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# Long-term changes in sedimentary diatom assemblages and their environmental implications in the Changjiang (Yangtze) River estuary, China*

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**Abstract** Long-term data on diatom assemblages in a sediment core (60 cm) obtained from the Changjiang (Yangtze) River estuary were analyzed in order to assess the environmental changes that took place in the approximately 38 years (as determined by $^{210}$Pb measurements), i.e., between 1974 and 2012, of sediment accumulation. From the sediment core, 62 diatom taxa and genera were identified. The diatom biomass in the core generally increased beginning in the mid-1990s (core depth: 35 cm), accompanied by a shift in the dominant species from *Podosira stelliger* and two species of *Cyclotella* (*C. stylorum* and *C. striata*) to *Paralia sulcata*, three species of *Thalassiosira* (*T. eccentria*, *T. oestrupii*, and *T. excentrica*), *Actinoptychus undulates*, and *Thalassionema nitzschioides*. The changes in both species diversity and abundance suggested that since the 1980s the estuary has undergone extensive eutrophication. This conclusion was supported by the increased proportion of planktonic species, another indicator of high nutrients inputs, in the Changjiang River estuary.

**Keyword**: diatom assemblages; Changjiang River estuary; East China Sea; environmental implications

## 1 INTRODUCTION

The Changjiang (Yangtze) River of China is 6 300 km long and is thus one of the largest rivers in the world. It drains an area of $1.96\times10^6$ km$^2$, which is about one fifth of the total land area of the whole country (Milliman et al., 1992). The characteristics of the river strongly influence those of its estuary and the adjacent shelf in terms of both the volume of water (920 km$^3$/a) and sediment discharge (480 million tonnes/a) entering the estuary and emptying into the East China Sea (ECS) (Wang et al., 2008). Since the end of the last century, the estuary has been greatly modified by anthropogenic activities. Especially since the 1980s, the rapid development of the Chinese economy and the large number of water conservation projects have caused wide-scale changes in the Changjiang River estuary, its tributaries and its run-off areas. These in turn have led to serious environmental problems because of eutrophication and the frequent occurrence of harmful algal blooms (red tides) (Zhou, 2008). Eutrophication has altered the phytoplankton community with respect to biomass, species composition, and community succession. Thus, studies of the long-term changes in the Changjiang River's phytoplankton will reveal the environmental variations in temperature, salinity, nutrient levels, and other related parameters that have favored their development (Fritz et al., 1991; Liu et al., 2008). Previous studies documented variations in the phytoplankton of the Changjiang River estuary (Shen et al. 1995; Xu et al., 1999; Ning et al., 2004) but focused exclusively on alterations in abundances and species composition in the short term while

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ignoring the long-term changes in the phytoplankton community and the causes thereof. In recent years, the evolution of the environmental features of the Changjiang River estuary has been studied using a variety of indicators, such as plant pigments, sterols, stable isotopes, and foraminifera in sediments (Li et al., 2011). These indicators are useful both in paleo-environmental studies and in determining more recent environmental changes.

Diatoms play an important role in the phytoplankton community and are major primary producers in marine ecosystems. They are known to be sensitive to changes in nutrients status, temperature, pH, salinity and organic pollution (Anderson et al., 1992; Charles et al., 1994). Diatom assemblages are usually spatially and temporally dynamic in terms of their biomass and community structure. Moreover, they occupy a wide range of ecological habitats including those characterized by highly variable physical and chemical gradients, such as results from strong interactions between land and ocean. Diatom frustules are usually well preserved in the sediments and thus provide a unique indicator of the temporal and spatial trends in environmental changes. Specifically, frustules extracted from the sediments can be analyzed for taxonomic identification, which in turn allows the ecological habits of the respective taxa to be determined; taxonomic shifts indicate changes in environmental conditions. Diatom-based paleo-environmental studies have been carried out world-wide (Stoermer et al., 1999) and they justify the use of this approach to assess the environmental changes that have occurred in the Changjiang River estuary.

In this study, we sought to assess the influence of environmental changes on the temporal variations in diatom assemblages present in a sediment core collected from the Changjiang River estuary, China. We document the distribution of diatom species in the sediments and discuss the possible causes of the observed changes. Our aim was to define a set of paleo-indicators relevant to conducting an in-depth analysis of fossil assemblages that would reveal the long- and short-term environmental change in the Changjiang River estuary.

## 2 MATERIAL AND METHOD

### 2.1 Site description

The study site DH2-1 (31°N, 123°E) was located in the ECS adjacent to the Changjiang River estuary (Fig.1). Both the estuary and the adjacent sea are

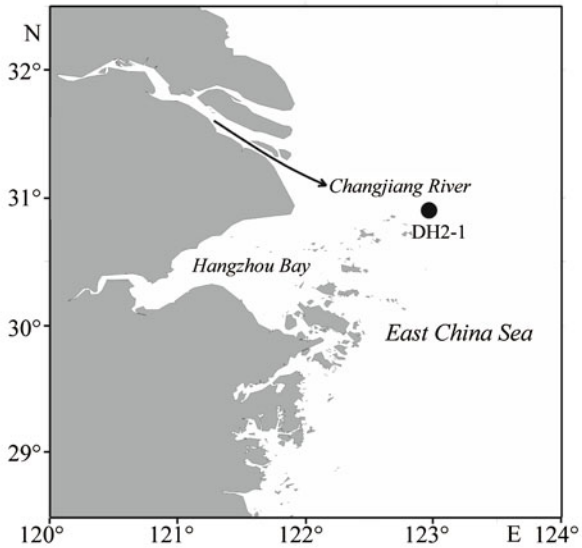


**Fig.1 Map showing the study area and core collection location**

mainly affected by coastal currents along mainland China (the East China Sea coastal current, ECSCC; the Yellow Sea coastal current, YSCC), by the Taiwan warm current (TWC) from Taiwan Strait, by a branch of the Kuroshio current and by freshwater runoff from the Changjiang River. The circulation patterns of these currents are different in winter and in summer, primarily because of the effects of monsoons and the changing scale of the Changjiang River runoff. During the winter season, when north or northeast winds prevail, the major runoff from the Changjiang River flows southeastward along the coast of Zhejiang province. The region affected by freshwater discharge is generally confined to the area west of 123°E, bordered by the TWC in the offshore area. During the summer season, southwest winds prevail and the intensified runoff from the Changjiang River normally turns eastwards or northeastwards, towards Cheju Island, Korea. During this same period, the ECSCC moves northeastward along the coast, driven by the southwest monsoon. This forcing causes the freshwater-affected area to extend northward, occupying a large area of the ECS and YS. In fact, during a huge flood from the Changjiang River the affected area even reached Cheju Island (Su, 1998; Liu et al., 2007).

### 2.2 Sample collection

The sediment core was collected in 2012 from the Changjiang River estuary and the adjacent ECS during an open research cruise carried out by the Institute of Oceanology, Chinese Academy of Sciences. A gravity corer with a 7.6 cm internal diameter was used to obtain core DH2-1 (60-cm length), which was taken at a water depth of 25 m on 22 July 2012. The sediment core was sectioned at 1-cm intervals within 24 h of its collection and stored frozen at -20°C.

### 2.3 Dating

Core DH2-1was dated at the Qingdao Institute of Marine Geology. The sediments were analyzed for $^{210}Pb$ using an HPGe gamma spectrometer, following the method described by Appleby et al. (1986). The constant rate of supply (CRS) model was used to calculate the chronologies of the analyzed parameters (Appleby et al., 1978, 1986).

### 2.4 Diatoms

The diatom analysis followed the methods of Battarbee (1986) and Ronnberg and Bonsdorff (2004). Sediment samples were freeze-dried and then treated with 10% HCl and 30% $H_2O_2$ for 3 h to remove carbonate and organic matter. They were subsequently rinsed several times to remove chemical residues and then gently added to a specific gravity fluid (density 2.45) containing zinc bromide followed by centrifugation at 2 700 r/min for 5 min to separate the diatoms. A 200-μL aliquot of the diatom suspension was placed on a cover slip and dried at 85°C on an electric hot plate. Permanent slides were prepared with by Naphrax™ mounting medium. Diatoms were identified and counted at ×1 000 magnification with an Olympus CX-1 light microscope equipped with differential interference contrast. Diatom taxonomy, nomenclature and ecological information were assessed according to Lan et al. (1995), Hasle et al. (1996), Stoermer et al. (1999), Guo et al. (2003) and Qi (2003). A total of at least 300 diatom valves (Scherader et al., 1978) were counted from each sample.

### 2.5 Data analysis

An unconstrained cluster analysis based on unweighted Euclidean distance (CONISS), as provied within the TILIA package (Grimm, 1987, 1991), and a detrended correspondence analysis (DCA) (Terbraak et al., 1995) of the diatom assemblages were used together with a combined diatom species listing to determine the percent abundances of the identified species. A cluster analysis was performed using the Primer 5.0 and CANOCO 4.52 programs. The absolute abundance ($N_a$) was calculated using the following equation:

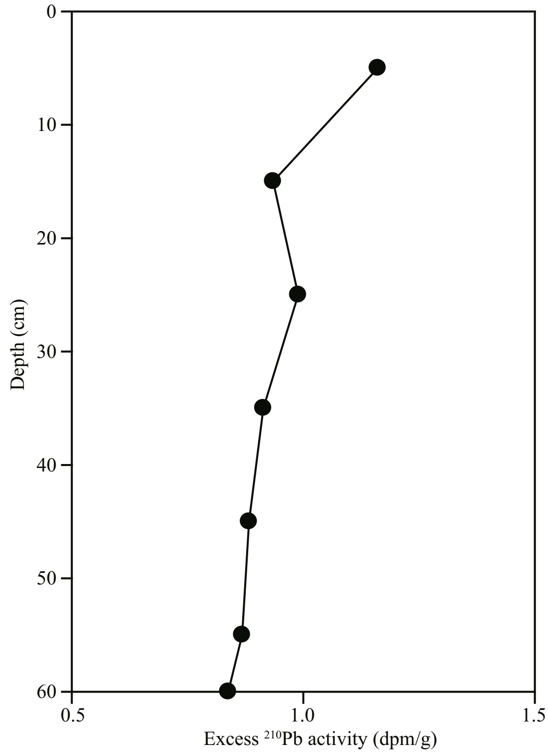


**Fig.2 Depth profiles of excess $^{210}$Pb activity in core DH2-1**

$$N_a=[nAV/avW],$$

where $n$ is the total number of diatom valves counted, $A$ is the area of the cover-slip (mm$^2$), $V$ is the total volume of the diatom extract suspension (mL), $a$ is the area of one field of view (mm$^2$), $v$ is the volume of the suspension placed on the cover-slip (mL), and $W$ is the dry weight of the sample (g). The relative abundance of diatom valves ($N_r$) was defined as the percentage of each species in a sample according to the $N_a$.

The community diversity ($H'$) of the diatom assemblage was estimated by the equation:

$$H' = \sum_{i=1}^{s} P_i \times \log_2 P_i \quad \text{(Shannon et al., 1949)},$$

where $P_i$ is the relative diatom abundance ($N_r$) and $S$ is the total number of species (species richness).

## 3 RESULT

### 3.1 Core chronology

The core showed no evidence (e.g., burrows or fragments of animals) of major biological or physical disturbance of the sediments.

Excess $^{210}Pb$ activity was measured in the sediments of core DH2-1 from the surface to a true depth of 60 cm (Fig.2), which was determined to represent ca.

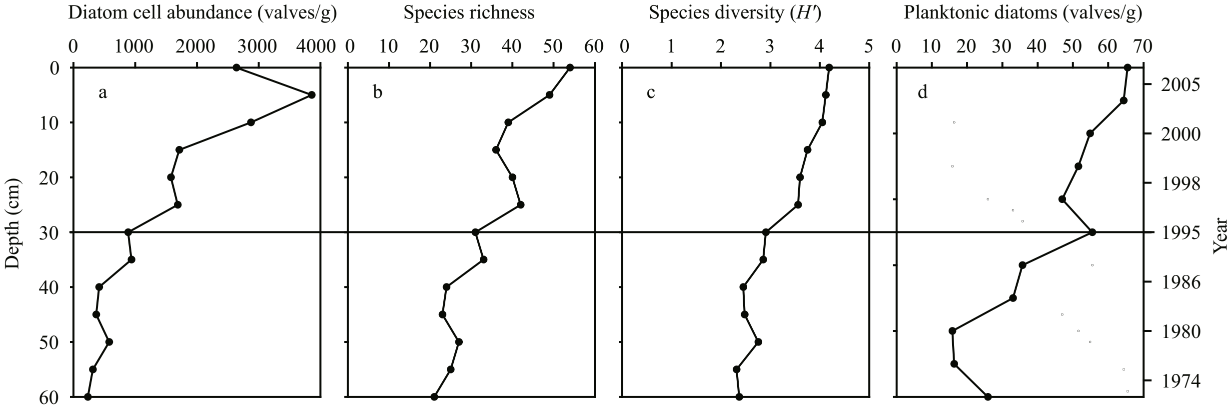


**Fig.3 Core profiles of diatom cell abundance ($N_a$) (a), species richness ($S$) (b), diversity ($H'$) (c), and proportions of planktonic diatoms in core DH2-1 (d)**

38 years of sediment accumulation. Based on the CRS model, two distinct rates of sedimentation were calculated. From 60 cm to the surface, the average sedimentation rate was ca. 1.57 cm/year.

Huh and Su (1999) pointed out that the sedimentation center in the muddy area of the Changjiang River is located in the continental shelf to the west of 123°15′E. The estimated sedimentation rate for the Changjiang River estuary based on our core (1.57 cm/year) is slightly lower than the 1–5 cm/year determined in previous studies. However, this high rate was attributed to sediment reworking by the complicated tides and currents in this coastal area (Demaster et al., 1985; Liu et al., 2006).

### 3.2 Diatom assemblages

The 62 diatom species identified in the core DH2-1 comprised 61 diatom species and one silicoflagellate (*Dictyocha fibula*), with 34 species of centric diatoms and 27 species of pennate diatoms. In this study, dominant species were defined as those occurring in percentages >5%; hence 15 species were considered common enough to be used in a further analysis of the data. The cluster analysis showed a break at 30 cm depth, based upon diatom biomass and composition, producing two zones in the core (Fig.3).

The diatom cell abundance ($N_a$) was consistent with an increasing trend in the core (Fig.3a). Thus, in zone 1, from 60 to 30 cm (ca. 1974–1995), diatom abundance was relatively low. The total $N_a$ ranged from 234 to 941 valves/g, with an average of 534 valves/g. In zone 2, covering a depth of 25 cm to the surface (ca. 1996–2012) there was a sudden increase in abundance, as indicated by the $N_a$ of 1 689–3 858 valves/g, with an average of 2 393 valves/g. The highest abundance in the core occurred in the 5-cm layer (corresponding to the year 2005).

The species richness ($S$) of the diatom assemblages ranged from 21 to 54. The diatom species numbers in zone 1 were lower than those of zone 2 (Fig.3b). There was a major peak in richness at the sediment surface, which followed a dramatic rise from 30 cm (ca. 1996). The Shannon-Weaver index ($H'$) showed an increasing tendency from the bottom to the surface, with a range of 2.32–4.19 (Fig.3c). The $N_a$ for planktonic diatoms ranged from 15.84% to 65.48%, with a significantly increasing trend up the core (Fig.3d).

The increase in diatom cell abundance was associated with changes in diatom assemblage composition. Thus, zone 1 was dominated by *Podosira stelliger* (~47%) and two species of *Cyclotella* (*C. stylorum* and *C. striata*) (~34%). Evidence of *P. stelliger* in the core sediments usually consisted only of broken fragments of the heavily silicified central part of the frustule. A significant shift in the dominant species occurred in zone 2, which was dominated by *Paralia sulcata*, *Actinoptychus undulatus*, *Thalassionema nitzschioides*, and three species of *Thalassoisra* (*T. simonsenii*, *T. oestrupii*, and *T. excentrica*). The relative abundance ($N_r$) of *P. stelliger* decreased sharply, to <1%, in the upper 10 cm of the core (Fig.4).

## 4 DISCUSSION

In this study the diatom distribution in a sediment core from the Changjiang River estuary was examined. The chronologies of the changes in the diatom assemblages suggest environmental variations over the past 40 years.

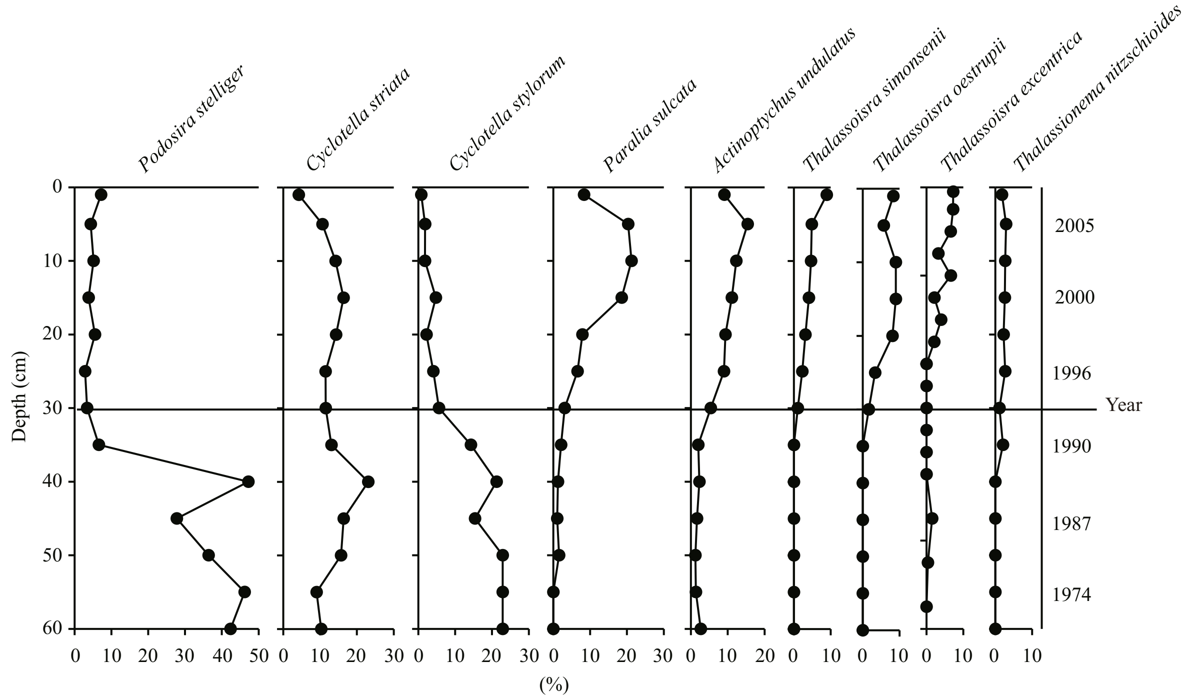


**Fig.4 Diagram indicating the relative abundance ($N_r$) of several common diatom species in sediment core DH2-1**

### 4.1 The diatom community in the Changjiang River estuary and the adjacent East China Sea

According to previous studies, diatoms account for 70.41%–82.71% of the total phytoplankton in the Changjiang River estuary and adjacent ECS, and diatom cell abundance was estimated to be in the range of $10^3$–$10^4$ cell/L (Wu et al., 2004; Xie, 2006). Diatom blooms forming red tides are a common phenomenon in the study area, with *Skeletonema costatum* and *Pseudo-nitzschia pungens* as the most common causative species. However, we did not detect *S. costatum* in the core, perhaps because its frustules are easily broken and dissolve in the sediments.

### 4.2 Diatom preservation in the sediment core and primary production

In previous studies diatom accumulations and fluxes in bottom sediments were in good agreement with measurements of primary production (phytoplankton standing stock) in surface waters (Steven, 1971; Lapointe, 2000). Here, the increasing trend in diatom abundances since 1980 was consistent with an increase in the phytoplankton standing stock in the Changjiang River estuary. As seen in Fig.4, diatom biomass between the mid-1990s and mid-2000s was characterized by an intense upwardly increasing trend, indicating the enhancement of phytoplankton activity. According to these findings the Changjiang River estuary has become a highly productive marine system over the last 40 years. Our interpretations of the diatom data are also supported by indicators of phytoplankton primary production, i.e., the frequency and intensity of red tides and the increasing Chl-*a* concentration in the water column. Previous studies likewise reported rising Chl-*a* concentrations in the surface water of the Changjiang River estuary and the adjacent ECS, specifically during the summers of 1980–2000 (Zhou et al., 2003; Wang, 2006), and, since the 1980s, a dramatic increase in the occurrence of red tides in these waters (Zhou et al., 2008). In fact, the estuary has suffered from increased nutrient inputs, primarily of anthropogenic origin and especially the intense use of chemical fertilizers since the 1970s, which have greatly stimulated primary production (Duan et al., 2008).

### 4.3 Diatom composition and its environmental implications

The main change in the diatom assemblage in the core was a shift of the dominant species. *Podosira stelliger* and two species of *Cyclotella* (*C. stylorum* and *C. striata*) were more abundant before the 1980s, but their proportions in the core gradually decreased thereafter (Fig.4). Some species in the upper part of the core (*P*. *sulcata*, *T*. *nitzschioides*, *A*. *undulatus*, and *A*. *normanii*) were highly abundant. For *P*. *sulcata*, there was a significant increasing trend in its abundance beginning in the 1980s and it became the dominant species in the upper 10 cm sediments between 2000 and 2012. Previous studies suggested the use of *P*. *sulcata* as an indicator of nutrient enrichment (McQuoid et al., 2003; Liu et al., 2008). *T*. *nitzschioides* is also commonly found in nutrient-rich upwelling regions and its presence indicates conditions of high productivity (Abrantes, 1988; Kobayashi et al., 2002). Additionally, Zhi (2005) reported the frequent occurrence of *A*. *undulatus* in eutrophication areas in the ECS, while Hasle and Syvertsen (1996) observed that the presence of *A*. *normanii* is indicative of high levels of eutrophication. Taken together, these findings suggest that the DH2-1 core reflects nutrient enhancement in the overlying water column, in agreement with the eutrophication of the Changjiang River estuary since the 1980s (Chai et al., 2006). We identified *Pseudo-nitzschia pungens* and a species of *Chaetoceros* in the uppermost sediments, both of which are common causes of red tide. Their detection is consistent with the more frequent outbreaks of harmful algal blooms in this area in recent years.

The diatom assemblages in the core also underwent proportional changes. Previous studies showed that in marine systems an increase in the abundance of planktonic species was a response to eutrophication (Cooper et al., 1991; Andrén, 1999), which would meet the high nutrient requirements of these species. Moreover, nutrient enrichment increases the turbidity of the water column and thus reduces the depth of the photic layer, in turn favoring planktonic over benthic species (Andrén, 1999). In this study, there was a significant increasing trend in the abundances of planktonic species. For example, the three species of *Thalassiosira* (*T*. *simonsenii*, *T*. *oestrupii*, and *T*. *excentrica*), which are considered to be typical planktonic species, contributed nearly 30% of the diatom assemblages in the uppermost sediments.

## 5 CONCLUSION

The species richness and diversity of the diatom assemblages that occurred in the core increased from 1980 to the present. The increase in diatom biomass reflected increases in both the number and the abundances of eutrophic species, which paralleled greater nutrient input into the waters of the Changjiang River estuary. Thus, the changes in the diatom assemblages in a sediment core from the estuary served as an indicator of the environmental changes in this coastal area. The predominance of species preferring nutrient-enriched waters in the upper part of the core evidences the serious eutrophication that has taken place in the Changjiang River estuary over the last 30 years.

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**References**

Abrantes F. 1988. Diatom assemblages as upwelling indicators in surface sediments off Portugal. *Mar*. *Geol*., **85**(1): 15-39.

Anderson N J, Vos P. 1992. Learning from the past: diatoms as palaeoecological indicators of changes in marine environments. *Neth*. *J*. *Aquat*. *Ecol*., **26**(1): 19-30.

Andrén E. 1999. Changes in the composition of the diatom flora during the last century indicate increased eutrophication of the Oder estuary, south-western Baltic Sea. *Estuar*. *Coast*. *Shelf S*., **48**(6): 665-676.

Appleby P G, Nolan P J, Gifford D W, Godfrey M J, Oldfield F, Anderson N J, Battarbee R W. 1986. $^{210}$Pb dating by low background gamma counting. *Hydrobiologia*, **143**(1): 21-27.

Appleby P G, Oldfield F. 1978. The calculation of lead-210 dates assuming a constant rate of supply of unsupported $^{210}$Pb to the sediment. *Catena*, **5**(1): 1-8.

Battarbee R W. 1986. Diatom analysis. *In*: Berglund B E ed. Handbook of Holocene Palaeoecology and Palaeohydrology. Wiley, Chichester. p.527-570.

Chai C, Yu Z M, Song X X, Cao X H. 2006. The status and characteristics of eutrophication in the Yangtze River (Changjiang) estuary and the adjacent East China Sea, China. *Hydrobiologia*, **563**: 313-328.

Charles D F, Smol J P, Engstrom D R. 1994. Paleolimnological approaches to biological monitoring. *In*: Loeb S L, Spacie A eds. Biological Monitoring of Aquatic Systems. Lewis Publishers, Boca Raton, p.233-293.

Cooper S R, Brush G S. 1991. Long-term history of chesapeake bay anoxia. *Science*, **254**(5034): 992-996.

Demaster D J, McKee B A, Nittrouer C A, Qian J C, Cheng G D. 1985. Rates of sediment accumulation and particle reworking based on radiochemical measurements from continental-shelf deposit in the East China Sea. *Cont*. *Shelf Res*., **4**(1-2): 143-158.

Duan S, Liang T, Zhang S, Wang L, Zhang X, Chen X. 2008. Seasonal changes in nitrogen and phosphorus transport in the lower Changjiang River before the construction of the Three Gorges Dam. *Estuar*. *Coast*. *Shelf S*., **79**(2): 239-250.

Fritz S C, Juggins, S, Battarbee R W, Engstrom D R. 1991. Reconstruction of past changes in salinity and climate using a diatom-based transfer function. *Nature*, **352**: 706-708.

Grimm E C. 1987. CONISS—a fortran-77 program for strtigraphically constrained cluster-analysis by the method of incremental sum of squares. *Comput Geosci*., **13**(1): 13-35.

Grimm E C. 1991. TILIA, Version 1.11. TILIAGRAPH, Version 1.18. *In*: A G ed. A Users Notebook. Illinois State Museum, Springfield, USA.

Guo Y, Qian S. 2003. Bacillariophyta in Flora Alarum Marginatum Sinistrum. Science Press, Beijing. p.1-493. (in Chinese)

Hasle G R, Syvertsen E E. 1996. Marine Diatoms. *In*: Tomas C R ed. Identifying Marine Diatoms and Dinoflagellates. Academic Press, San Diego. p.5-385.

Huh C A, Su C C. 1999. Sedimentation dynamics in the East China Sea elucidated from Pb-210, Cs-137 and Pu-239, Pu-240. *Mar*. *Geol*., **160**(1-2): 183-196.

Kobayashi F, Takahashi K. 2002. Distribution of diatoms along the equatorial transect in the western and central Pacific during the 1999 La Nina conditions. *Deep-Sea Res*. *Pt*. *II*, **49**(13-14): 2 801-2 821.

Lan D Z, Cheng Z D, Liu S Z. 1995. Diatoms in late Quaternary sediments from the South China Sea. Ocean Press, Beijing. p.1-138. (in Chinese)

Lapointe M. 2000. Modern diatom assemblages in surface sediments from the Maritime Estuary and the Gulf of St. Lawrence, Quebec (Canada). *Mar*. *Micropaleontol*., **40**(1-2): 43-65.

Li X X, Thomas S B, Yang Z S, Lisa E O, Mead A A, Steven F D, Yang G P. 2011. Historical trends of hypoxia in Changjiang River estuary: applications of chemical biomarkers and microfossils. *J. Mar. Syst*., **86**(2011): 57-68.

Liu D, Sun J, Zhang J, Liu G. 2008. Response of the diatom flora in Jiaozhou Bay, China to environmental changes during the last century. *Mar*. *Micropaleontol*., **66**(3-4): 279-290.

Liu J P, Li A C, Xu K H, Veiozzi D M, Yang Z S, Milliman J D, DeMaster D. 2006. Sedimentary features of the Yangtze River-derived along-shelf clinoform deposit in the East China Sea. *Cont*. *Shelf Res*., **26**(17-18): 2 141-2 156.

Liu J P, Xu K H, Li A C, Milliman J D, Velozzi D M, Xiao S B, Yang Z S. 2007. Flux and fate of Yangtze river sediment delivered to the East China Sea. *Geomorphology*, **85**(3-4): 208-224.

McQuoid M R, Nordberg K. 2003. The diatom *Paralia sulcata* as an environmental indicator species in coastal sediments. *Estuar*. *Coast*. *Shelf S*., **56**(2): 339-354.

Milliman J D, Syvitski J P M. 1992. Geomorphic teconic control of sediment discharge ot the ocean - the importance of small mountainous rivers. *J*. *Geol*., **100**(5): 525-544.

Ning X R, Shi J X, Cai Y M, Liu C G. 2004. Biological productivity front in the Changjiang Estuary and the Hangzhou Bay and its ecological effects. *Acta Oceanol Sin*., **26**(6): 96-106. (in Chinese)

Qi Y Z. 2003. Red Tides in China Coastal Areas. Science Press, Beijing. p.1-348. (in Chinese)

Ronnberg C, Bonsdorff E. 2004. Baltic Sea eutrophication: area-specific ecological consequences. *Hydrobiologia*, **514**(1-3): 227-241.

Scherader H J, Gersonde R. 1978. Diatoms and silicoflagellates. *Utr*. *Micropaleontol*. *Bull*., **19**: 439-444.

Shannon C E, Weaver W. 1949. The Mathematical Theory of Communication. University of Illinois Press, Urbana IL. p.1-144.

Shen X Q, Hu R, Wang G L. 1995. Studies on phytoplankton in waters adjacent to islands of Shanghai. *Mar*. *Sci*. *Bull*., **14**(4): 26-37. (in Chinese with English abstract)

Steven D M. 1971. International biological programme study of the Gulf of St. Lawrence, 2nd Gulf of St. Lawrence Workshop-Bedford Institute of Oceanography. p.146-159.

Stoermer E F, Smol J P. 1999. The Diatoms: Applications for Environmental and Earth Sciences. Cambridge University Press, Cambridge. p.1-469.

Su J L. 1998. Circulation dynamics of the China Seas north of 18°N. *In*: Robinson A R, Brinks K H eds. The Sea. John Willey & Sons Inc, New York. p.483-505.

Terbraak C J F, Verdonschot P F M. 1995. Canonical correspondence-analysis and related multivariate methods in aquatic ecology. *Aquat*. *Sci*., **57**(3): 255-289.

Wang B. 2006. Cultural eutrophication in the Changjiang (Yangtze River) plume: history and perspective. *Estuar*. *Coast*. *Shelf S*., **69**(3-4): 471-477.

Wang X, Wang B, Zhang C, Shi X, Zhu C, Xie L, Han X, Xin Y, Wang J. 2008. Nutrient composition and distributions in coastal waters impacted by the Changjiang plume. *Acta Oceanol. Sin*., **27**(5): 111-125. (in Chinese)

Wu Y L, Fu Y N, Zhang Y S, Pu X M, Zhou C X. 2004. Phytoplankton distribution and its relation to the runoff in the Changjiang (Yangtze) Estuary. *Oceanologica et Limnologia Sinica*, **35**(3): 246-251. (in Chinese with English abstract)

Xie W L. 2006. Community Structure and Dynamics of Planktonic Diatoms in Typical Areas of East China Sea. Xiamen University. Xiamen, China. p.1-236. (in Chinese)

Xu Z L, Bai X M, Yuan Q, Jiang M, Gu X G. 1999. An ecological study on phytoplankton in the Changjiang estuary. *J*. *Fish*. *Sci*. *China*, **6**(5): 52-54. (in Chinese)

Zhi C Y. 2005. Diatom and Paleoenvironment—Diatom on the Margin of the East China Sea and Paleoenvironment. Ocean Press, Beijing. p.1-141. (in Chinese)

Zhou M J, Shen Z L, Yu R C. 2008. Responses of a coastal phytoplankton community to increased nutrient input from the Changjiang (Yangtze) River. *Cont*. *Shelf Res*., **28**(12): 1 483-1 489.

Zhou W H, Huo W Y, Yuan X C, Yin K D. 2003. Distribution features of chlorophyll *a* and primary productivity in high frequency area of red tide in East China Sea during spring. *Chin*. *J*. *Appl*. *Ecol*., **14**(7): 1 055-1 059. (in Chinese)