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The Ecosystem of the Southern Coastal Water of the East Sea, Korea

II. Primary Productivity in and around Cold Water Mass*

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^{14}C uptake experiments were carried out in and around the cold water mass in the southern part of the Korean East Sea in August and October 1995 to assess spatial and seasonal variability of primary productivity and its relation to physical and chemical factors. The cold and high saline water mass in the bottom layer extended upward to the surface layer and developed along the eastern coast of Korea in August. Chlorophyll-*a* concentration was maintained high in the cold water mass through August to October and its maximum concentration was 6.3 μg l^{-1} at Stn. 209-4 in August. Primary productivity and daily primary productivity ranged from 0.29 to 8.02 mgC m^{-3} hr^{-1} and from 58.3 to 63.1 mgC m^{-2} d^{-1}, respectively, throughout the study period. Primary productivity of the cold water mass was higher than that of offshore waters in both summer and autumn seasons. P_{max} and I_{max} of the cold water mass in August were higher than those in October, except Stn. 208-5. These results suggest that high primary productivity in the cold water mass may be established by the upwelled nutrients and light adaptaion to convected phytoplankton due to upwelling of the bottom waters.

INTRODUCTION

Throughout the world oceans, meso- and micro-scale rings, eddies, fronts and upwelling occur. They are separated from the respective currents and fronts and moved into water masses with different physical, chemical and biological characteristics (The Ring Group, 1981; Andrews and Gentien, 1982; Lochte and Pfannkuche, 1987; Han, 1988; Han *et al.*, 1989; Mann and Lazier, 1996; Kudela *et al.*, 1997).

The cold water mass of 12—15°C and several kilometers wide occurs almost every summer in the southern part of the Korean East Sea. It persists for several days to 2 weeks. The physico-chemical properties of the cold water mass have been well studied (Gong and Park, 1969; Park, 1978; Kim and Kim 1983; Yang *et al.*, 1994; Lie *et al.*, 1995). However, very little is known the distribution of nutrients and productivity in the cold water mass (Lee *et al.*, 1997; Yang *et al.*, 1998), although some studies on primary production system in the East Sea have been done (Chin and Hong, 1985; Shim *et al.*, 1985; Shim and Park, 1986; Shim *et al.*, 1992; Moon *et al.*, 1996; Cho *et al.*, 1997).

In the present study, we carried out ^{14}C uptake experiments in and around the cold water mass in the southern part of the Korean East Sea to assess the spatial and seasonal variability of primary productivity in relation to physico-chemical factors.

MATERIALS AND METHODS

^{14}C uptake experiments were carried out in inshore and offshore stations of 3 lines (102, 209, 208) in the southern part of the Korean East Sea in summer (August, 1—5 1995) and autumn (October, 16—19 1995) (Fig. 1).

Water temperature and salinity were measured by CTD (Sea Bird 9). *Chl. a* concentration was determinated by fluorometry (Turner Designs Model 10) after extraction with 90% aceton (Holm-Hansen *et al.*, 1965).

Water samples for carbon experiments were collected using a Nansen sampler from the surface water. Light intensity of polycarbonate incubation

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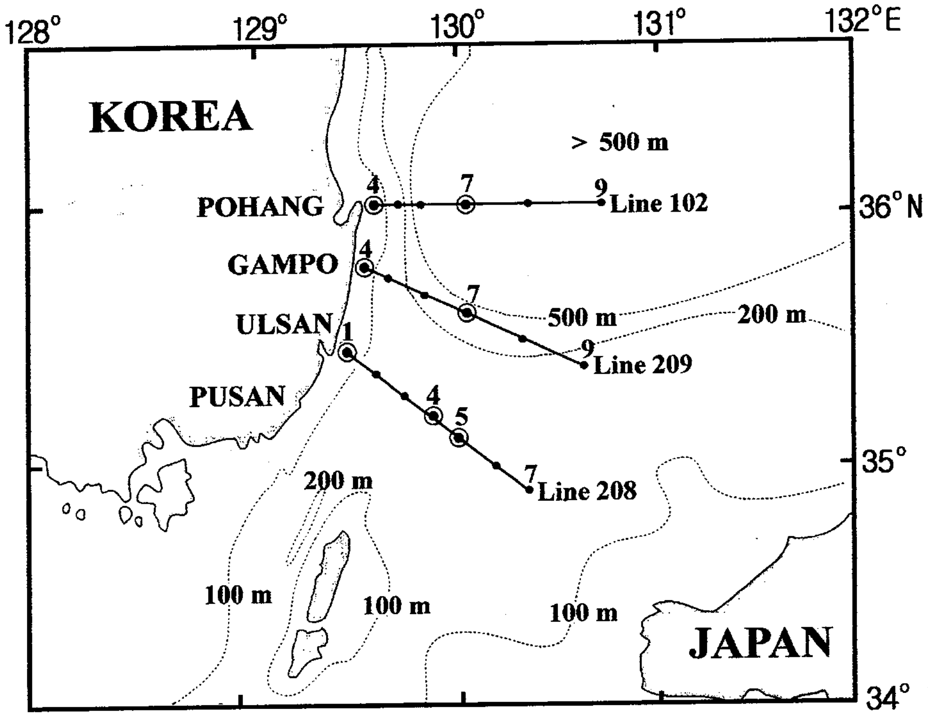

Fig. 1. Bathymetry and sampling stations in the southern part of the Korean East Sea, along 3 lines in summer (1—5 August 1995) and autumn (16—19 October 1995). ⊙: measuring stations of primary productivity.

bottles was controlled with nylon screen in 7 steps (100, 96, 57, 39, 16, 11, and 0% of I_o layer). The daily surface irradiation was monitored by a Scalar sensor (Li-cor, LI-190S). Total CO_2 was determined by estimating total alkalinity of seawater in the study area (Parsons *et al*, 1985). Carbon uptake rate was determined by a light and dark bottle method: each bottle was incubated in 250 ml bottle for 1 to 3 hrs with $NaH^{14}CO_3$ at 370 KBq at simulated *in situ* temperature on the deck using a field incubator. Incubated phytoplankton was harvested on Whatman GF/F filters under a vacuum pressure of < 250 mmHg and transferred to scintillation vials. After addition of 0.5*N* HCl to purge unused $NaH^{14}CO_3$ overnight and the radioactivity was counted in Aquasol II by a liquid scintillation counter (LKB Wallack Rackbeta 1215). Quench correction was made by the external standard channel ratio method.

Photosynthesis-irradiance models were fitted to the data using non-linear regression anlysis to calculate the photosynthetic paramenters. Photoinhibition was evident in all; the model of Platt *et al.* (1980) thus suited the data best and was used to dertermine the P-I parameters.

For the calculation of depth-integrated primary productivity, extinction coefficient was estimated with Secchi-depth for the daily primary production. Daily insolation was measured for the daily primary production.

RESULTS

Physico-chemical conditions

Detailed physico-chemical conditions in the southern part of the Korean East Sea in August and October 1995 were shown elsewhere (Yang *et al.*, 1998). Water temperatures and salinities are here shown in Figs. 2, 3 and 4.

Summer cruise: Horizontal distribution of the surface water temperature in August (Fig. 2) showed that the cold water mass was well developed along the eastern coast of Korea. The width of the cold water mass ranged from 2 to 5 kilometers. During the study period, surface water temperature of the cold water mass was below 13°C, while that of offshore waters was about 24°C. Temperature of the bottom layer (120—150 m deep) of the cold water mass was 1—2°C (Fig. 3). Thermocline with steep gradient was found at 10—50 m depth at a coastal station (Stn. 209-4) and at 140 m at an offshore station (Stn. 209-7). High saline and cold water of the bottom layer extended upward to the surface layer of inshore water in summer. Salinity of the cold water mass was higher (34.1 psu) (Stn. 209-4) at coastal area than that of offshore waters (Fig. 3). The lowest salinity (32.8 psu) was found at Station 209-7 during the summer cruise. These results suggest that high saline and cold water mass

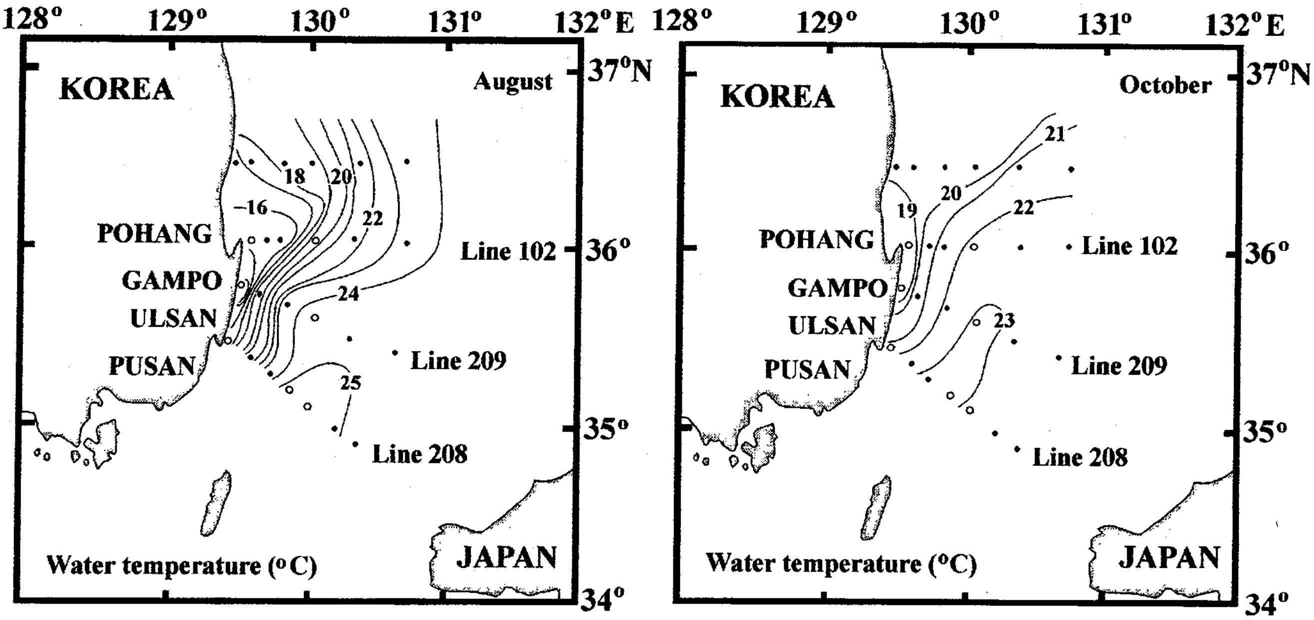

Fig. 2. Horizontal distribution of surface water temperature along 3 lines in August and October 1995.

of the bottom layer upwelled to the surface water of coastal side in summer, became warmer and slightly less saline, and was then isolated from the inshore waters.

Autumn cruise; Horizontal distribution of the surface water temperature in October is shown Fig. 2. The surface water temperature was 19°C in inshore and 23°C in offshore. The inshore water temperature was higher in October than that in August. Vertical distribution of water temperature in October was similar to that in August. The cold water mass still existed at the subsurface layer in October, although the surface water temperature falled down to approximately 19°C (Fig. 4). Thermocline was found at shallow depths at a coastal station (209-4) and became deeper toward an

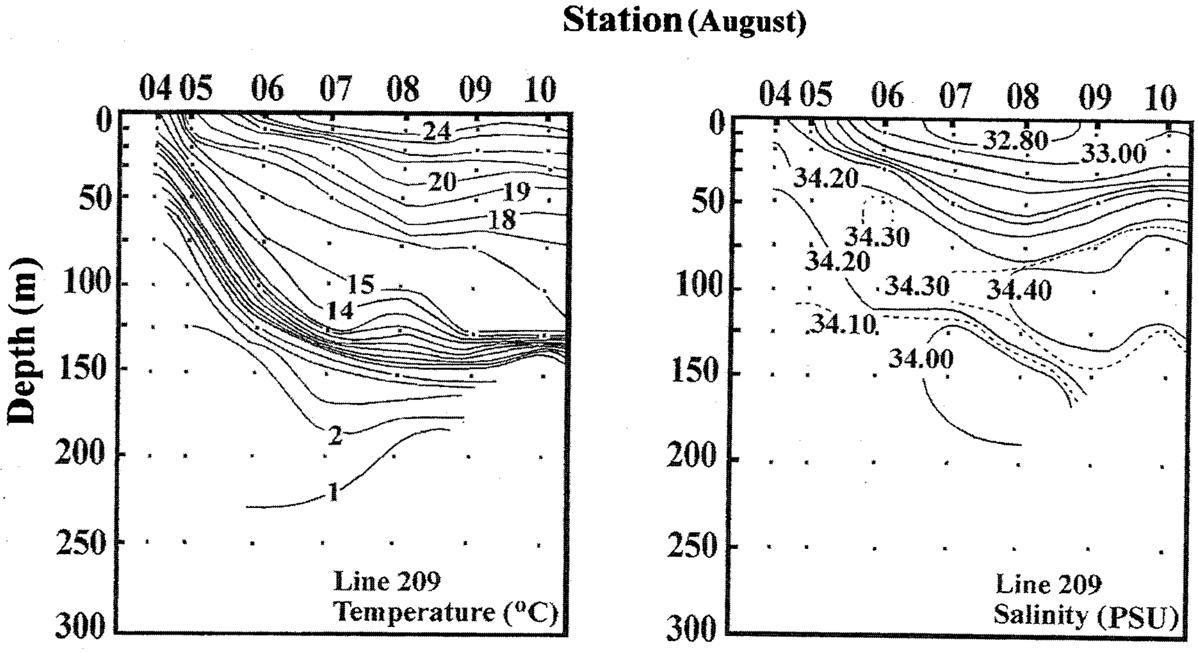

Fig. 3. Vertical distribution of water temperature and salinity along line 209 in August 1995.

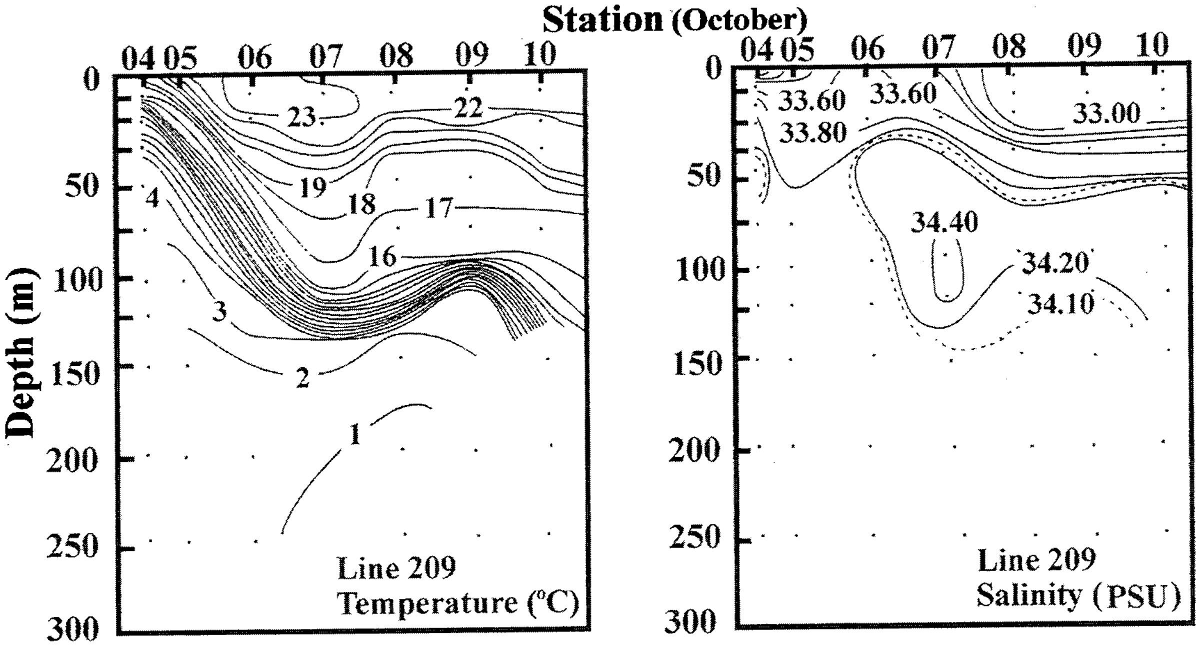

Fig. 4. Vertical distribution of water temperature and salinity along line 209 in October 1995.

offshore station (209-7) (Fig. 4). The surface layer in inshore waters was less saline in terms of vertical salinity profile, while high saline waters lying on the bottom layer extended upward to the subsurface layer at Stn. 209-6. Salinity of Stn. 209-6 was slightly higher than those of other stations along line 209. Warmer and slightly high saline water mass was located at the surface layer between inshore and offshore waters.

Chlorophyll a, nutrients and primary productivity

Chlorophyll *a* concentration: Chl. *a* concentrations in August and October are summarized in Table 1. The chl. *a* concentration of the surface layer in coastal waters was higher than that in offshore waters, except the station along Line 208 in August. However, the chl. *a* concentration in August was lower than that in October. The chl. *a*

Table 1. Vertical distribution of chlorophyll *a* concentration (μg l^{-1}) at each depth of stations in and around cold water mass of the southeastern part of the Korean East Sea in August and October 1995

Date	Depth (m)	Station					
		102-4	102-7	209-4	209-7	208-1	208-5
August 1—5	0	1.34	0.35	3.55	0.29	0.29	0.53
	10	2.93	0.19	0.76	0.02	1.22	0.43
	20	1.45	0.23	0.08	0.07	0.15	0.27
	30	0.50	0.18	0.11	0.11	0.21	0.29
	50	0.40	0.05	0.02	0.31	0.16	0.15
	60	0.39	–	–	–	0.11	–
	75	–	0.01	–	0.14	–	0.11
	100	–	0.01	–	0.04	–	0.08
		102-4	102-7	209-4	209-7	208-1	208-4
October 16—19	0	1.55	1.14	4.51	1.67	3.48	0.15
	10	4.38	0.24	6.34	0.16	0.97	0.12
	20	1.16	0.54	2.00	0.16	0.16	0.45
	30	0.17	1.36	0.05	0.99	0.04	0.47
	40	0.19	–	0.13	–	0.04	–
	50	0.18	0.05	0.10 (55m)	0.37	–	0.37
	60	–	–	–	–	0.04	–
	75	–	0.01	–	0.02	–	0.02
	100	–	0.02	–	0.01	–	0.01
	125	–	–	–	–	–	–
	150	–	0.01	–	0.01	–	–

concentration of the surface water at Stn. 209-4 in October was the highest (4.5 μg l^{-1}) through the study periods. Chl. *a* concentration varied vertically, mainly above the euphotic zone (30—100 m deep), and showed distinctive spatial variability throughout water column, ranging from 0.1 to 6.3 μg l^{-1} (Stn. 209-4, in October). Subsurface chlorophyll maximum (SCM) layers were often observed at 10—30 m depths at Stns. 102-4 and 208-01 in August, and at Stns. 102-4, 102-7, 209-4 and 208-4 in October. The chl. *a* concentration in the SCM layer was 1.4 (Stn. 209-4) to 4.0 (Stn. 208-1) times as high as that of the surface layer.

Nutrients: Vertical profiles of DIN and silicate in August and October are shown in Figs. 5 and 6. DIN and silicate concentration of costal waters in subsurface layer were higher than those of offshore water throughout the water column in both summer

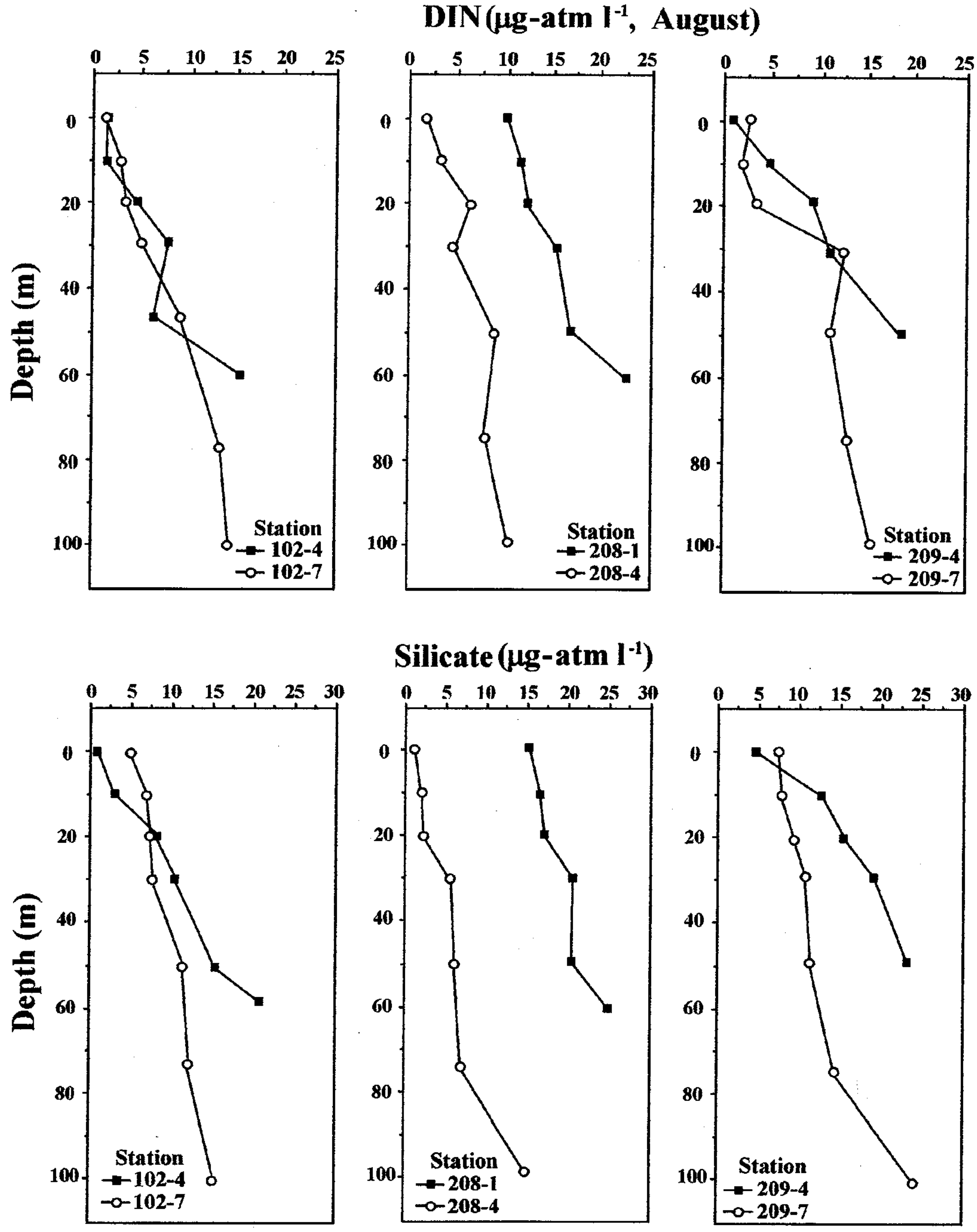

Fig. 5. Vertical profiles of DIN and silicate in inshore and offshore stations of 3 lines of southern coastal water of the East Sea, Korea in August 1995.

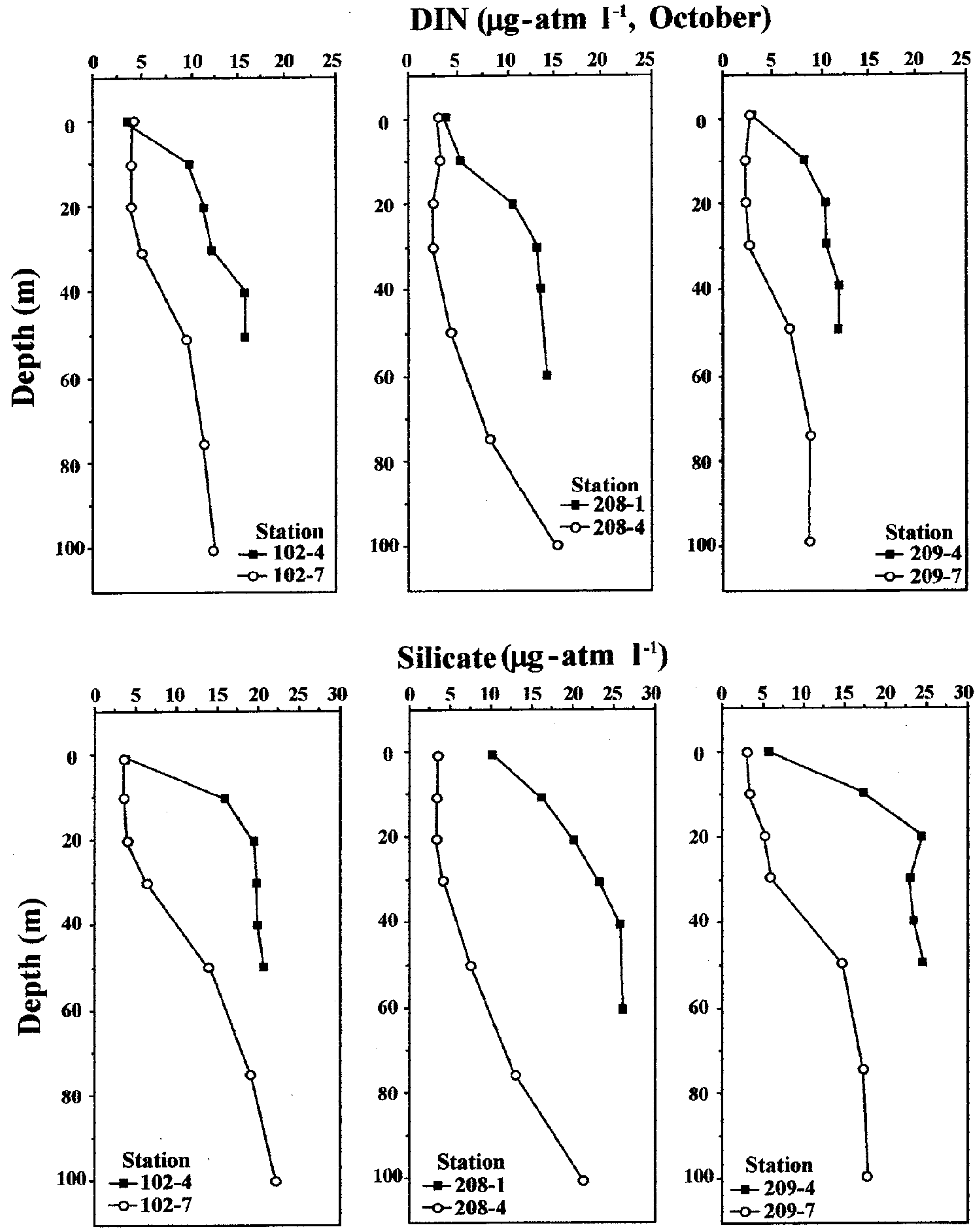

Fig. 6. Vertical profiles of DIN and silicate in inshore and offshore stations lines of southern coastal waters of the East Sea, Korea in October 1995.

and autumn seasons. Nutrient concentration in vertical profiles increased gradually with depth in both seasons. Silicate and DIN in the cold water mass were sometimes lower at surface layer of coastal stations along lines 209 and 102 than those in offshore in summer.

Primary productivity: Primary productivity, photosynthetic parameters and P-I curves in August and October are summarized in Table 2 and Fig. 7. Primary productivity showed distinctive spatial variability throughout the study area and ranged from 0.29 to 8.02 mgC m^{-3} hr^{-1}. High primary productivity was found in coastal waters in both August and October. Primary productivity was higher in coastal waters than that in offshore at each survey line. Primary productivity in August was higher than that in October, except for Stn. 208-5. Primary productivity of Stn. 209-4 in cold

Table 2. Primary productivity and photosynthetic parameters in and around the cold water mass of the southeastern part of the Korean East Sea in August and October 1995

Date	Station	Primary productivity (mgC m^{-3} hr^{-1})	Daily primary productivity (mgC m^{-2} d^{-1})	α^1	β^1	P$_{max}$ (mgC mgChl. a^{-1} hr^{-1})	I$_{max}$ (μE m^{-2} S^{-1})
August 1—5	102-4	4.59	–	–	–	–	–
	102-7	3.25	631.1	4.03	1.45	9.2	660
	209-4	8.02	–	–	–	–	–
	209-7	0.83	168.2	1.05	0.7	2.1	570
	208-1	5.85	–	–	–	–	–
	208-5	0.29	91.3	1.07	0.12	0.5	160
October 16—19	102-4	1.0	–	–	–	–	–
	102-7	0.71	134.0	0.6	0.08	0.6	350
	209-4	1.2	206.1	0.21	0.52	0.3	360
	209-7	0.59	142.6	0.36	0.43	0.4	290
	208-1	2.07	357.0	1.0	0.02	0.6	280
	208-4	0.32	58.3	2.21	3.53	2.2	270

[1]: (mgC mgChl. a^{-1} hr^{-1})/(μE m^{-2} S^{-1}).

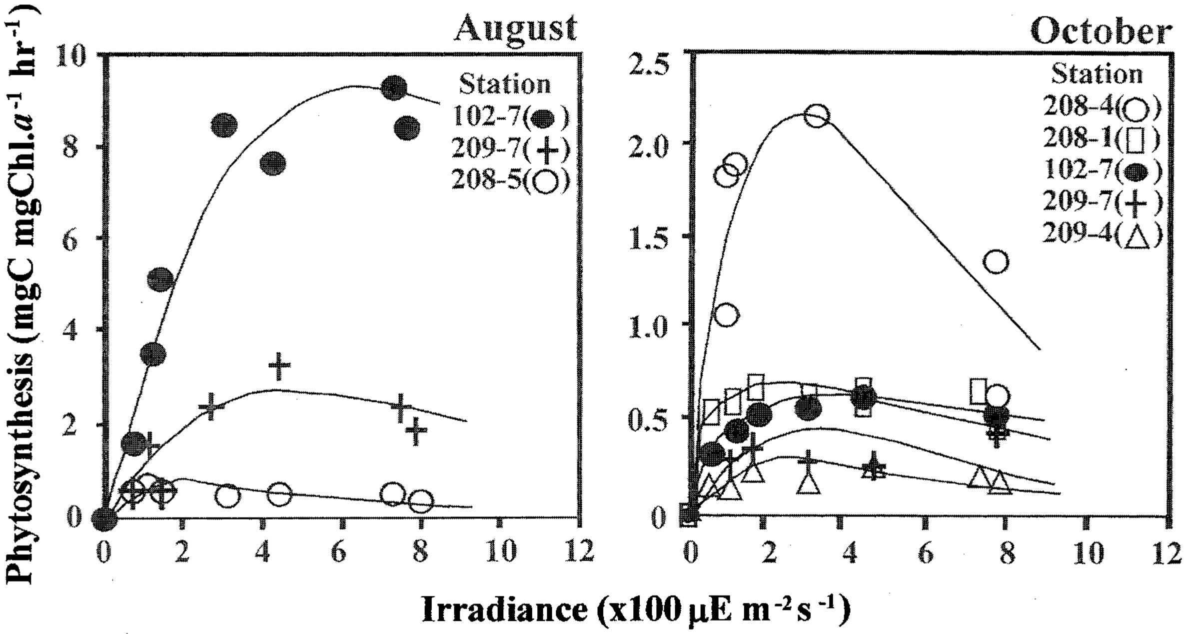

Fig. 7. P-I curves of phytoplankton communities in and around the cold water mass of the southern part of the Korean East Sea in August and October 1995.

water mass of August was the highest (8.02 mgC m^{-3} hr^{-1}).

Daily primary productivity showed distinctive spatial variability throughout the stations and ranged from 58.3 to 631.1 mgC m^{-2} d^{-1}. The highest value of daily primary productivity was observed in offshore water (Stn. 102-7) in August.

P$_{max}$ (maximum photosynthetic rate) was 0.5—9.2 and 0.3—2.2 mgC mg Chl. a^{-1} hr^{-1} in August and October, respectively. Higher P$_{max}$ was found in summer. α value determined by the initial slope of the P-I curve varied from 0.21 (Stn. 209-4, October) to 4.03 (Stn. 102-7, August). α value in coastal water was lower than that in offshore water (Table 2). Photosynthetic photon flux density (I$_{max}$), where maximum carbon uptake occurs, was relatively higher in August than those of October.

DISCUSSION

It has been reported that the cold water mass occurs almost every summer in the southern part of the Korean East Sea. There are two postulations on the occurrence of the cold water mass along the eastern coast of Korea. First, the cold water mass is a southward point of North Korean Cold Current

(NKCW) along the east coast (Park, 1978; Kim and Kim, 1983; Yang *et al.*, 1994). According to NOAA infrared images, the appearance of the cold water mass is possibly related to the presence of mesoscale eddies (Lie *et al.*, 1995). Yang *et al.* (1994) pointed out that the cold water mass originates from NKCW by measuring of activity ratios of Ra-228. Lie *et al.* (1995) reported using the combined data of drifter and NOAA infrared images that cyclonic eddy formed in Ulleung Basin moved southward in the coastal area of East Sea during the summer, and it was closely related to the existence of the cold water mass. Another suggestion is upward movement of East Sea Proper Water in the Ulleung Basin (Lee and Na, 1985). However, these postulations have not yet properly tested.

In the present study, primary productivity, chl. *a* concentration, DIN and silicate were measured highly from the cold water mass in the coastal area of the East Sea. The results show good agreement with the reports of Yang *et al.* (1998) who noted that inshore waters contained relatively high POC and PON in total suspended materials and low detritus percentage compared with offshore waters. Salinity in the cold water mass was also higher than that of the offshore waters in summer. These results suggest that high primary productivity in the cold water mass is greatly affected by the upwelled nutrients from the bottom layer, although the origin of the cold water mass is not yet clear. However, nutrients such as silicate and nitrate in the cold water mass of lines 209 and 102 were sometimes lower in surface layer of coastal stations than those in offshore stations during the summer cruise. Depleation of nutrients maybe due to rigorous photosynthetic activity of phytoplankton community in August.

Unfortunately, in our ^{14}C experiments, daily primary productivity and P_{max} in the cold water mass in summer could not be properly estimated due to insufficient data for the mathematical models described. However, it is possible that daily primary productivity and P_{max} are high in the cold water mass in summer because primary productivity and chl. *a* concentration in coastal waters were always higher than those of offshore waters in both aummer and autumn seasons.

Upwelling zone exhibits temporal change in phytoplankton nutrient uptake rates which was rapidly fluctuated according to ambient light and nutrients (Mann and Lazier, 1996; Kudela *et al.*, 1997). In the present study, relatively high primary productivity in the cold water mass may be explained with 2 possibilities. One is the upwelled nutrients from bottom layer. MacIsaac and Dugdale (1969) have shown that nitrate uptake by phytoplankotn increase with nitrate concentration only to nitrate levels of about 4 μg atm l^{-1}. DIN and silicate concentration in cold water mass of upwelling region exceeded 4 μg atm l^{-1} compared with those of offshore waters in the upper water column in summer. It suggested that high primary productivity in cold water mass may be supported by upwelled nutrients to the euphotic zone, although depletion of nutrients occurred in surface layer of Stns. 102-4 and 209-4 in summer.

Another is creation of more favorable light condition for the deep phytoplankton populations. Upwelling creates a vertical movement in the water column and produces a mixed layer that extends 30—100 m below the surface. Deep (shade adapted) populations will be show a marked depression in assimilation values when they are exposed to abruptly high light condition (Susan and Richard, 1977). However, deep populations can be fully adapted to high light intensities only for 2 days (Steemann-Nielsen and Jorgensen, 1968). Cold water mass in upwelling region usually persisted from several days to 2 weeks. Therefore, deep populations can be in the upper mixed layers for a enough long period to adapt to suface light intesnisty. Eventually, assmilation rate will be increased due to creation of more favorable light conditionin of the cold water mass in summer.

In this study, it is clearly shown that high primary productivity in the cold water mass is greatly affected by upwelled nutrients from the bottom layer and light adaptaion of phytoplankton. However, In spite of upwelled nutrients from the bottom layer, primary productivity in this study was relatively low compared with the previous studies made in different seasons of the year and in surrounding waters of the southeastern part of the Korean East Sea (Shim and Park, 1986; Shim *et al.*, 1992; Lee *et al.*, 1997). It can be not explained by our present data. Further detailed studies are required to clarify the role of the availability of ambient nutrients, lights, water temperature and local variation in primary productivity, and the relationship between variance in primary productivity and water movement in eddies, fronts and major currents.

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