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# Hydromorphological Mechanisms Leading to Hypoxia off the Changjiang Estuary

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## Abstract

Based on the seasonal surveying data and long-term data, the annual changes in the geographical locations, occurrence frequency, affected areas and the minimum oxygen level as well as the formation mechanism of the summer hypoxia off the Changjiang estuary are summarized and discussed in this paper. The historical data indicates that there were episodes of hypoxia in the past 50 years but not every year, and the event of summer hypoxia could be traced back to as early as late 1950s off the Changjiang estuary. The minimum oxygen levels in the hypoxia zone did not show any decline in the past 50 years, but all the events with large size of affected-area ( $>5000\text{km}^2$ ) were observed after the late 1990s, suggesting an enlarging trend. The author argues that the development of summer hypoxia off the Changjiang estuary was related not only to stratification and input of suspended particulate matter, but also to the inflow of Taiwan Warm Current Water as well as the bottom topography.

Keywords: Hypoxia; Dissolved oxygen; Oxygen depletion; Hydrography; Morphology; Bottom topography; The Changjiang (Yangtze River) estuary; The East China Sea

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## 26 **1 Introduction**

27 Because of their geomorphology and circulation patterns, some marine systems  
28 have a greater tendency to develop hypoxic conditions. The basic features of a  
29 system that make it prone to hypoxia are low physical energy (tidal, currents, or  
30 wind) and large freshwater input (Diaz, 2001). These features combine to form  
31 stratified or stable water masses near the bottom that become hypoxic when they are  
32 isolated from reoxygenation with surface waters.

33 Hypoxia and anoxia have been widely observed in many estuarine and coastal  
34 regions over the last several decades, of which the most well-known areas for  
35 hypoxia/anoxia are the Gulf of Mexico, Chesapeake Bay, the North Sea, Tokyo Bay,  
36 the Black Sea, and the Baltic Sea (Diaz, 2001; Rabalais, Turner and Wiseman, 2001,  
37 2002). Hypoxic zones also occur in coastal waters of China Seas, such as the  
38 summer hypoxia off the estuaries of Changjiang and Pearl River (e.g., Chen, Gong  
39 and Shiah, 2007; Wei, He, Li, Liu and Wang, 2007; Dai, Guo, Zhai, Yuan, Wang and  
40 Wang et al., 2006; Li, Zhang, Huang, Wu and Liang, 2002; Yin, Lin and Ke, 2004).  
41 Previous studies have obtained some preliminary understanding about the formation  
42 mechanism of the summer hypoxia off the Changjiang estuary; however, these  
43 findings were based on the data of some single cruises (Chen et al., 2007; Li et al.,  
44 2002; Wei et al., 2007). The annual changes in the geographical locations, the  
45 frequency, the affected areas, the minimum oxygen levels, and the regional specific  
46 characteristics of summer hypoxia development in this area still remain unknown.

47 Based on the seasonal surveying data and the long-term data on summer hypoxia  
48 off the Changjiang estuary, the author attempted to answer the above questions and  
49 identify the regional specific hydromorphological mechanisms leading to the  
50 development of summer hypoxia off the Changjiang estuary.

## 51 **2 Materials and Methods**

52 The source of field data used in this paper is the same as that of Wang et al.  
53 (2003). Since this paper focuses on the chemical hydrography in areas adjacent to  
54 the Changjiang estuary, ten cross-shelf transects covering the shelves of the Yellow  
55 Sea (YS) and East China Sea (ECS) were selected from the original database. The  
56 data collected from November 1997, May 1998, August 1998 and January 1999  
57 cruises were designed to represent the autumn, spring, summer and winter  
58 conditions, respectively. The station locations, sampling resolution and analytical  
59 methods of temperature and salinity were described in detail elsewhere (Wang,  
60 Wang and Zhan, 2003). Dissolved oxygen was measured using Winkler titration  
61 method. The precision in the measurements of temperature, salinity and dissolved  
62 oxygen were  $\pm 0.005^{\circ}\text{C}$ ,  $\pm 0.005$ ,  $\pm 0.06 \text{ mg L}^{-1}$ , respectively.

63 Historical records of summer hypoxia were also compiled for comparison.

## 64 **3 Results**

65 In the winter, circulation in areas adjacent to the Changjiang estuary is  
66 characterized by northward extension of the Taiwan Warm Current (TWC) and  
67 southward flow of coastal currents along the banks (Guan, 1994). Bottom  
68 temperature distribution showed that the saline warm water of TWC flowed  
69 northward along  $123^{\circ}\text{E}$  from the south of ECS and turned northwestward at  $31^{\circ}\text{N}$   
70 into the trough off the Changjiang estuary, while the cold, less saline coastal water  
71 extended southeastward in a tongue-like shape from the west of YS to the northern  
72 ECS (Fig. 1a). The shapes of the isotherms were quite similar to isobaths (Fig. 1a).  
73 Similar distributions were also found for salinity (not shown) and dissolved oxygen  
74 (Fig. 1b). Water with  $\text{DO} < 8 \text{ mg L}^{-1}$  from the TWC occupied the trough off the  
75 Changjiang estuary, while  $> 8 \text{ mg L}^{-1}$  coastal water occupied the coastal areas as

76 well as the middle shelf of the northern ECS (Fig. 1b). The vertical profiles of T, S  
77 and DO showed that the water column was homogeneous and the TWC water in the  
78 trough was very distinct with high temperature ( $>15^{\circ}\text{C}$ ) and salinity ( $>34.2$ ) and  
79 lower oxygen level ( $<7.8\text{ mg L}^{-1}$ ) (Fig. 2a, b & c).

80  
81  
82  
Figure 1

83 With the southerly monsoon predominant in spring, the coastal current in ECS  
84 moved northward along the coast with increasing width and velocity, while the  
85 coastal current in YS extended southeastward into the northern ECS with less  
86 intensity than that in winter (Guan, 1994). The TWC at all levels below the sea  
87 surface moved north-northeastward along isobaths offshore with intensity stronger  
88 than that in winter (Guan, 1994). The bottom salinity distribution indicated that the  
89 saline frontal water of TWC extended far reaching into the trough off the  
90 Changjiang estuary, which could reach  $31.5^{\circ}\text{N}$  as shown by isohaline of 33 psu (Fig.  
91 1c). The oxygen level of the bottom water of TWC was lower than that in the winter.  
92 An area with oxygen level less than  $5.0\text{ mg L}^{-1}$  was found in the bottom water inside  
93 the trough and there were sharp gradients with surrounding waters (Fig. 1d).

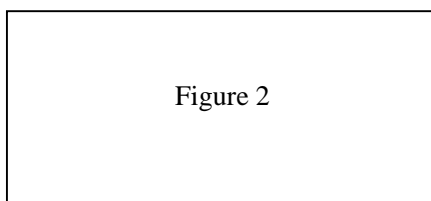
94 Solar radiation and river runoffs (mainly from the Changjiang River) made a  
95 strengthened stratification in the spring in the northern ECS shelf. In the area of the  
96 trough, there were a strong halocline, a weak thermocline and lower dissolved  
97 oxygen at the depth of 10 to 30 m (Fig. 2d~2f). Below the halocline and the  
98 thermocline lied the deep water of TWC inside the trough, which was characterized  
99 by low temperature ( $<19.0^{\circ}\text{C}$ ), high salinity ( $>33.5$ ) and low oxygen level ( $<5.0\text{ mg}$   
100  $\text{L}^{-1}$ ). In the middle shelf of the northern ECS, there was a stronger thermocline at the

101 depth of 10 to 20 m and below the thermocline lied a cold water ( $<13^{\circ}\text{C}$ ) with low  
102 salinity ( $<33.0$ ) and high oxygen starting level ( $> 8.0 \text{ mg L}^{-1}$ ) (Fig. 2d~2f).

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106 In the summer, the circulation pattern and the composition of water masses in the  
107 studied area were similar to that in the spring. However, the forces of the coastal  
108 current in ECS and TWC were enhanced due to higher runoffs and dominance of  
109 southerly wind (Guan, 1994). The surface of the northern ECS and south of YS was  
110 occupied by Changjiang Diluted Water with low salinity ( $< 31.0$ ) and high  
111 temperature (see Fig. 2 in Wang et al., 2003). The bottom water from TWC with low  
112 temperature ( $<21.0^{\circ}\text{C}$ ) and high salinity ( $>33.0$ ) occupied the middle shelf as well as  
113 the trough off the Changjiang estuary, and its frontal water could reach  $32^{\circ}\text{N}$  (as  
114 shown by the 33.0 isohaline) (Fig. 3a). The oxygen level of the bottom water of  
115 TWC was even lower than that in the spring. A closed area with oxygen level less  
116 than  $3.0 \text{ mg L}^{-1}$  was found in bottom water inside the trough as well as on its right  
117 slope (Fig. 3b) and there were sharp gradients both in temperature and oxygen levels  
118 with its eastern and northern surrounding waters (Fig. 3a & b).

119 Stronger solar radiation and higher river runoffs during the summer made a  
120 stronger stratification than that in the spring on the ECS shelf. In the inner shelf of  
121 the northern ECS, there were a very strong thermocline, a halocline and a spring  
122 layer of dissolved oxygen at the depth of 5 to 30 m (Fig. 2g~2i). The upper water in  
123 the northern ECS shelf was occupied by Changjiang Diluted Water with salinity less  
124 than 31.0 (Fig. 2h) and the lower layer water was the deep water of TWC with high  
125 salinity ( $>34.0$ ), low temperature ( $<19^{\circ}\text{C}$ ) and low oxygen level ( $<4.0 \text{ mg L}^{-1}$ ). The

126 remnant winter water with low temperature ( $<13^{\circ}\text{C}$ ), low salinity ( $<33.0$ ), and high  
127 oxygen level ( $> 7.0 \text{ mg L}^{-1}$ ) still lied on the bottom of the middle shelf of the  
128 northern ECS.

129 In the autumn, the circulation pattern and intensities of the currents were similar  
130 to that in the winter. The extending range of the bottom frontal water of TWC was  
131 almost the same as that in the winter (as shown by 33.0 isohaline, Fig. 3c). The  
132 oxygen levels in the bottom waters inside the deep trough as well as on the middle  
133 shelf of ECS were less than  $5.0 \text{ mg L}^{-1}$  (Fig. 3d). The vertical profiles showed that  
134 the water column was nearly vertically uniform on the northern ECS shelf except  
135 inside the deep trough, where there still existed a halocline and a spring layer of  
136 dissolved oxygen at the lower layer, which was the remnant deep water of TWC  
137 (Fig. 2j~2l).

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Figure 3

## 142 **4 Discussion**

### 143 *4.1 The locations of hypoxia zone off the Changjiang estuary*

144 Figure 4 shows the distribution of the locations of the centers of hypoxia zones  
145 (defined as the location where the oxygen level was the minimum in a campaign)  
146 observed off the Changjiang estuary in the past 50 years. Geographically, almost all  
147 of the centers of hypoxia zones were located inside the trough and most centered  
148 around  $123^{\circ}\text{E}$ ,  $30^{\circ}50'\text{N}$ ; the only exception is the hypoxia zone observed in August  
149 1998 which was outside the trough and far from the Changjiang estuary.  
150 Bathymetrically, they occurred in the water depth of 20 to 55 m and mostly in the



151 water depth of 40 m.

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157 *4.2 Variation of the minimum oxygen levels and the affected areas of the hypoxia*

158 *zone*

159 A historical picture of oxygen conditions off the Changjiang estuary, as shown in  
160 Table 1, indicates that there were episodes of hypoxia in the past 50 years but not  
161 every year. The overall probability of occurrence of summer hypoxia was 60% in  
162 the past 50 years, but up to nearly 90% after the 1990s, demonstrating an increasing  
163 trend. In terms of the duration of the hypoxic events, the available monthly  
164 surveying data conducted in 1959 revealed that hypoxic events occurred only in  
165 August, suggesting that the duration of the hypoxic events was probably rather short.  
166 The minimum oxygen concentrations observed in the area off the Changjiang  
167 estuary were different in different years, but there was no obvious trend of decline  
168 or increase. The size of the hypoxia zone also differed greatly in different years.  
169 However, all the events of hypoxia with affected area greater than 5000 km<sup>2</sup>  
170 occurred after the end of the 1990s, indicating that the extent of summer hypoxia  
171 became more severe in recent years, possibly due to the increasing input of  
172 anthropogenic nutrients to this area (Wang, 2006).

173

174

175

Figure 4

Table 1

176 *4.3 The formation mechanism of the hypoxia zone off the Changjiang estuary*

177 Based on the analysis of the seasonal distributions of temperature, salinity and  
178 dissolved oxygen, the formation mechanism of hypoxia zone off the Changjiang  
179 estuary may be described as the following: in the winter, the frontal water of TWC  
180 with high temperature and salinity and low oxygen level occupied the whole water  
181 column in the area of the trough off the Changjiang estuary; in the spring, the  
182 combination of higher runoff and stronger solar radiation made a strong  
183 stratification in the northern ECS shelf, especially in the area of the trough, resulting  
184 in decreased oxygen level at the lower layer through decomposition of organic  
185 matter; in the summer, the combination of the highest runoff and the strongest solar  
186 radiation made the strongest stratification in the northern ECS shelf, especially in  
187 the area of the trough, resulting in the continuous decrease in the oxygen level at the  
188 lower layer through decomposition of organic matters and finally the hypoxia zone  
189 formation inside the trough; and in the autumn, water column stratification is broken  
190 down was by strong vertical advection, the bottom water is reoxygenated, and the  
191 hypoxia zone disappears.

192 Previous studies emphasized two principal factors, i.e., water column stratification  
193 and decomposition of organic matter in the bottom water, leading to the  
194 development of hypoxia off the Changjiang estuary (Chen et al., 2007; Li et al.,  
195 2002; Wei et al., 2007). In this paper, the author argues that there are also some  
196 other factors controlling the development of summer hypoxia off the Changjiang  
197 estuary.

198 First, the inflow of the TWC water with high salinity and lower temperature  
199 (during spring and summer) provides an essential prerequisite for the formation of  
200 water column stratification in the area of the trough during the spring and the

201 summer and it also provides the bottom water which is originally low in oxygen  
202 level.

203 Secondly, the bottom topography might play a key role in the processes of the  
204 development of summer hypoxia off the Changjiang estuary. The deep trough just  
205 off the estuary isolated the bottom water inside the trough from exchange with  
206 surrounding oxygen-rich waters through advection, making the bottom water inside  
207 the trough to be rather stable, so that the hypoxia could develop and persist inside  
208 the trough. This is why almost all of the centers of hypoxia zones were located  
209 inside the trough in the past 50 years. As a matter of fact, the development of most  
210 of the well-known hypoxia or anoxia zones in the world oceans has something to do  
211 with bottom topography, such as the hypoxic zone in the deep channel of the  
212 Chesapeake Bay (Hagy, Boynton, Keefe and Wood, 2004), and the hypoxic zone in  
213 the V-shaped deep trough of the central Baltic Sea (Conley, Humborg, Rahm,  
214 Savchuk and Wulff, 2002), as well as the anoxic zone in the deep basin with steep  
215 slope in the Black Sea (Neretin, Volkov, Böttcher and Grinenko, 2001).

216 Moreover, owing to its special bottom topography and hydrographic condition,  
217 the deep trough is favorable for the sedimentation of fine sediments from the  
218 Changjiang River (Milliman, Shen, Yang and Mead, 1985; Shi, Zhang and Hamilton,  
219 2006). This could be supported by the existence of a closed area of muddy  
220 sediments inside the trough (Hu, 1984). Additionally, upwelling in this area is  
221 favorable for the resuspension of fine sediments (Hu, 1984; Wang and Wang, 2007;  
222 Zhao, 1993). All these processes accelerate the reduction of oxygen level through  
223 decomposition of organic matter in the bottom water which can lead to the  
224 development of hypoxia off the Changjiang estuary.

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314 Figure captions:

315 Fig. 1 Distributions of temperature ( $T$ , °C), salinity ( $S$ ) and dissolved oxygen (DO,  
316  $\text{mg L}^{-1}$ ) in bottom water adjacent to the Changjiang estuary in the winter and  
317 spring (a:  $T$ , Jan. 1999; b: DO, Jan. 1999; c:  $S$ , May 1998; d: DO, May 1998)

318 Fig. 2 Vertical profiles of temperature (°C), salinity and dissolved oxygen ( $\text{mg L}^{-1}$ )  
319 along transect  $31^{\circ}\text{N}$

320 Fig. 3 Distributions of temperature ( $T$ , °C), salinity ( $S$ ) and dissolved oxygen (DO,  
321  $\text{mg L}^{-1}$ ) in bottom water adjacent to the Changjiang estuary in the summer and  
322 autumn (a:  $T$ , Aug. 1998; b: DO, Aug. 1998; c:  $S$ , Nov. 1997; d: DO, Nov.  
323 1997)

324 Fig. 4 Bathymetry in the Changjiang estuary and adjacent areas, and the locations of  
325 centers of hypoxia zones observed in the past 50 years (1959-2006)



Table 1 Historical record of the locations of the minimum values of dissolved oxygen concentrations and affected areas of the hypoxia zone off the Changjiang estuary

Time	Location		Min. of DO Conc. (mg L <sup>-1</sup> )	Affected area (km <sup>2</sup> )	Reference
	longitude	latitude			
Aug.,1959	122°45'	31°15'	0.34	1000	Office of Integrated Oceanographic Survey of China ,1961
Aug.,1976-85	123°00'	31°00'	≥0.80	?	Zhang, 1990
Aug.,1981	123°00'	30°50'	2.0	-	Limeburner, Beardsley and Zhao,1983
Aug.,1982	122°30'	31°15'	2.85	-	Chen, Chen and Yang, 1988
Aug.,1985	122°30'	31°30'	2.29	-	Ren, 1992
Aug.,1988	123°00'	30°50'	1.96	<200	Tian, Hu and Martin, 1993
Aug.,1998	124°00'	32°10'	1.44	600	Wang and Wang, 2007
Aug.,1999	122°59'	30°51'	1.0	13700	Li et al., 2002
Aug., 2002	122°29'	32°00'	1.73	<500	Shi, Lu, Zhang and Wang, 2006
	123°00'	31°00'	1.99		
Jun., 2003	122°50'	30°50'	~1.0	5000	Xu, 2005
Aug., 2003	123°30'	31°30'	2.0	-	Chen et al., 2007
Sept., 2003	122°56'	30°49'	0.8	20000	Wei et al., 2007
	122°45'	31°55'	<1.5		
Aug., 2004	122°40'	31°15'	>2.0	-	Pei, 2007
Sept., 2006	123°06'	30°09'	1.96	<300	Zou, Yang, Liu and Shi, 2007

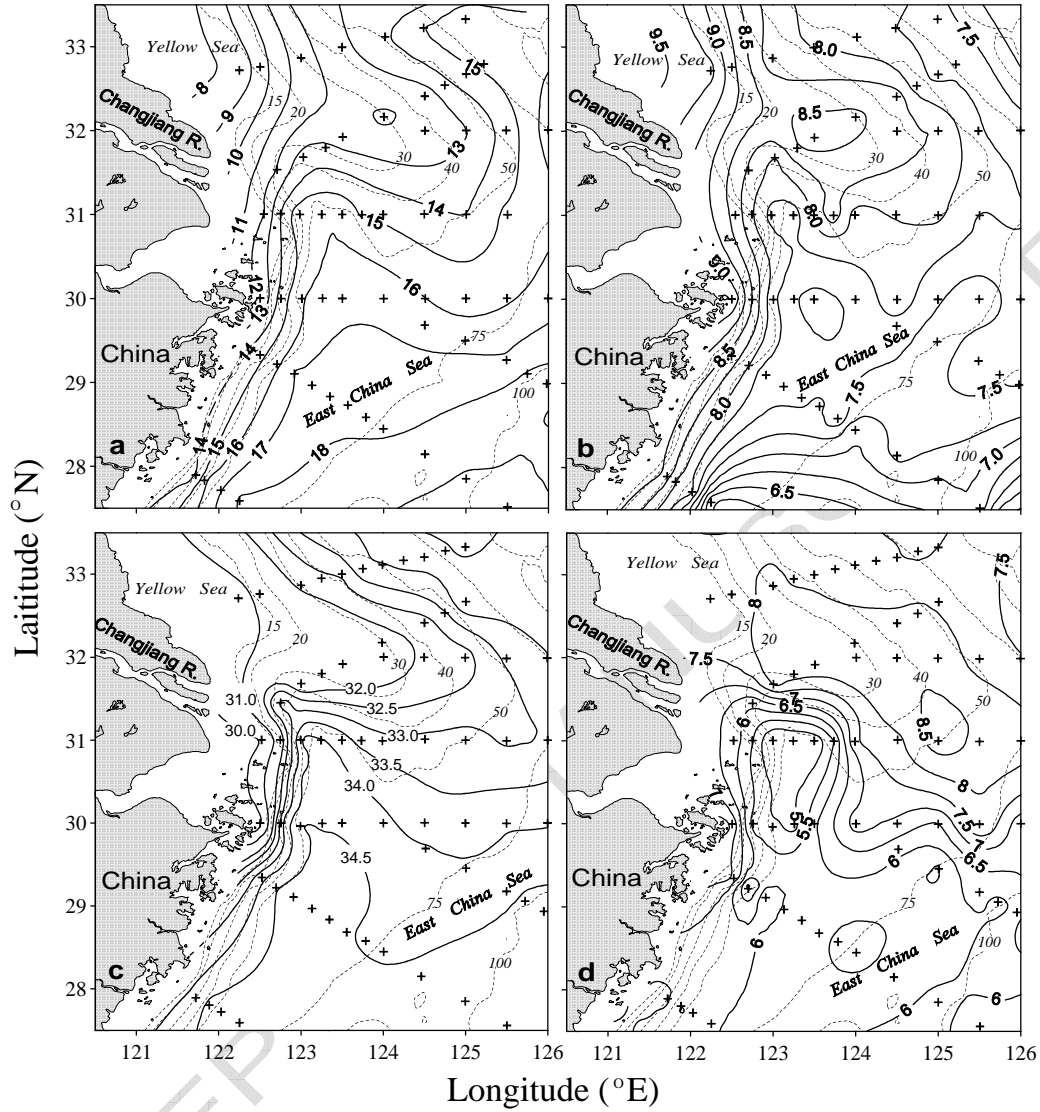


Figure 1

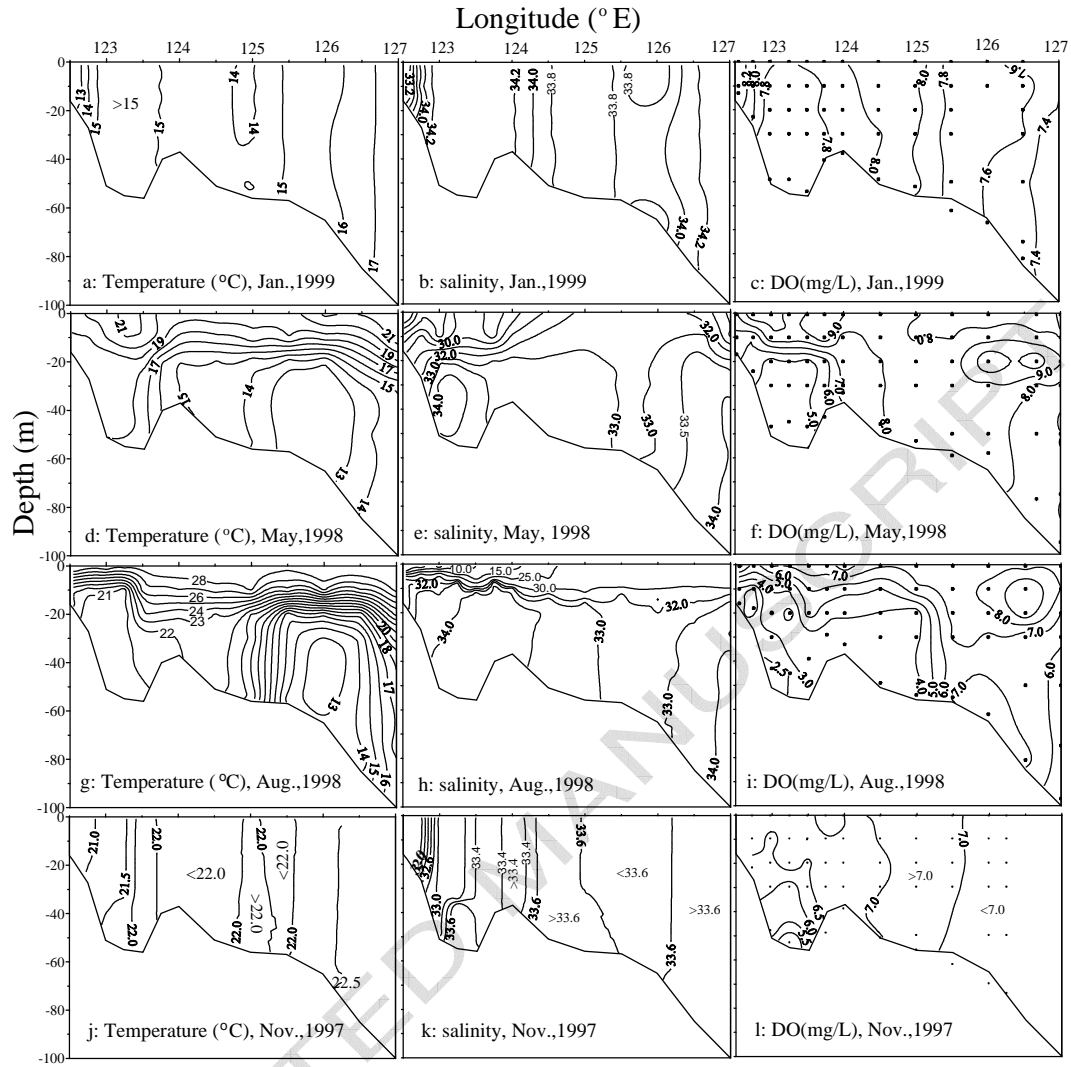


Figure 2

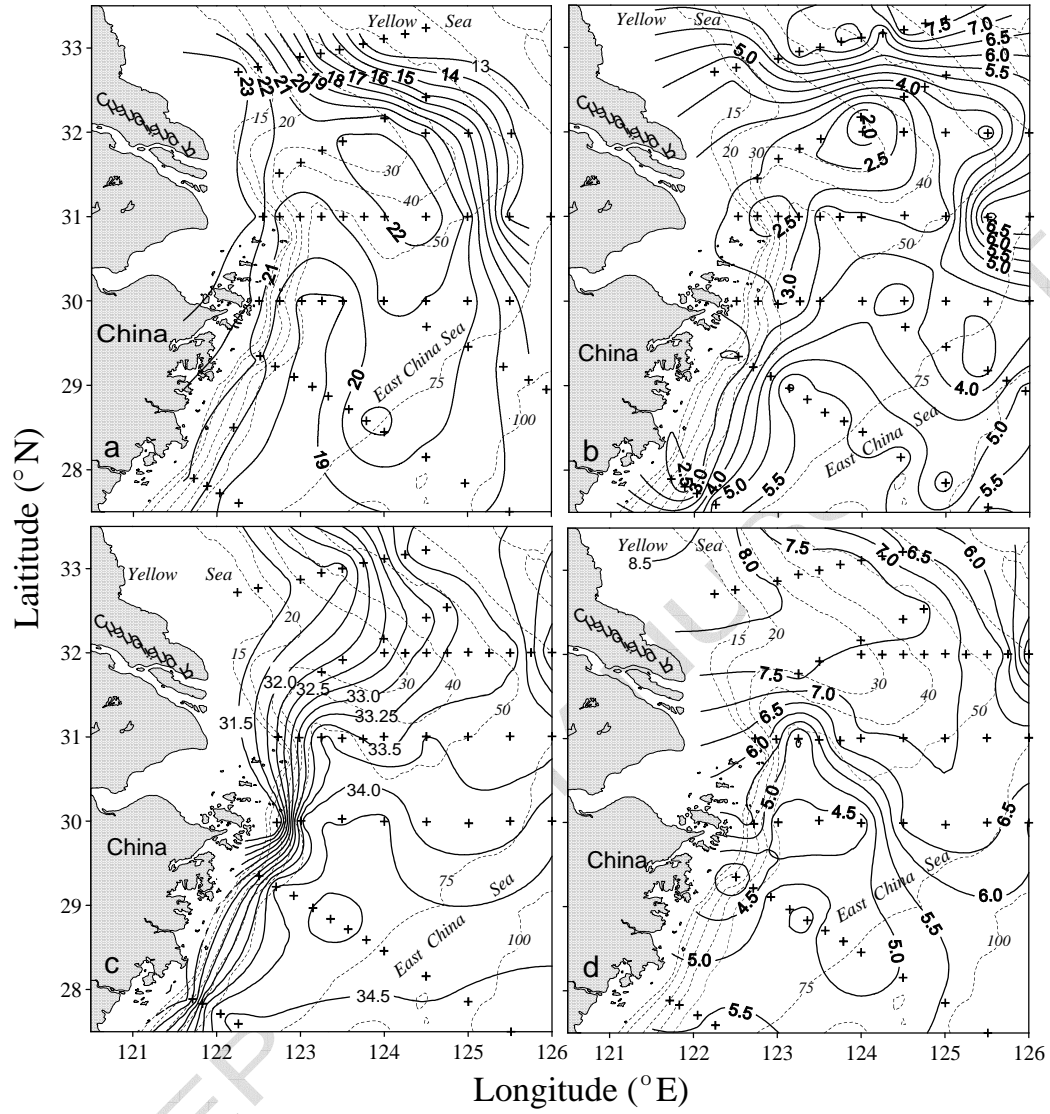


Figure 3

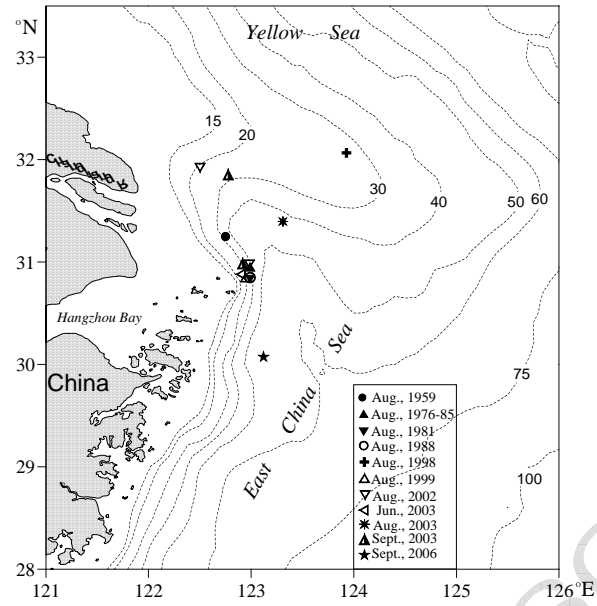


Figure 4