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Species diversity, community structure and distribution of phytoplankton in the Changjiang estuary during dry and flood periods

P.Y. GUO[1], H.T. SHEN[2] AND J.H. WANG[3]

[1]Department of Environmental Science and Engineering, College of Chemical Engineering, Huaqiao University, Xiamen 361021, Fujian, China, [2]State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai, 200062 China, [3]East China Sea Monitoring Center, SOA, Shanghai, 200137 China

This paper reports on the phytoplankton community, its composition, structure and distribution in Changjiang estuary from February 1999 to March 2000. Two hundred and eight species were identified in the dry and flood periods. Diatoms, with 143 species observed, was the most abundant phytoplankton group, accounting for 68.75% of the total phytoplankton species number. Skeletonema costatum *was dominant among all the species. The phytoplankton of Changjiang estuary in China was divided into five ecological categories: freshwater species, estuary brackish water species, inshore low salinity species, inshore widespread species and off-sea high salinity species. During the dry period, the major phytoplankton populations in the surface layer were estuary inshore and offshore populations, distinguished from the composition of the bottom layer. The community structure was similar in the two layers during the flood period. The phytoplankton species diversity was calculated for Simpson, Shannon–Weaver diversity and evenness indices, and found to be higher in the dry period, due to the simple dominant species and low spatial heterogeneity in the flood period. Higher phytoplankton abundance was observed in the surface layer during the flood period. The phytoplankton species distribution, coinciding with the dominant species distribution, varied with salinity, and their abundance correlated significantly with nutrients and light.*

Keywords: Changjiang estuary, phytoplankton, species composition, community structure, diversity

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INTRODUCTION

Estuaries are transition zones between rivers and the sea. The phytoplankton of these important zones is the main source for primary production, and plays a key role in estuary ecosystems via the composition diversity and abundance variation (Yoshiyama & Sharp, 2006; Gonzalez del Rio *et al.*, 2007; Popovich & Marcovecchio, 2008; Costa *et al.*, 2009; Domingues *et al.*, 2011a, b). The basis of all the food webs in estuary ecosystems (Juhl & Murrell, 2005; Lionard *et al.*, 2005; Thompson *et al.*, 2008; Quinlan *et al.*, 2009), some of phytoplankton species occasionally bloom and accumulate into 'red tides', posing a threat to the aquatic ecosystem (Thomas *et al.*, 2005; Badylak *et al.*, 2007; Livingston, 2007; Boyer *et al.*, 2009; Tas *et al.*, 2009; Guinder *et al.*, 2010). Information on the phytoplankton of an estuary is necessary to understand the structure and function of the ecosystem, and to monitor the fisheries resource productivity and water quality.

The Changjiang estuary is one of the largest estuaries in the world. It has formed a large wet, sandy delta with moderate tides, featuring a geomorphological pattern of 'three bifurcations and four outlets'. The Changjiang River Three Gorges Project, damming the river, was implemented in November 1997 and completed in 2009. The phytoplankton community in the Changjiang estuary has been extensively investigated (Guo & Yang, 1992; Gu *et al.*, 1995b; Gao & Song 2005; Zhou *et al.*, 2008; Zhu *et al.*, 2009; Jiang *et al.*, 2010; Li *et al.*, 2010). The present paper outlines a comprehensive analysis of the phytoplankton community of the Changjiang estuary, focusing on its important ecological features.

MATERIALS AND METHODS

Study area and sampling

The Changjiang estuary covers a large portion of Shanghai and a portion of Jiangsu Province. It includes a near-shore zone (the near-shore zone of the East China Sea) (Mikhailov *et al.*, 2001) and a river section, the upper boundary of which is Datong on the main course of the Changjiang River (624 km upstream from the estuary). The morphometric characteristics of this area are: maximum water flow of 9.26×10^7 dm^{3}s^{-1} and minimum of 4.62×10^6dm^{3}s^{-1}, with a mean annual water flow of 2.93×10^7 dm^{3}s^{-1}, and the annual water discharge amountsd to 9.21×10^{14}dm^3. Water discharge is

Corresponding author:
P.Y. Guo
Email: peiyongguo@126.com

highly variable at different times in the Changjiang estuary, with 71.7% of the annual value in the flood period (May–October) and 28.3% in the dry period (November–April). The convergence of near-bottom flow associated with the estuarine circulation maintains the turbidity at a maximum, a typical phenomenon reflecting the settling and resuspension of fine sediment and acting as a filter in the estuary (Shen & Pan, 2001).

Sixteen sampling stations were located in Changjiang estuary between the coordinates 31°00′–31°32′N and 121°21′25″–122°30′E (Figure 1). The stations from SX01 to SX06 were continuous sampling stations. The biological, chemical and hydrological investigations were carried out in February and March 1999 (the dry period), August 1999 (the flood period) and February and March 2000 (the dry period). Quasi synoptic observation for spring–neap tide was conducted at each continuous station. Water flow velocity and direction were simultaneously sampled at 1 h interval for a period of at least 12 h. The sampling interval was reduced to 0.5 h during slack tide, peak flood tide and peak ebb tide. Samples for hydrochemical and chlorophyll-a investigations were collected at surface, medium and bottom layers at different phases during rapid tidal flow. Phytoplankton was collected after tidal fluctuation. Unlike the continuous sampling stations SX01–06, irregular phytoplankton sampling was adopted for the other stations (SX7–14, E1001, *a*).

Phytoplankton acquisition and processing

A qualitative phytoplankton sampler (shallow water type III) was employed for different layers, and the samples were fixed with neutral formaldehyde solution (5% sample volume). The phytoplankton samples for quantitative analysis were prepared according to the specification for oceanographic marine biological survey (GB 12763.6-91) (State Bureau of Technical Supervision of China, 1991). A quantitative phytoplankton sampler was used in the surface layer and the bottom layer to a final volume of 1 dm^3, and the samples were fixed with saturated iodine solution (6–8 ml). The collected samples were brought back to the laboratory for further study. The fixed water samples were concentrated or diluted to an appropriate volume according to the amount of phytoplankton in the samples. The sample was stirred with a sampling tube. The tube was quickly turned upright in the sample and 0.5 ml samples were placed into plankton counting chamber. A cover slip was put on the chamber, then the phytoplankton was identified and counted by microscope. Dinoflagellates and other flagellates were identified by a combination of *in vivo* and fixed water samples. Sediment concentration was estimated by the gravimetric method, and salinity and nutrients were estimated by salinometer and spectrophotometric methods under the specification for marine monitoring (GB17378-1998) (State Bureau of Technical Supervision of China, 1998).

Statistical analysis

DETERMINATION OF DOMINANT SPECIES

The Dominance Index (Y) (Xu *et al.*, 1995), was found using the equation:

$$Y = (n_i/N) \times f_i,$$

where n_i is individual amount of the species organism, N is total individual amount and f_i is occurrence frequency. Dominant species was determined to $>$0.01 significance level.

PHYTOPLANKTON COMMUNITY STRUCTURE

Phytoplanktonic taxa with high frequency of occurrence were included in a cluster analysis. The Pearson correlation

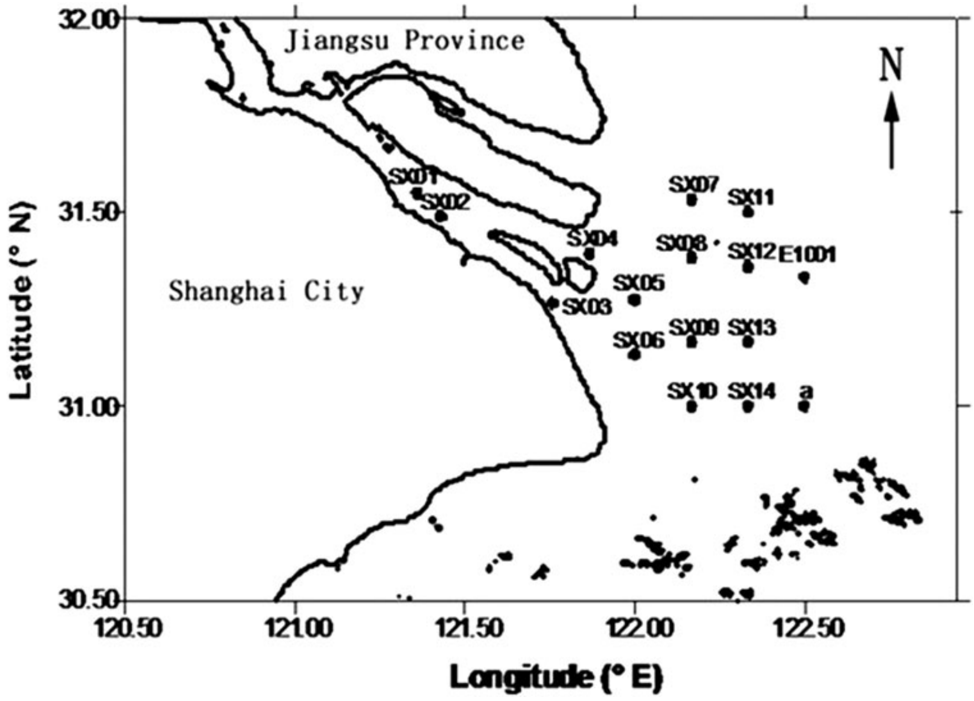

Fig. 1. Hydrographic basin of Changjiang estuary and the location of sampling stations.

coefficient was employed as the distance measure between the group centres (Sneath & Sokal, 1973).

BIODIVERSITY INDEX

The Simpson diversity index (D) (Simpson, 1949), the Shannon–Weaver diversity index (H) (Shannon & Weaver, 1963), and the evenness index (J) (Pielou, 1966), were calculated according to the following equations:

$$D = 1 - \sum_{i=1}^{S} (n_i/N)^2$$

$$H = -\sum_{i=1}^{S} (n_i/N) \log_2 (n_i/N)$$

$$J = \frac{H}{\log_2^S},$$

where N_i is individual amount of the species organism, N is total individual amount and S is total species at any station.

RESULTS

Species diversity and ecotypes of phytoplankton

PHYTOPLANKTON COMPOSITION

In summary, 208 species (varieties included) were recorded in this study, belonging to 109 genera (Table 1). Diatoms was the group with the highest specific richness of 143 species (68.75%), while Chlorophyta were represented by 31 species (14.76%) in 19 genera, and Cyanobacteria contributed 17 species (8.10%) in 14 genera. There were 10 species of Dinoflagellata in six genera, four species of Euglenophyta in three genera, two species (one genus) of Xanthophyta and only one species in Ochrophyta. The diatoms genera with the highest species number were *Chaetoceros* (14 species), *Coscinodiscus* (14 species) and *Thalassiosira* (nine species).

PHYTOPLANKTON ECOTYPES

Judging from the distribution and ecological characteristics of phytoplankton in the Changjiang estuary, the phytoplankton community was divided into the following five ecotypes:

(1) Freshwater species, including *Aulacoseira granulata*, *Fragilaria* sp., *Cymatopleura solea*, *Cyclotella comta*, *Pediastrum simplex* var. *clathratum*, *Monoraphidium griffithii*, *Monactinus simplex*, *Tribonema* sp. and others. Due to the river run-off in the estuary, this ecotype species was observed in waters with a salinity value of <5.

(2) Estuary brackish water species, including *Paralia sulcata*, *Ceratoneis closterium Nitzschia sigma*, *Nitzschia punctata* and others. Highest abundance (2.80×10^3 ind. dm^{-3}) of these species was observed in the bottom layer, compared to the surface layer (1.45×10^3 ind. dm^{-3}) during the flood period in 1999.

(3) Inshore low salinity species, including *Thalassionema frauenfeldii*, *Odontella sinensis*, *Thalassiosira angustelineata*, *Ditylum brightwelli*, *Neoceratium tripos*, *Neoceratium fusus*, *Neoceratium longissimum*, *Chaetoceros*

Table 1. Phytoplankton species collected in the Changjiang estuary during the entire sampling period.

Division	No.	Name of species
Bacillariophyta	1	*Acanthoceras zachariasii* (Brun) Simonsen
	2	*Achnanthes* sp.
	3	*Actinocyclus divisus* (Grunow) Hustedt
	4	*Actinocyclus ehrenbergii* Ralfs
	5	*Actinocyclus* sp.
	6	*Actinoptychus senarius* (Ehrenberg) Ehrenberg
	7	*Actinoptychus* sp.
	8	*Actinoptychus trilingulatus* (Brightwell) Ralfs
	9	*Amphora commutata* Grunow
	10	*Arachnoidiscus ornatus* (Ehrenberg) Ehrenberg
	11	*Asterionella formosa* Hassall
	12	**Asterionella formosa* var. *gracillima* (Hanztsch) Grunow
	13	*Asterionellopsis glacialis*
	14	*Asteromphalus flabellatus* (Brébisson) Greville
	15	*Asteromphalus* sp.
	16	**Aulacoseira granulata* (Ehrenberg) Simonsen
	17	*Azpeitia nodulifera* (A.W.F. Schmidt) G.A. Fryxell & P.A. Sims
	18	*Bacillaria paxillifera* (O.F. Müller) T. Marsson
	19	*Bacteriastrum* sp.
	20	*Bellerochea horologicalis* Stosch
	21	*Biddulphia rhombus* (Ehrenberg) W. Smith
	22	*Biddulphia* sp.
	23	*Cerataulina pelagica* (Cleve) Hendey
	24	*Ceratoneis closterium* Ehrenberg
	25	*Chaetoceros affinis* Lauder
	26	*Chaetoceros borealis* Bail
	27	*Chaetoceros castracanei* Karst
	28	*Chaetoceros constrictus* Gran
	29	*Chaetoceros convolutus* Castr
	30	*Chaetoceros curvisetus* Cleve
	31	*Chaetoceros decipiens* Cleve
	32	*Chaetoceros densus* (Cleve) Cleve
	33	*Chaetoceros denticulatus* H.S. Lauder
	34	*Chaetoceros dichaetus* Ehrenberg
	35	*Chaetoceros didymus* Her
	36	*Chaetoceros lorenzianus* Grunow
	37	*Chaetoceros socialis* f. *radians* (F. Schütt) A.I. Proshkina-Lavrenko
	38	*Chaetoceros* sp.
	39	*Climacosphenia* sp.
	40	*Climacosphenia moniligera* Ehrenberg
	41	*Corethron hystrix* Hensen
	42	*Corethron pennatum* (Grunow) Ostenfeld
	43	*Coscinodiscus argus* Ehrenberg
	44	*Coscinodiscus asteromphalus* Ehrenberg
	45	*Coscinodiscus centralis* Ehrenberg
	46	*Coscinodiscus curvatulus* Grunow ex A. Schmidt
	47	*Coscinodiscus jonesianus* (Greville) Ostenfeld
	48	*Coscinodiscus oculus* Ehrenberg
	49	*Coscinodiscus oculus-iridis* (Ehrenberg) Ehrenberg
	50	**Coscinodiscus radiatus* Ehrenberg
	51	*Coscinodiscus* sp.
	52	*Coscinodiscus spinosus* Chin
	53	*Coscinodiscus subtilis* Ehrenberg
	54	*Coscinodiscus temperei* J. Brun

Continued

Table 1. Continued.

Division	No.	Name of species
	55	*Coscinodiscus thorii*
	56	*Coscinodiscus wailesii* Gran et Angst
	57	*Cyclotella comta* (Ehrenberg) Kützing
	58	*Cyclotella* sp.
	59	*Cymatopleura solea* (Brébisson) W. Smith
	60	*Cymbella* sp.
	61	*Detonula pumila* (Castracane) Gran
	62	*Diploneis bombus* Ehr
	63	*Diploneis* sp.
	64	*Ditylum brightwelli* (West) Grun
	65	*Ditylum sol* (Grunow) De Toni
	66	*Fragilaria capucina* Desmazières
	67	*Fragilaria crotonensis* Kitton
	68	*Fragilaria* sp.
	69	*Gomphonema* sp.
	70	*Grammatophora* sp.
	71	*Guinardia delicatula* (Cleve) Hasle
	72	*Guinardia flaccida* (Castr.) Peragallo
	73	*Gyrosigma* sp.
	74	*Hantzschia amphioxys* (Ehrenberg) Grunow
	75	*Hemiaulus membranaceus* Cleve
	76	*Hemiaulus sinensis* Grev
	77	*Lauderia annulata* Cleve
	78	*Lauderia* sp.
	79	*_Leptocylindrus danicus_ Cleve
	80	*Leptocylindrus mediterraneus* (H. Peragallo) Hasle
	81	*Leptocylindrus* sp.
	82	*Licmophora abbreviata* Agardh
	83	*_Melosira moniliformis_ (O.F. Müller) C. Agardh
	84	*Navicula cryptocephala* Kutz
	85	*Navicula* sp.
	86	*Neocalyptrella robusta* (G. Norman ex Ralfs) Hernández-Becerril & Meave del Castillo
	87	*Nitzschia acicularis* (Kützing) W. Smith
	88	*Nitzschia cursoria* (Donkin) Grunow
	89	*Nitzschia lanceolata* W. Smith
	90	*Nitzschia longissima* (Brébisson) Ralfs
	91	*Nitzschia lorenziana* Grunow
	92	*Nitzschia recta* Hantzsch ex Rabenhorst
	93	*Nitzschia sigma* (Kützing) W. Smith
	94	*Nitzschia* sp.
	95	*Odontella granulata* (Roper) R. Ross
	96	*Odontella mobiliensis* (J.W. Bailey) Grunow
	97	*Odontella regia* (Schultze) Simonsen
	98	*Odontella sinensis* (Greville) Grunow
	99	*_Paralia sulcata_ (Ehrenberg) Cleve
	100	*Pinnularia microstauron* (Ehrenberg) Cleve
	101	*Planktoniella blanda* (A. Schmidt) E.E. Syvertsen & G.R. Hasle
	102	*Pleurosigma formosum* W. Smith
	103	*Pleurosigma normanii* Ralfs
	104	*Pleurosigma pelagicum* Peragallo
	105	*Pleurosigma* sp.
	106	*Pleurosira laevis* (Ehrenberg) Compère
	107	*Porosira glacialis* (Grunow) Jorgensen
	108	*Proboscia alata* (Brightwell) Sundstrom
	109	*Proboscia alata* f. *gracillima* (Brightwell) Sundstrom
	110	*Proboscia indica* (H. Peragallo) Hernández-Becerril
	111	*Pseudo-nitzschia pungens* (Grunow ex Cleve) G.R. Hasle

Continued

Table 1. Continued.

Division	No.	Name of species
	112	*Pseudosolenia calcar-avis* (Schultze) B.G. Sundström
	113	*Rhabdonema arcuatum* (Ag.) Kutz
	114	*Rhizosolenia bergonii* H. Peragallo
	115	*Rhizosolenia crassispina* J.L.B. Schroder
	116	*Rhizosolenia formosa* H. Peragallo
	117	*Rhizosolenia setigera* Brightwell
	118	*Rhizosolenia* sp.
	119	*Rhizosolenia styliformis* T. Brightwell
	120	*_Skeletonema costatum_ (Greville) Cleve
	121	*Stephanodisus* sp.
	122	*Stephanopyxis palmeriana* (Greville) Grunow
	123	*Streptotheca* sp.
	124	*Surirella fastuosa* (Ehrenberg) Ehrenberg
	125	*Surirella* sp.
	126	*Synedra acus* Kützing
	127	*Synedra* sp.
	128	*Synedra ulna* (Nitzsch) Ehrenberg
	129	*Tabellaria* sp.
	130	*Thalassionema frauenfeldii* (Grunow) Tempère & Peragallo
	131	*Thalassionema nitzschioides* Grunow
	132	*Thalassiosira anguste-lineata* (A. Schmidt) G.Fryxell & Hasle
	133	*Thalassiosira eccentrica* (Ehrenberg) Cleve
	134	*Thalassiosira hyalina* (Grunow) Gran
	135	*Thalassiosira leptopus* (Grunow ex Van Heurck) Hasle & G. Fryxell
	136	*Thalassiosira nordenskioeldii* Cleve
	137	*Thalassiosira pacifica* Gran & Angst
	138	*Thalassiosira rotula* Meunier
	139	*Thalassiosira* sp.
	140	*Thalassiosira subtilis* (Ostenfeld) Gran
	141	*Thalassiothrix longissima* Cl. et Grun
	142	*Triceratium favus* Her
	143	*Tryblionella compressa* (J.W. Bailey) M.Poulin
Chlorophyta	144	*Actinastrum hantzschii* Lagerheim
	145	*Acutodesmus dimorphus* (Turpin) Tsarenko
	146	*Acutodesmus obliquus* (Turpin) Hegewald & Hanagata
	147	*Ankistrodesmus falcatus* (Corda) Ralfs
	148	*Closterium macilentum* Brébisson
	149	*Closterium venus* Kützing ex Ralfs
	150	*Cosmarium pyramidatum* Brébisson ex Ralfs
	151	*Cosmarium* sp.
	152	*Desmodesmus magnus* (Meyen) P. Tsarenko
	153	*Desmodesmus opoliensis* (P.G. Richter) E.H. Hegewald
	154	*Desmodesmus perforatus* (Lemmermann) E. Hegewald
	155	*Desmodesmus quadricaudatus* (Turpin) Hegewald
	156	*Gonatozygon monotaenium* De Bary
	157	*Micrasterias* sp.
	158	*Monactinus simplex* (Meyen) Corda
	159	*Monoraphidium contortum* (Thuret) Komàrková-Legnerová
	160	*Monoraphidium griffithii* (Berkeley) Komárková-Legnerová
	161	*Oocystis* sp.
	162	*Parapediastrum biradiatum* (Meyen) E. Hegewald
	163	*Pediastrum simplex* var. *clathratum* Schroter
	164	*Pediastrum* sp.

Continued

Table 1. Continued.

Division	No.	Name of species
	165	*Pleodorina illinoisensis* Kofoid
	166	*Scenedesmus bijuga* Turp
	167	*Scenedesmus* sp.
	168	*Staurastrum arctiscon* (Ehrenberg ex Ralfs) P. Lundell
	169	*Staurastrum paradoxum* Menegh
	170	*Staurastrum* sp.
	171	*Stauridium tetras* (Ehrenberg) E. Hegewald
	172	*Treubaria crassispina* G.M. Smith
	173	*Treubaria triappendiculata* C. Bernard
	174	*Volvox aureus* Ehrenberg
Dinoflagellata	175	*Ceratium hirundinella* (O.F. Müller) Dujardin
	176	*Ceratium* sp.
	177	*Dinophysis* sp.
	178	*Neoceratium furca* (Ehrenberg) F. Gomez, D. Moreira & P. Lopez-Garcia
	179	*Neoceratium fusus* (Ehrenberg) F. Gomez, D. Moreira & P. Lopez-Garcia
	180	*Neoceratium longissimum* (Schroder) F. Gomez, D. Moreira & P. Lopez-Garcia
	181	*Neoceratium tripos* (O.F. Müller) F. Gomez, D. Moreira & P. Lopez-Garcia
	182	*Peridinium* sp.
	183	*Protoperidinium depressum* (Bailey) Balech
	184	*Pyrocystis* sp.
Cyanobacteria	185	*Anabeana* sp.
	186	*Aphanocapsa grevillei* (Hassall) Rabenhorst
	187	*Chroococcus minimus* (Keissler) Lemmermann
	188	*Dolichospermum spiroides* (Kleb.) Wacklin, L. Hoffm. & Komárek
	189	*Leptolyngbya tenuis* (Gomont) Anagnostidis & Komárek
	190	*Limnococcus limneticus* (Lemmermann) Komárková, Jezberová, O. Komárek & Zapomelová
	191	*Merismopedia punctata* Meyen
	192	*Merismopedia* sp.
	193	*Microcystis* sp.
	194	*Monoraphidium griffithii* (Berkeley) Komárková-Legnerová
	195	*Oscillatoria* sp.
	196	*Oscillatoria tenuis* C. Agardh ex Gomont
	197	*Phormidium* sp.
	198	*Raphidiopsis curvata* Frisch et Rich
	199	*Spirulina princeps* West & G.S. West
	200	*Trichodesmium* sp.
	201	*Trichodesmium thiebautii* Gomont
Euglenophyta	202	*Euglena* sp.
	203	*Euglena wangi* Chu
	204	*Lepocinclis tripteris* (Dujardin) Marin & Melkonian
	205	*Phacus longicauda* (Ehr.) Duj
Xanthophyta	206	*Tribonema* sp.
	207	*Tribonema viride* Pascher
Ochrophyta	208	*Dictyocha speculum* Ehrenberg

*, Dominant species

castracanei, *Chaetoceros denticulatus*, *Actinoptychus trilingulatus*, *Bellerochea malleus* and others.

(4) Inshore widespread species, including *Skeletonema costatum*, *Rhizosolenia setigera*, *Thalassionema nitzschioides* and others. *Skeletonema costatum* was the dominant species during all the periods for all the sampling stations, with a minimum 45.21% of the whole phytoplankton abundance in the dry period.

(5) Off-sea high salinity species, including *Neocalyptrella robusta*, *Pseudosolenia calcar-avis*, *Chaetoceros lorenzianus*, *Proboscia alata*, *Thalassiosira subtilis*, *Rhizosolenia styliformis* and others. *Neocalyptrella robusta* and *Pseudosolenia calcar-avis* were widespread species.

Phytoplankton community structure

The classification for the phytoplankton community (Figure 2A–F) was produced using cluster analysis. During the dry period in 1999, there was no significant difference in community structure among the sampling stations SX01–SX14, with *a*, SX12, E1001 stations as the exceptions (Figure 2A). Thus, phytoplankton in the surface layer in the dry period can be generally classified into estuary inshore and offshore populations. Community structure in the bottom layer is distinguished from that in the surface layer over the same time scale (Figure 2B). The whole phytoplankton community structure fell into two major groups. Based on high similarity, SX05, SX08, SX09, SX12, SX13, SX14 and *a* sampling stations were considered as one group, whilst the rest fell into the other group. During the flood period in 1999, the population structures of the two layers were different in only three stations: SX01, SX02 and SX04 (Figure 2C, D), consisted of estuary, inshore and offshore populations. This may have resulted from the within river estuary locations of these stations. The river run-off was obviously increased during the flood period, leading to relatively lower salinity. Therefore, more freshwater species in waters affected by the run-off resulted in the inshore and offshore population difference. For the dry period in 2000, the population structure of the surface layer (Figure 2E) was similar to that of 1999, and there was no significant difference in community structure among the sampling stations, with the exceptions of *a* and E1001. Moreover, community structure of the bottom layer in 2000 was distinguished from that of the surface layer (Figure 2F), coinciding with that in 1999. Notably, only sampling stations SX01–SX03 in the estuary and sampling station E1001 offshore were different, suggesting that the bottom layer in the estuary was composed of the estuary low salinity ecotype represented by freshwater and low-salinity phytoplankton.

Analysis of the biodiversity

PHYTOPLANKTON PERIOD CHANGE

The phytoplankton biomass was most abundant in the flood period in 1999, with 142 species observed, including 85 diatoms, 26 Chlorophyta, 16 Cyanobacteria, nine Dinoflagellata, three Euglenophyta, two Xanthophyta and one Ochrophyta. There were only 86 phytoplankton species in the dry period of 1999, with 81 diatoms, two Chlorophyta, two Dinoflagellata and one Cyanobacteria. During the dry period in 2000, 116 species were found: 85 diatoms, 15 Chlorophyta, six Dinoflagellata, three Euglenophyta, seven Cyanobacteria. Xanthophyceae and Chrysophyceae were only present in August, 1999.

SPECIES DIVERSITY

Overall, the Simpson index (*D*) coincided with Shannon–Weaver index (*H*) for the phytoplankton community in the

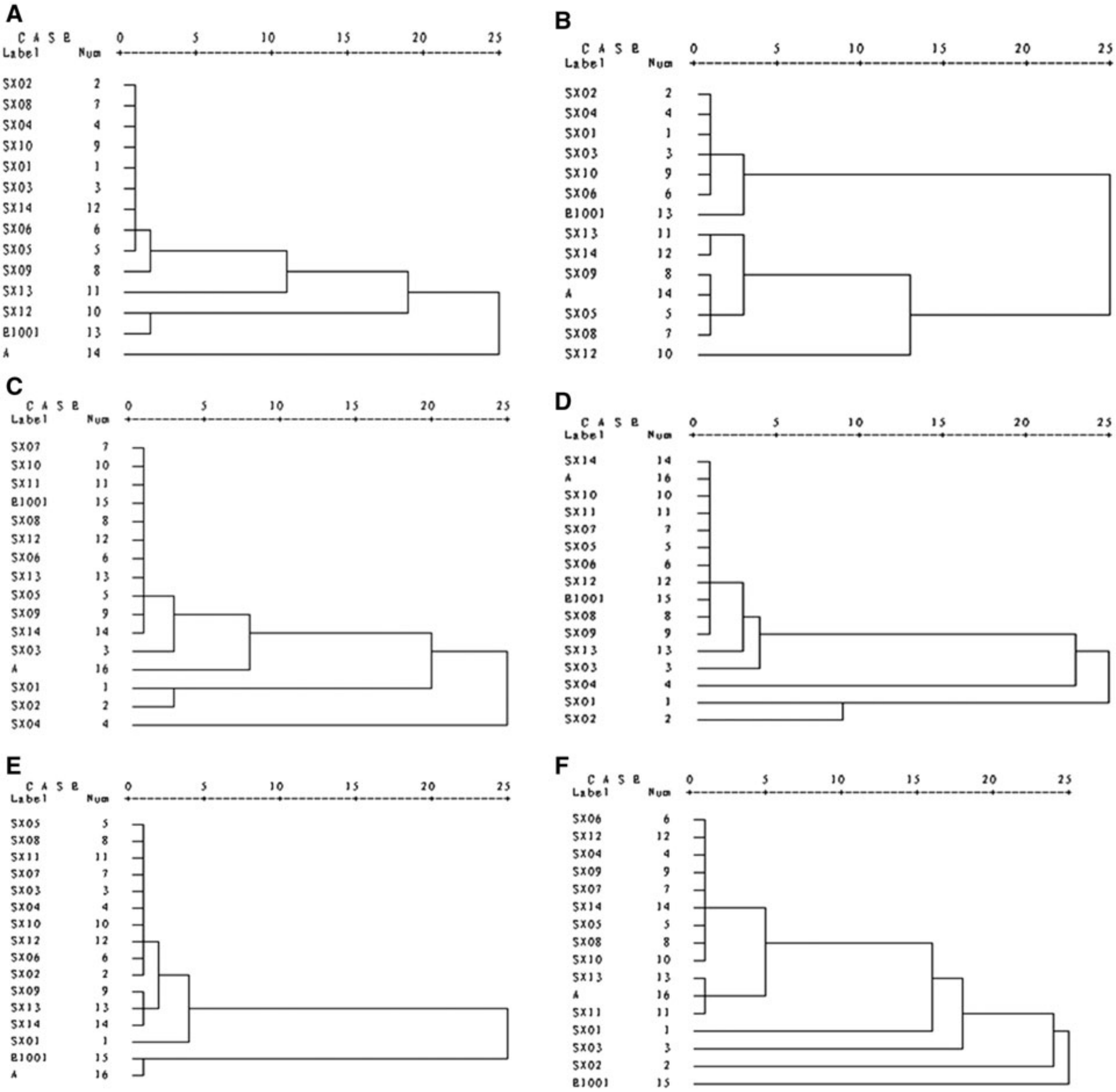

Fig. 2. Dendrogram of phytoplankton in the Changjiang estuary during dry and flood periods: (A) during the dry period in 1999 in the surface layer; (B) during the dry period in 1999 in the bottom layer; (C) during the flood period in 1999 in the surface layer; (D) during the flood period in 1999 in the bottom layer; (E) during the dry period in 2000 in the surface layer; and (F) during the dry period in 2000 in the bottom layer.

Changjiang estuary (Table 2). Highest values of the diversity indices (*D* and *H*), evenness index (*J*), and spatial heterogeneity were in the dry period of 1999, with 48 and 44 species present in the surface and bottom layers, respectively, and 4–5 dominant species for both layers. The dominance of *Skeletonema costatum* in the surface and bottom layer varied between 62.99% and 54.58%, coupled with *Paralia sulcata* between 10.22% and 19.77%. For the flood period in 1999, 68 and 45 species were observed in the surface and bottom layers, respectively, with *Skeletonema costatum* (91.28% and 93.66%, respectively) and *Aulacoseira granulata* (2.83% and 4.12%, respectively) as the dominant species. For the dry period in 2000, there were 49 species in the surface layer and *Skeletonema costatum* and *Paralia sulcata* were the dominant species. Algae abundance was relative and restricted to *Skeletonema costatum* (87.61%). However, higher diversity (0.7446, 2.8681) and evenness (0.5222) registered in the bottom layer, compared with the values in the surface layer (0.2296, 0.9677 and 0.1724). *Skeletonema costatum* accounted for 45.12% of the total abundance, along with other three dominant species.

Table 2. Diversity Index and Evenness Index of phytoplankton in the Changjiang estuary.

Season	Layer	Simpson index (*D*)	Shannon–Weaver index (*H*)	Evenness index (*J*)
Dry period 1999	Surface	0.5863	2.3868	0.4274
	Bottom	0.6569	2.5141	0.4605
Flood period 1999	Surface	0.1652	0.7121	0.1170
	Bottom	0.1219	0.5365	0.0977
Dry period 2000	Surface	0.2296	0.9677	0.1724
	Bottom	0.7446	2.8681	0.5222

Quantitative distribution

PHYTOPLANKTON DISTRIBUTION

The salinity and nutrients in the Changjiang estuary during the dry periods in 1999 are shown in Table 3. The phytoplankton abundance in the surface layer decreased from the estuary (38.17 × 10^3 ind. dm^{-3}) to the offshore during the dry period in 1999, with the highest density area (20.64 × 10^3 ind. dm^{-3}) at the south near-shore SX10 sampling station and lowest density area (15.44 × 10^3 ind. dm^{-3}) at the SX12 sampling station (Figure 3A). Higher abundance in the estuary was also observed in the bottom layer (Figure 3B), highest at the SX02 sampling station (40.47 × 10^3 ind. dm^{-3}) and decreased offshore. At the SX09 and SX10 stations the phytoplankton was distributed unevenly, with high density (17.09 × 10^3 ind. dm^{-3}) and low density (4.17 × 10^3 ind. dm^{-3}) areas.

For the surface layer in the flood period in 1999, abundance was lower in the estuary and offshore area (Figure 3C), reaching 65.90 × 10^3 and 56.65 × 10^3 ind. dm^{-3} at estuary locations SX03 and SX04, and 33.20 × 10^3 ind. dm^{-3} at the offshore *a* sampling station. Two concentrated areas emerged in the inshore region: SX06 (1277.88 × 10^3 ind. dm^{-3} and SX08 (757.70 × 10^3 ind. dm^{-3}). The general observation of the bottom layer was similar to the results from the surface, (Figure 3D). Sampling stations SX05 and SX06 in the estuary formed a concentrated area, with 237.15 × 10^3 ind. dm^{-3} and 294.45 × 10^3 ind. dm^{-3}, respectively. Highest concentration was located at the SX11 (785.81 × 10^3 ind. dm^{-3}) and SX12 (674.20 × 10^3 ind. dm^{-3}) stations. Sampling station *a* only obtained a value of 6.80 × 10^3 ind. dm^{-3}.

For the surface layer in the dry period in 2000 (Figure 3E), the SX11 sampling station (611.0 × 10^3 ind. dm^{-3}) on the north coast of the inshore was the highest concentration area. The other stations varied from 8.9 × 10^3 to 55.3 × 10^3 ind. dm^{-3}. For the bottom layer (Figure 3F), estuary and offshore had the highest abundance, with the highest amount of 46.90 × 10^3 ind. dm^{-3} at station SX01. In the inshore area, SX10 was as low as 2.45 × 10^{3}ind. dm^{-3}, and the only concentrated region was located at SX08 (20.6 × 10^3 ind. dm^{-3}).

Notably, some species can predominate in some local waters. During the dry period in 1999, *Aulacoseira granulata* accounted for 2.26% and 2.09% in the surface and bottom layers, respectively. In the surface layers of SX06 and SX08 sampling stations, this species can reach 1.03 × 10^3 and 2.2 × 10^3 ind. dm^{-3}, respectively. In the surface layers of SX10, SX13 and SX14 sampling stations, it was 1.23 × 10^3, 1.54 × 10^3 and 1.39 × 10^3 ind. dm^{-3}, respectively. During the dry period in 2000, *Asterionella formosa* var. *gracillima* accounted for 3.26% in the surface layer, with 16.00 × 10^3 and 13.20 × 10^3 ind. dm^{-3} at SX01 and SX02 sampling stations, respectively. At SX01 sampling station, 5.40 × 10^3 ind. dm^{-3} and 10.80 × 10^3 Ind. dm^{-3} were observed for *Synedra* sp. (3.13%) and Cyanobacteria (6.70%). During the flood period in 1999, *Trichodesmium thiebautii* accounted for 2.32% and 1.08% in surface and bottom layers, respectively, with 30.00 × 10^3, 20.00 × 10^3 and 27.70 × 10^{3}ind. dm^{-3} at SX04, SX05 and SX14 sampling stations, respectively.

DOMINANT SPECIES DISTRIBUTION

Inferred from the Dominance Index (Y) for the dominant phytoplankton species (Table 4), diatoms had the greatest species richness in both the dry and flood periods. They were mainly freshwater species, estuary brackish water species and inshore widespread species. *Skeletonema costatum* was dominant in the surface and bottom layers, accounting for up to 90% of the total phytoplankton abundance during the flood period.

The dry period in 1999

The following results are based on the analysis of the dominant species *Paralia sulcata* and *Skeletonema costatum*. *Paralia sulcata* formed two concentrated areas close together in the inshore and offshore regions: one was centred on SX09 (4.05 × 10^3 ind. dm^{-3}) and the other on SX12 (5.9 × 10^3 ind. dm^{-3}) and E1001 (4.50 × 10^3 ind. dm^{-3}) (Figure 4A). The abundance of *Skeletonema costatum* decreased from estuary to the offshore (Figure 4B), similar to the previous results for total abundance in the surface layer (Figure 3A). The concentrated areas were located at estuary station SX01 (34.31 × 10^3 ind. dm^{-3}) and inshore station SX10 (16.12 × 10^3 ind. dm^{-3}), respectively.

Table 3. Salinity and nutrients in the Changjiang estuary during the dry periods in 1999.

Sampling station	Surface layer			Bottom layer		
	Salinity	TIN(mg/dm^3)	PO$_4$-P(mg/dm^3)	Salinity	TIN(mg/dm^3)	PO$_4$-P(mg/dm^3)
SX01	1.87	1.841	0.0336	1.979	1.962	0.0325
SX02	2.05	2.01	0.0369	2.117	2.28	0.034
SX03	2.23	2.41	0.0418	3.857	2.169	0.037
SX04	3.61	1.83	0.0273	7.689	1.924	0.026
SX05	13.57	1.36	0.0215	15.56	1.362	0.02
SX06	20.04	1.21	0.023	21.026	1.364	0.022
SX07	/	/	/	/	/	/
SX08	21.437	1.47	0.022	26.539	0.842	0.031
SX09	22.135	0.8	0.018	25.322	0.539	0.014
SX10	21.873	1.13	0.018	25.894	1.032	0.017
SX11	/	/	/	/	/	/
SX12	26.322	0.42	0.015	30.735	0.376	0.018
SX13	25.034	0.53	0.013	29.254	0.84	0.011
SX14	25.752	0.78	0.02	29.788	0.989	0.0175
E1001	29.528	0.39	0.014	33.367	0.214	0.01
a	29.787	0.45	0.017	30.562	0.656	0.012

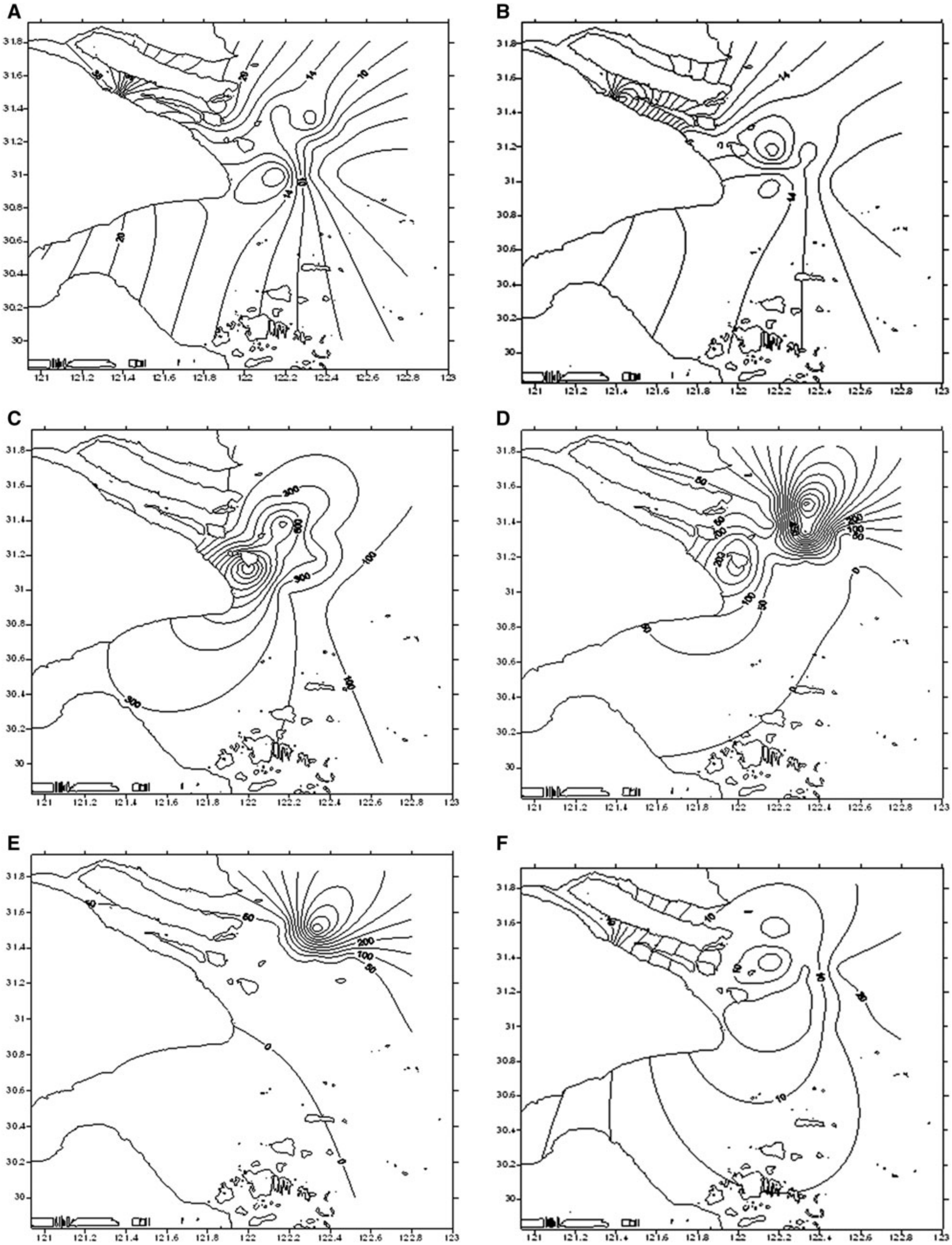

Fig. 3. The distribution of phytoplankton in the Changjiang estuary during dry and flood periods: (A) during the dry period in 1999 in the surface layer; (B) during the dry period in 1999 in the bottom layer; (C) during the flood period in 1999 in the surface layer; (D) during the flood period in 1999 in the bottom layer; (E) during the dry period in 2000 in the surface layer; and (F) during the dry period in 2000 in the bottom layer.

Table 4. Dominant species of phytoplankton in the Changjiang estuary.

Season	Layer	Dominant species	% of total	Dominance
Dry period in 1999	Surface	*Skeletonema costatum*	62.99	0.4949
		Paralia sulcata	10.22	0.0657
		Leptocylindrus danicus	5.23	0.0336
		Melosira moniliformis	4.09	0.0117
	Bottom	*Skeletonema costatum*	54.58	0.3899
		Paralia sulcata	19.77	0.1977
		Melosira moniliformis	5.77	0.0165
		Leptocylindrus danicus	2.93	0.0126
		Coscinodiscus radiatus	1.75	0.0138
Flood period in 1999	Surface	*Skeletonema costatum*	91.28	0.8558
		Aulacoseira granulata	2.83	0.0242
	Bottom	*Skeletonema costatum*	93.66	0.819
		Aulacoseira granulata	2.74	0.0176
Dry period in 2000	Surface	*Skeletonema costatum*	87.61	0.8761
		Paralia sulcata	4.12	0.0258
	Bottom	*Skeletonema costatum*	45.21	0.4521
		Paralia sulcata	18.39	0.0805
		Asterionella formosa var. *gracillima*	8.82	0.0220
		Aulacoseira granulata	5.58	0.0105

In the bottom layer (Figure 4C), among the three concentrated regions observed for *Paralia sulcata*, the inshore region centred around stations SX05 and SX08 contributed to the concentrated region found in Figure 3B. There was a decrease from the estuary to the offshore for *Skeletonema costatum* (Figure 4D).

The flood period in 1999

The distribution pattern for *Skeletonema costatum* was observed for this period. The two concentrated areas for the surface layers at the inshore stations SX06 (1260.38 × 10^{3}ind. dm^{-3}) and SX08 (740.30 × 10^3 ind. dm^{-3}) represented 98.63% and 97.70%, respectively (Figure 4E). The two concentrated areas for the bottom layers were around SX05 and SX06 (229.28 × 10^3 289.23 × 10^3 ind. dm^{-3}, respectively) and SX11 and SX12 (784.60 × 10^3 and 664.60 × 10^3 ind. dm^{-3}, respectively) (Figure 4F).

The dry period in 2000

There were no *Paralia sulcata* in the surface layer in the estuary, but an increase was observed from the inshore to offshore (Figure 4G). *Skeletonema costatum* was abundant in the north inshore (Figure 4H), especially at the SX11 sampling station (606.20 × 10^3 ind. dm^{-3}), probably resulting in the concentrated area in Figure 3E.

For the bottom layer, *Paralia sulcata* increased from the estuary moving offshore, reaching 14.70 × 10^{3}ind. dm^{-3} at the offshore E1001 station (Figure 4I). The species accounted for 66.82% of the total abundance, having an major influence on the distribution of Figure 3F. *Skeletonema costatum* decreased as *Paralia sulcata* increased (Figure 4J). *Skeletonema costatum* formed concentrated areas, with different densities in the estuary and inshore regions, leading to the distribution pattern in Figure 3F.

In summary, the distribution for the two layers in the different period was mainly determined by the distribution of the dominant species.

DISCUSSION

Zhu *et al.* (2009) investigated the phytoplankton community in the Changjiang estuary. Results indicated that in spring diatoms and chlorophytes contribute equally to phytoplankton biomass, while phytoplankton community structure is mainly composed of diatoms in the summer. A comparative study analysing the shift of phytoplankton composition from the mid-1980s to the 2000s was also made in the Changjiang estuary. The proportion of diatoms in the whole phytoplankton community showed a decreasing trend from about 85% in 1984 to about 60% in 2000 (Zhou *et al.*, 2008) and from 84.6% during 1985–1986 to 69.8% during 2004–2005 (Jiang *et al.*, 2010). Gao *et al.* (2005) examined phytoplankton taxonomic composition, abundance, diurnal variability and spatial distribution in the Changjiang estuary from 19 to 26 May 2003. Eighty-seven species, including 54 species of diatoms were identified. Correlation between phosphorus and abundance supported the conclusion that phosphorus is the controlling factor in phytoplankton growth in the Changjiang estuary, where light is not limiting. However, there is only limited long-term ecological data, especially from the period before the completion of the Three Gorges Project completion. Such a study, emphasizing the influences of human activities is a prerequisite for improving the estuarine ecosystem and its response to environmental stress. There are 35 species simultaneously found in our three surveys, including 33 diatoms, together with *Pediastrum simplex* var. *clathratum* (Chlorophyceae) and *Neoceratium fusus* (Dinophyceae). The diatoms with the highest number of species were also observed in the studies of the Buragauranga estuary (Ahmed *et al.*, 2010), the Tagus estuary (Gameiro & Brotas, 2010), the Pearl River estuary (Qiu *et al.*, 2010), the Mahanadi estuary (Naik *et al.*, 2009) and the Karstic Zrmanja estuary (Buric *et al.*, 2007), with different phytoplankton compositions and relative proportions. Dominant species for the Changjiang estuary in 1999 and 2000 were different from the previous report in 1988 (Gu *et al.*, 1995a, b). *Pseudo-nitzschia pungens*, *Neocalyptrella robusta*, *Chaetoceros lorenzianus* and *Pseudosolenia calcar-avis* were dominant species in 1988, but less observed in 1999 and 2000. *Eucampia zoodiacus* was dominant during 1988, but was absent during this study. It is concluded that the phytoplankton community changed during the intervening ten years, reflecting the variation of aquatic environmental factors. The dominance of *Skeletonema costatum* was similar to the results in 1996 and 1997 (Xu *et al.*, 1999), but the other dominant species, *Oscillatoria* and *Cosmarium*, decreased significantly in this study. A higher diversity index and evenness index appeared in the dry period because of the simple dominant species composition in the flood period. Moreover, during the flood period, *Skeletonema costatum* showed an overwhelming dominance and was crucial to the population structure. *Skeletonema costatum* was also the dominant species in other estuaries. Thompson *et al.* (2008) investigated diatom abundance in the microtidal, salt wedge Huon estuary in Tasmania. Diatoms dominated the spring bloom, when *Skeletonema costatum* had the highest net growth rates, and fucoxanthin-specific gross growth rates were similar to 0.9 d (−1). Seasonal changes in the diatoms was examined in the neritic zone of the Urdaibai estuary (northern Spain). Cell

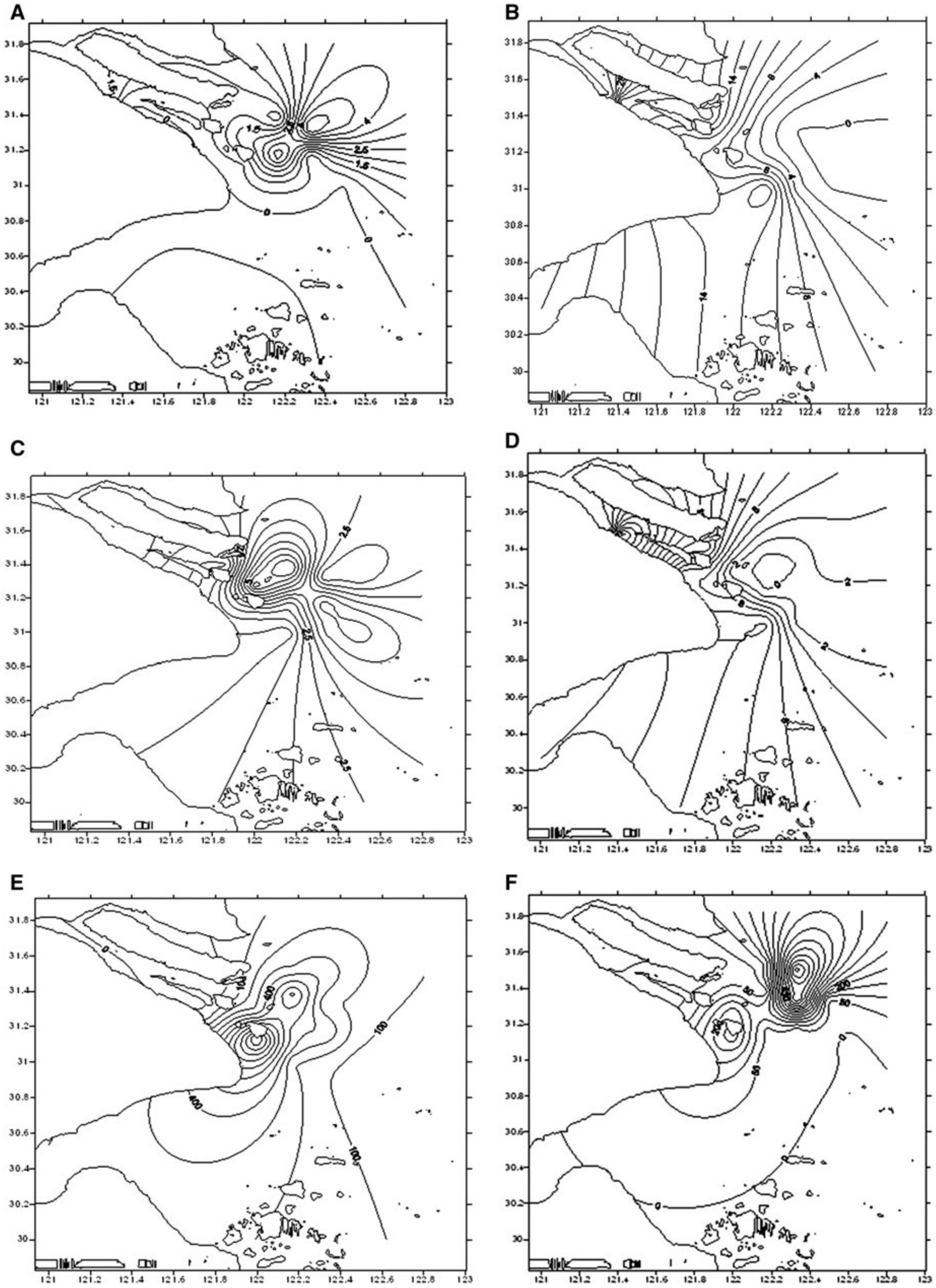

Fig. 4. The distribution of dominant species of phytoplankton in the Changjiang estuary during dry and flood periods: (A) *Paralia sulcata* (the dry period in 1999 in the surface layer); (B) *Skeletonema costatum* (the dry period in 1999 in the surface layer); (C) *Paralia sulcata* (the dry period in 1999 in the bottom layer); (D) *Skeletonema costatum* (the dry period in 1999 in the bottom layer); (E) *Skeletonema costatum* (the flood period in 1999 in the surface layer). The distribution of dominant species of phytoplankton in the Changjiang estuary during dry and flood periods: (F) *Skeletonema costatum* (the flood period in 1999 in the bottom layer).

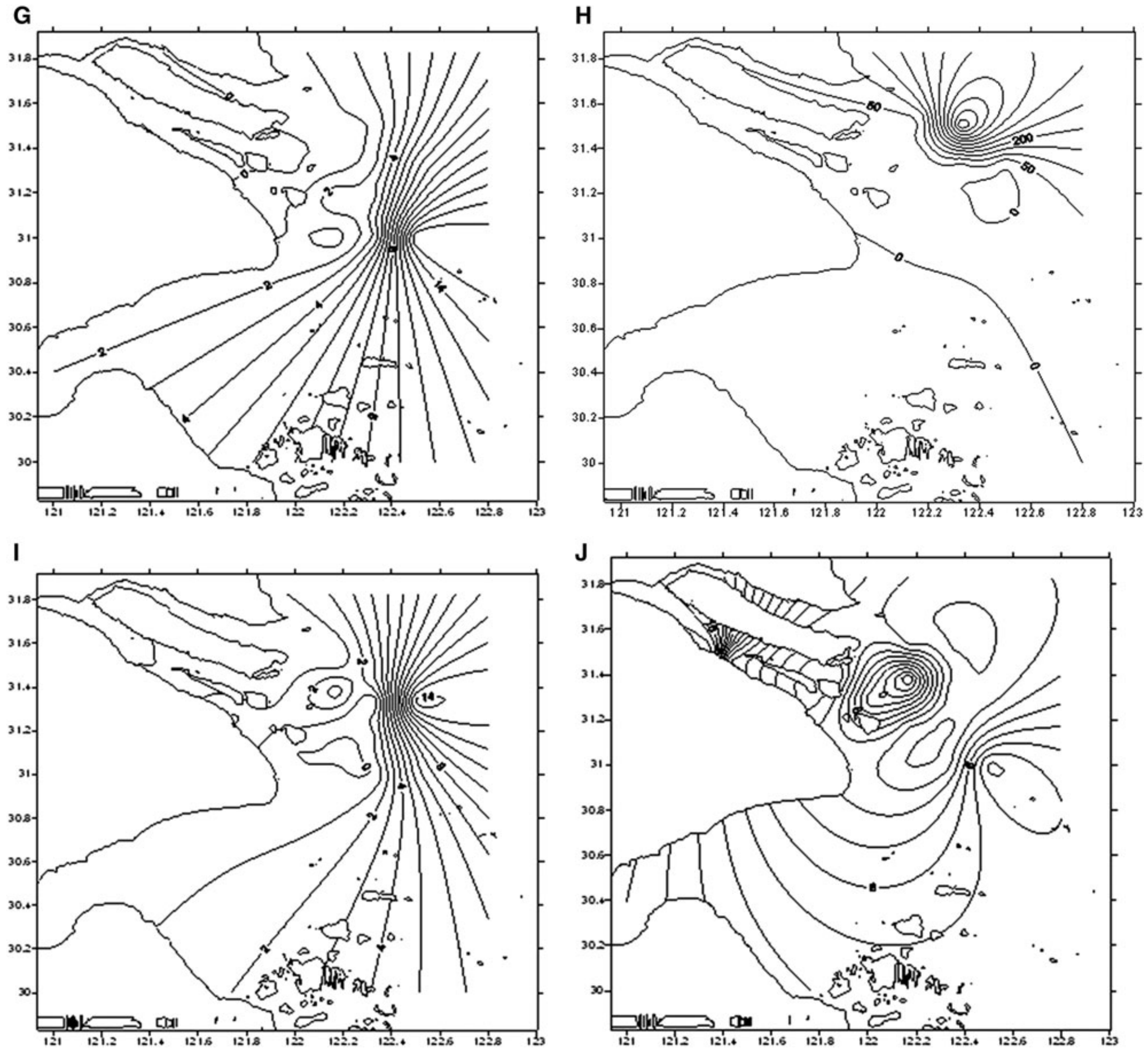

Fig. 4. continued. (G) *Paralia sulcata* (the dry period in 2000 in the surface layer); (H) *Skeletonema costatum* (the dry period in 2000 in the surface layer); (I) *Paralia sulcata* (the dry period in 2000 in the bottom layer); (J) *Skeletonema costatum* (the dry period in 2000 in the bottom layer).

maxima in late summer were produced by the diatoms *Chaetoceros salsugineum* and *Skeletonema costatum* (Trigueros & Orive, 2001).

Among all the ecotypes, the freshwater ecotype *Aulacoseira granulata* was one of the most abundant species during the flood period in 1999. The species covered the 122°20′E at sampling station SX14, with the observation of 9.08×10^3 and 4.10×10^3 ind. dm^{-3} in the surface and bottom layers, respectively. As one of the dominant phytoplankton in the dry period, the centric diatom *Paralia sulcata* is a typical species of brackish and marine waters, and at the sampling stations *a* and E1001 showed a relatively wide distribution. *Paralia sulcata* also was one of the most common and dominant at all stations in both water column and surface sediment in the Akkeshi-ko estuary, eastern part of Hokkaido, Japan (Kasim *et al.*, 2006). Inshore low salinity species was in the east of the 122°10′E, found during all the periods with low quantity. Although there were few tropical coastal low-salinity species, but it indicated the influence of the warm current on the Changjiang estuary. A small quantity of the coastal cold water species *Thalassiosira nordenskioeldii* (0.6×10^3ind. dm^{-3}) was restricted to the SX12 station during the dry period in 2000. The inshore widespread species *Skeletonema costatum* had a dominance of over 90% in the two layers during the flood period. The off-sea high salinity species *Neocalyptrella robusta* extended as far as the SX03 station, suggesting its adaptability to the low-salinity waters. In 1999, the run-off of the Changjiang River had a considerable effect on the population structure during the flood period. And during the dry period in 1999, the population in the near-shore region was mainly composed of estuary and inshore species, while the offshore region was mainly high-salinity species. The inshore population is found at the mouth of the Changjiang River. High turbidity due to suspended sediment in the bottom layer contributes to the difference between this area and its surroundings, as well as the difference in the phytoplankton composition. During the dry period in 2000, phytoplankton of the surface layer was divided into estuary inshore and offshore populations.

Vertically, during the flood period in 1999, phytoplankton abundance was higher in the surface of the estuary and inshore than in the bottom layer, but lower in the surface of the offshore region. Overall, the abundance difference between the two layers amounted to 1–3 times, with a maximum of 5 times. As one of the dominant species, *Paralia sulcata* made a slight contribution to the concentrated area in the surface layer of the near-shore, but showed a significant influence on the small concentrated area around station SX12. Moreover, it was the major contributor for the two concentrated regions in the surface layers in the same areas (Figure 3A). In the bottom layer, *Paralia sulcata* appeared a plaque distribution. It is clear that the concentrated area of phytoplankton in the estuary (Figure 3B) results from the dominant species *Skeletonema costatum*. Higher phytoplankton abundance was observed in the two layers during the flood period in 1999, compared with that during the dry period. The maximum abundance for the surface layer in the flood period was nearly 40 times greater than the minimum. In general, the surface layers possess higher abundance than the bottom layers, with the exceptions of stations SX11 and SX12. This may be due to the salinity stratification in the estuary in the flood period, with lower salinity in the surface. During this period in 1999, the concentration in the surface layer (Figure 3C) was mainly formed by *Skeletonema costatum*, which also determined the quantity distribution in the bottom layer (Figure 3D). For the dry period in 2000, the surface layers had higher abundance than the bottom layers. However, for the dry period in 1999, the abundance was similar in the two layers, but the quantity in the surface layer at all sampling station was lower, with SX11 as the only exception. Thus, phytoplankton abundance was usually higher in the flood period for the two layers, and the surface layer was higher than the bottom layer for all the periods.

As the primary producer, the distribution and change of phytoplankton affects higher forms of life through the food web. Phytoplankton distribution and change have a close correlation with environmental factors and indicate variations in the estuary water environments. Sunlight is the main photosynthesis driver of phytoplankton, and phytoplankton growth and distribution are affected by the sunlight period and intensity. Gameiro & Brotas (2010) considered that light availability was one of the major factors shaping phytoplankton variability patterns in the Tagus estuary. Domingues *et al.* (2011) concluded that phytoplankton growth in the freshwater tidal reaches of the Guadiana estuary was light-limited throughout the year; although primary production was not photoinhibited at least up to 615 mmol photons m^{-2} s^{-1}. Furthermore, diatoms showed the most prominent responses to light enrichment throughout the year, High saturating irradiances, high light-saturated rates of primary production and low photosynthetic efficiencies suggest that the photoplankton community was not acclimated to the low-light conditions. For Changjiang estuary, light limitation caused by suspended particles in the water reduces the photosynthesis activity, resulting in a change of the phytoplankton primary productivity and community structure. And besides light condition, temperature, nutrients and zooplankton prey also take effect as controlling factors (Quinlan *et al.*, 2009; Choudhury & Pal, 2011; Shen *et al.*, 2011; Altman *et al.*, 2012). Linear regression analysis suggests a positive correlation between phytoplankton abundance and sediment concentration for the bottom layer in August 1999. The assumption was described by $y = 9.649 + 235.046\chi$, ($r = 0.8550$, $P < 0.05$). The abundance for the bottom layer of the dry period in 2000 correlated negatively with the sediment concentration: $y = 24.674 - 20.291\chi$, ($r = -0.7155$, $P < 0.05$). The salinity maintains the osmotic relation between the protoplast and water, and phytoplankton show various responses to different salinities. The linear regression analysis for the phytoplankton abundance and salinity data expressed a negative correlation. The regression equations for the surface and bottom layers during the dry period in 1999 were $y = 75.614 - 0.651\chi$, ($r = -0.7387$, $P < 0.05$) and $y = 24.08 - 0.489\chi$, ($r =$ -0.6292, $P < 0.05$). These estimates were significantly affected by the freshwater run-off, and the decrease in the abundance from the low-salinity estuary to the high-salinity inshore and offshore was also observed. The study of the Jucar River estuary by González del Río *et al.* (2007) reported that along the salinity gradient, as the influence of fresh water and nutrient loads decreases, a decrease in the population density of eukaryotic phytoplankton is observed. Typical freshwater phytoplankton groups clearly decrease in density and percentage as salinity increases. The density of diatoms is highest in the salt-wedge area due to nutrient accumulation. Considerable attention has been paid to nutrients in recent years. A positive correlation of phytoplankton with $NO_2{-}N$ and $NH_4{-}N$ was recorded for the Mahanadi estuary (Naik *et al.*, 2009), indicating that the phytoplankton population was controlled by these nutrients. Diatoms were dependent on $NO_2{-}N$ and $NH_4{-}N$, and dinoflagellates were dependent on $NO_2{-}N$ and SiO_4. Buric *et al.* (2007) pointed out that nutrients strongly limited phytoplankton growth in summer when the Karstic Zrmanja river discharge was at a minimum. Choudhury *et al.* (2011) stated that nutrients like DIN-DIP and DIN-DSi influenced periodical phytoplankton assemblages within the Bhagirathi–Hooghly estuary. In this study, linear regression analysis for phytoplankton abundance, total inorganic nitrogen and phosphate content showed a positive correlation between abundance and the total inorganic nitrogen in the surface and bottom layers during the dry period in 1999, which can be expressed as $y = 3.932 + 8.652\chi$ ($r = 0.6049$, $P < 0.05$); $y = 3.786 + 8.783\chi$ ($r = 0.6565$, $P < 0.05$). The same correlation was established for abundance and phosphate content in the surface layer: $y = 1.034 + 574.434\chi$ ($r = 0.5403$, $P < 0.05$). No significant negative correlations were observed during the other periods in the two layers. Thus, the correlations of phytoplankton abundance and nutrients are probably influenced by some additional factors. This conclusion was also supported by Costa *et al.* (2009); in Paraíba do Sul River estuary, remarkable shifts in composition and biomass occurred from the low to high flushing reasons, due much more to the river discharge than to nutrient availability. The overall results showed no nitrogen, phosphorus, or silica limitations to phytoplankton growth.

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Correspondence should be addressed to:
Peiyong Guo
Department of Environmental Science and Engineering
College of Chemical Engineering, Huaqiao University
Xiamen 361021, Fujian, China
email: peiyongguo@126.com