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Standing stock and production of phytoplankton in the estuary of the Changjiang (Yangtse River) and the adjacent East China Sea*

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ABSTRACT: We determined cell density and dominant species of eukaryotic phytoplankton, chlorophyll concentration and primary production in the Changjiang estuary and dilution zone in January and July 1986. In winter, phytoplankton was dominated by small cells (< 10 μm), closely associated to particulate matter. In summer, the most striking feature of chlorophyll and primary production distributions was the presence of sharp maxima localized about 100 km offshore at salinities between 25 and 30 ‰ and related to diatom populations. The critical factor responsible for these maxima was the increased light availability following sedimentation of the particulate matter originating from the river, as observed in front of other major world rivers such as the Zaire and the Amazon. This photosynthetic activity resulted in high oxygen concentrations and phosphate depletion in the surface layer. In both seasons, in situ areal productivity and light availability were related by a simple empirical relationship similar to that established for other medium-sized estuaries.

INTRODUCTION

The Changjiang (Yangtse river) is one of the major world rivers, its discharge (9×10^{11} m^3 yr^{-1}) being exceeded only by the Amazon and the Zaire (Fairbridge 1980). It plays a fundamental role in the terrigenous inputs to the East China Sea and the Pacific Ocean. Despite the importance of primary productivity in the transformation of dissolved elements, phytoplankton has been little studied in estuaries of large rivers (Amazon: Cadée 1975, Milliman & Boyle 1975, DeMaster et al. 1986; Zaire: Cadée 1978, Cadée 1984) in comparison to medium-sized estuaries (e.g. Kroon 1971, Cadée & Hegeman 1974, Malone 1977, Joint & Pomroy 1981, Cloern et al. 1983, Colijn & Ludden 1983, 1985, Harding et al. 1986, Pennock & Sharp 1986), where it has been demonstrated that light penetration is the main control for photosynthetic productivity (Cole & Cloern 1987). One fundamental question is whether the same control acts in large rivers.

Recent investigations in the Changjiang estuary and its dilution zone (Chai & Yuan 1986, Ning et al. 1986, Ning et al. unpubl.) revealed that the highest values of phytoplankton standing stock and production were generally located on the continental shelf more than 100 km away from the river mouth with decreasing gradients in both onshore and offshore directions. These investigations were achieved, however, within large-scale surveys of the South Yellow and East China Seas with few stations in the Changjiang dilution zone itself. In contrast, the present study focused on the latter region as part of a multidiscipline project, which offered an excellent opportunity to understand how photosynthetic production was related to both physical (hydrology and sediment load) and chemical (nutrients) environmental factors.

MATERIALS AND METHODS

Sampling. The area surveyed is located roughly between 121° 00′ and 124° 00′ E longitude and 30° 45′ and 32° 00′ N latitude (Fig. 1). Water depth ranges from 10 m in the river to 50 m offshore where the seafloor deepens to the southeast.

Two cruises were conducted aboard the research vessel 'Xiang Yang Hong 09' in January and July 1986.

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An array of 23 stations (Fig. 1) was sampled over a 3 d period to provide a quasi-synoptic view of the area. River stations (R1 to R5, Fig. 1) were sampled with the small vessels 'Hai Jian 42' in January and 'Xiang Yang Hong 01' in July.

At these stations, seawater samples were taken with a Rosette of Niskin bottles attached to a CTD probe measuring salinity and temperature. Water samples for chlorophyll (Chl) determinations were taken at 3 depths (surface, middle layer, bottom) inside the river and 7 depths (0, 5, 10, 20, 30, 40 m and bottom) outside the river. For phytoplankton species identification and direct counts of Chl-containing cells, samples were taken at the surface in winter, and at the surface and below the thermocline in summer.

Photosynthetic rates and chlorophyll concentrations were determined at selected survey stations (9, R3, R4 in January and 1, 8, 10, 11, 18, R5 in July) and at additional anchor stations (C1 to C4, Fig. 1). Sampled depths corresponded to light levels of 100, 50, 25, 10, and 1 % of the surface irradiance.

Methods. Surface light intensity was obtained from annual data collected by the Meteorological Groups of the Institutes for Marine Research and Geographic Research, Academy Sinica. Euphotic depth (corresponding to 1 % of the surface irradiance) was estimated from Secchi disc readings (Poole & Atkins 1929, Holmes 1970) at the stations sampled during daylight and interpolated from nearby values at the other stations. Suspended matter was determined gravimetrically. Nitrate and phosphate were analysed by standard spectrophotometric methods (Strickland & Parsons 1972) on 0.45 µm filtered water samples. Photosynthetic pigments (Chl *a* and phaeopigments) were measured from 100 ml samples filtered through Whatman GF/C filters and determined with a Turner Designs Fluorometer Model 10, according to Holm-Hansen et al. (1965).

Direct cell counts were obtained by epifluorescence microscopy (Murphy & Haugen 1985). For each sample, from 10 to 40 ml were filtered onto 0.2 µm pore-size black Nuclepore filters at a vacuum less than 200 mm Hg. Cells were immediately counted with an Olympus BH-2 epifluorescence microscope. Chl-containing cells fluoresced brick-red under blue light (broad band excitation centered around 450 nm) and could easily be distinguished from orange-fluorescing cyanobacteria. In summer, 2 size classes were distinguished, below and above 10 µm, separating pico and nanoplankton from large cells such as diatoms and dinoflagellates. Absolute cell concentrations were computed from the enumeration of at least 2 transects per slide. Phytoplankton species identifications were carried out on preserved (Lugol's solution) samples using an Olympus inverted microscope.

Photosynthetic rates were determined for each sampling depth using 2 light and 2 dark 250 ml bottles. Light bottles were covered with neutral density screens to allow transmission of the percentage of incident light corresponding to the depth of collection. They were incubated for 4 h on deck after addition of 1 ml of 8 µCi $NaH^{14}CO_3$. In the incubator the bottles were attached to a wheel rotated by running seawater, which provided both agitation and temperature control. At the end of the incubation, the samples were filtered onto a Millipore HA membrane filter (0.45 µm) using a low vacuum of 150 mm Hg to minimize cell damage. The filters were fumed over concentrated HCl for 10 min, placed into scintillation vials and kept in a desiccator until returned to the laboratory. A 1,4-dioxane-based scintillation cocktail was added to the vials, which were counted in a LKB 1215 liquid scintillation counter. The counting efficiency was determined by the external-standard channel-ratio method. The amount of ^{14}C added to the experimental bottles was also counted in the laboratory. Photosynthetic

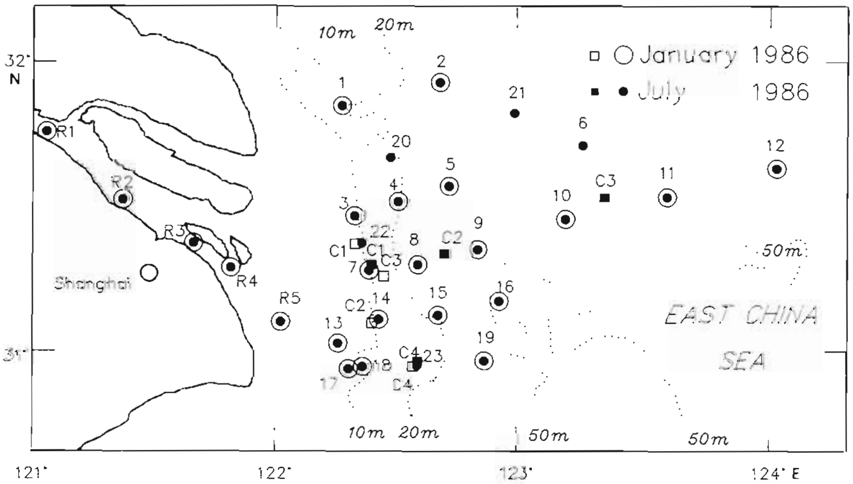

Fig. 1. Sampling stations in Changjiang estuary and East China Sea. Circles: survey stations; squares: anchor stations for photosynthetic rate measurements. Open symbols: Jan 1986 cruise; closed symbols: Jul 1986 cruise. Bottom topography indicated by dotted lines with water depths (m)

rates and potential primary production were calculated using the equations of Parsons et al. (1984) and in situ primary production was estimated using Cadée & Hegeman's (1974) equation, which has been shown to be valid for turbid coastal waters (Wadden Sea, Guyana coast off the Amazon mouth). At stations where it could not be directly measured, the average potential primary production was estimated as the product of the mean chlorophyll content in the euphotic zone by the average assimilation number in the surveyed area (Table 1).

RESULTS

Environmental factors

Only a brief overview of the main environmental factors relevant to the observed phytoplankton production processes is provided, since the detailed physical and chemical features of the area under study will be presented elsewhere (Martin & Yu unpubl.).

Hydrological conditions

In winter, the Changjiang discharge was low (9.5 × 10^3 m^3 s^{-1} in January 1986, Wang et al. unpubl.). The fresh and cold (5 °C) water from the Changjiang flowed southeastwards from of the river mouth (Fig. 2A). The Taiwan Warm Current (an onshore branch of the Kuroshio) brought saline (34 ‰) and warm (13 °C) water from the southeast. In the north, the Yellow Sea Coastal Current carried relatively less saline (30 ‰), cold (5 °C) and particle-rich water southward along Jiangsu coast, as noted previously by Wang et al. (1984) and Beardsley et al. (1985). In winter, no thermal stratification occurred because of the relatively low solar heating and the presence of strong vertical mixing.

During summer, river discharge was much higher (47.3 × 10^3 m^3 s^{-1} in July 1986, Wang et al. unpubl.) and the water column was thermally stratified in the dilution zone. The fresh and warm (25 °C) Changjiang water plume spread in surface, first towards the southeast, then towards the northeast. Its influence extended much further offshore than in winter as a result of thermal stratification and higher runoff (Fig. 2B). In 1986, the Changjiang plume was weaker than usual: for example the 30 ‰ isohaline reached only 123° 30′ E in comparison to 125° E in August 1981 (Yu et al. 1983) (Fig. 2B). In the bottom layer, the fresh water influence was limited to the river mouth, while colder and more saline Taiwan Current water intruded from the southeast, matching winter observations.

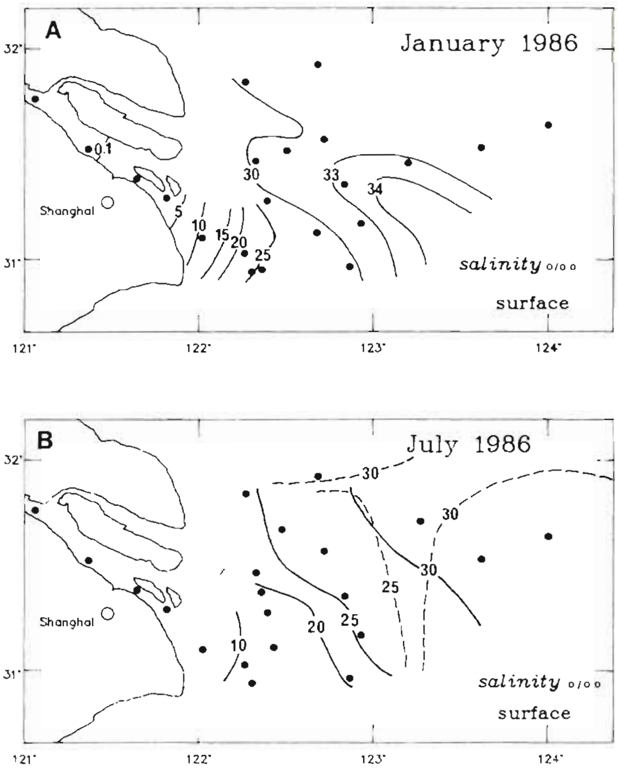

Fig. 2. Surface salinity (‰) in Jan 1986 (A) and Jul 1986 (B). Broken lines: Aug 1981 survey (Yu et al. 1983)

Suspended matter and euphotic depth

The Changjiang brings large quantities of suspended matter into the East China Sea. During the present survey, the average suspended matter concentration in surface was higher in winter (93 mg l^{-1}, Table 1) than in summer (27 mg l^{-1}) despite lower runoff in winter. Maximum concentrations were encountered at the river mouth and then decreased gradually offshore. In winter, the Yellow Sea Coastal Current also carried into the zone particulate matter originating from the Huanghe (Yellow River) located north of the study area, as observed by Milliman et al. (1985). As a result of the decreased suspended load, average euphotic depth increased from 5 m in winter to 12 m in summer (Table 1). In both seasons, the 10 m euphotic depth isopleth corresponded to the 5 mg l^{-1} suspended matter isopleth.

Nutrients

Along with its suspended load the Changjiang carries large quantities of dissolved nutrients. Concentrations decreased gradually in the offshore direction (Table 1), but, in contrast to previous measurements (Edmond et al. 1985), the highest values were not encountered in the river itself but rather at the river

Table 1. Mean (standard deviation) of physical, chemical and biological parameters at the water surface in the Changjiang dilution area in 1986. In July the area was divided into 3 regions according to salinity

	Jan whole area	Jul whole area	Jul river & mouth	Jul dilution zone	Jul far offshore
Number of samples	21	21	13	5	3
Salinity (‰)	0–33	0–34	0–25	25–30	30–34
Temperature	7.7	24.0	25.5	23.2	20.9
(°C)	(2.8)	(1.4)	(1.5)	(1.4)	(1.3)
Surface irradiance $(\mathrm{cal\ cm^{-2}\ d^{-1}})$	228	430			
Suspended matter	93.0	27.4	43.1	2.2	1.5
$(\mathrm{mg\ l^{-1}})$	(13.5)	(39.9)	(42.4)	(0.6)	(0.2)
Euphotic depth	5	12	5	18	32
(m)	(4)	(12)	(6)	(4)	(8)
NO_3-N	8.79	23.03	34.62	6.37	0.54
(µ*M*)	(3.32)	(20.63)	(17.01)	(6.39)	(0.35)
PO_4-P	0.87	0.35	0.50	0.04	0.06
(µ*M*)	(0.28)	(0.43)	(0.36)	(0.00)	(0.10)
Chl *a*	0.23	2.03	1.44	3.44	2.18
$(\mathrm{\mu g\ l^{-1}})$	(0.09)	(1.96)	(0.97)	(3.02)	(2.34)
Cell $\mathrm{ml^{-1}}$					
<10 µm	319	532	669	423	118
	(56)	(375)	(398)	(308)	(92)
>10 µm		142	81	394	83
		(221)	(66)	(427)	(94)
Potential production	0.4	10.6	5.5	24.3	9.8
$(\mathrm{mgC\ m^{-3}\ h^{-1}})$	(0.2)	(12.7)	(3.8)	(19.8)	(10.3)
In situ production	13	674	169	1514	1460
$(\mathrm{mgC\ m^{-2}\ d^{-1}})$	(11)	(899)	(224)	(1145)	(898)
Assimilation number	1.8	5.1	4.1	6.8	4.6
$(\mathrm{mgC\ mgChl^{-1}\ h^{-1}})$	(0.5)	(2.0)	(1.7)	(1.7)	
	(n = 8)	(n = 11)	(n = 6)	(n = 4)	(n = 1)

mouth. In July 1986, high nutrient concentrations spread less further offshore than in a previous survey achieved at the same period of the year (Huang et al. 1983). For example, the 10 µ*M* nitrate isopleth extended to 123° E in July 1986 and to 124° E in August 1981. This was the consequence of a lesser extension of the Changjiang plume in 1986 (Fig. 2 B). In July, a severe phosphate depletion (<0.05 µ*M*) was recorded in the surface at several stations in the dilution zone. Below the thermocline, nutrient concentrations were up to 10 fold higher than in the surface.

Standing stock

Cell concentrations

In winter, the majority of Chl-containing eukaryotic cells were smaller than 10 µm and exhibited a uniform spatial distribution, with concentrations ranging from 10^2 to 10^3 cell $\mathrm{ml^{-1}}$. The highest values were associated with river waters. Among diatoms, the following species dominated: *Melosira varians* Agardh, *M. granulata* (Ehr.) Ralfs, *M. distans* (Ehr.) Ralfs, *M. sulcata* (Ehr.) Cleve, *Skeletonema costatum* (Grev.) Cleve, *Chaetoceros lorenzianus* Grunow, *Rhizosolenia calcaravis* Schultz and *Coscinodiscus* sp.

In summer, cells smaller than 10 µm had a fairly uniform distribution in the surface waters (Table 1) with high concentrations encountered in the river, near its mouth (5×10^3 cell $\mathrm{ml^{-1}}$), and north of the study zone (Station 2). Large cells (>10 µm) were in general less abundant than small cells (Table 1). A significant feature of their distribution was the presence of 2 local maxima (Stations 16 and 5), both attributed to the diatom genus *Chaetoceros*; cell densities reached 800 cells $\mathrm{ml^{-1}}$. Other diatom species included *Skeletonema costatum* (Greville) Cleve, *Thalassionema nitzschioides*

Grunow, *Cyclotella comta* (Ehr.) Kutzing, and *Coscinodiscus* sp. The dinoflagellate *Ceratium fusus* (Ehr.) Dujardin was also abundant. Most of these species are known to be eurythermal and euryhaline (Jin et al. 1965). Below the thermocline, both small and large cells were in general less abundant than in the surface waters.

Chlorophyll *a*

In winter, the average Chl *a* concentration was low (0.23 µg l^{-1} in surface, Table 1). The distribution over the survey area was fairly uniform and the highest values (above 0.30 µg l^{-1}) occurred in the south (Fig. 3 A).

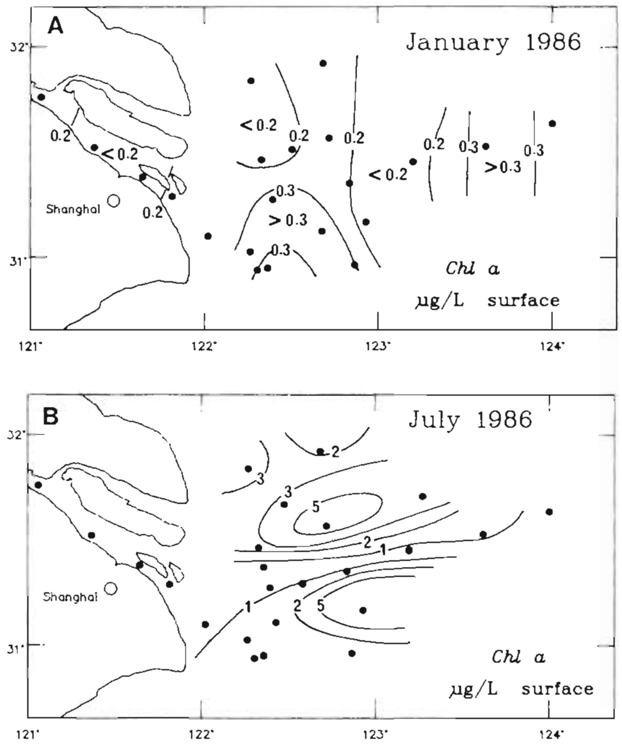

Fig. 3. Chl *a* concentration (µg l^{-1}) in surface in Jan 1986 (A) and Jul 1986 (B)

In summer, the average Chl *a* concentration was 10 times higher than in winter (2.0 µg l^{-1} at surface, Table 1). The lowest values in the surface waters were encountered in the river and its mouth as well as far offshore, while the highest values were found in the middle of the dilution zone in the salinity range 25 to 30 ‰ (Fig. 3 B). Two local maxima (above 6 µg l^{-1}) occurred at Stations 16 and 5 (Fig. 3 B) and corresponded to maxima of the density of large cells. Below the thermocline, average Chl *a* was half the surface value and was more uniformly distributed than in the surface.

Primary production

In winter, primary production was very low and uniform over the study zone with an average potential primary production (PP) of 0.4 mgC m^{-3} h^{-1} at the surface, and an average in situ production of 13 mgC m^{-2} d^{-1} (Table 1). Higher values (> 0.5 mgC m^{-3} h^{-1}) were encountered in the middle of the sampled area and far offshore. In contrast the in situ primary production increased gradually in the offshore direction (Fig. 4 A).

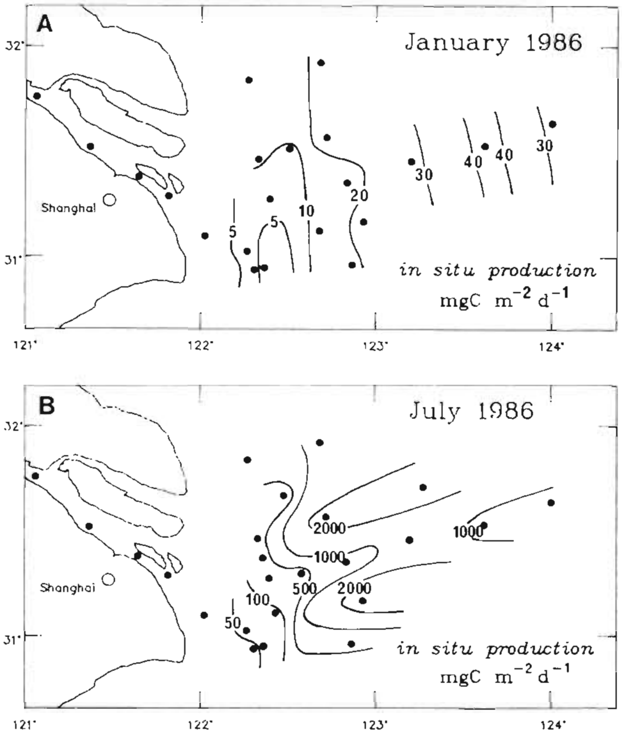

Fig. 4. In situ primary production (mgC m^{-2} d^{-1}) in Jan 1986 (A) and Jul 1986 (B)

Both potential and in situ primary production were an order of magnitude higher in summer than in winter (Table 1). At 2 locations PP exceeded 40 mgC m^{-3} h^{-1} and in situ production 2000 mgC m^{-2} d^{-1} (Fig. 4 B). In the vicinity of the river, both potential and in situ productions decreased sharply. Offshore PP was also very low, but in situ production did not drop as sharply as inshore (Fig. 4 B).

DISCUSSION

Population structure

Photosynthetic plankton populations include a wide variety of organisms with different physiological capabilities, ranging from micron-sized picoplankton cells to 100 µm-long diatom chains. The significance of the smallest form has been recently recognized in oceanic waters (Joint & Pomroy 1983, Platt et al. 1983, Takahashi & Bienfang 1983, Glover et al. 1986) as well as in coastal waters (Berman et al. 1986). In the Changjiang dilution zone, they were also found to be important. At some locations, populations of picoplanktonic cyanobacteria (*Synechococcus* spp.) could reach densities 100 times higher than eukaryotic populations (Vaulot & Ning 1988), and among the latter, from 30 to near 100 % of the cells were smaller than 10 µm in summer. In turbid waters, observations by microscopy revealed that small cells were frequently attached to particulate detritus, as it has been reported in other estuaries (Cloern et al. 1983). This was confirmed by the good correlation found both in winter and summer between cell densities and suspended matter for values of the latter above 10 mg l^{-1} (Fig. 5). For these values, small cell concentration ranges were overlapping between winter and summer, indicating that temperature had little influence on the development of these particle-bound cells. In clearer waters small cell density was undoubtedly independent of suspended load (Fig. 5), and observations indicated that very few small cells were attached to particles.

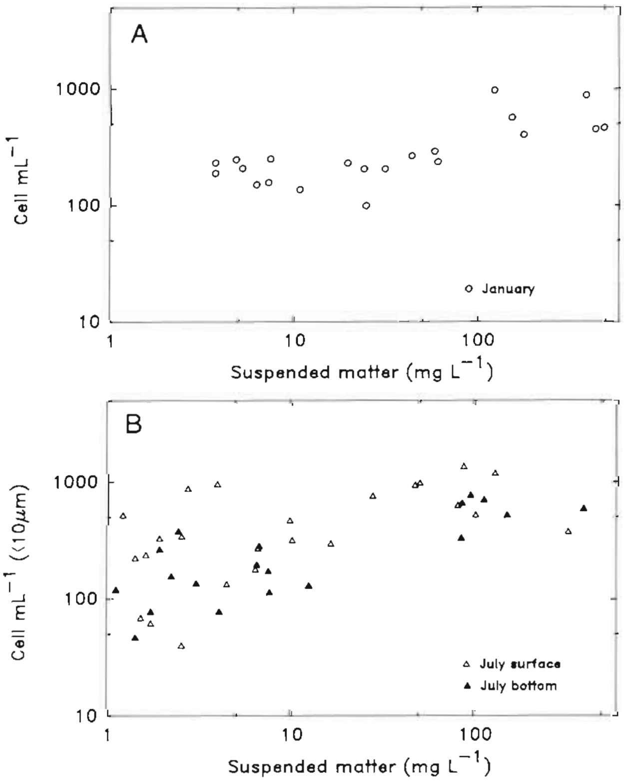

Fig. 5. Density of small (< 10 µm) Chl-containing cell as a function of suspended matter (log-log scale) in Jan 1986 (A) and Jul 1986 (B)

Large cells were only abundant in summer and in a localized region of the dilution zone. However they were most important in the overall production of the zone, since the highest densities of large cells (diatoms *Chaetoceros paradoxus* and *C. lorenzianus* at Stations 16 and 5) corresponded to both Chl *a* and primary production maxima.

Spatial zonation

Estuaries and coastal waters are subjected to numerous influences which include: water mass mixing, tidal and wind-induced currents, and bottom topography. The interplay of these factors results in very complicated spatial patterns of physical and biological variables as observed by remote sensing (Yun & Wan 1982). However in most cases major gradients are recorded in a direction perpendicular to the coast.

In winter, phytoplankton distribution over the region was almost uniform, although weak offshore gradients could be observed for properties such as cell concentration or in situ production (Fig. 4 A). These gradients were a mere consequence of the decreasing suspended matter gradient. In the first case, the decrease in photosynthetic eukaryotes was clearly associated with the decrease in suspended matter (see above) and in the second case, increasing light penetration resulted in increasing the productive part of the water column. The absence of strong phytoplankton gradients is clearly typical of low production periods as observed by Pennock (1985) in the Delaware estuary.

In contrast, a clear zonation was observed in summer (Figs. 3 B, 4 B and 6). For salinities lower than 10 ‰, both Chl *a* and in situ production were very low (Fig. 6). Phytoplankton activity gradually increased for salinities above 10 ‰. Maximum values were reached between 25 to 30 ‰. Coccoid photosynthetic cyanobacteria (*Synechococcus* spp.) were also observed to reach their maximum density (> 10^5 cells ml^{-1}) in this region (Vaulot & Ning 1988). Beyond 30 ‰, phytoplankton variables decreased with salinity (Fig. 6). In summary, the surveyed area could be divided into 3 regions according to salinity: (1) river and its mouth, (2) dilution zone, and (3) offshore zone (Table 1).

In the first region, although nutrients were abundant, high suspended load and strong mixing reduced average light intensity to very low levels which were insufficient for active phytoplankton growth.

In the second region, increase in standing stock and primary production was essentially the result of decreased suspended matter load. In this region, photosynthetic production had a definite impact on oxygen and nutrient concentrations. For example, oxygen saturation in surface reached 140 and 126 % at

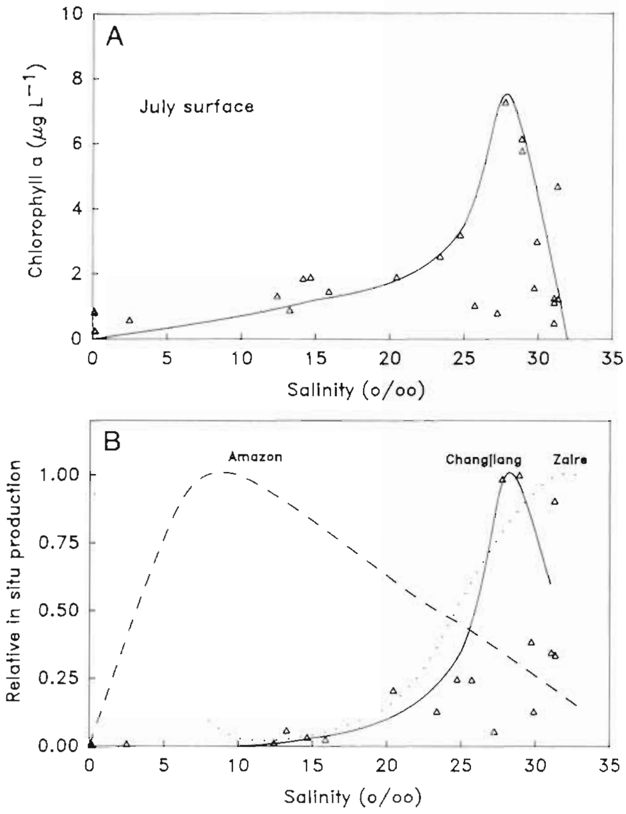

Fig. 6. Surface Chl *a* (A) and in situ primary production normalized to its maximum value in the zone (B) vs salinity in July 1986. Changjiang curves were drawn freehand. Curves for the Amazon (broken line) and the Zaire (dotted) are quoted from Cadée (1978)

Stations 5 and 16 respectively where absolute maxima of standing stock and primary production were recorded (Courties et al. unpubl.). In contrast, oxygen saturation was reduced to less than 75 % below the thermocline. At these stations, phosphates were nearly depleted in surface, while the large nutrient concentrations observed below the thermocline could not diffuse up to the surface layer because of the strong stratification of the water column (Fig. 7). This surface depletion could have indicated that these stations were sampled at the end of a phytoplankton growth phase, when nutrients were becoming limiting. This was corroborated by the large proportion of dead diatoms observed by epifluorescence microscopy: 48 and 26 % at Stations 5 and 16 respectively.

In the third region, both phytoplankton biomass and potential production decreased rapidly most likely because of the lack of nutrients resulting from phytoplankton consumption and river plume dilution. The phenomenon might have been amplified in 1986 since the Changjiang plume was much weaker than usual (see above). Far offshore in situ primary production was still high since the deepening of the euphotic zone compensated the lower potential primary production.

Phytoplankton spatial distributions similar to that observed in the Changjiang dilution zone, with a maximum localized at intermediate salinities, have also been recorded for other large rivers (Fig. 6). The exact localization of the maximum with respect to salinity varies from one estuary to the other: around 10 ‰ in the Amazon (Cadée 1975), between 25 and 30 ‰ in the Changjiang and above 30 ‰ in the Zaire (Cadée 1978). In contrast, maximum standing stock occurs between 10 and 1 mg l^{-1} suspended matter in the Amazon (DeMaster et al. 1986), between 10 and 1 mg l^{-1} in the Zaire (Cadée 1978, Eisma et al. 1978), and between 3 and 2 mg l^{-1} in the Changjiang. Therefore, rather than the increase in salinity, it is the decline of suspended matter between 10 and 1 mg l^{-1} which appears to trigger the biomass maximum in large rivers. This was

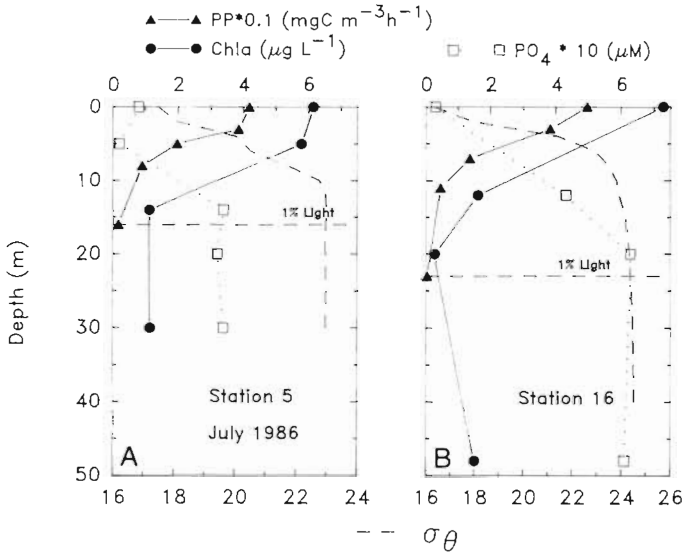

Fig. 7. Depth profiles of density (sigma-t), Chl *a* (µg l^{-1}), PP (mgC m^{-3} h^{-1}), and phosphate (µM) in Jul 1986 at Stations 5 (A) and 16 (B)

noted previously by Edmond et al. (1985). The difference in the location of the maxima with respect to salinity between the Amazon and the 2 other rivers (Fig. 6) is related to the presence of a shoal in front of the Amazon river mouth which results in a rate of sedimentation much faster than the rate of salinity mixing. Therefore more than 95 % of the Amazon terrigenous sediment settles out before salinity reaches 3 ‰ (Milliman et al. 1975). In contrast, suspended matter remains in suspension to much higher salinities in front of the Changjiang and Zaire estuaries, where the seafloor is deeper. At a salinity of 10 ‰, the Amazon plume contains only 1 mg l^{-1} of suspended matter (Milliman & Boyle 1975), the Zaire plume 15 mg l^{-1} (Eisma et al. 1978) and the Changjiang plume more than 50 mg l^{-1}.

The similarity between the Zaire and the Changjiang is strengthened by the fact that, for both rivers, in situ primary production values recorded far offshore were only slightly different from those in the plume (Fig. 6 B). This is in marked contrast with the Amazon, where in situ primary production was one order of magnitude higher in the plume than in the adjacent ocean (Cadée 1975). The presence of a secondary maximum of production in the river itself is observed in the Zaire, but not in the Changjiang nor in the Amazon (Fig. 6 B). Finally, maximum Chl *a* levels in the Changjiang plume (Table 1) compared well with those recorded for the Zaire (5 µg l^{-1}, Cadée 1984), but were clearly below those observed for the Amazon (55 µg l^{-1}, DeMaster et al. 1986) and for medium-sized estuaries (Delaware: 60 µg l^{-1}, Pennock 1985; San Francisco Bay: 50 µg l^{-1}, Wienke & Cloern 1987). However as diatom blooms tend to occur in the spring in the Changjiang dilution zone (Ning et al. unpubl.), peak densities were probably missed by this summer survey. This would explain why diatom densities recorded in the present study were quite low in comparison to other estuaries (e.g. 4×10^3 cell ml^{-1} in the Chesapeake Bay, Marshall & Lacouture 1986).

Light control of primary productivity

As seen previously, light appears to be the most critical of all the factors involved in the regulation of phytoplankton in the Changjiang dilution zone. This corroborates recent observations on estuaries (Cole & Cloern 1984, Harding et al. 1986, Pennock & Sharp 1986). More specifically, Cole & Cloern (1987) have shown that in several medium-sized estuaries euphotic zone production (P) is a linear function of the composite variable $B.I_o.Z_p$, where B = average euphotic zone biomass; I_o = surface irradiance; Z_p = euphotic depth. In the Changjiang estuary, this empirical model held very well (Fig. 8), and in both seasons, the correlation between P and $B.I_o.Z_p$ was highly significant ($p < 0.001$). This suggests that nutrients, which were depleted at some stations (see above), may have limited biomass but not productivity during the summer survey. The model slope (i.e. the productivity) was larger in summer (0.40) than in winter (0.29). Such seasonal variation was also observed in the Delaware estuary (Pennock & Sharp 1986) and in the Bedford Basin (Harrison & Platt 1980). Since the seasonal variation of light is included in the term I_o, the slope modification was a likely consequence of the change in temperature. In comparison to other medium-sized estuaries (Cole & Cloern 1987; Fig 8), Changjiang waters appeared to be less productive. However it should be noted again that maximum biomass and production occur usually in spring (Ning et al. unpubl.), a season which was not sampled in this study

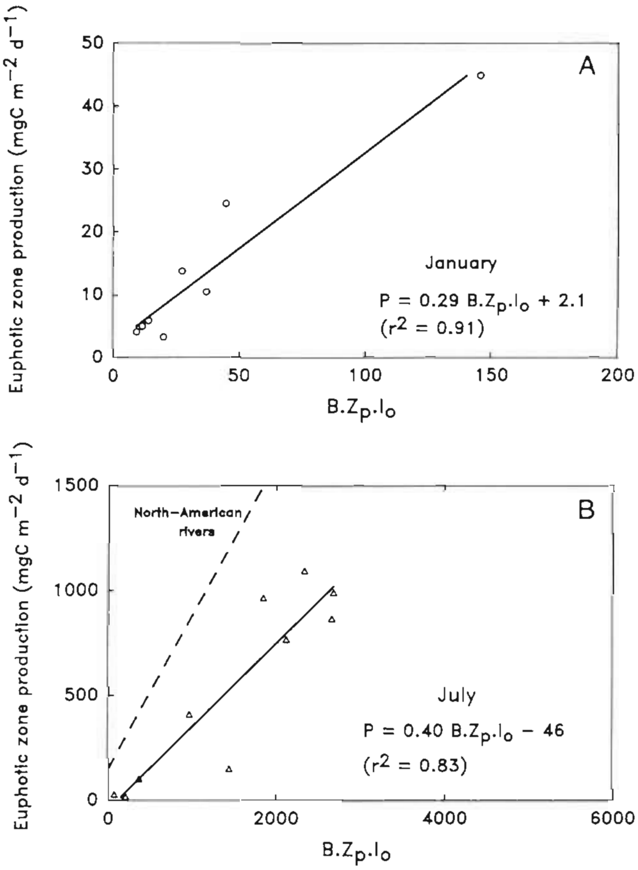

Fig. 8. Euphotic zone production vs $B.Z_p.I_o$, where B = average Chl *a* concentration in the euphotic zone (mg m^{-3}); Z_p = euphotic depth (m); I_o = surface irradiance (E m^{-2} d^{-1}); in Jan 1986 (A), and Jul 1986 (B). Broken line: combined data set of San Francisco Bay, Puget Sound and Hudson river plume (Cole & Cloern 1987)

CONCLUSION

Although the investigated area is subject to a variety of influences from the Changjiang, the Taiwan Current, and the Yellow Sea Current – resulting in very complicated spatial patterns (Yun & Wan 1982) that classical oceanographic ship observations can only imperfectly resolve – the present survey revealed a clear zonation of phytoplankton in summer. Moreover, the established validity of a simple empirical relationship between productivity and light availability could considerably simplify future biological oceanography studies in this zone since photosynthetic production could be computed from surface irradiance, concentrations of chlorophyll, and suspended matter obtained either from shipboard measurements or remote sensing (Cloern 1987); however this would require further validation of the empirical relation on finer spatial and temporal grids than those sampled in the present study.

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