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Contribution of Micro- and Nanophytoplankton Cell Carbon to Particulate Organic Carbon in the East China Sea during May 1980

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Abstract In May, 1980, micro- (>10 μm) and nanophytoplankton (<10 μm) biomass in the East China Sea were measured in terms of chlorophyll *a* concentration and cell number. Analysis of particulate organic carbon was also done. Microplankton cell volume was estimated by approximated assignment of cell shape to the geometrical configuration, and cellular carbon content was estimated using conversion equations. Nanoplankton cell carbon was estimated using the microplankton C:chlorophyll *a* ratio. Total phytoplankton (microplankton + nanoplankton) cell carbon in the euphotic layer accounted for <6.6 % of particulate organic carbon in the oligotrophic Kuroshio water, and <40 % even in the coastal water near Kyushu. The contribution of micro- and nanoplankton carbon to total phytoplankton carbon showed the areal difference; >90 % of the total consisted of microplankton in the coastal water, while >90 % consisted of nanoplankton in the offshore Kuroshio water. Low values of microplankton C:chlorophyll *a* ratio suggested high photosynthetic activity. Possible mechanisms of local nutrient supply maintaining the high photosynthetic activity of phytoplankton in the East China Sea were also discussed.

Key words: chlorophyll, carbon, East China Sea, phytoplankton, nutrient, upwelling

INTRODUCTION

Suspended matter in the sea water contains both living and non-living particles. Major part of living particles are thought to consist of phytoplankton. Non-living particles are usually called as detritus. Detritus originated from living sources, however, often offer the substrate for the microbial community. We do not have much information on the contribution of phytoplankton biomass to whole suspended particle. Previous investigations on the phytoplankton size distribution and their biomass as well as the productivity have generally demonstrated that small-sized phytoplankton account for the most part of the total phytoplankton biomass and primary production in both temperate and tropical oceanic environments (YENTSCH and RYTHER, 1959; SAIJO and TAKESUE, 1965). On the other hand, the contribution of large-sized phytoplankton is often significant in neritic waters (MALONE, 1971a, b). These imply that not only the phytoplankton abundance is higher in neritic waters than oceanic ones but also the phytoplankton species composition is different between neritic eutrophic regime and oceanic oligotrophic regime.

To estimate the phytoplankton carbon biomass *in situ*, we often adopt a arbitrary conversion factor (C:chlorophyll *a* ratio) which was obtained from cultured phytoplankton species. However, we know the C:chlorophyll *a* ratio is variable, depending on the physiological condition of the cells. The variability of the ratio is thought to be mainly due to the variability of cellular chlorophyll *a* content, which is said to be influenced by some environmental conditions including temperature, light intensity and nutrient concentration (MULLIN *et al.*, 1966). Then, the alternative method, conversion from cell volume to cell carbon (MULLIN *et al.*, 1966; STRATHMANN, 1967) is accepted to be more useful for the estimation of phytoplankton biomass, although the measurement of individual cell dimension under a microscope is largely troublesome work.

The Kuroshio flows northwards adjoining to the shelf edge in the East China Sea. Several surveys on the planktonic diatom communities were carried out in the East China Sea (KAWARADA, 1965; KAWARADA *et al.*, 1968; ASAOKA, 1975), but our knowledge is still lacking on the size of phytoplankton assemblage and the contribution of phytoplankton biomass to particulate organic carbon (POC). The East China Sea is selected as a representative field to compare the areal difference of their characteristics, because the demarcation among the coastal water near Kyushu, the shelf water and the oligotrophic Kuroshio water is distinct (Fukase, 1975). In the present study, we estimated the carbon biomass of both micro- and nanoplankton from those characteristic localities, and compared them to POC concentration which was chemically determined.

OBSERVATIONS AND ANALYTICAL METHODS

Observation was made at 21 stations in the East China Sea on May 9–24, 1980 (Fig. 1). CTD operation was carried out at all stations. Sea water was collected with rosette Niskin bottles that has been coupled to a CTD system at Stns. 1–3, 5, 7, 9, 11, 13 and 16–21 for the determination of concentrations of nutrient salts and chlorophyll *a* (Chl *a*). Sampling depths of sea water were 0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250 and 300m. The sea water sampled at Stns. 2, 3, 5, 16, 18 and 20 were filtered through precombused glass fiber filter (Whatman GF/C, 450°C, 4hrs) to determine the concentration of POC. The determination of POC concentration was done using an infrared gas analyser (STRICKLAND and PARSONS, 1972).

Size fractionation of particulate matter using 10 μm netting was performed for the water samples collected at Stns. 2, 3, 5, 16, 18 and 20. One liter of the filtrate was again filtered through a glass fiber filter (Whatman GF/C). Chl *a* concentration was determined for the precipitate on the filter as nanoplankton Chl *a*. Sea water without netting was also filtered through a glass fiber filter (Whatman GF/C), and Chl *a* was determined for total phytoplankton assemblage. Chl *a* concentration was determined fluorometrically according to the method of Yentsch and Menzel (1963). Then, the Chl *a* of microplankton fraction larger than 10 μm was calculated by subtracting the former from the latter.

The sieving size of 10 μm is thought to be useful to separate small-sized single cell from some chain forming species of diatoms (Van VALKENBURG and FLEMER, 1974) and is assumed to be the critical size for the identification of species in natural assemblages under a light microscopy (YAMAMOTO, 1983). In this report, the data from the euphotic layer,

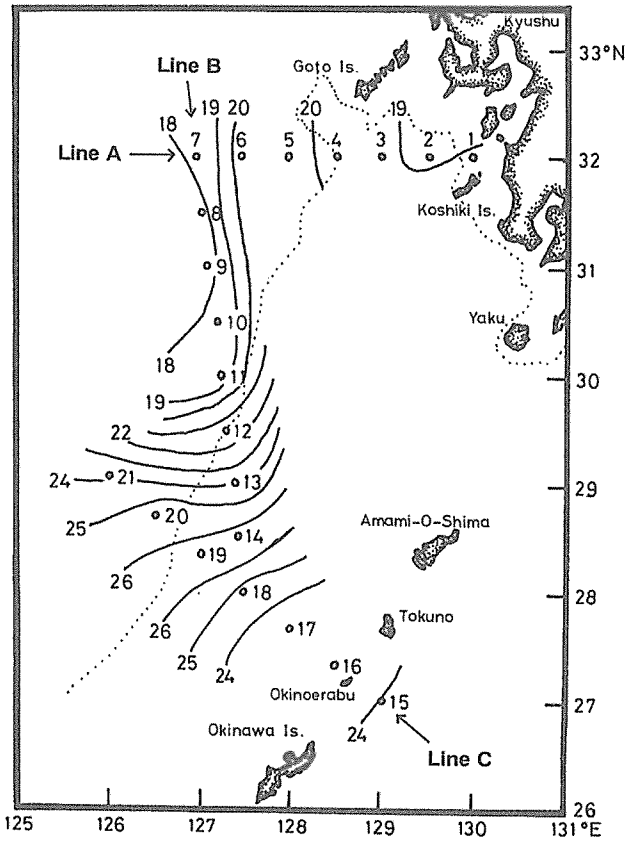

Fig. 1. Map showing the sampling stations and the surface temperature distribution.

which was determined 3 × secci disk depth, were used for the analysis, concerning to the photosynthetically active phytoplankton; the data from 0−50m of Stns. 2, 3 and 5, 0−75m of Stn. 20, and 0−100m of Stns. 16 and 18 were used.

One liter aliquot of natural sea water sample was preserved by adding 1 % neutralized formaldehyde for identification and cell count of microplankton larger than 10 μm. After removing micro-sized particles through a 10 μm netting, subsample of 10 ml filtrate was fixed with the mixture of gluteraldehyde and formaldehyde, and then filtered again through a membrane filter (Gelman, GA-8) for investigation of nanoplankton. Microplankton and nanoplankton were investigated using an inverted microscope (TANIGUCHI, 1977) and a epifluorescent microscope (TSUJI and ADACHI, 1979), respectively. Although the fixatives were added in concentration as low as possible to maintain the original shape of micro-organisms, some fragile species might be broken.

Microplankton cell volume was estimated by approximated assignment of cell shape to the geometrical configuration. KOVALA and LARRANCE (1966) proposed 17 applicable configurations for phytoplankton shape. In the present study, for the practical convenience, each cell was assigned to cylinder, elliptic cylinder, sphere, ellipsoid or spindle, respectively (Table 1). Cellular carbon content (C) was estimated from the cell volume (V) using the

conversion equations of Strathmann (1967);

$$\log_{10}C=0.758\log_{10}V-0.422$$

for diatoms, and

$$\log_{10}C=0.866\log_{10}V-0.460$$

for the other microplankton. For nanoplankton, since accurate measurement of cell dimension was difficult under a fluorescent microscope because of the smallness, the cell carbon was estimated supposing that the C:Chl *a* ratio is the same as that of microplankton at each station.

RESULTS AND DISCUSSION

Hydrographic condition and distribution of nutrient salts

Surface temperature distribution was illustrated with the location of sampling stations

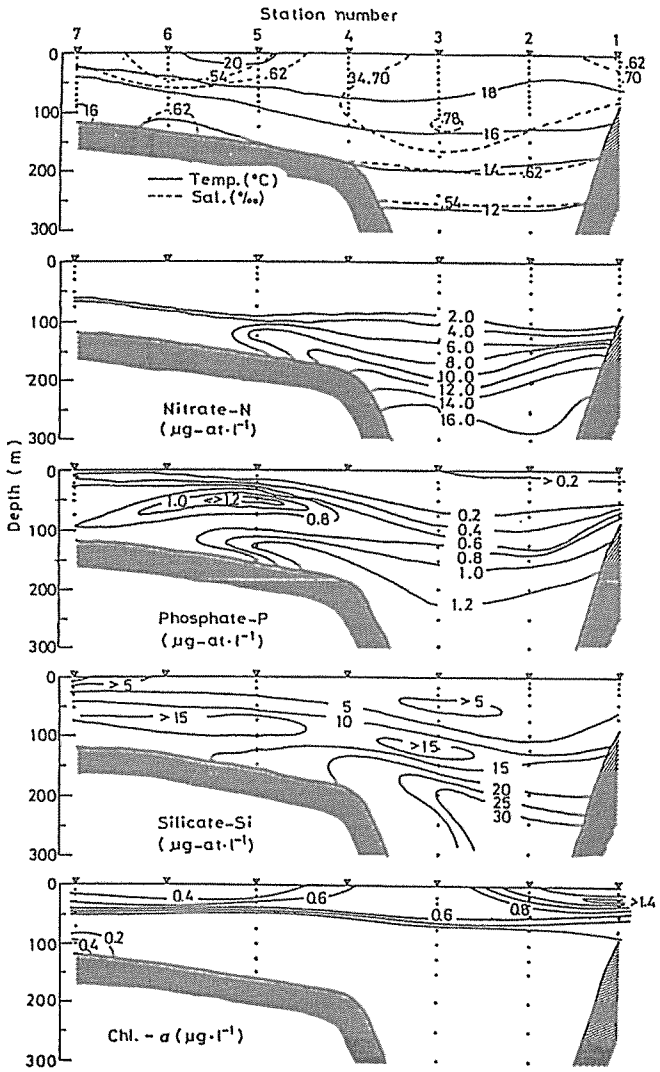

Fig. 2. Vertical distributions of temperature, salinity, essential nutrients and chlorophyll *a* in Line A. May 1980.

in the study area (Fig. 1). Vertical distribution of temperature, salinity, major nutrient salts and Chl *a* concentrations on Line A, B and C were shown in Figs. 2, 3 and 4, respectively. Temperature was the highest (>26°C) at the surface of Stns. 14 through 19 and also relatively high at the surface of Stn. 5. High salinity core was observed at 150m depth of Stns. 19 and 14, at 200m depth of Stn. 18 and at 100m depth of Stn. 3. Although the definition of Kuroshio warm core is difficult because the characteristics change during the process of flow (KAWAI, 1969), these high temperature and high salinity core are identified as the parent Kuroshio Current in Line C, and the Tsushima Warm Current (a branch of the Kuroshio Current) in Line A, respectively. On the other hand, low temperature and low salinity shelf water extending from northwest to southeast was observed around Stns. 10 and 11 on Line B (Fig. 1) and was cascading along the shelf slope (Fig. 3). "Cascading"

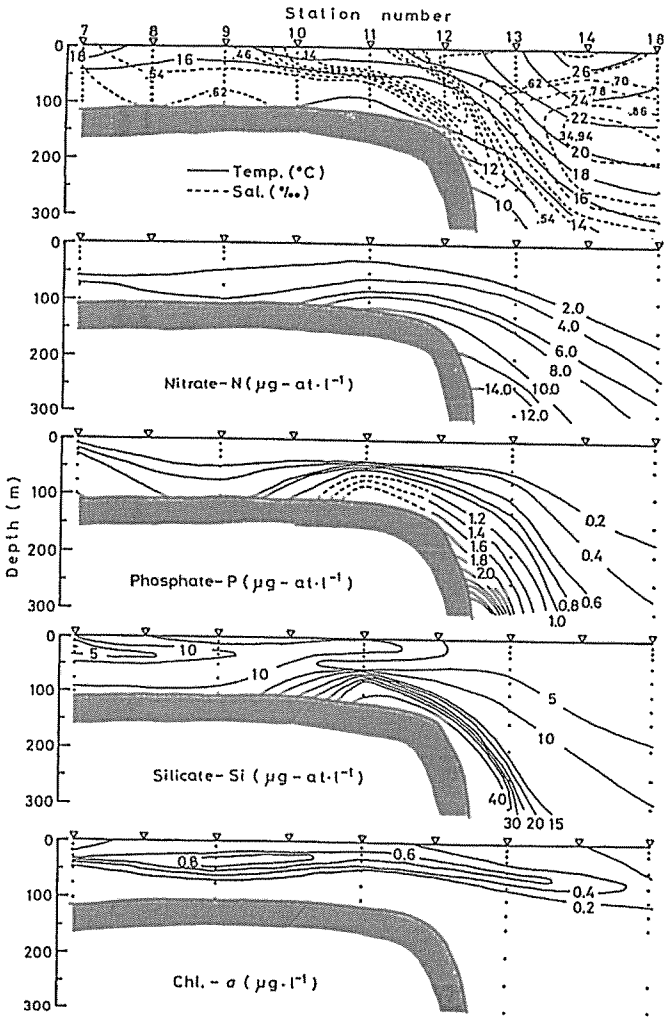

Fig. 3. Vertical distributions of temperature, salinity, essential nutrients and chlorophyll *a* in Line B. May 1980.

of the shelf water was reported earlier by TSUJITA (1957) and FUKASE (1975). FUKASE (1975) mentioned that a branch of the "cascading" of the shelf water is frequently found at northwest of Amami-O-Shima Island, where the similar phenomenon was observed in the present study.

Concentrations of nutrient salts were usually low in the euphotic layer; nitrate-N<2 μg at l^{-1}, phosphate-P<0.2μg at l^{-1}, silicate-Si<5μg at l^{-1} (Figs. 2, 3 and 4). Concentration of ammonium-N and nitrite-N were below the detection limits in whole water column. It was

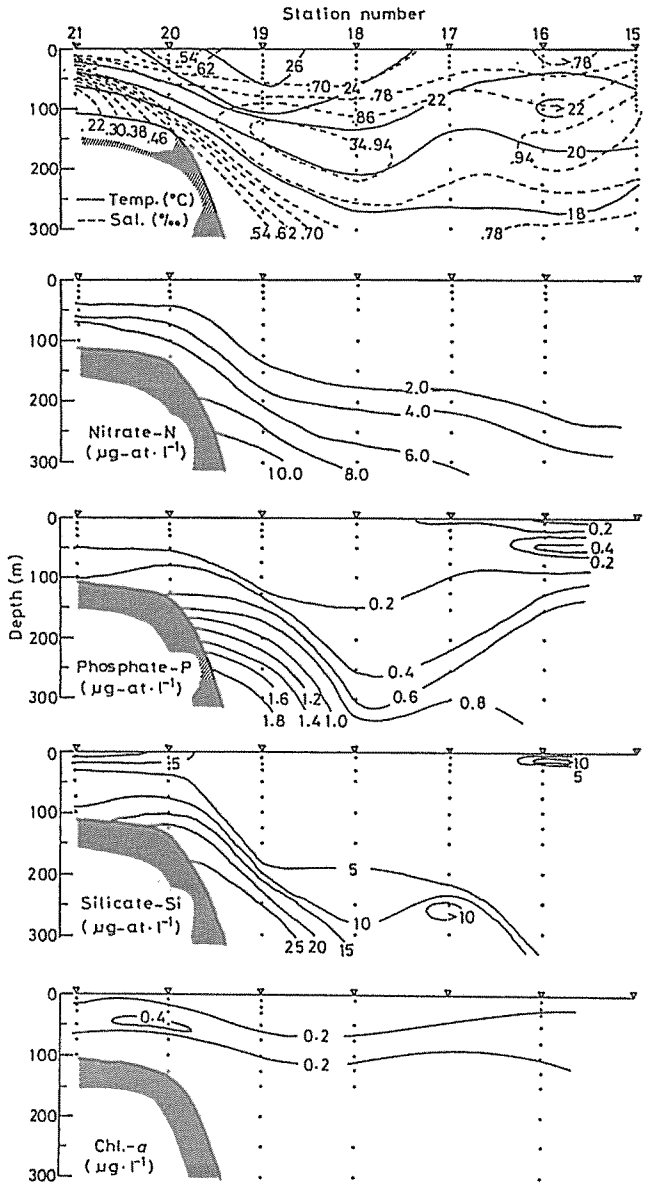

Fig. 4. Vertical distributions of temperature, salinity, essential nutrients and chlorophyll *a* in Line C. May 1980.

noticeable that the contour of nutrient salts showed an intrusion-like pattern of the slope water beneath the Kuroshio onto the shelf .

Chlorophyll a concentration

Chl *a* concentration was high where the land effect is large (surface of Stns. 1–2, max $>1.2\mu g\ l^{-1}$) and low in the Kuroshio water and the Tsushima Warm Water. Relatively high Chl *a* concentration along the shelf edge, which is considered to correspond to the Kuroshio front, showed north-south gradient, *i.e.*, it was low in Line C (maximum concentration of $0.4\ \mu g\ l^{-1}$ at 50m depth of Stn. 20) and high in Line B ($0.8\ \mu g\ l^{-1}$ at 30m depth at Stn. 9).

Vertical profiles of micro- and nanoplankton Chl *a* at Stns. 2, 3, 5, 16, 18 and 20 were shown in Fig. 5. Contribution of microplankton Chl *a* to the total was obviously high in the euphotic layer at Stns. 2 and 3 near Kyushu (68 % and 89 %, respectively), while contribution of nanoplankton Chl *a* was exclusively large at Stns. 16, 18 and 20 (89 %, 91 %, 87 %, respectively).

Distribution of phytoplankton species and contribution of the cellular carbon to POC

Phytoplankton species found in the present investigation were listed in Table 1 with their size and estimated carbon contents. Estimated microplankton cell volume and carbon content ranged from $2.0\times10^2\ \mu m^3$ and 2.1×10 pgC of *Chaetoceros laevis* to $1.1\times10^7\ \mu m^3$ and 8.3×10^4 pgC of *Rhizosolenia styliformis* v. *latissima*. The cellular carbon contents of individual species calculated here were different from those obtained at other coastal area

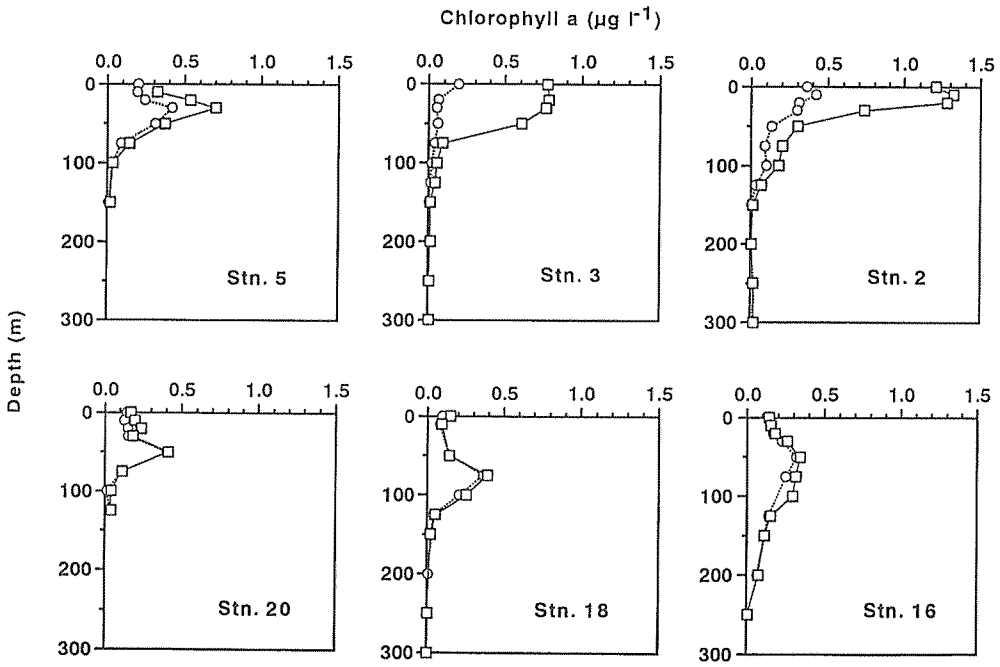

Fig. 5. Vertical distributions of microplankton chlorophyll *a* and nanoplankton chlorophyll *a* at selected stations. May 1980. Circle and square indicate the nanoplankton chlorophyll *a* and micro- + nanoplankton chlorophyll *a*, respectively.

Table 1. Cell dimensions of representative phytoplankton species found in the East China Sea in May, 1980. Cell volume was estimated by approximated assignment of cell shape to the geometrical configuration. Shape 1, disc or cylinder; 2, elliptic cylinder; 3, sphere; 4, ellipsoid; 5, spindle. Cell carbon was estimated using conversion equations of Strathmann (1967).

Species	Shape	Major axis (μm)	Minor axis (μm)	Hight (μm)	Volume (μm^3)	Carbon (pgC $cell^{-1}$)
Diatoms						
Actinoptychus senarius	1	60	–	10	28000	890
Asteromphalus heptactis	2	70	50	7	19000	660
Bacillaria paradoxa	2	80	8	8	4000	200
Bacteriastrum delicatulum	1	13	–	20	2700	150
B. elongatum	1	15	–	13	2300	130
B. varians	1	15	–	25	4400	220
B. varians v. *hispida*	1	18	–	30	7600	330
Chaetoceros affine	2	25	8	23	3600	190
C. anastomosans	1	15	–	20	3500	180
C. atlanticum v. *neapolitanum*	1	15	–	29	5100	250
C. compressum	1	10	–	15	1200	82
C. curvisetum	2	16	10	17	2100	130
C. dadayi	1	10	–	10	790	59
C. danicus	1	11	–	18	1700	110
C. decipiens	2	18	12	13	2200	130
C. denticulatum	1	20	–	42	13000	500
C. didymum	1	24	–	18	8100	350
C. frichei	2	27	12	35	8900	370
C. laciniosum	2	18	12	20	3400	180
C. laevis	2	7	4	9	200	21
C. lorenzianum	2	22	42	20	15000	550
C. messanense	2	30	10	26	6100	280
C. okamurai	1	28	–	30	18000	640
C. pendulum	1	18	–	10	2500	140
C. peruvianum	1	30	–	25	18000	640
C. seiracanthus	2	19	12	22	3900	200
C. seychellarum	1	22	–	38	14000	530
Climacodium frauenfeldianum	2	80	3	32	6000	280
Corethron hystrix	1	20	–	65	20000	690
C. pelagicum	1	50	–	98	190000	3800
Coscinodiscus jonesianum v. *commutata*	1	68	–	45	160000	3300
C. radiatus	1	49	–	25	47000	1300
Dactyliosolen mediterraneus	1	18	–	100	25000	820
Ditylum brightwellii	1	38	–	80	91000	2200
Eucampia zodiacus	2	45	4	44	6200	280
E. cornuta	2	45	4	70	9900	400
Guinardia flaccida	1	48	–	100	180000	3600
Hemiaulus hauckii	2	16	12	75	11000	440
Leptocylindrus danicus	1	7	–	50	1900	120
Lauderia borealis	1	45	–	40	64000	1700
Melosira sulcata	1	19	–	10	2800	160
Nitzschia pungens	2	11	7	140	8500	360
Navicula membranacea	2	80	17	35	37000	1100
Planktoniella sol	1	46	–	10	17000	610
Pseudoeunotia doliolus	2	48	7	8	2100	130
Rhizosolenia alata	1	19	–	320	91000	2200
R. alata f. *gracillima*	1	10	–	300	24000	790
R. alata f. *indica*	1	34	–	340	310000	5500

R. bergonii	1	60	–	280	790000	11000
R. calcar–avis	1	25	–	500	250000	4700
R. cylindrus	1	16	–	190	38000	1100
R. hebetata f. *hiemalis*	1	16	–	410	82000	2000
R. hebetata f. *semispina*	1	18	–	160	41000	1200
R. robusta	1	53	–	650	1400000	17000
R. storterfothii	1	29	–	100	66000	1700
R. styliformis	1	58	–	550	1500000	18000
R. styliformis v. *latissima*	1	150	–	630	11000000	82000
Skeletonema costatum	1	10	–	20	1600	100
Thalassionema nitzschioides	2	61	3	3	430	38
Thalassiosira eccentrica	1	43	–	8	12000	470
Thalassiothrix frauenfeldii	2	280	3	3	2000	120
T. mediteranea v. *pacifica*	2	980	5	5	19000	660
Dinoflagellates						
Amphisolenia globifera	1	10	–	200	16000	1500
Ceratium arietinum	3	51	–	–	69000	5400
C. boehmii	3	27	–	–	10000	1000
C. extensum	1	18	–	350	89000	6700
C. furca	1	27	–	190	110000	8100
C. fusus	1	18	–	500	130000	9300
C. gravidum	3	125	–	–	1000000	54000
C. inflexum	3	51	–	–	69000	5400
C. lineatum	3	31	–	–	16000	1500
C. macroceros v. *gallicum*	3	48	–	–	58000	4600
C. massiliense v. *protuberans*	3	65	–	–	140000	9900
C. pentagonum	3	60	–	–	110000	8100
C. pulchellum	3	55	–	–	87000	6600
C. tripos v. *atlanticum*	3	43	–	–	42000	3500
Dinophysis caudata	4	30	25	50	20000	1800
D. mitra	4	55	35	65	65000	5100
Gonyaulax bruunii	4	20	20	25	5200	570
G. polygramma	4	50	50	55	72000	5600
Oxytoxum milneri	4	23	23	60	17000	1600
O. scolopax	4	17	17	66	10000	1000
Parahistioneis para	4	45	40	60	57000	4600
Podolampas spinifera	4	26	26	110	39000	3300
Prorocentrum micans	4	27	10	45	6400	690
Protoperidinium acutipes	5	60	–	60	57000	4600
P. crassipes	5	100	–	100	260000	17000
P. depressum	5	100	–	130	340000	21000
P. oceanicum v. *oblongum*	5	140	–	160	820000	46000
P. pallidum	5	50	–	50	33000	2800
P. pyriforme	5	51	–	52	35000	3000
P. trochoideum	5	15	–	23	1400	180
Pyrocystis fusiformis	4	15	15	48	5700	620

(*e.g.*, MIYAI *et al.*, 1988). This indicates that the cell dimensions are much variable even in the same species by the location and season. Therefore, we had better to understand that the cell volume and the carbon content obtained from this sort of study are not applicable for phytoplankton assemblages of any other place and season.

On Line A, two large diatom species, *i.e.*, *Rhizosolenia styliformis* and its variety *latissima* were predominant, and occupied 92 % of microplankton carbon. *Guinardia fluccida*

and *R. alata* f. *glacillima* were also abundant at Stns. 2 and 3. On Line C, *R. styliformis* was also a dominant species in the chlorophyll maximum layer, but several subdominant species such as *Nitzschia* sp., *Thalassionema nitzschioides*, *Thalassiothrix frauenfeldii* and *Leptocylindrus danicus* were also highly present. As reported by Asaoka (1975, 1980), a benthic diatom, *Melosira sulcata* was found on the continental shelf (100m depth of Stn. 20).

Cell density of dinoflagellates was very low being usually less than 10 cells l^{-1}. *Ceratium fusus*, *C. lineatum*, *Prorocentrum micans*, *Protoperidinium trochoideum* and *Pyrosystis fusiformis* were found both in Line A and Line C. As pointed out by FURUYA and NEMOTO (1986), there are some dinoflagellate species which have complexed figure in their shape, and the assignment of simple configuration to these species produce an error. In the present study, such kind of error is also included, but the contribution is assumed to be very low considering from their low cell density.

Cell density of nanoplankton varied from the order of 10^3-10^5. Although a positive linear correlation was found between the nanoplankton cell density and nanoplankton Chl *a* fraction in the samples collected at individual station, no such relationship was found between these two parameters for all the data. This may be attributed to the difference in species composition and their size frequency at respective locations.

Average POC concentration and estimated micro- and nanoplankton cell carbon in the

Table 2. Micro- and nanoplankton cell carbon and their contribution to POC. Chlorophyll *a* concentrations of their fraction were also shown. Upper, microplankton; middle, nanoplankton and lower, total. ND, no data.

Stn.	Cell C ($\mu g\ l^{-1}$)	Cell C/POC (%)	Chl *a* ($\mu g\ l^{-1}$)	C/Chl *a* (%)	POC ($\mu g\ l^{-1}$)
2	12	18	0.622	19	65.0
	5.7	8.7	0.299	ND	
	18	27	0.921	ND	
3	18	30	0.657	27	59.1
	2.3	3.8	0.084	ND	
	20	34	0.741	ND	
5	8.0	16	0.196	41	49.7
	12	24	0.293	ND	
	20	40	0.424	ND	
16	0.3	0.67	0.029	10	44.5
	2.4	5.4	0.242	ND	
	2.7	6.1	0.271	ND	
18	0.26	0.55	0.019	14	47.1
	2.6	5.6	0.187	ND	
	2.9	6.1	0.206	ND	
20	0.54	0.84	0.031	17	64.1
	3.7	5.7	0.216	ND	
	4.2	6.6	0.247	ND	

euphotic layer at each station were presented in Table 2. Small variation was observed in POC concentration in the euphotic layer among stations (44.5–65.0 μg l^{-1}). Microplankton cell carbon was definitely higher in Line A (8.0–18 μg l^{-1}) than Line C (0.26–0.54 μg l^{-1}). Thus, the resulted contribution of microplankton to POC was also higher in Line A (16–30 %) than Line C (0.55–0.84 %).

Nanoplankton cell carbon estimated from microplankton C:Chl *a* ratio ranged 2.3–12 μg l^{-1} and their contribution to POC were 3.8–24 %. These values appear to be relatively constant compared to those of microplankton. This is also supported by their Chl *a* standing stocks (Fig. 5) which showed that the variable part is microplankton fraction. This tendency appear to be expandable as a general trend for the offshore waters around Japan as shown by YAMAMOTO and TANIGUCHI (1993).

Total phytoplankton cell carbon (microplankton+nanoplankton) was low in the offshore Line C (2.7–4.2 μg l^{-1}), while it was high in Line A (18–20 μg l^{-1}). Consequently, the contribution of total phytoplankton carbon to POC was consistently small in Line C (6.1–6.6 %), and large in Line A (27–40 %). These percentages in Line C were low but those of Line A were considerably high compared to the value (9.4 %) observed in the water of the Gulf of California (ZEITZSCHEL, 1970). As deduced from the data shown above, microplankton contributed much to total phytoplankton carbon stock at the stations near Kyushu (67 % at Stn. 2 and 90 % at Stn. 3). On the other hand, at the offshore stations, nanoplankton contribution was considerably large, *i.e.*, 88–90 % at 3 stations in Line C. However, almost all of POC (>90 %) in Line C is occupied by detrital carbon, and even in the coastal area near Kyushu more than 60 % of POC is detrital carbon.

C:Chl a *ratio and photosynthetic activity*

Microplankton C:Chl *a* ratio in Line A was 19–41 (Table 2). These values are comparable to the value (37.8) obtained in the Gulf of California by ZEITZSCHEL (1970). As he mentioned, C:Chl *a* ratio larger than 50 is considered to be usually observed in unfavourable conditions such as nutrient depleted water and aphotic layer. Since the C:Chl *a* ratios obtained in the present study were those from euphotic layer, the mechanisms of nutrient supply should be discussed. For Stns. 2 and 3 in Line A, the major nutrient source is thought to be the discharge from Kyushu judging from the location.

How can I explain the much lower C:Chl *a* ratio (10–17) obtained in Line C? This means that the higher photosynthetic activity is achieved even in the oligotrophic Kuroshio water. One plausible explanation is nutrient supply from the main land of China. Since the fresh water discharge from the Yangtze River is extraordinarily large (*ca.* 900 km^3 yr^{-1}) as MILLIMAN (1991) reported, the nutrient flux accompanied with the fresh water discharge would also be large. Another possible explanation is the local upwelling of nutrient rich slope water. Cross sectional distribution of nutrient salts showed an intrusion-like pattern of the slope water beneath the Kuroshio current onto the shelf (Figs. 2, 3 and 4). ITO *et al.* (1994) have described on the upwelling process of the intermediate water of the Kuroshio. MATSUDA *et al.* (1989) also observed high Chl *a* concentration accompanied with supersaturated dissolved oxygen water along the line of 31°40'N latitude in June, 1987. They explained that the high phytoplankton biomass may be due to the supply of nutrients

from bottom water and the availability of sufficient underwater irradiance. This process is considered to occur by the offshore movement of the Kuroshio current axis, as mentioned by ATKINSON (1977) as "bottom intrusion" for the Gulf Stream. The quantification of the several possible mechanisms mentioned above which are sustaining the photosynthetic activity of phytoplankton is important to understand the ecosystem of the East China Sea.

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東シナ海の1980年5月における小型および微細植物プランクトン態炭素の粒状態有機炭素に占める割合

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東シナ海において1980年5月に，小型（>10μm）および微細（<10μm）植物プランクトンのバイオマスをクロロフィル a および細胞数として測定した。同時に粒状態有機炭素を測定した。小型植物プランクトンの細胞容積を幾何学的形状に当てはめて求め，変換式を用いて細胞当たり炭素量を算出した。微細植物プランクトンの炭素量は小型植物プランクトンの炭素：クロロフィル a 比を用いて見積もった。有光層内の全植物プランクトン態炭素は貧栄養な黒潮水中で<6.6 %と低く，九州に近い沿岸水中でも<40 %であった。全植物プランクトン態炭素に占める小型植物プランクトンおよび微細植物プランクトンの炭素量は海域間の違いが非常に明瞭であった。すなわち，黒潮水中で微細植物プランクトン態の炭素が>90 %を占めるのに対して，沿岸水中では小型植物プランクトン態の炭素が>90 %を占めた。小型植物プランクトンの炭素：クロロフィル a 比が41以下と全体的に低いことから，現場の光合成活性が高いことが想像された。この高い光合成活性を維持している栄養塩の供給機構についても議論した。