The Journal of the Korean Society of Oceanography
Vol. 29, No. 3, pp. 258-268, September 1994

New and Regenerated Production Based on Nitrogen in the Southern Part of the Yellow Sea in Late April, 1993

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1993년 4월말 황해 남부 해역의 질소 新生産과 再生産

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Nitrogenous new production and regenerated production were measured in the southern part of the Yellow Sea (Hwanghae) using a stable isotope ^{15}N nitrate and ammonia between April 25~30, 1993. Nitrogen production varied between 155 and 688 mg N m^{-2} d^{-1}, which belongs to meso- to eutrophic area values. This is equivalent to 881~3909 mg C m^{-2} d^{-1}, assuming the Redfield ratio for C:N of 5.7:1 (by weight). The f-ratio, which is the fraction of new production from primary production, varied between 0.12 and 0.26, indicating that 74 to 88% of primary production was supported by the regeneration of nutrients within the euphotic zone. This low f-ratio is the characteristics of the oligo- to mesotrophic area. Contrary to the expected, the ambient nutrient concentration was not an important factor for controlling productivity in this area during the study period. The difference in productivity among stations was mainly due to the variations in phytoplankton biomass in different water masses.

황해 남부해역에서 1993년 4월 25일부터 30일까지 안정동위원소인 ^{15}N 질산염과 암모니아를 이용하여 질소 신생산과 재생산을 측정하였다. 질소생산은 155~688 mg N m^{-2} d^{-1}의 값을 보였는데 이는 중영양 또는 부영양 해역의 특성이다. 탄소량으로 환산하면 C:N Redfield비 5.7:1을 가정하였을 때 881~3909 mg C m^{-2} d^{-1}에 해당한다. 기초생산 중 신생산이 차지하는 비율인 f-ratio의 범위는 0.12~0.26으로, 기초생산의 74~88%가 수층 내에서 순환되는 암모니아에 의하여 유지된다는 것을 시사한다. 이러한 낮은 f-ratio 값은 빈영양 또는 중영양 해역의 특징이다. 영양염의 농도는 예상했던 바와 달리 이 해역에서의 조사기간에는 생산성을 조절하는 중요한 요인이 아니었으며, 정점간 생산성의 차이는 수괴에 따른 생물 현존량의 차이에 주로 기인하는 것으로 보인다.

INTRODUCTION

New production, which was introduced by Dugdale and Goering (1967), is the portion of primary production supported by newly available forms of nitrogen. New production is also equivalent to export production, which can be harvested or sink from an ecosystem without the system being exhausted (Eppley and Peterson, 1979). Regenerated production, to the contrary, is supported by nutrients recycled within the euphotic zone including ammonia and urea. However, this portion of primary production can not be used for export. To estimate the vertical flux of material in the water column, information on new production is required. Also, new production removes CO_2 from the atmosphere, which is an important green house gas, by converting it into organic carbon. Through the removal of CO_2 from the system, new production can act as a buffering process for global warming, because the oceanic carbon reservoir is the ultimate sink for the increase in atmospheric CO_2 by fossil fuel burning (Volk and Liu, 1988).

In the ocean, new nitrogen sources include nitrate input by vertical mixing and diffusion, dinitrogen fixation (Carpenter and Romans, 1991), and precipitation (Duce *et al.*, 1991). In the open ocean, nitrogen fixation and precipitation are usually small compared to nitrate influx from below the thermocline (Eppley and Peterson, 1979). However, in applying the concept of new nitogen to coastal areas, where riverine flux could be significant, some precautions are needed. Ammonia and urea which are dominant forms of regenerated nitrogen in the open ocean, may have been derived from the river discharge and should be included in new nitrogen depending on the origin. There are increasing number of studies on the primary productivity in the Yellow Sea, but most of them are confined to coastal areas (Choi *et al.*, 1988; Chung and Park, 1988; Kang *et al.*, 1992). Furthermore, there is no report on the measurement of new and regenerated production in this area.

THE STUDY AREA

The Yellow Sea (Hwanghae) is a semi-enclosed water mass between Korean Peninsula and China. Its area is approximately 0.487×10^6 km^2. The maximum depth is less than 100 m (c.a. 91 m) and the average depth is approximately 44 m. Due to its proximity to land masses, the effect of terrestrial input could be significant. This region is strongly influenced by Monsoon, with high precipitation during the summer (Lie, 1985). The movement of water is strongly tidal driven and the circulation pattern changes with season. Water masses of this area are reported to be composed of 4 components (Lie, 1984); Hwanghae Warn Current (HWC), Hwanghae Cold Water (HCW), Coastal Waters of China and Korea coast, and Changjiang River Diluted Water (CRDW). The HWC is a branch of Tsushima Warm Current with high temperature (11~15℃ in mid-winter), high salinity (34.0~35.0 psu), and low phytoplankton biomass (Shim and Park, 1984). The regional extent of the HWC is controversial, but its main influence is thought to be confined to the southeast region of Hwanghae. The HCW is a cold (below 10℃) and less saline (32~33 psu) water mass which is the remnant of cold water cooled during the wintertime (Kang and Kim, 1987). Its presence is persistent in the mid-trough zone even during the summer. The CRDW is characterized by low salinity due to the influence of Changjiang River and extends towards the northeast of the estuary.

The water column is well mixed to the bottom during the winter, and highly stratified during the spring and summer. However, coastal areas are strongly influenced by tidal currents and relatively well mixed even during the summer (Seung *et al.*, 1990). Because of the strong seasonality, the circulation pattern in Hwanghae is not well defined and sometimes controversial. The riverine flux is not well documented, but this portion is usually insignificant during the spring when this study was conducted.

MATERIALS AND METHODS

To determine new and regenerated production of water column in the Yellow Sea, $^{15}N\text{-}NO_3$ and $^{15}N\text{-}NH_4$ uptake measurements were performed at 3 stations during a cruise on R/V Eardo of KORDI between April 25~30, 1993 (Fig. 1). Depth profiles of temperature, salinity, fluorescence, beam attenuation coefficient (wavelength=665 nm, r=0.05 m), and PAR (Photosynthetically Available Radiation; 400~700 nm) were collected with a Sea Bird Electronics CTD (Model #SBE 25-03) mounted with a Sea-Tech florometer, a transmissometer, and a scalar irradiance meter. Water samples were collected at 100, 49, 30, 15, 3.5, and 1% LPD (Light penetration depth) with 10 liter Niskin bottles attached to a Rosette sampler. Niskin bottles were modified according to Chavez *et al.* (1990) to reduce the heavy metal toxicity. Polycarbonate bottles (250 m*l* or 2 liter) wrapped with perforated

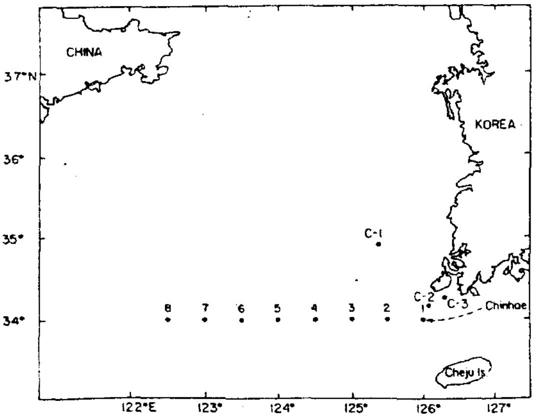

Fig. 1. Map of the study area showing sampling stations in the Yellow Sea between April 25-30, 1993.

nickel screens (Stork Veco, Bedford, MA, U.S.A.) were used for incubation in a surface seawater cooled on-deck incubator to simulate the *in situ* light intensity. Before the start of incubation, ^{15}N-KNO_3 (99%) and ^{15}N-NH_4Cl (99%; Cambridge Isotope Laboratory, Woburn, MA, U.S.A.) were inoculated to make the final concentration of 1 μM and 0.2 μM, respectively. The incubation period was 6 hours around the local noon.

After the incubation, samples were filtered onto pre-combusted (4 hours at 450°C) 25 mm GF/F filters and stored dry at 60°C until the analysis of $^{15}N/^{14}N$ ratio with a mass spectrometer (Europa Scientific GC-MS). Calculations of new and regenerated production were done according to Wilkerson and Dugdale (1987). ρ_{NO_3} (Rho_{NO_3}; nitrate transport rate: μM h^{-1}) and ρ_{NH_4} (Rho_{NH_4}; ammonia transport rate; μM h^{-1}) indicate nitrate and ammonia uptake rate per unit volume of seawater and equivalent to new and regenerated production, respectively. V_{NO_3} (biomass specific nitrate uptake rate; h^{-1}) and V_{NH_4} (biomass specific ammonia uptake rate: h^{-1}) are in rate terms, and equivalent to the growth rate of phytoplankton based on nitrate and ammonia nutrition, based on the assumption of exponential growth.

The "f-ratio", which is the portion of new production from primary production (Eppley and Peterson, 1979), was calculated using the equation.

$$f-ratio = \rho_{NO_3}/(\rho_{NO_3} + \rho_{NH_4}).$$

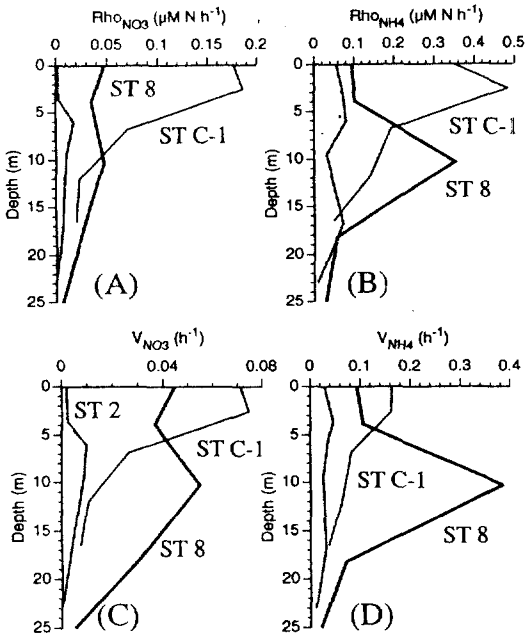

Fig. 2. Vertical distributions of (A) new production (ρ_{NO_3}: Rho_{NO_3}). (B) regenerated production (ρ_{NH_4}; Rho_{NH_4}). (C) biomass specific nitrate uptake rate (V_{NO_3}) and (D) ammonia (V_{NH_4}) uptake rate.

Vertically integrated water column production was calculated down to 1% LPD. Int ρ_{NO_3}, Int ρ_{NH_4}, and Int $\rho(3+4)$ are measures of new production, regenerated production, and nitrogen primary production per unit area, respectively. Daily rates were converted from hourly rates by multiplying nitrate uptake by 12 and ammonia uptake by 18, to compensate for the light cycle and dark uptake of ammonia.

For the measurement of chlorophyll *a* concentration, 1 liter seawater samples were collected from Niskin bottles and filtered onto GF/F filters. Filters were stored frozen at −20°C, extracted with 90% acetone, and absorbances were read with a spectrophotometer (Milton Roy Spectronic 3000 Array). Chlorophyll a concentration was calculated according to Parsons *et al.* (1984).

RESULTS

New and Regenerated Production

Vertical distributions of new and regenerated production (ρ_{NO_3}, ρ_{NH_4}; μM N h^{-1}) and biomass specific nitrogen uptake rate (V_{NO_3}, V_{NH_4}; h^{-1}) are shown in Fig. 2. New production was high at station C-1 (near Heugsan Island) and low at station 2. The vertical pattern at station 2 shows very low production at 100% (0.0021 μM N h^{-1}) and 49% (0.0027 μM N h^{-1}) LPD's, and the maximum appeared at 30% LPD (0.0177 μM N h^{-1}). At station 8, there was no distinct vertical structure down to 15% LPD, with values around 0.04 μM N h^{-1}. At station C-1, new production was very high at 100, 49% LPD's with values around 0.18 μM N h^{-1}, and decreased rapidly below that depth (0.07 ~0.02 μM N h^{-1}). Regenerated production (ρ_{NH_4}) varied between 0.03 and 0.5 μM N h^{-1} and showed maxima at 49, 30% LPD's.

Biomass specific nitrate uptake rate (V_{NO_3}; h^{-1}), which has the same meaning as the growth rate based on nitrate uptake, showed a similar vertical pattern to that of ρ_{NO_3}. However, the difference between station 8 and station C-1 was smaller than that of ρ_{NO_3}. V_{NO_3} at station 8 (0.04 μM N h^{-1}) was more than half of V_{NO_3} at station C-1 (0.07 μM N h^{-1}) at 100% and 49% LPD's, and was even higher below 15% LPD. Biomass specific ammonia uptake rate (V_{NH_4}) at station C-1 (0.16 h^{-1}) is about 60% higher than at station 8 (0.10 h^{-1}) at 100% and 49% LPD's, but station 8 showed the highest V_{NH_4} at 15% LPD (0.38 h^{-1}). This suggests that ammonia regeneration by grazers (including bacteria) and its subsequent utilization by phytoplankton are very rapid (up to 7 day^{-1} for phytoplankton nitrogen) at station 8. Station 2 showed the lowest V_{NH_4} (0.01~0.045 h^{-1}) among three stations. Overall, V_{NH_4} values were much higher (2~20 times) than V_{NO_3} values.

The vertical distribution of f-ratio (Table 1) at station 2 was very low at the surface (0.036 and 0.035 at 100% and 49% LPD's, respectively) and showed a maximum at 15% LPD (0.248). This indicates that most of the primary production at this station was due to the regeneration of ammonia in the surface layer. However, at station 8 and station C-1, f-ratios showed maxima at the surface (0.334 and 0.337) and the variation of f-ratio with depth were smaller than at station 2.

The vertically integrated daily new production (Int ρ_{NO_3}) values at station 2, 8, and C-1 were 18.45, 109.97, and 180.92 mg N m^{-2} d^{-1}, respectively (Table 2). Regenerated production (Int ρ_{NH_4}) was 3~8 times higher than new production, with values ranging between 136.71 and 507.49 mg N m^{-2} d^{-1}.

Table 1. New production (ρ_{NO_3}), biomass specific nitrate uptake rate (V_{NO_3}), regenerated production(ρ_{NH_4}), biomass specific ammonia uptake rate (V_{NH_4}), nitrogen primary production (ρ(3+4)), and the f-ratio in the southern part of the Yellow Sea in late April, 1993.

STN #	Depth (m)	Light (%)	ρ_{NO_3} (μM h^{-1})	V_{NO_3} (h^{-1})	ρ_{NH_4} (μM h^{-1})	V_{NH_4} (h^{-1})	ρ(3+4) (μM h^{-1})	f-ratio
2	0.0	100	0.0021	0.0021	0.0559	0.0290	0.0580	0.036
	3.6	49	0.0027	0.0023	0.0748	0.0451	0.0776	0.035
	6.0	30	0.0177	0.0099	0.0798	0.0343	0.0975	0.181
	9.5	15	0.0102	0.0088	0.0310	0.0258	0.0412	0.248
	16.7	3.5	0.0071	0.0039	0.0720	0.0314	0.0791	0.090
	23.0	1	0.0001	0.0001	0.0082	0.0106	0.0083	0.012
8	0.0	100	0.0477	0.0448	0.0950	0.0942	0.1427	0.334
	3.9	49	0.0353	0.0367	0.1021	0.1054	0.1373	0.257
	10.3	15	0.0476	0.0546	0.3512	0.3849	0.3988	0.119
	18.2	3.5	0.0245	0.0295	0.0569	0.0714	0.0814	0.301
	25.0	1	0.0068	0.0053	0.0289	0.0213	0.0357	0.191
C-1	0.0	100	0.1769	0.0713	0.3486	0.1635	0.5255	0.337
	2.6	49	0.1861	0.0746	0.4841	0.1624	0.6702	0.278
	6.8	15	0.0701	0.0265	0.1925	0.0827	0.2626	0.267
	12.0	3.5	0.0234	0.0105	0.1380	0.0632	0.1614	0.145
	16.5	1	0.0201	0.0076	0.0496	0.0373	0.0697	0.288

Table 2. The depth of euphotic layer, vertically integrated new production (Int ρ_{NO_3}), regenerated production (Int ρ_{NH_4}), nitrogen primary production (Int ρ(3+4)) and the f-ratio in the southern part of the Yellow Sea in late April, 1993.

STN #	Euphotic Depth (m)	Int ρ_{NO_3} (mgN m^{-2} d^{-1})	Int ρ_{NH_4} (mgN m^{-2} d^{-1})	Int ρ(3+4) (mgN $m^{-2}d^{-1}$)	Int f-ratio
2	23.0	18.45	136.71	155.16	0.119
8	25.0	109.97	502.96	612.93	0.179
C-1	16.5	180.92	507.49	688.41	0.263

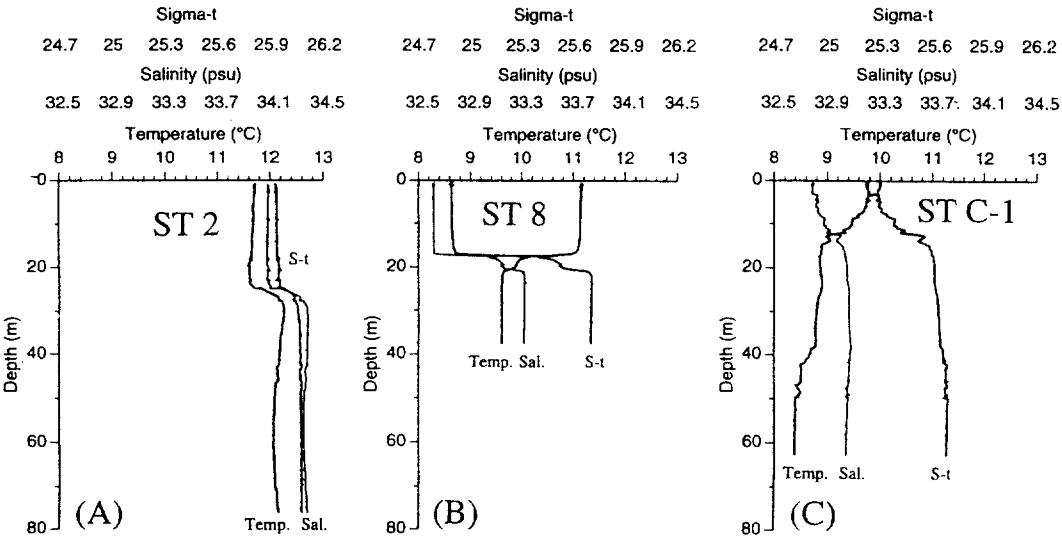

Fig. 3. Vertical distribution of temperature (℃), salinity (psu), and sigma-t at (a) ST2, (b) ST8, and (c) ST C-1.

Total nitrogen production was between 155.16 and 688.41 mg N m^{-2} d^{-1}. If we assume the Redfield ratio for C:N of 5.7:1 (by weight), carbon production will be between 881.09 and 3909.19 mg C m^{-2} d^{-1}. This range is comparable to the average productivity in the southern sea of Korea in April, 1989 (1727 mg C m^{-2} d^{-1}; Chung and Yang, 1991).

Water column integrated f-ratio of station 2 and 8 were 0.12 and 0.18, which indicates that more than 82% of primary production depends on regenerated nitrogen. This f-ratio is at the lower end of coastal zone values and characteristics of oligotrophic area (Dugdale and Wilkerson, 1992). However, the f-ratio of station C-1 (0.263) was higher than the other two stations, and was in the range of mesotrophic area values.

Physical Properties (Temperature, Salinity and Sigma-t)

To elucidate the cause of the difference in nitrogen productivity among stations, vertical profiles of temperature, salinity, and sigma-t were examined (Fig. 3a-c). Station 2 showed relatively low temperature (11.7℃) and low salinity (34.1 psu) in the surface mixed layer, and high temperature (12.0℃) and high salinity (34.4 psu) below 25 m depth. This temperature inversion is reported in the Yellow Sea area during the early spring (Lee, 1992; and references therein). From the temperature profile alone, the water column appears to be unstable, but the salinity gradient between the surface mixed layer and the water column below maintains the stability. The difference in sigma-t between two layers is 0.14 (25.94 and 26.08), the smallest among three stations. At station 8, a relatively high temperature (11.2℃) and low salinity (32.6 psu) water mass exists at the surface mixed

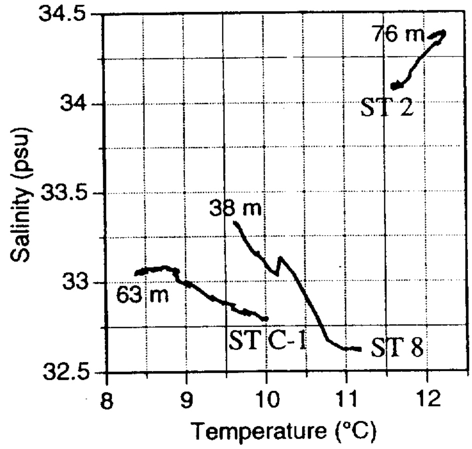

Fig. 4. Temperature, salinity diagram of three stations.

layer down to 18 m, and a low temperature (9.5℃) and relatively high salinity (33.3 psu) water mass exists beneath. The difference in density between the surface mixed layer (sigma-t 24.9) and below the thermocline (sigma-t 25.7) is very large (0.8). Station C-1 showed gradual changes in temperature (10~9℃) and salinity (32.8~33.0 psu) in the surface layer. This structure is unique from either station 2 or 8 which showed homogeneous structures of temperature and salinity in the surface mixed layer. This may be due to tidal mixing caused by the island effect, because station C-1 is nearby the Hugsando Island (Lie, 1986; Seung *et al*., 1990).

The T, S diagram is shown in Fig. 4 to characterize different water masses for each staion. Station 2 had the highest temperature and salinity and station C-1 had the lowest temperature. The low salinity (32.6 psu) water at the surface of station 8 appears to be influenced by the Changjiang River Diluted Water (CRDW). At station 2, both temperature and salinity increased slightly with depth. This station appears to be the frontal region between the HWC (Hwanghae Warm Current) and the KCW (Korean Coastal Waters). Temperature and salinity ranges at station 2 are within the ranges of the characteristic HWC (11-15℃, 34.0 ~35.0 psu). At stations 8 and C-1, temperature decreased with depth while salinity showed increases. Bottom waters of stations 8 and C-1 seem to belong to the HCW, even though salinity is a little higher than the historical range (Lie, 1985). But there are reports that the salinity range of the HCW is higher than historical values (Lie, 1984a).

Nutrient, Fluorescence, and Beam Attenuation Coefficient

Vertical distributions of nutrients (nitrate, ammonia and silicate) differ among stations (Figs. 5, 6, and 7). At station 2, nitrate concentrations ranged between 1.8 and 3.6 μM and increased slightly with depth. At station 8, nitrate was depleted below the detection limit of the conventional Autoanalyzer method (0.1 μM) in the surface mixed layer, and increased a little to 0.8 μM and 1.4 μM at 20 m and 30 m, respectively. At station C-1, nitrate was depleted at the surface, but it increased up to 5 μM with depth. Ammonia concentrations were fairly high (>2 μM) and highest concentration was observed at 10 m depth of station 8 (Fig. 6). Overall, it was low at the surface and increased and decreased again near the bottom. The vertical structure of silicate concentration is similar to nitrate, but silicate was not depleted at the surface (>1.2 μM) and highest concentration (>9 μM) was twice that of nitrate (Fig. 7). Nutrient concentration at the surface was the highest at station 2 where productivity was the lowest. It appears that phytoplankton at that station was unable to utilize the ambient nutrient. This station appears to be influenced by the HWC, which is a branch of the Tsushima Warm Current. The TWC is oligotrophic and low in biomass and productivity (Shim and Park, 1984; Chung and Yang, 1991).

Vertical distributions of fluorescence (arbitrary unit), beam attenuation coefficient (Beam C; m^{-1}) and stability (E; m^{-1}) are shown in Fig. 8 a-c. Water column stability (E; $-1/\rho\ (d\sigma_t/dz)$; m^{-1}) was calculated at 2 meter intervals. At station 2, fluorescence showed a broad peak at the bottom of surface mixed layer above the stability maximum and decreased below 22 m. Beam C was fairly constant (4 m^{-1}) in the mixed layer and increased below

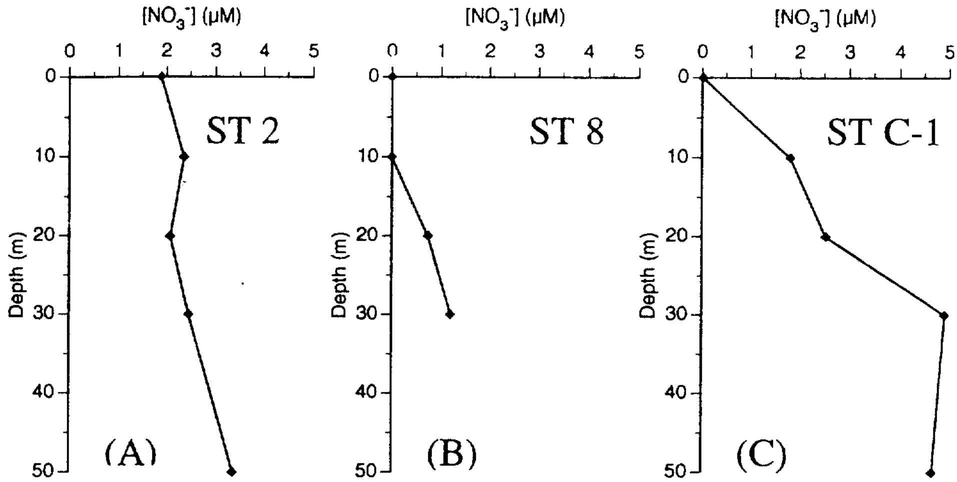

Fig. 5. Vertical distribution of nitrate at (a) ST2, (b) ST8, and (c) STC-1.

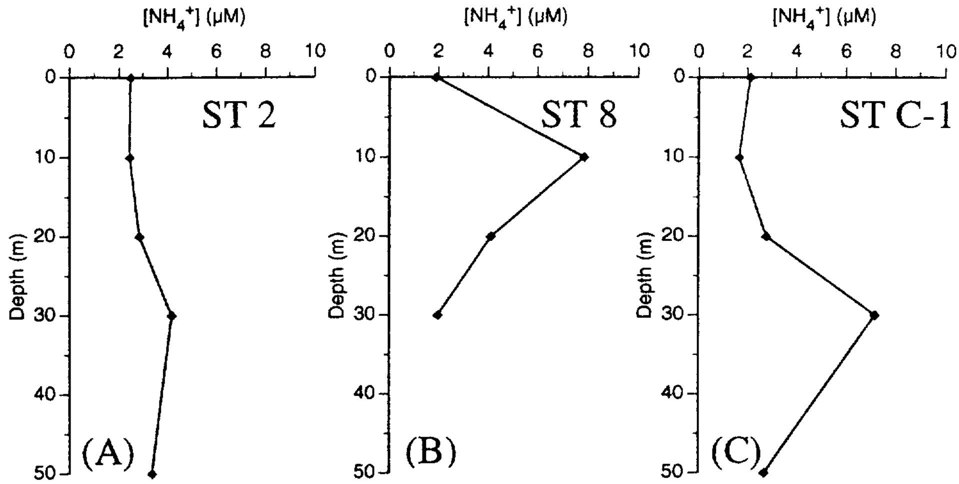

Fig. 6. Vertical distribution of ammonia at (a) ST2, (b) ST8, and (c) STC-1.

up to 15 m^{-1}. Near the bottom, where there is an increase in Beam C, fluorescence increased slightly. At station 8, fluorescence was low and fairly constant in the surface mixed layer (1~1.2) and peaked (2.6) around 20 m below the stability maximum at 18 m. Below the maximum, fluorescence decreased a litttle and stayed fairly constant (approximately 2) which is twice the value of surface mixed layer. Beam C was constant and low (<3 m^{-1}) in the upper mixed layer and increased a little below the thermocline (4 m^{-1}). At station C-1, fluorescence increased rapidly with decreasing temperature and showed a maximum (>7) at the bottom of high stability layer. Below the maximum, fluorescence decreased rapidly and stayed fairly constant below 20 m. Near the bottom, fluorescence showed a small increase with increasing Beam C. This indicates that chlorophyll and/or its partially degraded products can contribute to the light absorption near the bottom. The reason for the difference between staion 2, where the fluorescence maximum occured above the stability maximum, and stations 8 and C-1, where the maximum appeared below, appears to be due to nitrate concentration in the surface layer. At staion 2, nitrate concentration was farily high (2 μM) in

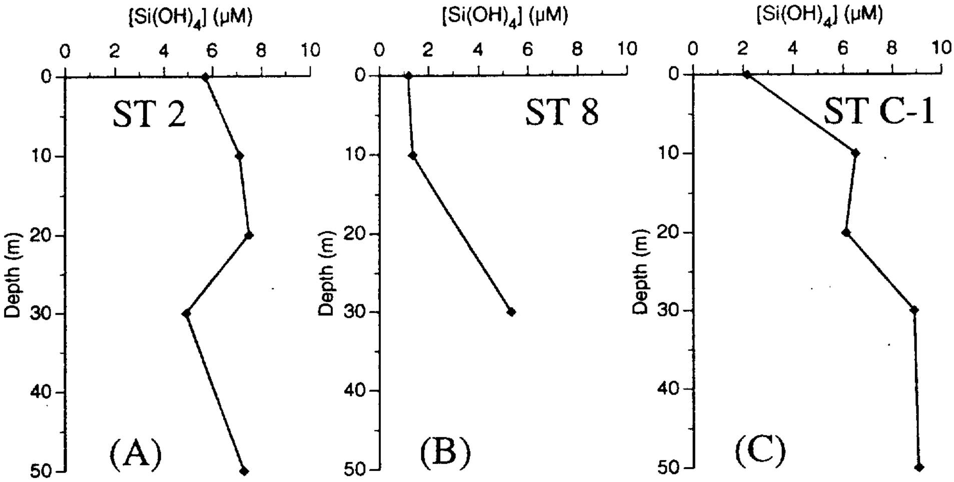

Fig. 7. Vertical distribution of silicate at (a) ST2, (b) ST8, and (c) STC-1.

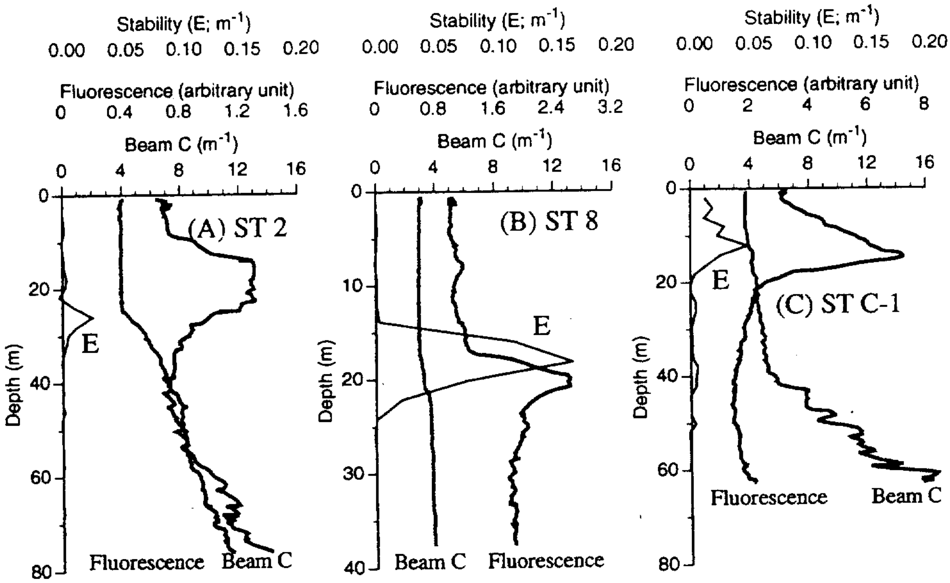

Fig. 8. Vertical distribution of stability (E; m^{-1}), beam attenuation coefficient (Beam C; m^{-1}), and fluorescence (arbitrary unit) at (a) ST2, (b) ST8, and (c) STC-1. Note that fluorescence scale is different among three stations. Also, ST8 has a different depth scale from ST2 and STC-1.

the upper mixed layer whereas almost undetectable level at station 8 and C-1. Station 8 had the highest stability at 18 m (0.17 m^{-1}) due to large changes in salinity and temperature. Station 2 had a density barrier at 24 m, but the magnitude (0.03 m^{-1}) was much smaller than station 8. Both stations 2 and 8 showed very low stability values above and below the barrier, indicating strong mixing processes above and below the thermocline. High stability at 18 m of station 8 suggests that it can act as an effective barrier for vertical mixing and hence prevent nutrient flux from below the thermocline to the upper mixed layer where most of the primary production occurs. In contrast, positive values of stability at top 15 meter (0.01~0.05 m^{-1}) appeared at station C-1, due to gradual cha-

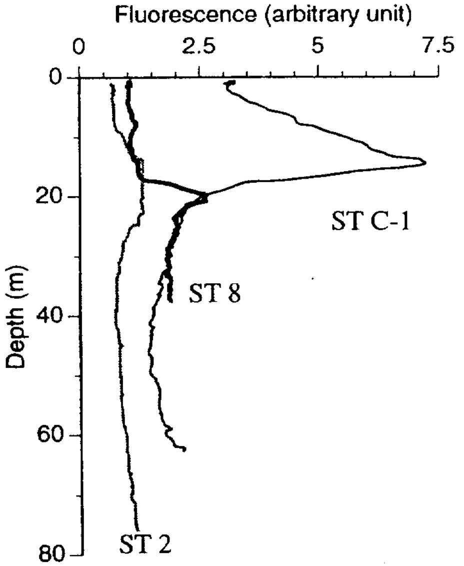

Fig. 9. Vertical distribution of fluorescence from three stations on a same scale.

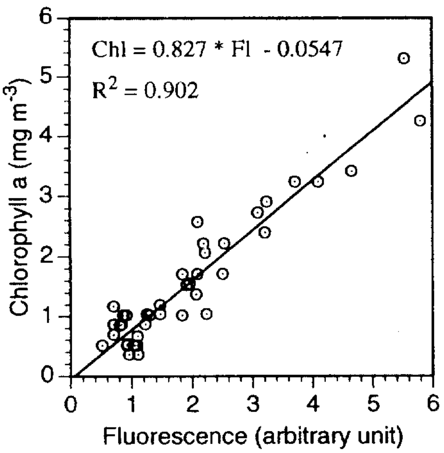

Fig. 10. The relationship between fluorescence and chlorophyll a concentration.

nges in salinity and temperature at the surface.

In Fig. 8, scales of fluorescence and depth are different among stations. On the same scale, the difference among stations are more conspicuous (Fig. 9). Station C-1, which had the highest productivity, showed the highest fluorescence. Station 2 had the lowest fluorescence and the lowest productivity. The relationship between fluorescence and extracted chlorophyll *a* was linear with R^2 of 0.90 (Fig. 10). The slope of the regression was 0.83 and the intercept on Y (chlorophyll) axis was close to 0 (−0.0547). We can safely assume that fluorescence indicates chlorophyll concentration and to a certain degree related to photosynthetic capacity. However, there are reports that chlorophyll fluorescence is vulnerable to physiological adaptation to environmental conditions including light and nutrient regime (Falkowski and Kiefer, 1985). From the results stated above, it appears that one of the major reason for the difference in new production among stations is the difference in phytoplankton biomass represented by fluorescence.

DISCUSSION

Three stations where productivity measurements were conducted, showed distinct vertical structures of temperature and salinity. At station 2, which had the lowest productivity and lowest f-ratio among three stations, there was a temperature inversion and showed the highest temperature and salinity among three stations. However, nitrate at the surface was not depleted (2 μM). Low phytoplankton biomass (from fluorescence and chlorophyll *a* concentration), which is the characteristics of the HWC, seems to be the main reason for low productivity at this station. Low f-ratio (0.12) suggests that most of the production is supported by nutrients recycled within the euphotic layer. Station 8 showed a very high stability (E) at 18 m which effectively blocks nutrient flux from below the thermocline and limits new production. At station C-1, the upper mixed layer was not developed and a gradual temprature gradient in the upper layer suggests a significant nutrient flux from below the thermocline. This matches well with the highest productivity and highest f-ratio at this station.

If we compare regenerated production and fluorescence between stations 8 and C-1, station 8 had higher regenerated production per biomass than station C-1. This suggests that community structure at station 8 is more mature and the grazing activity by zooplankton and microheteroflagellates is greater than at station C-1. This is reflected in the f-ratio; low at station 8 (0.18) and relatively high at station C-1 (0.263). But both of them are characterictics of oligo- to mesotrophic area. However, ρ_{NO_3} values are 2-3 orders higher than oligotrophic area values and comparable to meso- to eutrophic area values (Dugdale and Wilkerson, 1992). The discrepancy between the f-ratio and new production implies that the study area during the study period was highly productive, yet nutrient regeneration rate was also high.

In addition to nitrate and ammonia, new nitrogen sources can include dinitrogen fixation and precipitation (both nitrate and ammonia) and regenerated nitrogen can include urea and dissolved free amino acids. However, these sources are not included in the calculation of the f-ratio and may lead to some errors. But there are reports that these sources are minor compared to nitrate flux or ammonia regeneration (<20%; Kokkinakis and Wheeler, 1987). Also the precipitation and riverine input may not have been significant during this sampling period, because more than 60% of the precipitation occurs between June and September (Lie, 1986).

In the oceanic environment nutrient concentration, especially that of nitrate, is usually the limiting factor for primary production (Thomas, 1970; Ryther and Dunstan, 1971). Contrary to the expected, the ambient nutrient concentration alone could not account for the difference in productivity among stations. Other factors (e.g., differences in water mass, phytoplankton community structure, and rapid light attenuation due to high turbidity) could be more important in controlling primary production in the Yellow Sea. More study is warranted to elucidate the limiting factor in this area.

To estimate the theoretical upper boundary of new production in the Yellow Sea region, nitrogen flux measurements of riverine input and precipication is indispensable. However, information on the atmospheric nitrogen flux is inadequate and the situation is similar for the riverine flux. To fully understand the source and fate of the material flux in the Yellow Sea, more information on these two external sources and on benthic regeneration and resuspension is required.

ACKNOWLEDGEMENTS

We would like to thank captain and crew members of R/V Eardo; Drs. Heung-Jae Lie and Jae Hak Lee of KORDI for beneficial discussions on physical characteristics of the Yellow Sea; Professors Yong Chul Park, Joong-Ki Choi of Inha University, Jae Hyung Shim and Byung Chul Cho of Seoul National University for suggestions on chemical and biological processes; and two anonymous reviewers whose criticism and comments greatly improved the paper. We also appreciate Mr. Sung Rok Cho for the assistance during the cruise, Mr. Jong-Keun Kim for nutrient analyses, and Ms. Hyun Jung Koo for editorial help. ^{15}N samples were analyzed in Dr. Richard C. Dugdale's lab of the University of Southern California, U.S.A. This research was supported by Korean Ministry of Science and Technology.

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Accepted August 18, 1994