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► **To cite this version:**

Chung-Chi Chen, Gwo-Ching Gong, Fuh-Kwo Shiah. Hypoxia in the East China Sea: one of the largest coastal low-oxygen areas in the world. *Marine Environmental Research*, 2007, 64 (4), pp.399. 10.1016/j.marenvres.2007.01.007 . hal-00562971

**HAL Id: hal-00562971**

**<https://hal.science/hal-00562971>**

Submitted on 4 Feb 2011

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## Accepted Manuscript

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PII: S0141-1136(07)00041-4

DOI: [10.1016/j.marenvres.2007.01.007](https://doi.org/10.1016/j.marenvres.2007.01.007)

Reference: MERE 3108

To appear in: *Marine Environmental Research*

Received Date: 31 May 2006

Revised Date: 11 October 2006

Accepted Date: 14 January 2007



Please cite this article as: Chen, C-C., Gong, G-C., Shiah, F-K., Hypoxia in the East China Sea: one of the largest coastal low-oxygen areas in the world, *Marine Environmental Research* (2007), doi: [10.1016/j.marenvres.2007.01.007](https://doi.org/10.1016/j.marenvres.2007.01.007)

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## Hypoxia in the East China Sea: one of the largest coastal low-oxygen areas in the world

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Revised and resubmitted to "*Marine Environmental Research*" on 1/14/2007

## ABSTRACT

Anoxia and hypoxia have been widely observed in estuarine and coastal regions over the past few decades; however, few reports have focused on the East China Sea (ECS). In June and August 2003, two cruises sampled at stations covering almost the entire shelf of the ECS to examine hypoxic events and their potential causes. In August, DO concentrations  $< 2 - 3 \text{ mg l}^{-1}$  covered an area estimated at greater than  $12,000 \text{ km}^2$  (or  $432 \text{ km}^3$  volume). In contrast, water column DO concentrations exceeded  $4 \text{ mg l}^{-1}$  throughout most of the shelf region. A sharp density gradient was observed under the mixed layer in August, restricting vertical re-aeration across this strong pycnocline. Oxygen depletion events, such as that described here for the ECS shelf, are fueled by decomposition of newly produced marine and river-borne biogenic substances (as well as older residual organic matter) deposited to the bottom waters.

Key words: Oxygen depletion, Dissolved oxygen, Hypoxia, Chlorophyll, Coastal zone, The East China Sea, The Changjiang (Yangtze) Estuary

## INTRODUCTION

Hypoxia and anoxia have been widely observed in many estuarine and coastal regions over the last several decades (for review see Diaz, 2001; Rabalais et al., 2002). Even though hypoxic and anoxic environments have existed throughout geological time, it has been shown that the occurrence of hypoxia and anoxia in shallow, coastal and estuarine areas is most likely accelerated by human activities, through over-enrichment of anthropogenic nutrients (Diaz and Rosenberg, 1995). Excess nutrient loading often leads to eutrophication (e.g., Hecky and Kilham, 1988; Nixon, 1995; Kemp et al., 2005), which can result in oxygen depletion through decomposition of elevated organic matter from enhanced primary production. In addition to oxygen consumption, the formation of hypoxia and anoxia is also controlled, in part, by water column stratification which retards vertical oxygen diffusion from the surface to lower layers (Rosenberg et al., 1991; Rabalais et al., 2001). Major ecological impacts of hypoxic and anoxic environments include reduced biodiversity, alteration of community structure and ecology (e.g., Diaz and Rosenberg, 1995; Rabalais and Turner, 2001).

Interestingly, hypoxia and anoxia have rarely been documented in the East China Sea (ECS) which is one of the largest continental shelves in the world (e.g., Li et al., 2002).

Historically, the ECS has been one of the world's major fishing grounds, especially within

the Changjiang (Yangtze) River plume and its surrounding sea along China's coast. High fishery yield is normally supported by high primary production and abundant food sources from lower trophic levels (Caddy, 1993; Xu et al., 2004). Indeed, primary production can reach as high as  $2079 \text{ mg C m}^{-3} \text{ d}^{-1}$  in the Changjiang River plume region, mostly induced by high rates of riverine nutrient supply (e.g., Gong et al., 2003; Gong et al., 2006). In the past two decades, the anthropogenic nutrient load (e.g. nitrates) exported from the Changjiang River into the ECS has increased over ten-fold, and there is continuous growth expected in the future (Yan et al., 2003; Li and Dag, 2004; Bouwman et al., 2005). Excess nutrients cause eutrophication and stimulate noxious and toxic algal blooms, which have been observed with increased frequency on the inner shelf off Changjiang River (Chen et al., 2003; Gao and Song, 2005; Zhu, 2005; Zhu et al., 2005). There are, however, few studies reporting hypoxic conditions in the estuary and sea adjacent to the Changjiang River, much less associated causes and ecological consequences (Limeburner et al., 1983; Li et al., 2002; Li and Dag, 2004).

Hypoxia, in this study, is defined as a dissolved oxygen level less than  $3 \text{ mg l}^{-1}$  (equivalent to  $2.1 \text{ ml l}^{-1}$ ,  $3.0 - 0.2 \text{ ml l}^{-1}$  in Tyson and Pearson, 1991). To explore the potential causes of hypoxia in the sea adjacent to the Changjiang River, we compared hydrographic data observed prior to (June) and during (August) hypoxic events in 2003.

The estimated area of the hypoxic zone might be one of the largest in the world (Diaz, 2001; Rabalais et al., 2002 and citations therein).

## MATERIALS AND METHODS

**Study area, sampling, and hydrographic measurements.** This study is part of the Long-term Observation and Research of the East China Sea (LORECS) program. Samples were collected on board R/V *Ocean Researcher I* in June (6/18 – 6/26) and August (8/13 – 8/23) 2003 at a total of 21 and 35 stations in the East China Sea, respectively (Fig. 1). Using Teflon coated Go-Flo bottles (20 l, General Oceanics Inc., USA) mounted on a General Oceanic rosette assembly, seawater at each station was sampled at 6 to 10 water depths, at depth intervals of 3 to 20 m depending on the water column depth of each station. Subsamples were taken immediately for further analysis including dissolved oxygen, dissolved inorganic nutrient (e.g., nitrate and phosphate), and chlorophyll *a* (Chl *a*). Temperature, salinity and density were recorded throughout the water column with a SeaBird CTD (SBE 9/11 puls, SBE Inc., USA) with salinity calibrated by Autosal. It should be noted that the data used in this study have been partly published together with other components (Chen et al., 2006).

**Dissolved oxygen, nutrient, and chlorophyll *a*.** Water samples for dissolved oxygen

(DO) from every sampling depth were siphoned into 60 ml BOD bottles. They were fixed immediately by addition of 0.5 ml of manganese chloride and 0.5 ml of alkaline iodide reagent (Pai et al., 1993). Concentration of O<sub>2</sub> was measured using a direct spectrophotometry method with a precision of 0.02 mg l<sup>-1</sup> (Pai et al., 1993). Water subsamples for nutrient analysis were collected in 100 ml polypropylene bottles and frozen immediately in liquid nitrogen. A custom-made flow-injection analyzer was used for nitrate and phosphate analysis (Gong, 1992). Chlorophyll *a* was measured using fluorometry (Turner Design 10-AU-005) following acetone extraction (Parsons et al., 1984; Chen et al., 2005).

## RESULTS and DISCUSSION

### **Hypoxia in the East Chain Sea**

Low dissolved oxygen (DO) conditions in the ECS were first documented in the bottom waters of Changjiang Estuary in August 1981 (Limeburner et al., 1983). Previous the most comprehensive study of hypoxia in the ECS was in August 1999 (Li et al., 2002), and there have been only a few related reports (e.g., Tian et al., 1993). Li and colleagues (2002) showed that a large zone of low DO was oriented along the coast extending ~150 km offshore from the Changjiang River mouth in August of 1999. The low-oxygen region

that we observed in August 2003 appeared to have a different orientation, extending further (~400 km) offshore as a plume from the Changjiang River mouth. This 2003 hypoxic region, as defined by concentrations  $<3 \text{ mg l}^{-1}$ , covered an area of almost  $12,000 \text{ km}^2$  (Fig. 2b). The total volume of this hypoxic waters was about  $432 \text{ km}^3$  (using an averaged water column height of 36 m below mixed layer in August). The area of this low-oxygen region is close to that of the  $< 3.0 \text{ mg l}^{-1}$  zone estimated for the northern Gulf of Mexico, which was  $\sim 18,500 \text{ km}^2$  based on a 3-year average of bottom DO distributions (Fig. 2 in Rabalais et al., 2002). The largest corresponding  $< 2 \text{ mg l}^{-1}$  hypoxic zone reported for the northern Gulf of Mexico was  $21,000 \text{ km}^2$  (Diaz, 2001; Rabalais et al., 2002). In June of 2003, we observed DO concentrations in the bottom waters to be consistently higher than  $4 \text{ mg l}^{-1}$  in most of the ECS shelf region, with the exception of St. 29 which had values of  $3.84 \text{ mg l}^{-1}$  (Fig. 2a).

The pattern of bottom DO isopleths that we observed on the ECS shelf in August 2003 suggests that only a portion of the low-oxygen area was captured in our field sampling (Fig. 2b). It is apparent that DO concentrations were decreasing consistently in a northerly direction along the entire upper margin of our sampling area. Presumably, DO levels reaching  $1\text{-}2 \text{ mg l}^{-1}$  or lower were situated just north of our sampling transect. This interpretation is further supported by the fact that severely DO-depleted waters with such concentrations were reported in the previous study of this region (Fig. 2b; Li et al., 2002).

Thus, the actual hypoxic region during August 2003 may have been several times larger than our estimates, a point worthy of further focus in future studies.

To examine the vertical profile in the hypoxic area and adjacent sea, results for DO and other parameters (salinity, temperature, Chl *a*, nitrate, and phosphate) along transect stations in the northern ECS (Fig. 1) were compared between June and August (all mean values are accompanied by the calculated Standard Deviation). For the DO profiles along the transect, two general features could be derived. First, DO concentration was higher in June than August for most of the profiles at transect stations (Fig. 3a - e). Second, DO concentration was higher in the surface water and the values decreased with increasing depth, and this gradient was more pronounced in August. In June, subsurface oxygen maxima were observed at several stations including, Sts. 19, 21, 22, and 23 (Fig. 3a, c, d, and e). This indicated that DO was oversaturated due to high primary production at stations during this period. The saturation of DO was as high as 139 % (St. 19), and oversaturation (> 100 %) was observed in the surface 10 m of the water column at almost all measured stations in June (mean  $105.8 \pm 11.5$  %). During the hypoxic period (August) DO concentrations reached minimum values and extended throughout the water column from directly below the mixed layer depth (~7 – 17 m) to the sediment surface (~30 – 70 m) at most of the hypoxic stations (Fig. 3a, b, and c). The lowest DO concentration was observed

in the bottom water of Sts 18 and 21 with values of ca. 1.8 mg l<sup>-1</sup> (Fig. 3). The mean DO % saturation in the bottom water of hypoxic stations was 34.3% ( $\pm$  6.3 %). All our results indicate that hypoxia may not appear until middle to late summer in the Changjiang River plume and nearby sea (Li et al., 2002). To develop and maintain hypoxia, two principle factors are essential. First, the water column must be stratified to isolate the bottom layer from exchange with the oxygen-rich overlying surface water (Rosenberg et al., 1991; Diaz, 2001; Rabalais et al., 2002). Second, a large oxygen sink must be driven by decomposition of rich organic matter supply to the bottom waters (Turner and Rabalais, 1994; Diaz, 2001). These essential features have, however, rarely been examined in the hypoxic regions of the Changjiang River plume and adjacent areas of the ECS (Li et al., 2002).

#### **Causes of hypoxia in the ECS – isolation of oxygen supply to bottom waters**

Some marine systems have a great tendency to develop hypoxic conditions due to their geomorphology and circulation patterns. Diaz (2001) suggested that a marine system with low physical energy (tidal, currents, or wind) and large freshwater input is prone to hypoxia. Combinations of these features will result in stratification of the water column and the stabilization of water masses near the bottom which become hypoxic when they are isolated from reoxygenation with surface waters. In the ECS, a variety of water masses

(China coastal fresh water, the Kuroshio waters, the Yellow Sea waters, and the Taiwan Strait waters) contribute to this shelf ecosystem (e.g., Liu et al., 2003a). Among these sources, Chinese river discharge, especially the Changjiang River, might be one of the most important driving forces for the dynamic hydrography along the coast in the ECS. The average water discharge of the Changjiang River is ca.  $29,300 \text{ m}^3 \text{ s}^{-1}$ , annually, observed from the seaward-most station of the Changjiang River ([http://sqqx.hydroinfo.gov.cn/websq/river\\_jhcx/index\\_cx.asp](http://sqqx.hydroinfo.gov.cn/websq/river_jhcx/index_cx.asp)). This might explain general physical features observed year-round, which are low temperature and salinity in the inner shelf, and high temperature and salinity on the slope (Gong et al., 1996; Tseng et al., 2000). Spatially, sea surface temperature (SST) and salinity showed an increasing trend from the inner shelf to the slope in the ECS (see Fig. 2 in Chen et al., 2006), and a more dynamic hydrographic pattern was observed in the Changjiang River Plume.

These inshore-offshore gradients were especially pronounced during the high river flow period (late spring to the early summer) as our results showed in June (Chen et al., 1994; Tseng et al., 2000). Lower temperatures of saline waters predominated along the coast, especially in the Changjiang River Plume regions in the early summer (see Fig. 2a, b in Chen et al., 2006). To compare, SST in the hypoxic areas in June and August were in the range  $18.95 - 22.32 \text{ }^\circ\text{C}$  and  $27.27 - 29.31 \text{ }^\circ\text{C}$ , respectively (see Fig. 2a, c in Chen et al.,

2006). Lower salinity water was observed in early (June) rather than the middle (August) summer, the values in the hypoxic areas were in the range 26.98 to 32.26 and 31.27 to 32.81, respectively (see Fig. 2b, d in Chen et al., 2006). This indicates that more freshwater was discharged into the ECS during the early summer, and suggests that a large amount of low saline water, relative to water temperature, in the surface of water column in June might be the most important factor contributing to stratification. Indeed, this assumption may be evident from the vertical profiles of salinity at most stations, where a thin layer of low saline water on top of the water column was observed ( Sts.19, 20, and 21) in the hypoxic areas in June (Fig. 3f, j, and k). This feature has commonly been found in the Changjiang River plume regions in summer, and Beardsley et al. (1985) showed that this relatively shallow, low salinity plume-like structure extends to middle shelf, on average, towards the northeast (Chu et al., 2005). Surprising, this plume-like region is similar to the observed hypoxic area in our study.

Further analyses also showed that the mixed layer depths (MLD) were shallow in both June and August with mean values of  $7.6 \pm 2.6$  m and  $12.7 \pm 4.7$  m respectively (Table 1). Results also showed that salinity differences between the MLD and the bottom 10 m of the water column were larger in June than August with mean values of  $-2.4 \pm 2.1$  and  $-1.9 \pm 0.6$  respectively (Table 1). Interestingly, in addition to haline gradient, a thermal gradient

might also contribute significantly to stratification of the water column in August, which was mainly due to haline stratification in June. Stratification of the water column might be attributed to either the halocline or thermocline or both in different conditions or seasons (Wiseman et al., 1997). This may be evident in either the vertical profiles of salinity and temperature at transected stations (Fig. 3f–j, k–o) or from the large temperature difference between the MLD and the bottom 10 m in the water column in August compared to June, which had a mean value of  $6.9 \pm 1.9$  °C and  $4.4 \pm 2.8$  °C, respectively (Table 1). Sharper density gradients in the water column were observed in August compared to June where density differences between MLD and the bottom 10 m of the water column were  $-3.5 \pm 0.9$  kg m<sup>-3</sup> and  $-2.9 \pm 1.6$  kg m<sup>-3</sup> respectively (Table 1).

These data indicate that the water column was more stratified in August compared to June, and this phenomenon resulted from both temperature and salinity gradients in August. Our results also indicate that strong stratification of the water column in August was essential for hypoxic zone development, as it isolates the bottom layer from exchange with oxygen-rich overlying surface water.

### **Causes of hypoxia in the ECS – reduction of oxygen level in bottom waters**

Although seasonal variation in stratification and hydrodynamic transport were

important in establishing low oxygen conditions in the bottom layer, maintenance of these conditions required an elevated supply of organic matter. The source of organic matter in the hypoxic region might have been derived from sinking of *in situ* production or discharge from fluvial input, as seen in the northern Gulf of Mexico (Rabalais et al., 2002 and citations therein). The Changjiang River plume in the high flow period is dominated by two different sources of particulate organic carbon, river-borne detritus and marine plankton production (e.g., Cauwet and Mackenzie, 1993). Although we have no direct observations that would reveal the relative importance of these two sources of organic matter in the Changjiang River plume and adjacent ECS, indirect information can shed light on this question. For example, high water discharges observed at the seaward-most station of the Changjiang River ([http://sqqx.hydroinfo.gov.cn/websq/river\\_jhcx/index\\_cx.asp](http://sqqx.hydroinfo.gov.cn/websq/river_jhcx/index_cx.asp)), show relatively high flow in both June ( $37.1 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ ) and July ( $56.6 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ ) 2003 (compared to annual mean value =  $29.0 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ ). Therefore, significant amounts of freshwater flow into the ECS produce the low salinity plume-like structure observed in the same study (see Fig. 2 in Chen et al., 2006).

During high river flow periods, sediment load is especially pronounced in the Changjiang River (Chen et al., 2001). Monthly concentrations of suspended sediment averaged over thirty years can be as high as  $0.65 \text{ kg m}^{-3}$  at the river mouth during the wet

season which runs from May to October (e.g., Cauwet and Mackenzie, 1993; Chen et al., 2001). Even though most of the discharge sediment is deposited along the shore southward, patches of suspended sediment influenced by the Changjiang plume can reach eastward and northeastward from the middle to the outer shelves of the ECS in summer (Deng et al., 2006 and citations therein).

Seasonally, both biomass and production of phytoplankton were the highest in the late spring and early summer in the coastal region of the ECS (Gong and Liu, 2003; Gong et al., 2003). In our study, Chl *a* values were significantly higher in the early summer (June) than they were in August for both integrated and averaged values over the euphotic zone for the entire ECS (Chen et al., 2006). The difference in Chl *a* concentration between the periods was particularly pronounced at the hypoxic zone stations,  $6.44 \pm 12.00$  mg Chl  $\text{m}^{-3}$  in June compared to  $0.71 \pm 0.33$  mg Chl  $\text{m}^{-3}$  in August. Peak Chl *a* concentration reached 90.3 mg Chl  $\text{m}^{-3}$  at St. 20 in June (Fig. 4b). Substantial algal blooms dominated by *S. costatum* were also observed during a comparable period and location in previous studies (Gao and Song, 2005; Zhu et al., 2005). Even though occurrence of phytoplankton blooms in the Changjiang River plume varied temporally and spatially, they frequently appeared in a region bounded by  $30.5^{\circ} - 32.0^{\circ}\text{N}$  and  $122.25^{\circ} - 123.25^{\circ}\text{E}$  during the period May to August (Gao and Song, 2005 and citations therein). This suggests that a tremendous amount of

marine biogenic organic matter is deposited into the bottom water or sediment around the Changjiang River plume, which usually tends towards the northeast during this period (Beardsley et al., 1985; Chu et al., 2005). Large quantities of DO are therefore consumed during the decomposition processes, as evident from high values of apparent oxygen utilization (AOU) observed in the bottom water at the hypoxic stations in August ( $4.67 \pm 0.48 \text{ mg l}^{-1}$ ).

The main cause of phytoplankton blooms in the Changjiang River plume might be associated with the huge amount of nutrients from fluvial input. The average dissolved N flux is  $10 \times 10^9 \text{ mole month}^{-1}$  in the flood season (Gong et al., 2003; Liu et al., 2003b; Zhu et al., 2005; Chen et al., 2006). Significant linear relationships have been observed between nutrient concentrations and salinity in the surface water (Chen et al., 2006). Vertical profiles of nitrate and phosphate concentrations also showed that values were higher in the surface water of the Changjiang River plume and the adjacent sea area of the ECS during the high river flow period (June). Nitrate and phosphate concentrations were both relatively high in June reaching levels of  $10.4 - 22.2 \mu\text{M}$  and  $0.1 - 0.8 \mu\text{M}$ , respectively. In contrast, nitrate and phosphate concentrations in the surface water were low in August. Although surface nutrients were lower in August than in Jun, the bottom water concentrations in August exceeded those in June, especially at the hypoxic stations (Fig. 4f

- o). Previous studies have shown that low redox conditions, tend to cause higher effluxes of ammonium and phosphate from sediment to overlying water in coastal ecosystems (e.g., Kemp et al., 2005 and citations therein).

Our results suggest that the reduction of oxygen level in the bottom water might be due to increasing rates of bacterial decomposition as a consequence of elevation of organic matter from both fluvial input and marine origin during high river flow periods of late spring and early summer. In addition, water temperature not only plays an important role in water stability and O<sub>2</sub> dissolution, it also affects the rate of bacterial decomposition and growth. Rates of bacterial decomposition and growth are enhanced by higher water temperatures (White et al., 1991; Shiah et al., 2000). This could partially explain why hypoxia was not as evident during the high organic matter input period in June, since water temperature was low in the bottom water with average values ~16.6 °C at the hypoxic stations. Average water temperature in the bottom water was about 7 °C higher in August than June at the hypoxic stations (Fig. 3k - o). The decomposition rate may thereafter be accelerated by higher water temperature in the bottom water in August.

## CONCLUSION

In this study, a hypoxic area estimated at greater than 12,000 km<sup>2</sup>, with DO

concentrations  $< 2 - 3 \text{ mg l}^{-1}$ , extended from the Changjiang River plume  $\sim 400 \text{ km}$  offshore and  $\sim 300 \text{ km}$  southward along the coast of the ECS was observed in August 2003.

This hypoxic area is comparable to the largest coastal hypoxic zones observed in the world (Diaz, 2001; Rabalais et al., 2002 and citations therein). Vertically, DO concentrations promptly reached minimum values which extended throughout the water column directly below the mixed layer depth ( $\sim 7 - 17 \text{ m}$ ) in the hypoxic region. To further understand development and maintenance of hypoxia, two principle processes were examined. Our results indicated stratification through sharp density gradients in the water column in August where density difference between the MLD and the bottom 10 m of the water column were  $-3.5 \pm 0.9 \text{ kg m}^{-3}$ . Interestingly, this phenomenon was controlled primarily by temperature as well as salinity. Second, our data suggested that two important sources of organic matter, river-borne detrital and marine biogenic, are deposited in the hypoxic region in the Changjiang River plume and adjacent areas of the ECS. This was indirectly evident from the observed algal bloom in June in the hypoxic area, and was also supported indirectly by the high water discharge from the Changjiang River observed during the study period. Overall, our results suggest that hypoxia in the ECS might be mainly due to decomposition of elevated inputs of organic matter which resulted in reduction of oxygen levels in the bottom water, in conditions a strong pycnocline which restricted vertical

re-aeration. It also should be noted that the actual hypoxic area might have been significantly underestimated in our study, suggesting the need for broader sampling schemes in future studies of this ECS region.

#### ACKNOWLEDGEMENTS

This research was supported by the National Science Council (NSC), Taiwan under grant Nos. NSC-93-2611-M003-001 and NSC-94-2611-M003-001 to C.-C. Chen. This work done by G.-C. Gong was supported under grant no. NSC-95-2611-M-019-020-MY3 and by the Center for Marine Bioscience and Biotechnology at NTOU. We would like to thank Miss Y.-F. Tseng, C.-J. Tseng and Mr. K.-J. Liu for assistance with the analyses of dissolved oxygen, nutrients and chlorophyll *a* measurement. The authors are also grateful to Prof. W. M. Kemp and two anonymous reviewers for providing valuable and constructive comments to improve the manuscript. We are also indebted to the officers and crew of the *Ocean Researcher I* for their assistance. Part of this work done by C.-C. Chen was also supported by the NSC, Taiwan under grant No. NSC-95-2918-I-003-007 as a visiting scientist at Horn Point Lab., University of Maryland Center for Environmental Science.

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Table 1. The mean  $\pm$  SD values of difference in variables between averaged values of mixed layer and the bottom 10 m of the water column including temperature ( $^{\circ}$ C), salinity, and density ( $\text{kg m}^{-3}$ ) in June and August at hypoxic stations (i.e., Sts. 18, 19, 20, 21, 22, 23, and 19A). The mixed layer depth (MLD) was based on a 0.125 unit potential density criterion (Levitus, 1982), and the values of MLD are also shown for reference.

Variables				
Months	Temp	Salinity	Density	MLD
June	$4.4 \pm 2.8$	$-2.4 \pm 2.1$	$-2.9 \pm 1.6$	$7.6 \pm 2.6$
August	$6.9 \pm 1.9$	$-1.9 \pm 0.6$	$-3.5 \pm 0.9$	$12.7 \pm 4.7$

## FIGURES LEGENDS

Fig. 1. Map of stations in June (x) and August (o) 2003 in the East China Sea (ECS) with station number above the mark. Transect stations (i.e., Sts. 19, 20, 21, 22, and 23) for further data comparison is marked in grey line. Bottom depth contours (dashed lines) are also shown. It should be noted that the Changjiang River also has been known as Yangtze River.

Fig. 2. Contour plots of dissolved oxygen concentrations (DO;  $\text{mg l}^{-1}$ ) in the bottom waters of the ECS in June (a) and August (b) 2003. The contour interval of DO is  $0.5 \text{ mg l}^{-1}$ . The polygon in panel (b) also shows the estimated low oxygen zone ( $\text{DO} < 3 \text{ mg l}^{-1}$ ) from Li et al. (2002).

Fig. 3. Depth profiles of dissolved oxygen (DO; panels a - e), salinity (Sal; panels f - j), and temperature (Temp; panels k - o) in June (dashed line) and August (solid line) along transect stations as shown on top of panels. Please refer to Fig. 1 for transect stations. The mixed-layer depth is showed as horizontal lines for June (dashed line) and August (solid line).

Fig. 4. Depth profiles of concentrations of Chl *a* (panels a - e), nitrate ( $\text{NO}_3^-$ ; panels f - j), and phosphate ( $\text{PO}_4^{3-}$ ; panels k - o) in June (dashed line) and August (solid line) along transect stations as shown on top of panels. Please refer to Fig. 1 for transect stations.

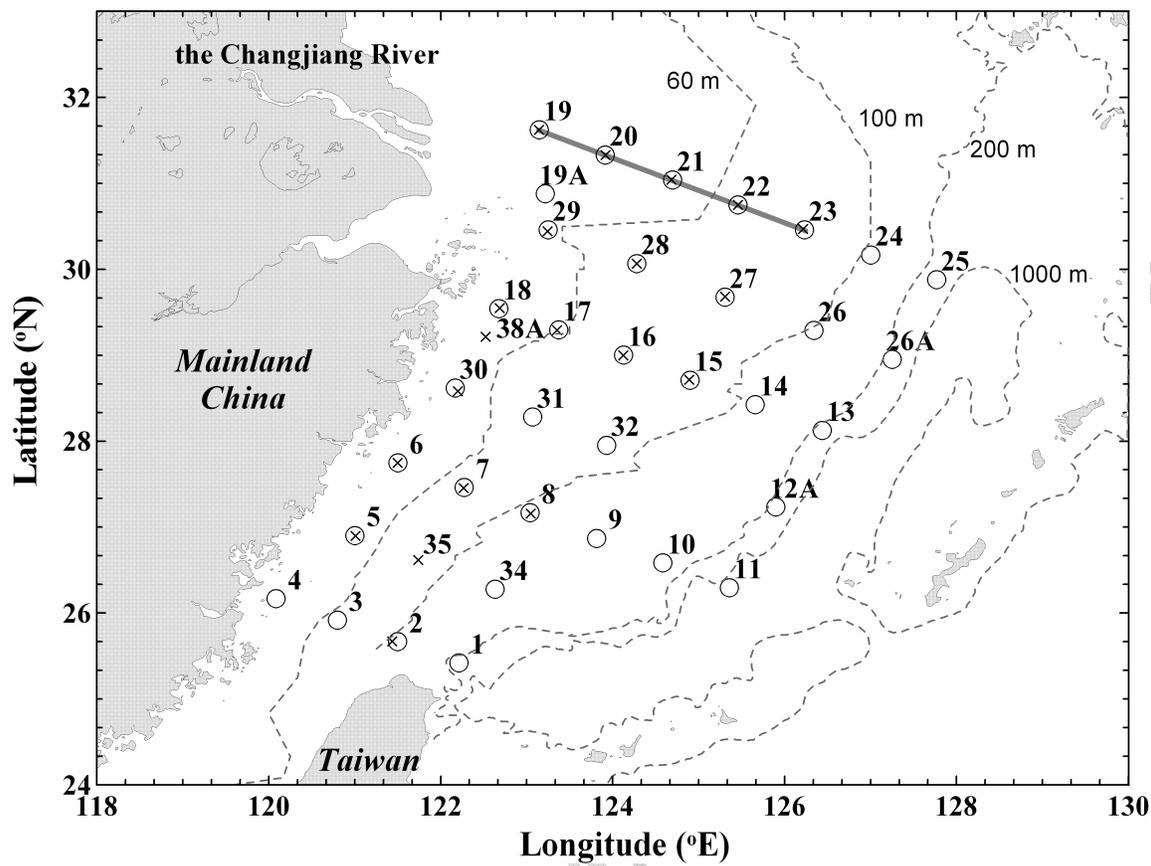


Fig. 1

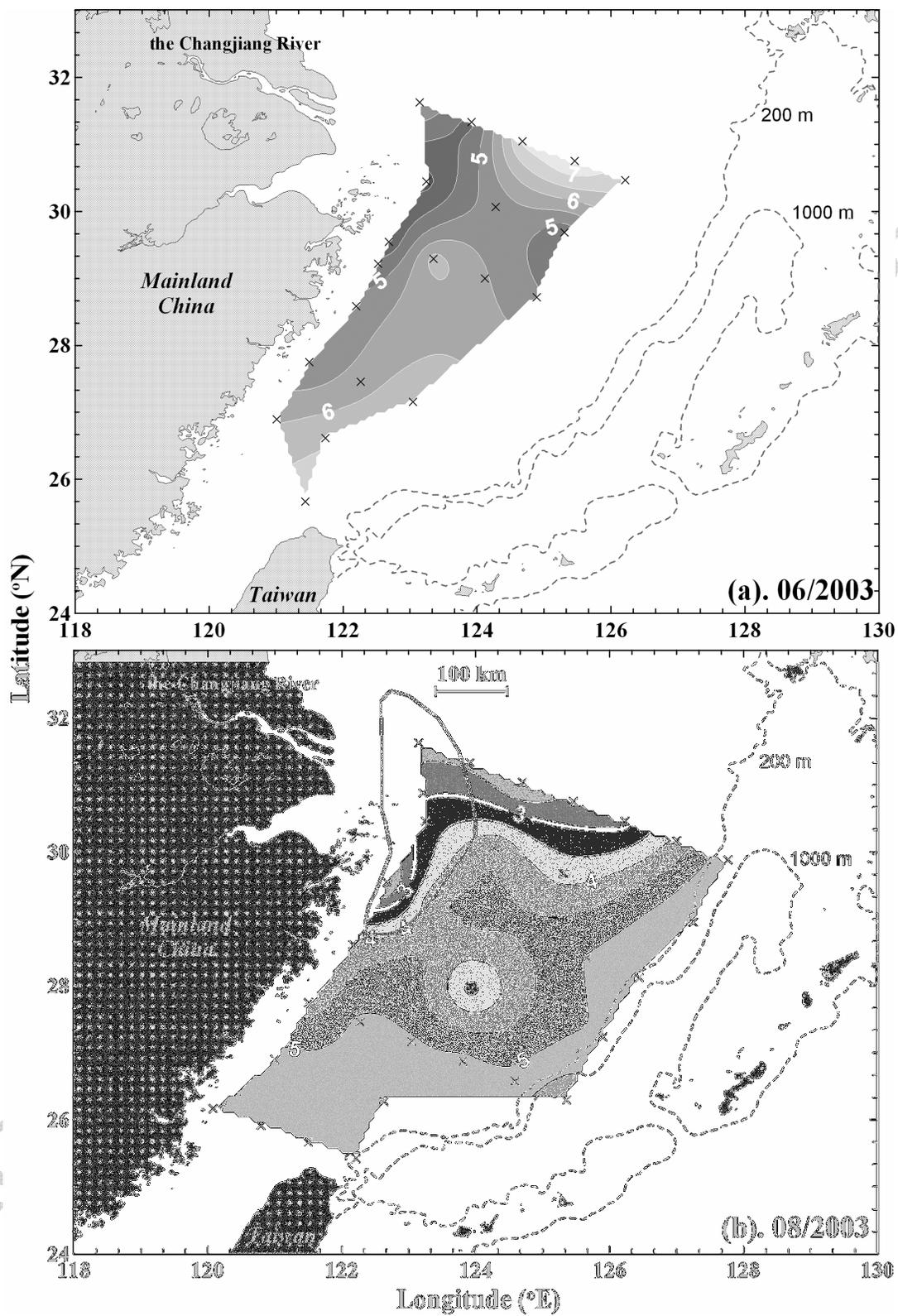


Fig. 2

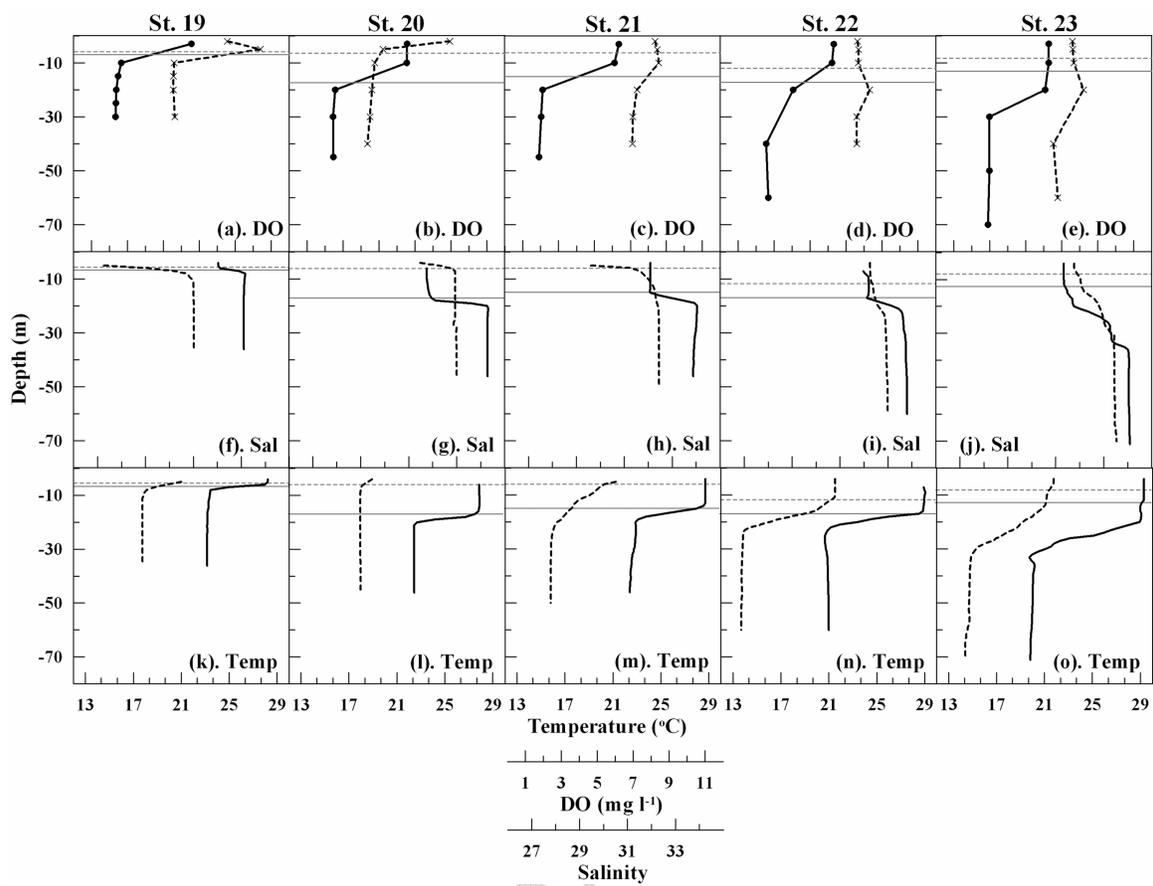


Fig. 3

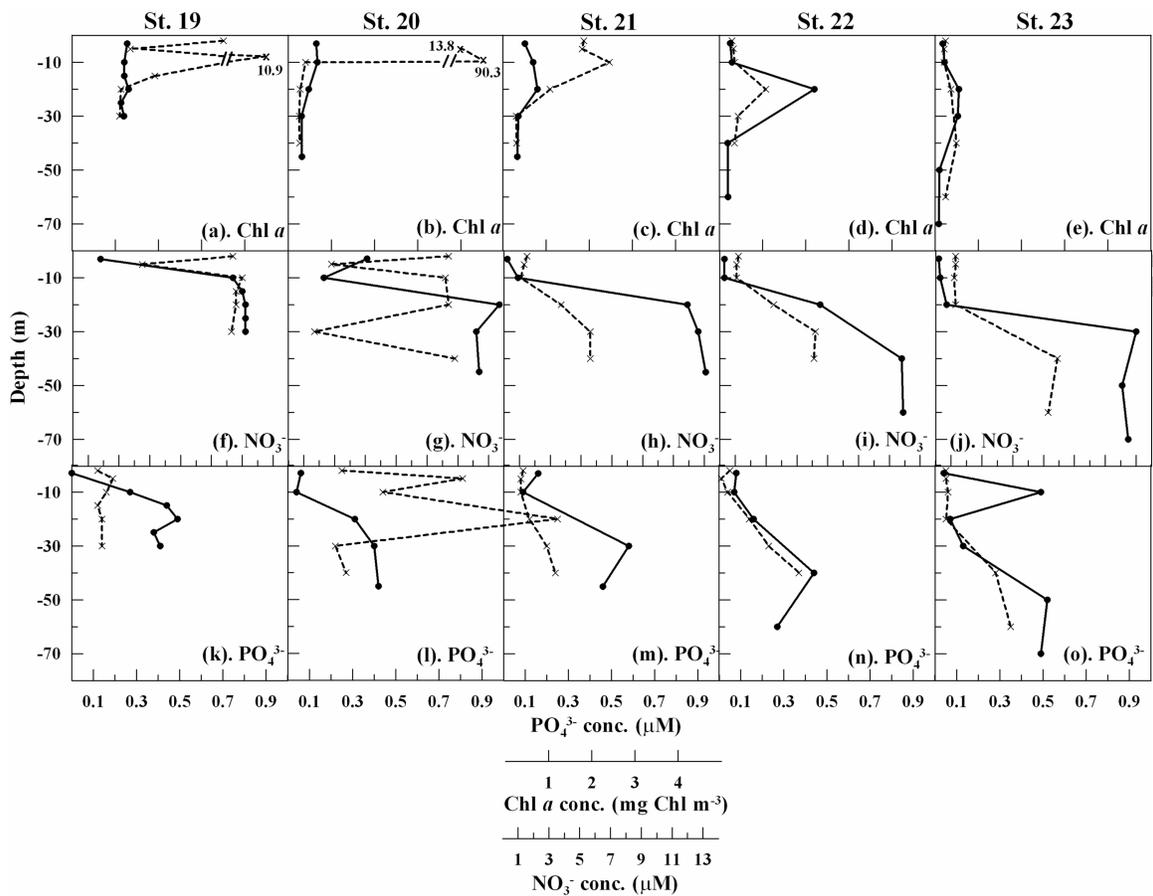


Fig. 4