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Community Structure and Spatial Distribution of Phytoplankton in the Polar Front Region off the East Coast of Korea in Summer

Joo-Suck PARK · Chang-Keun KANG · Kyeng-Ho AN
National Fisheries Research and Development Agency
Kijang-up, Kyoungsangnam-do 626-900, Korea

여름철 韓國 東海 極前線海域에서의 植物플랑크톤의 群集構造와 分布

朴周錫 · 姜昌根 · 安京鎬
國立水産振興院

To characterize the community structure and spatial distribution of phytoplankton, observations on seawater temperature, salinity, nutrients, primary productivity and abundance and species composition of phytoplankton were made in the polar front region and its neighborhood off the east coast of Korea in summer 1990.

Among the 96 taxa identified, *Rhizosolenia setigera* and *Thalassionema nitzschioides* were the most dominant species. The assemblage at the surface and 50 *m* depth was quite different in the northern inshore part of the study area but similar in the southern and offshore part. Principal component analysis by the species abundance showed that the phytoplankton consisted of the communities representing the surface of the northern inshore part with the neritic-warm dinoflagellates, the Northern Korean Cold Water with the cold water diatoms and the southern and offshore part, which seems to represent the Eastern Korean Warm Water, with the warm water diatoms. At the frontal region, diatoms were mixed with warm and cold water species. Primary productivity and phytoplankton standing crops were higher at the front than the neighboring waters. Nutrients were markedly high at the Northern Korean Cold Water. Horizontal advection of the Northern Korean Cold Water accompanied by nutrient supply seems to contribute to the high phytoplankton biomass at the front.

Introduction

At the boundary between two different water masses a front is formed. The frontal zone is often one of high productivity because of the good light penetration in the clear warm water and the high nutrient supply from the mixed areas(Raymont, 1980) and this also affects the distribution of fish-shoals(Uda, 1952). Yamamoto *et al.*(1988) showed the high phytoplankton standing stock just north of the Kuroshio front by the analysis of the species composition and water masses. The entrainment of coastal water and/or the Oyashio water was considerd to be an important factor for the formation of the phytoplankton peak abundance.

The Tsushima Current which enters through the Tsushima Strait flows northward and has three branches. The existence of three branches has been believed to be typical flow pattern of the Tsushima current. One of these branches flows northward along the east coast of Korea and is often called the Eastern Korean Warm Current(Kawabe, 1982). Gong and Son(1982) reported that a stable polar front between this Warm Current Core Water and the Northern Korean Cold Water was formed. In general the former is an oligotrophic, warm and high saline(>34.5‰) water, the latter is a cold, low saline(33.9~34.1‰) and nutrient rich watermass with high oxygen content(Park, 1979; Gong and Son, 1982; Lee, 1986).

Recently, the polar front has been investigated in relation to the physical and biological aspects by some workers. Kim(1991) reported the oceanographic condition in this polar front. Park *et al.*(1991) observed the zooplankton near this front. Shim *et al.*(1989) and Lee and Shim(1990) reproted that in the southern water of the Korean East Sea below 36° 50′ N phytoplankton community showed close correlation with hydrographic conditions and vertical distribution of phytoplankton was dependent upon stability of water column and nutrient concentration. However, there has been little information on the phytoplankton community and distribution near the polar front region over 36° 30′ N.

In the present study, a community structure of phytoplankton in and around the polar front off the east coast of Korea in summer was investigated by cluster analysis and principal component analysis. A relationship between this front and the spatial distribution of phytoplankton was also discussed with primary productivity.

Materials and Methods

Observations were made near the polar front in the middle part of Korean Eastern Sea between 37° 00′~38° 00′ N and 128° 30′~130° 00′ E during the cruises of the research vessel "Kwang Won 867" of National Fisheris Research and Development Agency(NFRDA), 3~10 August, 1990.

Phytoplankton samples were collected with van Dorn water samplers at three different depths(0, 20 and 50 *m* layers) of 11 stations(Fig. 1). Sub-samples were drained into 1 liter polyethylene bottles and preserved with modified Lugol's solution. Identification and cell counting were done with a Sedgwick-Rafter counting chamber under a microscope following to McAlice's treatment(1971). Chlorophyll *a* concentration was determined by the spectrophotometric method(DMS 80 UV Visible spectrophotometer) outlined in Strickland and Parsons(1968).

Water temperature, salinity and nutrients were investigated from surface to 200 *m* depth at the 31 serial oceanographic stations(Line 104~106) of NFRDA for the purpose of detecting the North Korean Cold Water and the Eastern Korean Warm Current. Water temperature and salinity were measured by CTD meter(SEABIRD Type). The method of Strickland and Parsons(1968) was used for the determination of phosphate and nitrate concentrations.

Primary productivity by phytoplankton was measured with the C-14 method described by Parsons *et al.*(1984). Euphotic zone at each station was determined from the calculation of the Secchi disc measurement.

The phytoplankton species analyzed were compared using the percent similarity index of Jaccard. Dendrograms were prepared from the similarity by unweighted-pair group method of Sneath and Sokal (1973). Orginal data matrix was reduced to exclude rare species which had occurred in less than 5% of samples, because random co-occurrence of

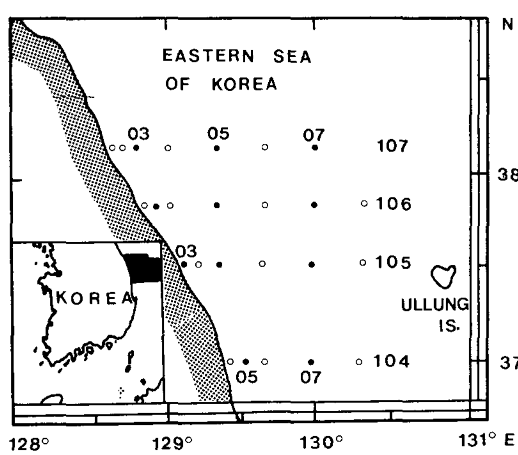

Fig. 1. Location of sampling stantions in August 1990 (• ; phytoplankton station, ◦ ; hydrographic station).

two rare species can result in their being grouped together as having identical distribution(Field *et al.*, 1982). To elucidate the relationships among the numerical abundances of species, observations were subjected to principal component analysis, using the log-transformed data. All abundances were augmented by 1.0 to preclude zero.

Results

Hydrography and nutrients

The horizontal distributions of water temperature were showen in Fig. 2. Temperature ranged from 3.7 to 28.4 ℃ in the upper layer of 50 *m* depth. Surface temperature were relatively homogeneous. At the 50 *m* depth, temperature ranged 3.7 to 16.9 ℃. A sharp thermal front was formed between the cold water with lower than 5 ℃ and the warm water with more than 15 ℃.

Fig. 3 showed the profiles of temperature, salinity and inorganic nutrients(phosphate and nitrate) in Line 106. Isoterms of cold water(lower than 10 ℃) formed a west-east slope from the 30 *m* depth of Station 10606 to the 150 *m* depth of Station 10608. Salinity distributions were also horizontally homogeneous in surface layer, from 33.8 to 34.1‰ in the coastal intermediate water and approximately 34.4‰ in the 50 *m* depth of offshore area. The temperature and salinity distribution indicated that the Eastern Korean Warm Current was flowing northward at the offshore side of the study area. In the coastal area, cold(lower than 10 ℃) water mass with low salinity occurred to the depth of 30 *m*.

The distribution of nutrients showed similar pattern of variation with that of temperature and were coincident with the trend of temperature and salinity(Fig. 3). Vertical distributions of phosphate and nitrate showed the low level near the surface and increased with depth. Nutrients were also richer at the cold and low-saline water than the warm and high-saline water. Average concentrations of phosphate at the 50 *m* depth were 0.47 $\mu g\text{-}at\ l^{-1}$ in the cold water and 0.24 $\mu g\text{-}at\ l^{-1}$ in the warm water. Average concentrations of nitrate were 3.02 and 0.61 $\mu g\text{-}at\ l^{-1}$ in the cold and warm water, respectively.

Community analysis of phytoplankton

Dendrograms for cluster analysis at three different depths, surface, 20 *m* and 50 *m*, were analyzed with the percent similarity of phytoplankton species. Phytohydrographic areas were demarcated by cluster analysis(Fig. 4).

Stations at surface and 20 *m* depth tended to

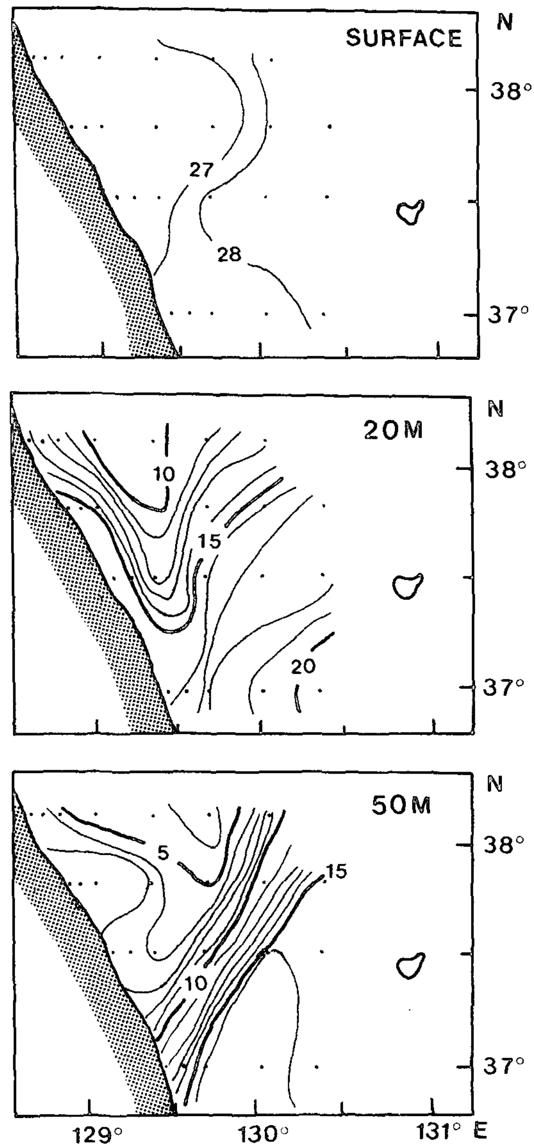

Fig. 2. Horizontal distribution of water temperature in the study area.

join the dendrograms with two groups at the 25% similarity level. On the surface layer, in particular, the coastal stations(Group A) seemed to group in long, narrow bands parallel to the northern coastline over 37° 30′ N. Group B were grouped with the southern and the eastern offshore stations. Stations of 20 *m* depth distinguished the northern stations such as Stations 10703, 10705 and 10605 from the southern stations.

But stations of the 50 *m* depth were divided into three areas. Group C was characterized by cold water mass(the Northern Korean Cold Water) having low temperature and salinity. Group B represented warm water mass(the Eastern Korean Warm Water) having high temperature and salinity. Group D reflected the mixing area of two conflicting water mass and showed the markedly high standing stock of phytoplankton.

Principal component analysis was made in an attempt to elucidate the relationship among the numerical abundances of the species. The data for the analysis were used with the 12 most dominant species occurred more than 70% of total number counted. All data were transformed log-normally. Table 1 showed the result of principal component analysis on the 12 species. Component I and II accounted for 35.9% and 28.8% of the variance in the system, respectively. Component I discriminated along taxonomic lines. Dinoflagellates and diatoms were negatively and positively correlated with Component I, respectively. Component II distinguished the cold water diatoms showing the negative corre-

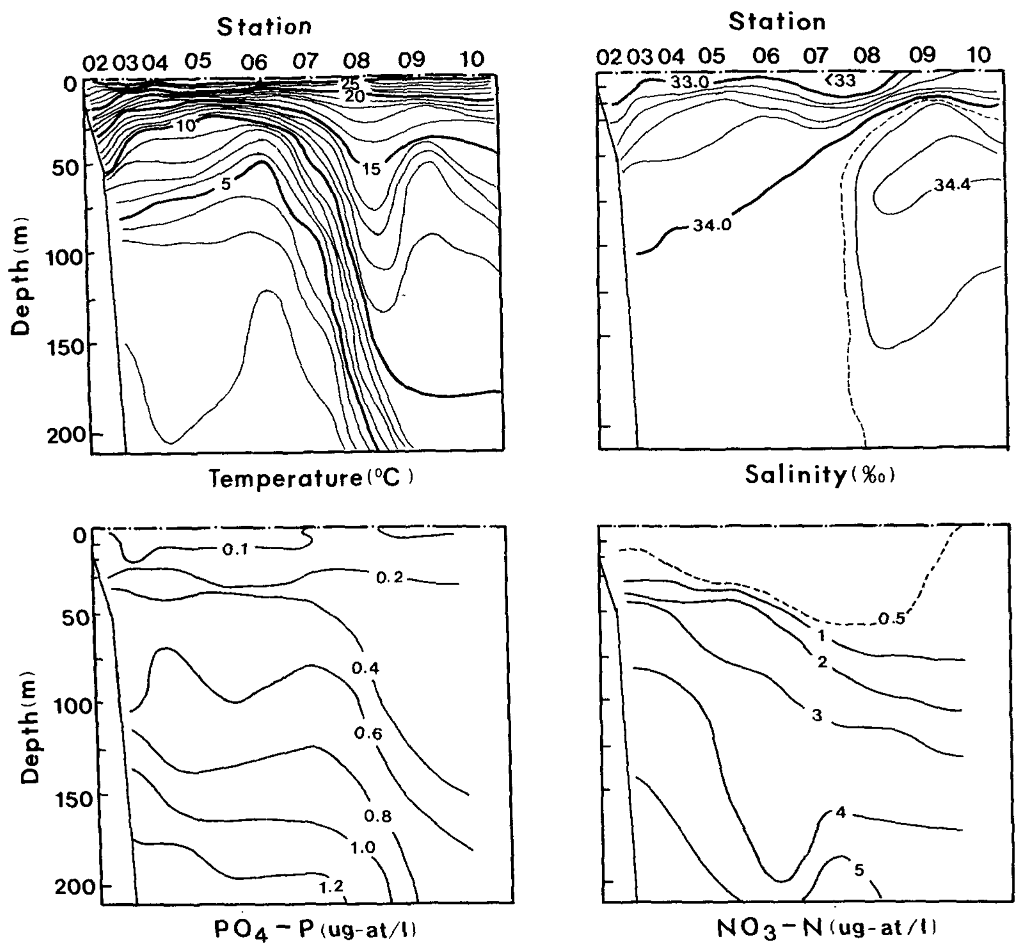

Fig. 3. Cross sections of temperature, salinity, phosphate and nitrate on the Line 106.

lation from the warm water diatoms showing the positive. Accordingly, Component II was comprised the parameter like temperature.

In Fig. 5, the cases of surface and 50 *m* depth samples were plotted in the space defined by Component I and II. Surface samples separated two clusters. The left cluster consisted of the samples from the northern coastal area and the upper right consisted of those from the southern and offshore area. But in the 50 *m* depth samples, three clusters were grouped. The upper right cluster was similar to suface samples but the lower left cluster was more or less separated from surface ones by Component II. The lower right cluster consisted of the samples from the mixing region such as Stations 10707, 10607 and 10405.

From these results, it showed that the surface

Table 1. Principal component analysis on the 12 most dominant species in the study area

Species	Component I	Component II	Component III
Rhyzosolenia setigera	.620	.626	-.112
Thalassionema nitzschioides	-.163	-.195	.524
Protoperidinum minitum	-.502	.151	-.218
Chaetoceros convolatus	.319	-.728	-.146
Leptocylindrus danicus	.092	.073	-.714
Chaetoceros curvisetus	.579	.512	-.062
Ch. danicus	.508	-.065	-.173
Prorocentrum micans	-.505	.282	-.175
Chaetoceros lorenzianus	.784	.480	.010
Guinardia flaccida	.611	.617	.167
Chaetoceros atlanticus	.639	-.591	-.175
Nitzschia spp.	-.037	.327	.072
% of variance	35.9	28.8	11.1

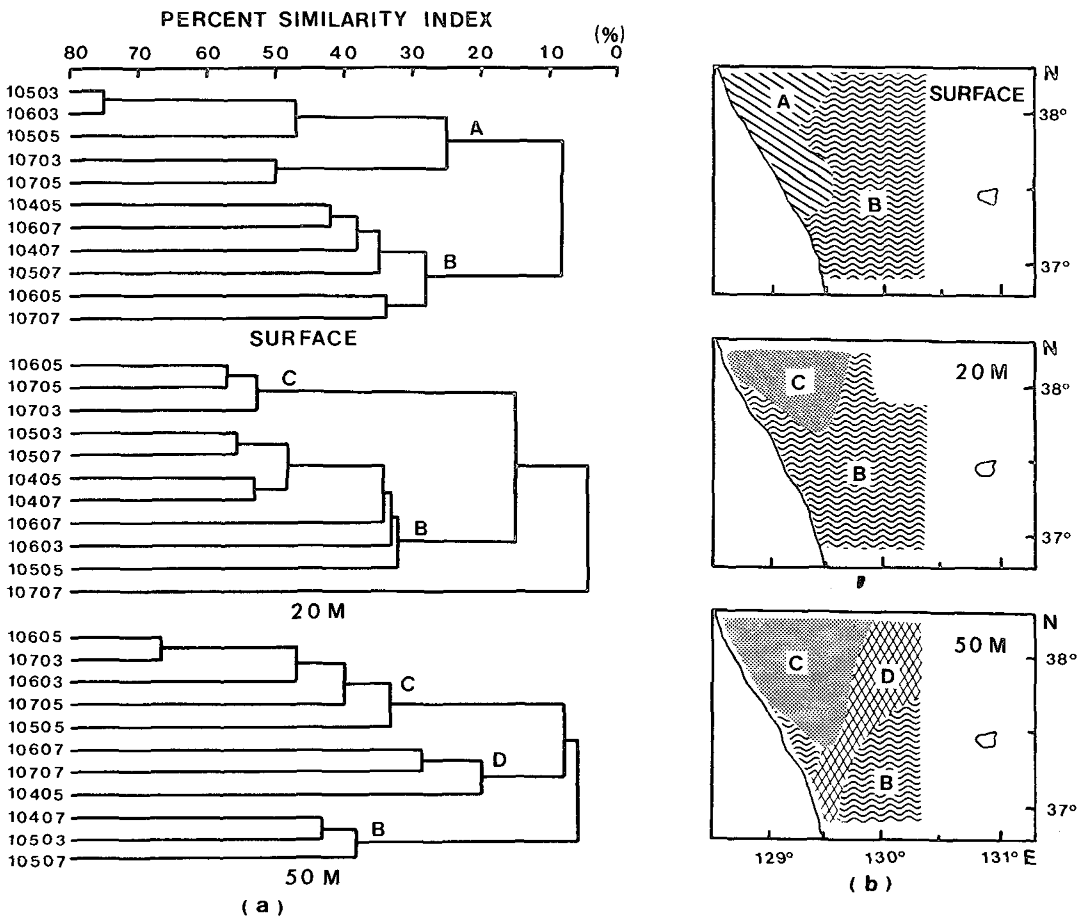

Fig. 4. Dendrograms showing the phytoplankton community structure(a) and phytohydrographic area(b).

samples of the northern part of coastal area segregated from the others along the axis of Component I and II. That is, these samples were distinguished by the abundance of dinofagellates and diatoms. At the 50 *m* depth, the northern stations were distinguished from the southern offshore stations by the different species composition. Theat is, cold water diatoms were mostly distributed at the former, and warm water diatoms were distributed at the latter. The mixing region was separated from the northern stations by the abundance of the group of diatoms.

Species composition

96 species of phytoplankton were identified and counted from the total of 33 samples. They consiso of 60 diatom species, 33 dinoflagellate species and 3 silicoflagellate species(Appendix I) and major species are listed in Table 2.

There were large numbers of the neritic, warm dinoflagellates, *Protoperidinium minutum* and *Prorocentrum micans* at surface stations in the northern part of the coastal area. The most dominant species at 20 *m* and 50 *m* depths of the northern part in that area were cold water diatoms such as *Chaetoceros convolatus* and *Ch. atlanticus.* Dominant species in the southern and offshore stations were

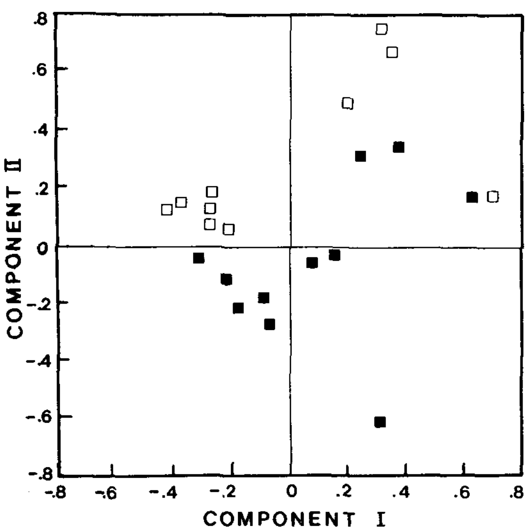

Fig. 5. Component II vs Component I (□; surface samples, ■; samples in 50 *m* depth).

mostly warm water diatoms such as *Rhyzosolenia setigera, Chaetoceros curvisetus, Ch. danicus, Ch. lorenzianus* and *Guinardia flaccida* as recorded the Kuroshio indicator species(Karawada, 1965).

Especially, samples from mixing region of 50 *m* depth were dominated by warm and cold water species such as *Chaetoceros curvisetus, Ch. lorenziaus* and *Ch. convolatum* and by *Corethron criophilum* and *Chaetoceros decipiens* which are less abundant at the other stations.

Horizontal distribution of phytoplankton abundance

The horizontal distributions of chlorophyll *a* and phytoplankton cell numbers in the study area are shown in Fig. 6.

Surface temperature and salinity were relatively homogeneous(Fig. 3). Chlorophyll *a* was from 0.46 to 1.00 *μg-at* l^{-1}. Phytoplankton cell numbers were greatest at Station 10407(about 10,000 cells l^{-1}) and lowest at Station 10505(about 1,000 cells l^{-1}). Those at the rest stations showed a range between 2,000 cells l^{-1} and 5,000 cells l^{-1}.

At the 20 *m* depth, the horizontal gradient of temperature between Station 10505 and 10405 was 0.1 ℃ Km^{-1}. Chlorophyll *a* was higher at Station 10701 with 1.53 μg l^{-1} and the other stations were less than 1.0 μg l^{-1}. Phytoplankton cell numbers were distributed from 2,000 to 8,000 cells l^{-1}.

At the 50 *m* depth, the largest temperature gradient was observed between Stations 10606 and 10608. Salinity was recorded from 33.6 to 34.4‰. Chlorophyll *a* showed a marked peak of 2.32 and

Table 2. Major species in each cluster group classified

Assemblage cluster	Species	
A	*Protoperidinium minitum*	*Prorocentrum micans*
B	*Rhyzosolenia setigera* *Ch. danicus* *Guinardia flaccida*	*Chaetoceros curvisetus* *Ch. lorenzianus* *Leptocylindrus danicus*
C	*Thalassionema nitzschioides* *Melosira nummuloides*	*Chaetoceros atlanticus* *Ch. convolatus*
D	*Chaetoceros convolatus* *Ch. danicus* *Ch. decipiens*	*Ch. curvisetus* *Corethron criophilum*

2.08 μg l^{-1} at Stations 10707 and 10607, respectively. Average value in the cold water mass less than 7 ℃ was 1.00 μg l^{-1} and was 0.74 μg l^{-1} in the warm water mass more than 15 ℃. Phytoplankton cell numbers were also higher at Stations 10707 and 10607(>10,000 cells l^{-1}) and at the rest stations they were more or less equally distributed less than 10,000 cells l^{-1} Accordingly, both chlorophyll *a* concentration and phytoplankton cell numbers at the stations of frontal zone was much higher than at the stations of cold and warm water masses.

Primary productivity and nitrogen requirement by phytoplankton

Euphotic depth(about 1% of surface light) calculated from the Secchi disc depth(14~20 *m*) was from 40 to 54 *m*. Horizontal distribution of total primary productivity by photoplankton in euphotic zone was from 0.6 at Station 10507 to 2.4 *g*C m^{-2} day^{-1} at Station 10707(Table 3). It was higher from 1.3 to 1.9 *g*C m^{-2} day^{-1} at Stations 10603, 10605, 10703 and 10705 in the norhtern area than from 0.6 to 0.7 *g*C m^{-2} day^{-1} at Stations 107407 and 10507 in the southern, offshore area and was highest from 2.1 to 2.4 *g*C m^{-2} day^{-1} at Stations 10707 and 10607 in the mixing region. Primary productivity at the base of euphotic zone near the 50 *m* depth showed the similar pattern to the total primary productivity.

N/P ratio of the average 6.1 in surface layer indicated that nitrogenous nutrients was the major limiting factor for phytoplankton growth in this area. Daily nitrogen requirement by phytoplankton ranged from 6.1 to 24.5 *mg-atN* m^{-2} day^{-1} with average 14.49 *mg-atN* m^{-2} day^{-1} assuming C/N ratio (Redfield's ratio) to be about 7.

Discussion

According to Gong and Son(1982) there were two oceanic thermal fronts in the southwestern Japan Sea. One major oceanic front was a polar

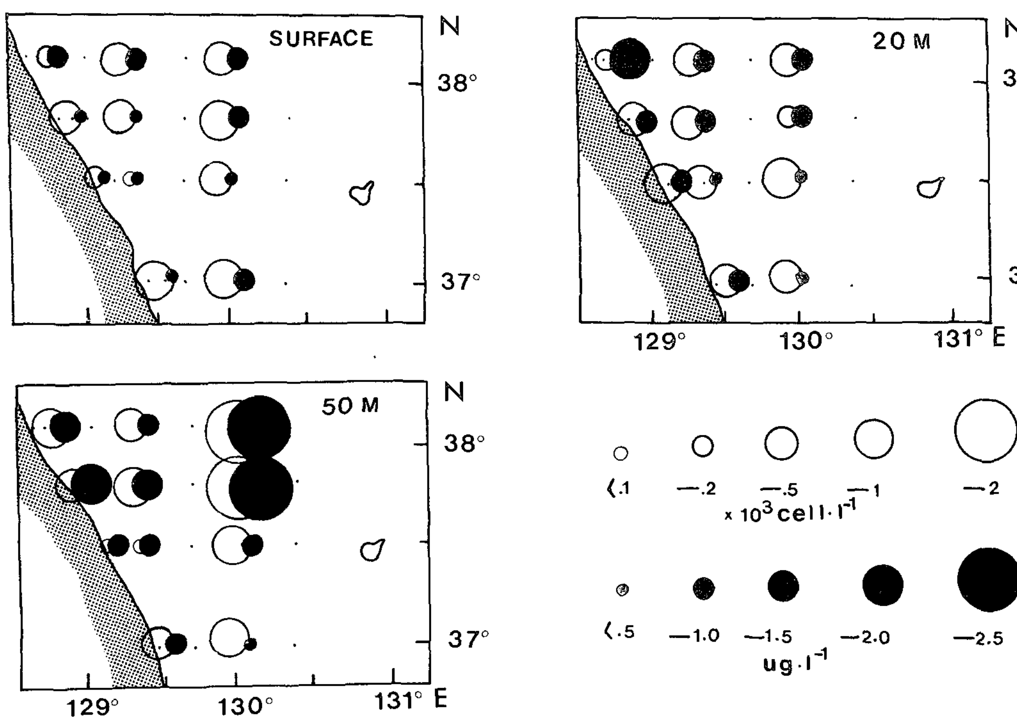

Fig. 6. Horizontal distribution of phytoplankton cell number(○) and chlorophyll *a*(●) in the study area.

front extending from the southeastern coast of Korea toward the Yamato Bank through Ullung Island. The other was a Tsushima Warm Current front extending from the Tsushima toward the area between Tokdo Island and Oki Island. Oceanic front in the study area was typical polar front formed between the Eastern Korean Warm Water and the Northern Korean Cold Water. It was the northern coast cold water type front classified by Gong and Son(1982). Thermal front was well developed at the 50 *m* depth which had the sharp temperature gradient than the surface layer. The thermal change of the polar front at the depth of 50 *m* was 0.23 ℃ Km^{-1} which was more or less low than the previous reports such as 0.28 ℃ Km^{-1}(Kim, 1991) and 0.5~1.2 ℃ $mile^{-1}$ (Gong and Son, 1982). Phytoplankton population density was similar to the previous study during summer in the study area (Choi, 1969). A dense population was found in the frontal zone formed by two different currents defined by hydrographic data in August.

Results of cluster analysis showed that the study area was divided into four phytohydrographic sectors. From the results of principal component analysis, the phytoplankton assemblages were characterized by the relative abudance of a few species rather than variation of spcies from cluster to cluster.

For the surface samples, inshore Cluster A was considered to be independent of offshore Cluster B in the abundant species(Component I discriminates along taxonomic lines). The abundant species found in the community were typical warm, neritic dinoflagellates, such as *Prorocentrum micans* and *Protoperidinium minutum* occurred in Jinhae Bay as the causative organisms of red tides(Park *et al.*, 1988). It seems that the low-saline coastal water have an important role in increasing population of the dinoflagellate species mentioned above.

On the other hand, at the 50 *m* depth, two clusters at the north and the south of temperature front from 7 ℃ to 15 ℃ were found. The assemblages of the two clusters were quite different. From the principal component analysis, the 12 most frequently occurring taxa were divided into the cold water species and the warm water species by Component II. The main taxa of Cluster A were typical cold water species. *Chaetoceros convolatus* and *Ch. atlanticus,* which appeared in Oyashio cold waters(Yamaji, 1974), were present in the cold waters below 7 ℃ of the coastal and northern part in the study area. Warm water species such as *Rhyzosolenia setigera, Chaetoceros curvisetus, Ch. danicus, Ch. lorenzianus* and *Guinardia flaccida*(Karawada, 1965; Yamaji, 1974, 1984) were dominant in the warm waters over 15 ℃ of the southern and offshore part. At the frontal zone developing phytoplankton peak abundance, *Chaetoceros curvisetus, Ch. lorenziaus, Ch. convolatus, Corethron criophilum* and *Ch. decipiens* were abundant and a mixture of species from both sides(the warm and the cold water) was

Table 3. Primary productivity and nitrogen requirement(NRP) by phytoplankton and N/P ratio at each station. NRP is calculated assuming C/N ratio to be 7

Station	Primary Productivity		NRP	N/P ratio
	Total ($gC\ m^{-2}\ day^{-1}$)	Base of euphotic zone ($mgC\ m^{-3}\ day^{-1}$)	(mg-atN $m^{-2}\ day^{-1}$)	
10407	0.7	6.7	7.1	11.5
10503	0.6	22.4	6.1	8.3
10505	1.0	26.2	10.2	1.8
10507	0.6	14.2	6.1	7.4
10603	1.9	50.9	19.4	4.4
10605	1.7	24.9	17.4	7.4
10607	2.1	43.5	21.4	3.4
10703	1.3	28.7	13.3	4.3
10705	1.9	27.1	19.4	7.2
10707	2.4	55.0	24.5	4.8
Average	1.4	30.0	14.5	6.1

apparent.

Forming the front could be also closely related to the distribution of chlorophyll *a* concentration and phytoplankton cell numbers. No high standing crop was seen in the surface with homogeneous distribution of water temperature. The strikingly high concentrations from 2.08 to 2.32 $\mu g\ l^{-1}$ were found at the frontal region of 50 *m* depth. Choi and Chung(1965) reported that large amount of chlorophyll *a* meant an increasing of primary productivity from the view point of relationships between chlorophyll *a* and primary productivity.

In the present study, primary productivity was higher at the cold waters that the warm waters. Largest values of the productivity from 2.1 to 2.4 $gC\ m^{-2}\ day^{-1}$ occured in the frontal region. The supply of nutrients to the euphotic zone has long been recognized as a major factor in the differences in productivity between various areas(Sverdrup *et al.*, 1942). No particular influence of the nutrient-rich cold water was seen in the upper layer of each station. However at the 50 *m* depth primary productivity was much higher in the mixing region with 43.5~55.0 $mgC\ m^{-3}\ day^{-1}$ than warm water with 6.7~14.2 $mgC\ m^{-3}\ day^{-1}$. Accordingly, horizontal advection flux from nutrient-rich Northern Korean Cold Water may be the major nutrient source for the phytoplankton growth. It has been reported that frontal eddies generated along the Gulf Stream raise the underlying North Atlantic Central Water to the surface(Lee *et al.*, 1981), which enhances the phytoplankton blooms(Yoder *et al.*, 1981). Yamamoto *et al.*(1988) showed that dome-like risings of isopleths of temperature and nutrients were demonstrated in the Kuroshio front and nutrient supply seemed to contribute to the retention of the phytoplankton peak in abundance at the front.

Nutrient concentrations in the study area were much higher at the Northern Korean Cold Water than at the Eastern Korean Warm Water. Therefore, southward Northern Korean Cold Water may supply considerable nutrients for this area by horizontal advection. It may be said that the high standing crops at the polar front is derived from the relatively high primary productivity when nutrients are supplied from the Northern Korean Cold Water to the polar front.

요 약

여름철 한국 동해 중부 극전선과 주변해역에서 식물플랑크톤의 군집구조와 분포를 밝히기 위하여 1990년 여름철에 수온, 염분, 영양염과 기초생산력 및 식물플랑크톤의 현존량에 대해서 조사하였다.

총 96종의 식물플랑크톤이 동정되었으며 그중 *Rhizosolenia setigera*와 *Thalassionema nitzschioides* 2종이 우점종으로 나타났다. 조사해역의 북부연안수역에서는 표층과 chlorophyll *a*가 최대로 나타난 50 *m*층의 군집이 아주 다르고 남부와 외해역에서는 유사했다. 주요인분석의 결과 북부연안 표층수역을 대표하는 식물플랑크톤 군집은 연안난수성 와편모조류였고 북한한류수역은 냉수성 규조류로 그리고 남부와 외해수역은 난수성 규조류였다. 또한 전선구역에서는 냉·온수성 규조류가 혼합하여 나타났고 기초생산력과 식물플랑크톤의 현존량 역시 전선구역에서 월등히 높았다. 영양염의 농도는 북한한류수역에서 현저히 높았는데 그 이유는 영양염의 공급과 함께 전선면에서의 식물플랑크톤 peak에 크게 기여하는 것으로 사료된다.

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Appendix Ⅰ. List of phytoplankton species occured in the study area

Species	Species
Actinotychus senarius	*Rhizosolenia styliformis*
Amphora hyalina	*Stephanopyxis nipponica*
Asteromphalus heptactis	*Steph. palmeriana*
Bacteriastrum hyalinum	*Steph. turris*
Bact. varians	*Streptotheca thamensis*
Chaetoceros affinis	*Synedra tabulata*
Ch. atlanticus	*Thalssionema nitzschioides*
Ch. convolatus	*Thalssiosira decipien*
Ch. curvisetus	*Thalassiosira eccentrica*
Ch. danicus	*Thala. leptopus*
Ch. debilis	*Thala. rotula*
Ch. decipiens	*Thala.* spp.
Ch. dichaeta	*Thalassiothrix frauenfeldii*
Ch. didymus	*Amphidinium* sp.
Ch. lauderi	*Alexandrium* sp.
Ch. lorenzianus	*Ceratium furca*
Ch. psedodichaeta	*Cera. fusus*
Climacodium frauenfeldianum	*Cera. lineata*
Cocconeis pellucida	*Cera. macroceros*
Corethron pelagicum	*Cera. massiliense*
Core. criophilum	*Cera. tripos*
Coscinodiscus asteromphalus	*Dinophysis acuminata*
Cos. gigas	*Dinop. fortii*
Cos. megalomma	*Dinop. ovum*
Cos. radiatus	*Dinop. rotundata*
Eucampia zodiacus	*Diplopsalis* sp.
Guinardia flaccida	*Dissodinium pseudolunula*
Hemiaulus hauckii	*Gonyaulax polygramma*
Hemi. membranaceus	*Gony. spinifera*
Lauderia annulata	*Gymnodinium* sp.
Leptocylindrus danicus	*Gyrodinium* sp.
Melosira nummuloides	*Prorocentrum compressum*
Navicula sp.	*Proro. micans*
Nitzschia longissima	*Proro. minimum*
Nit. seriata	*Proro. triestinum*
Nit. spp.	*Protoperidinium conicoides*
Pleurosigma angulatum	*Protop. conicum*
Pl. normanni	*Protop. depressum*
Pl. sp.	*Protop. minitum*
Rhizosolenia alata	*Protop. oblongum*
Rh. calcar-avis	*Protop. oceanicum*
Rh. casteracanei	*Proto.* sp.
Rh. fragilissima	*Proto. steinni*
Rh. hebetata	*Pyrophacus horologicum*
Rh. hebetata f. semispina	*Scrippsiella trochoidea*
Rh. robusta	*Dictyocha fibula*
Rh. setigera	*Distephanus speculum*
Rh. stolterfothii	*Ebria tripartita*