2007 (5 – 20°C) was lower than in October and November 2006 (8 – 25°C), while salinity in May 2007 (33–34.5) was higher than in fall 2006 (32.2–34.5) (Fig. 2). Temperature and salinity in surface waters increased gradually from on the shelf to off the shelf, reflecting the increasing influence of KWC with high temperature and salinity (Fig. 3).

Expansion and contraction of the bottom cold water mass ($<10^{\circ}\text{C}$) in the Korea Strait varied seasonally (Fig. 3). In May 2007, the Korea Strait Bottom Cold Water (KSBCW) ($<10^{\circ}\text{C}$) expanded to off the shelf (St. NK6) and reached up to 20 m in depth below the surface mixed layer on the shelf (St. NK1). Presence of the KSBCW in the bottom layer of the Korea Strait and its seasonal variability has been reported (Lim and Chang 1969; Cho and Kim 1998). Lim and Chang (1969) suggested that the KSBCW originates from the western region of the EJS (the southeastern coast of the Korean peninsula) and

Table 1. Initial pigment ratios used for the CHEMTAX program. *Pigment ratios from our cultures

	Perid	But-fuco	Fuco	Hex-fuco	Pras	Viola	Allo	Lut	Zea	Chl <i>b</i>
Prasino	0	0	0	0	0.3151	0.0616	0	0.0088	0	0.9452
Dino*	0.6547	0	0	0	0	0	0	0	0	0
Crypto	0	0	0	0	0	0	0.2292	0	0	0
Initial	0	0	0	1.7059	0	0	0	0	0	0
ratio	0	0.2453	0.5849	0.5377	0	0	0	0	0	0
Pelago	0	0	0	0	0	0.0321	0	0.2379	0.0076	0.3361
Chloro*	0	0	0	0	0	0	0	0	0.2808	0
Cyano*	0	0	0.5464	0	0	0	0	0	0	0
Diatoms*	0	0	0	0	0	0	0	0	0	0

¹Abbreviations: Prasino, Prasinophytes; Dino, Dinoflagellates; Crypto, Cryptophytes; Prymne, Prymnesiophytes; Pelago, Pelagophytes; Chloro, Chlorophytes; Cyano, Cyanobacteria; Perid, Peridinin; But-fuco, 19'-butanoyloxy-fucoxanthin; Fuco, Fucoxanthin; Hex-fuco, 19'-hexanoyloxy-fucoxanthin; Pras, Prasinoxanthin; Viola, Violaxanthin; Allo, Alloxanthin; Lut, Lutein; Zea, Zeaxanthin; and, Chl *b*, Chlorophyll *b*.

Fig. 2. T-S diagrams of the water column of the NK transect in the Korea Strait.

expands broadly in the summer compared to the winter season (Kim et al. 2006). The expansion and upwelling of the KSBCW on the shelf in May 2007 appears to have enhanced nutrient supply to the surface layer and, consequently, enhanced phytoplankton growth.

Surface mixed layer gradually increased offshore with increasing water depth. The surface mixed layer was 40–60 m thick and much shallower in November 2006 and May 2007 than in October 2006 (Fig. 3). Mixed layer depth is one of the main factors controlling the supply of nutrients from the subsurface layer to the euphotic zone, triggering phytoplankton growth. Chen and Chen (2006) reported that phytoplankton biomass was higher in the winter when surface mixed layer was shallow than in the

summer. A shallow surface mixed layer formed on the shelf in May 2007, especially, because of a strong KSBCW.

A more expanded region was examined to include the off shelf region (St. NK7–NK10) in May 2007. A cold eddy associated with the shallow surface mixed layer near Tsushima island station was observed in May 2007. Counterclockwise eddies in the Korea Strait have been observed frequently (Takikawa et al. 2005; Morimoto et al. 2009). This island-induced eddy has a significant impact on the nutrient supply from the subsurface layer to the euphotic zone, enhancing primary production (Morimoto et al. 2009; Onitsuka et al. 2009).

The concentration of dissolved inorganic nitrogen (NO_x : $\text{NO}_3^- + \text{NO}_2^-$) in the surface seawater (0–20 m) was mostly less than $2 \mu\text{M}$ (Fig. 4). In the euphotic zone (<40 m depth: approximately 1% of the surface light penetration), concentrations of dissolved inorganic phosphate (DIP) and silicate (DSi) were in the range of 0.0–1.50 and 0.19–36.9 μM , respectively. The nutrient (NO_x , DIP, and DSi) concentrations in the euphotic zone were higher in late fall (13 November 2006), when water column stratification was weakened, than in October 2006. In May 2007, although water column stratification was weakened, nutrient concentrations in the euphotic zone were low. Nutrient concentrations are mainly controlled by river discharge, water column stratification, and atmospheric deposition. Many studies have reported that excess nutrients in the Korea Strait are supplied by the YRDW (Onitsuka et al. 2007; Morimoto et al. 2009). High precipitation in summer influences salinity and chemical characteristics in the Korea Strait. Salinity in fall 2006

Fig. 3. Contour plots of temperature and salinity along the NK transect in the Korea Strait.

Fig. 4. Contour plots of dissolved inorganic nutrients (A) NO_x ($\text{NO}_3^- + \text{NO}_2^-$), (B) DIP, and (C) DSi along the NK transect in the Korea Strait.

was low compared to May 2007 (Fig. 2). The Yangtze-River discharge (approximately $9.25 \times 10^{11} \text{ m}^3 \text{ yr}^{-1}$) supplies a large amount of fresh water and various materials into the ECS and the Korea Strait (Tian et al. 1993). Surface water runoff, including the discharge of the Nakdong River from the southern coastal region of the Korean peninsula, is another main source of inorganic nutrients in the western channel of the Korea Strait (Lee et al. 1984). However, a narrow range of salinity was observed in November 2006 (33–34.5) compared to October 2006 (32–34.5). In November 2006, by destruction of stratified water column, high nutrient concentrations seem to be related to nutrient supply from the subsurface layer to the euphotic zone. On the other hand, lower nutrient concentrations in the euphotic zone associated with a shallow surface mixed layer in May 2007 seem to be caused by nutrient consumption by phytoplankton.

Distribution of phytoplankton community structure

The dynamic change of water mass properties in the Korea Strait is expected to affect primary producer biomass. As an index of phytoplankton abundance, chlorophyll *a* concentrations, integrated in the euphotic zone (<40 m depth) of the NK transect in the Korea Strait, ranged from 6 to 110 mg m^{-2} (Fig. 5). Average integrated chlorophyll *a* concentration from NK1 to NK6 in May 2007 (34.1 ± 5.5

Fig. 5. Distributions of chlorophyll *a* average inventory (0–40 m) along the NK transect in the Korea Strait.

mg m^{-2}) was higher than in October 2006 ($15.4 \pm 10.6 \text{ mg m}^{-2}$) by approximately two-fold (Table 2; Fig. 5). Chlorophyll *a* concentration decreased with increasing offshore bottom water depth in May 2007. The high phytoplankton biomass seems to be related to the expansion of the KSBCW to the euphotic zone on the shelf in May 2007. Although wind-driven coastal upwelling has a different nutrient supply mechanism into the euphotic

Table 2. Marker pigment concentrations (ng m⁻²) integrated in the upper 40 m of each sampling station in the transect of the Korea Strait

Station	Perid	But-fuco	Fuco	Hex-fuco	Pras	Viola	Allo	Lut	Zea	Chl <i>b</i>	Chl <i>a</i>
9 Oct. 2006											
NK1	506	27	6095	339	1033	108	418	188	1496	14739	16226
NK2	173	219	3025	130	1022	76	213	53	2322	9384	12244
NK3	267	582	5637	111	1561	16	245	11	592	9040	8854
NK4	127	703	13386	118	2295	161	460	35	413	9528	16391
NK5	173	515	4950	236	2968	75	346	18	1230	13927	45697
NK6	168	1088	2719	803	1973	37	256	4	950	10404	11681
26 Oct. 2006											
NK1	0	61	2700	436	171	58	187	72	508	30514	8336
NK2	299	36	4827	583	361	45	276	35	843	27054	11184
NK3	219	0	2021	225	147	65	478	530	133	21472	8228
NK4	39	259	1361	209	615	2	119	3	411	19742	6295
NK5	499	1048	5952	4758	0	133	453	48	1043	28023	18636
NK6	284	1231	10687	57	3623	8	632	36	528	21499	21235
13 Nov. 2006											
NK1	1085	8331	8223	1284	2163	137	636	191	535	18441	26558
NK2	368	204	8265	340	1852	100	422	106	399	11047	18255
NK3	845	354	13184	4502	950	554	2135	3892	267	36075	109535
NK4	715	1238	5191	927	5160	67	535	121	980	14534	22089
NK5	463	713	28715	61	1739	0	1074	2755	161	4823	28410
NK6	391	546	18531	12	1397	0	712	162	104	3316	18905
28 May 2007											
NK1	7160	472	26481	1087	735	1242	243	62	141	18551	37809
NK2	3702	481	17357	1435	0	610	140	69	17	13833	36584
NK3	11863	768	9698	1404	0	453	8	50	372	9007	32844
NK4	13779	590	8894	1241	0	0	93	236	0	6201	30199
NK5	12148	359	7232	866	0	71	62	318	39	6262	25906
NK6	19271	1340	14997	650	973	491	177	253	170	10496	41063
NK7	6353	920	11735	3045	0	229	121	286	112	7057	26555
NK8	11338	1160	26272	3354	0	65	214	251	27	19567	46402
NK9	2784	331	7901	966	13	0	11	373	0	4174	19586
NK10	2265	450	7098	1393	0	9	97	238	0	4719	18960

¹Abbreviations of pigment names are listed in Table 1.

zone with the KSBCW, it has frequently occurred in the southeastern part of Korea in summer (Lee and Na, 1985; Kim and Lee, 2004; Yoo and Park, 2009). Yoo and Park (2009) suggested that high primary production in the region is associated with nutrient supply from the subsurface region to the euphotic zone due to coastal upwelling.

Upwelling, induced by a cold eddy, was observed at NK8 in May 2007. Chlorophyll *a* concentration (46 mg m⁻²) integrated at this station was approximately two-fold

higher than at adjacent stations. By supplying nutrients from the subsurface layer to the euphotic zone, this island-induced eddy has significant impacts on the distribution and productivity of phytoplankton and zooplankton (Morimoto et al. 2009; Onitsuka et al. 2009). The high phytoplankton biomass in the Korea Strait in May 2007 seems to be related to the expansion of the KSBCW and the eddy event on the shelf and off the shelf, respectively.

The most abundant diagnostic pigments in the Korea Strait were fucoxanthin and peridinin, indices of diatoms

Fig. 6. Contour plots of main marker pigments along the NK transect in the Korea Strait on 28 May 2007.

and dinoflagellates, respectively. In May 2007, fucoxanthin and peridinin, in a transect of the Korea Strait (<40 m depth), varied between 69 and 1794 ng L^{-1} with a mean of $380 \pm 388 \text{ ng L}^{-1}$ and between 0 and 848 ng L^{-1} with a mean of $237 \pm 211 \text{ ng L}^{-1}$, respectively (Table 2). Concentrations of 19'-hexanoyloxy-fucoxanthin, 19'-butanoyloxy-fucoxanthin, and prasinoxanthin, indices of small-sized phytoplankton, increased off the shelf as a whole (Fig. 6, Table 2). Diatoms and dinoflagellates in the Korea Strait may flourish when nutrients are supplied from upwelling caused by KSBCW expansion and eddy events, YRDW, and coastal water. However, the relatively lower nutrient conditions off the shelf in the Korea Strait may reduce the growth of larger-sized diatoms or dinoflagellates. Nano- or pico-plankton community may have an advantage off the shelf where nutrient concentrations are low (Furuya et al. 2003).

To understand the temporal and spatial variation of phytoplankton community structure along the NK transect, each marker pigment was integrated in the euphotic zone (<40 m depth). Based on the integrated pigment data, the

CHEMTAX program was used to estimate phytoplankton class-specific contributions to total chlorophyll *a*. Dominant phytoplankton community in the Korea Strait was diatoms and dinoflagellates. Diatoms accounted for approximately 60-70% of total biomass during the sampling period (Fig. 7), while other phytoplankton groups accounted for less than 40% at most stations. Dinoflagellates accounted for over 40% of total biomass between NK3 and NK6 where low silicate concentrations (<2 μM) may have limited diatom growth (Egge and Aksnes 1992) (Fig. 7). The dominant phytoplankton community shifted to dinoflagellates, which grew better than diatoms in low silicate conditions. Typically, community changes from large-sized phytoplankton to small-sized phytoplankton from the coast to the outer shelf due to nutrient conditions (Furuya et al. 2003). However, in the Korea Strait, other patterns of phytoplankton community structure and biomass were observed in November 2006 and May 2007. Our results suggest that nutrient supply by expansion of the KSBCW and eddies favor the growth of diatoms and dinoflagellates in the Korea Strait.

Fig. 7. Distributions of average inventory (0–40 m) of phytoplankton algal groups on (A) 9 October and (B) 26 October 2006, (C) 13 November 2006, and (D) 28 May 2007 along the NK transect in the Korea Strait.

Acknowledgements

We would like to thank J. Hwang at POSTECH for providing valuable comments, and C. Kang's Stable Isotope Ecology Lab. members for help with sample collection and laboratory analyses. This work was supported by Korean EAST-I program of the Ministry of Land, Transport, and Maritime Affairs.

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Received Aug. 11, 2010

Revised Sep. 1, 2010

Accepted Sep. 13, 2010