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The temporal-spatial distribution and changes of dissolved oxygen in the Changjiang Estuary and its adjacent waters for the last 50 a

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Abstract

The Changjiang Estuary and its adjacent waters form one of the most important estuarine and coastal areas in China. Multi source and long-term data are assembled to examine the temporal-spatial distribution features of dissolved oxygen (DO) in the Changjiang Estuary and its adjacent waters for the past 50 a. The results show that the DO concentration in the surface of different seasons generally stays stable, while the DO concentration in winter displays a slight increase for the last 50 a. The DO average concentration in winter and spring varies from 7 to 11 mg/L, and in summer and autumn from 6 to 8 mg/L. Hypoxic values first appear in May, and low DO value plume can be observed on the bottom in spring along coastal areas of Zhejiang and Fujian Provinces, China. In summer, the plume advances northward, and the hypoxic intensity of northern transects is much higher than southern transects. Until autumn, hypoxia areas fade away little by little, and completely disappear in winter. Within last 50 a, hypoxia in the Changjiang Estuary and its adjacent waters starts to appear in the 1980s. Since 2000, the degree of hypoxia has increased seriously and the distribution depth has become smaller. It is performed based on a large amount of historical data, and the research results will be of great significance to further study on the dynamic development of hypoxia around the Changjiang Estuary.

Key words: coastal region, long-term trend, dissolved oxygen, hypoxia

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1 Introduction

Seawater dissolved oxygen (DO) is one of the key parameters in seawater chemistry and also an indispensable substance for marine life. The change of the DO concentration can be a complex interaction of physical, chemical and biological processes. Therefore, studies on the seawater DO concentration are of great significance in solving chemical, biological, hydrological and geological problems in the ocean (Wei et al., 2010).

Near shore and estuarine hypoxia is usually defined as the DO concentration lower than 3 mg/L. When the DO concentration is below 0, it is known as anoxia (Wang et al., 2012). Severe hypoxia may cause a dramatic deterioration of aquatic environment (Stramma et al., 2010), therefore it has become a common factor in affecting an estuarine/nearshore ecosystem (Rahalais et al., 2010). Currently, hypoxia has been accelerated year after year, and over 400 hypoxia zones were reported worldwide (Diaz and Rosenberg, 2008). In-depth studies on hypoxia were conducted including the Gulf of Mexico (Turner et al., 2005), the Chesapeake Bay (Hagy et al., 2004; Najjar et al., 2010), the Baltic Sea (Bendtsen and Hansen, 2013; Meier et al., 2011), the Black Sea (Diaz, 2001), the estuarine bays in southern South Korea (Lim et al., 2006), the Seto Inland Sea in southern Japan (Kasai et al., 2007), and so on. In China, hypoxia zones were observed in the Liaohe Estuary (Lei et al., 2004; Li and Wang, 2006; Yang et al., 2011), the Xiaoqing Estuary (Meng et al., 2005), the Changjiang Estuary (Li et al., 2002), the Sansha Bay (Wang et al., 2014), and the Zhujiang Estuary (Lin and Li, 2002; Ye et al., 2012), whose distribution features and formations have been studied and reported.

The Changjiang Estuary and its adjacent waters serve as one of the most important estuarine and coastal regions in China. Since the 1980s, Chinese scholars have begun raising awareness about the DO issue, but at that time they have mostly focused on the minimal DO concentration values (Zhang, 1990). In the last decade or so, there have been an increasing number of studies and reports about the distribution of hypoxia in the Changjiang Estuary, as well as the changing mechanisms, relations to physical-chemical factors and biotic impacts. It has been reported that hypoxia around the Changjiang Estuary and its adjacent waters usually occurs between July and September, with the lowest DO concentration value of 0.34 mg/L (Song, 2008) and a total area of 1 028–58 300 km^2 (Ma et al., 2013; Zhu, 2007). All the hypoxia over 5 000 km^2 occurred at the end of the 1990s (Liu, 2011). A number of experts had explored the formation and acceleration of hypoxia around the Changjiang Estuary. Liu et al. (2012a) found that hypoxia in the Changjiang Estuary has been expanding and worsening, the formation was mainly subject to physical and natural processes. Zhang et al. (2012) considered the stratification caused by diluted water of the Changjiang River as the most important factor in forming hypoxia. In addition, the over-

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consumption of DO by organic decomposition process after red tide outbreaks was also attributed to continuous hypoxia. Comparing with historical statistics, Zhang et al. (2007) found a significant drop of the DO concentration in hypoxia zones, which was related to enormous increase of nutrient loading for the last 20 a. Liu et al. (2012b), Hua et al. (2006) and Wang et al. (2008) focused on the biological effect, and revealed the relationship between a benthic community distribution and the hypoxia zones in the Changjiang Estuary. However, the aforementioned studies were mainly based on only one or a few investigations. In this study, a variety of multi source and long-term data was assembled in the last 50 a from 1965 to 2014. Meanwhile, the temporal-spatial distribution features of DO concentration were analyzed in the Changjiang Estuary and its adjacent waters. The results can be of great significance for further study on the evolutionary mechanisms and dynamic changes of hypoxia around the Changjiang Estuary.

2 Methods

The Changjiang River is the most important terrigenous matter source in the continental shelf of the East China Sea. The Changjiang Estuary and its adjacent waters are also one of the most important estuarine and coastal regions in China. The area is characterized by a sub tropical climate, distinctive seasons, numerous islands, and such famous fisheries as the Lusi Fishery, the Changjiang Estuary Fishery, and Zhoushan Fishery. Topographically, there is a 55 m deep trough in the northwest–outh-seast direction at approximate 123°E off the Changjiang Estuary, which forms a great depth gradient as compared with surrounding waters (Ma, 2013). The circulation regimes in the Changjiang Estuary and its adjacent waters comprise the eastern Kuroshio system and the western coastal current system, including the Yellow Sea coastal water, the northern Jiangsu coastal water, the Zhejiang and Fujian coastal water and the Changjiang Diluted Water. The Kuroshio system mainly works through its tributary, known as the Taiwan Warm Current. The northern Jiangsu coastal water, the Zhejiang and Fujian coastal water and the Yellow Sea cold water may impact the diversion of the Changjiang Diluted Water during spring and summer (Li, 2010).

For convenience, a square area (28°–33°N, 121°–126°E) was selected for further study in the Changjiang Estuary and its adjacent waters (Fig. 1). The data collected included the following: (1) world ocean data (WOD) from May 1965 to September 2008; (2) climate variability and predictability (CLIVAR) data in January 2006; (3) national marine environmental monitoring data set from September 2000 to May 2015; (4) national environmental impact assessment data set of marine engineering from November 2010 to June 2013; (5) the second pollution baseline investigation data in June–October 1998; (6) national island resource investigation data from February 1990 to August 1991; (7) national economic zones and continent shelf exploration projects data from October 1997 to September 2000; (8) national coastal integrated investigation and evaluation data from July 2006 to August 2008; and (9) marine transect monitoring data from January 1960 to November 2013.

Deriving from various countries and institutions, our data were able to supplement each other in both temporal and spatial scales. Multi source data facilitated the large-scale and long-term study on DO distribution and influencing factors, but also brought a new problem. Owing to the differences in sampling methods, laboratory analysis methods and other aspects, there were many differences in the data format, data structure, the number of valid parameters and measuring units. Therefore, all the basic information (including sampling time, longitude, latitude and water depth) was unified firstly, and the data format, measuring units, and significant digits were normalized afterward.

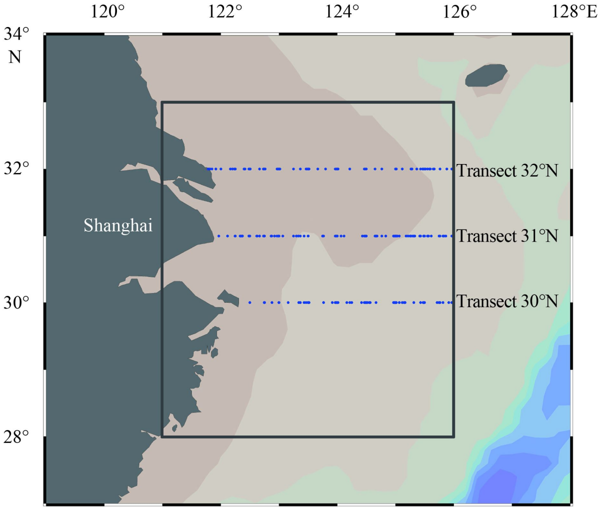


Fig. 1. Map of study area and transect stations. The grey box refers to temporal-spatial distribution area of DO and the blue dots refer to the transect stations.

After normalization, the data quality was further controlled. A quality control followed such procedures: (1) duplicate records check; (2) geographic information check (deleting missing or on land records); (3) time information check (deleting missing records or those out of the starting–ending time); (4) sampling depth data check (deleting missing data or that exceeding the water depth); (5) range check (screening unreasonable data of DO concentration, water temperature and salinity based on the climatology range and spatial statistics recommended by the World Ocean Atlas (WOA)); (6) outliners check by scatter diagrams; and (7) identifying the causes of suspicious data screened in Steps (5) and (6), verifying the availability with the help of experts' experiences.

3 Results and discussion

3.1 *Temporal distribution*

3.1.1 *Annual variation trend*

The annual variation of the DO concentration in the surface was shown (Fig. 2). For the last 50 a, DO concentration on the surface of different seasons generally stayed stable, while the DO concentration in winter displayed a slight increase. Prior to 1990, the annual variation of the DO concentration on the surface was reasonably small, but has started to increase since then. The average concentration in winter and spring was overall higher than that in summer and autumn on the surface. The DO average concentration in winter and spring varied between 7 and 11 mg/L, and in summer and autumn between 6 and 8 mg/L. The surface DO average concentration reached the maximum (11.3 mg/L) in the winter of 2008, and the minimum (5.6 mg/L) in the summer of 1990.

3.1.2 *Monthly variation trend*

The monthly variation trend of DO concentration over years was recorded (Fig. 3). In the last 50 a, apart from January and

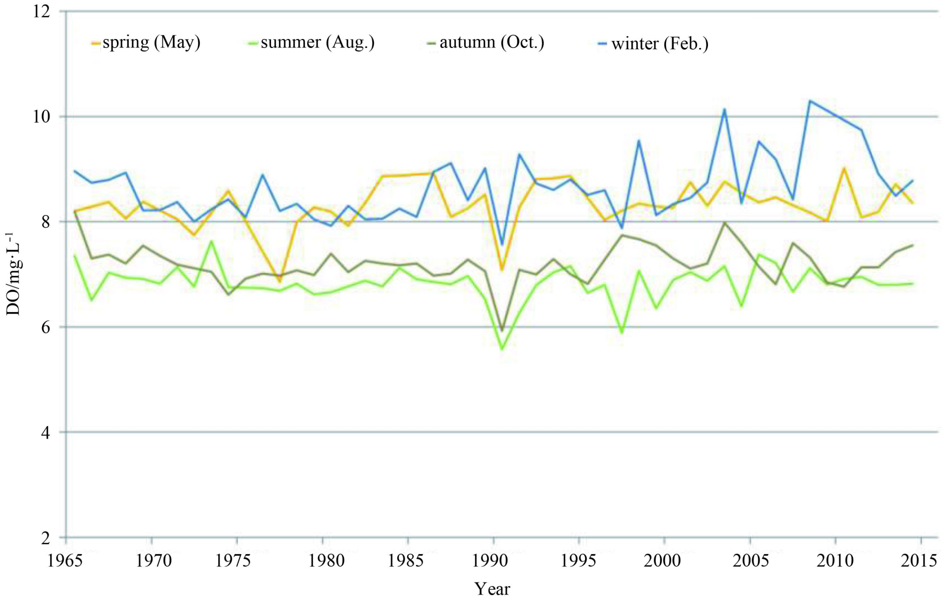


Fig. 2. Annual variation trend of DO concentration in the Changjiang Estuary and its adjacent waters during 1965–2014.

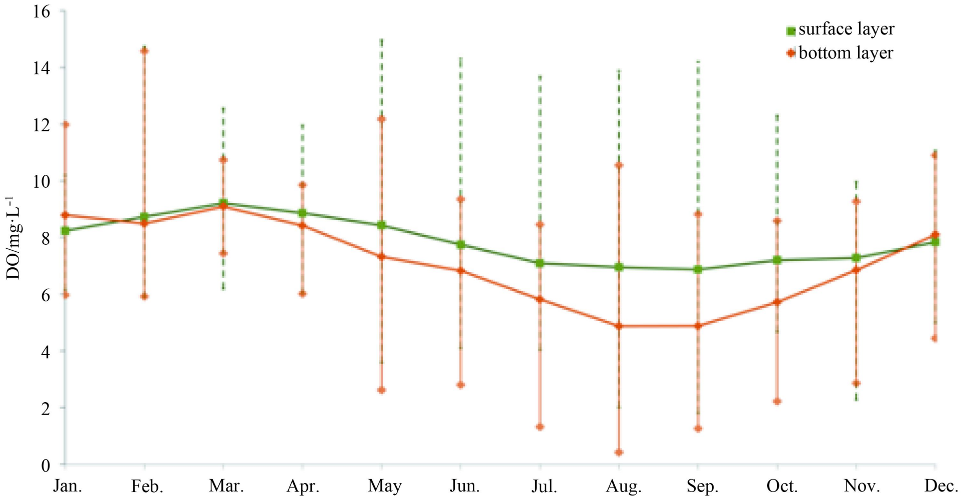


Fig. 3. Monthly variation trend of DO concentration in the Changjiang Estuary and its adjacent waters in 1965–2014.

December, the monthly values of bottom were generally smaller than those on the surface, but their distribution patterns were rather similar. The maximal monthly mean value of DO concentration was 9.21 mg/L, which appeared on the surface in March. The minimum was 4.87 mg/L, which appeared on the bottom in August.

The above results show that the DO concentration in summer and autumn is generally smaller than that in winter and spring, and hypoxia is more likely to occur in summer and autumn. The DO distribution in the Changjiang Estuary and its adjacent waters was mainly subject to the influence of coastal currents, water vertical movement and organic decomposition (Liu et al., 2012a; Ma et al., 2013; Zhang et al., 2012). As the aforementioned factors remained every year, DO variation exhibited a regular pattern to some extent. In summer and autumn, affected by high-salinity and low-oxygen waters of the Taiwan Warm Current, massive organic decomposition and the formation of thermocline and halocline impeded the oxygen exchange, resulting in the relatively low DO concentration.

The results also show that, the maximal concentration is usually distributed on the surface, whereas the minimum on the bottom. As we know, the surface DO is mainly affected by the Changjiang Diluted Water and the multiplication of phytoplankton, while DO concentration on the bottom is mainly affected by bottom currents, seasonal spring layers and organic settlement and decomposition. As the supply of DO on the bottom is very limited and the consumption can be quite high, the minimal values usually appeared on the bottom, and the variation was relatively larger as well.

3.2 *Spatial distribution*

3.2.1 *Horizontal distribution*

Objective analysis methods were used in this study to depict the spatial distribution of DO. Levitus (1983) utilized a successive correction method (one of the objective analysis methods) to compute the global seawater temperature and salinity. His results have been widely applied since then, such as the renowned

World Ocean Atlas (WOA). The main procedure of Levitus' method was to correct the guess value by using the distance-weighted mean value of all grid points that lie within the area around the grid point defined by the influence radius, thereby acquiring the next guess field. That cycle then repeated until the correction approximated the observed field. The calculation formulae are as follows:

$$G_{i,j} = F_{i,j} + C_{i,j}, \tag{1}$$

where i and j represent the coordinates of the analyzed grid point; $G_{i,j}$ represents the analyzed value; $F_{i,j}$ is the guess value; and $C_{i,j}$ is the correction value.

$$C_{i,j} = \frac{\sum\limits_{s=1}^{n} w_s Q_s}{\sum\limits_{s=1}^{n} w_s}, \tag{2}$$

where n represents the number of observations that fall within the area around the point; i, j defined by the influence radius; Q_s represents the difference between the observed value and the guess at the sth point; and w_s is the weight function. The expression for w_s is

$$w_s = \exp\left(-4r^2R^2\right) \qquad r \leqslant R, \tag{3}$$

where r represents the distance of the observation from the grid point; and R is the influence radius.

In this study, based on 0.2°×0.2° squares, the mean DO concentration values in each season were separately calculated on the surface and the bottom. Mean DO concentration values of all the squares were used as the initial guess field, and the spatial grid distribution results were derived by a stepwise iteration.

The horizontal distribution of DO concentration in each season was depicted (Fig. 4). In winter, the mean value on the surface was 8.61 mg/L and on the bottom 8.46 mg/L. The horizontal distributions of the surface and bottom were essentially consistent. The higher DO concentration values were mainly distributed in the Changjiang Estuary and the Hangzhou Bay, while the lower values (<7 mg/L) were in the south of the Zhoushan Islands.

In spring, the mean value on the surface was 8.64 mg/L, which was slightly higher than that in winter, and the mean value on the bottom was 7.84 mg/L. With the water temperature rising and various water masses strengthening, the vertical distribution was quite uneven, so that the values on the surface were dramatically higher than those on the bottom. A plume was spreaded along the coastal areas of Zhejiang and Fujian Provinces, characterized by the DO concentration of 7 mg/L. This could be regarded as the flow path of the Taiwan Warm Current.

In summer, the DO concentration values continued to decrease with the surface mean value of 7.07 mg/L and the bottom mean value 5.53 mg/L, ending in the extremely uneven distribution. On the bottom, the plume found in spring has moved northward, with the DO concentration decreasing below 5 mg/L. Meanwhile the plume could reach as far as 33°N (the northern boundary of this study).

In autumn, the DO concentration rose slightly compared with summer and displayed the surface mean value of 7.12 mg/L and the bottom mean value of 5.73 mg/L. The surface DO showed an even distribution with DO concentration values varying between 6 and 8 mg/L. The low DO plume on the bottom started to fade away, with the northern limit at approximately 31.5°N and the affecting areas moving eastward.

On the basis of multi source data for the last 50 a in 1965 and 2014, this study has constituted the objective analysis field for DO over the years. Compared with previous studies, the spatial features were in good agreement with the historical reports on the low DO concentration zones (Wei et al., 2015; Ye et al., 2012).

3.2.2 *Vertical distribution*

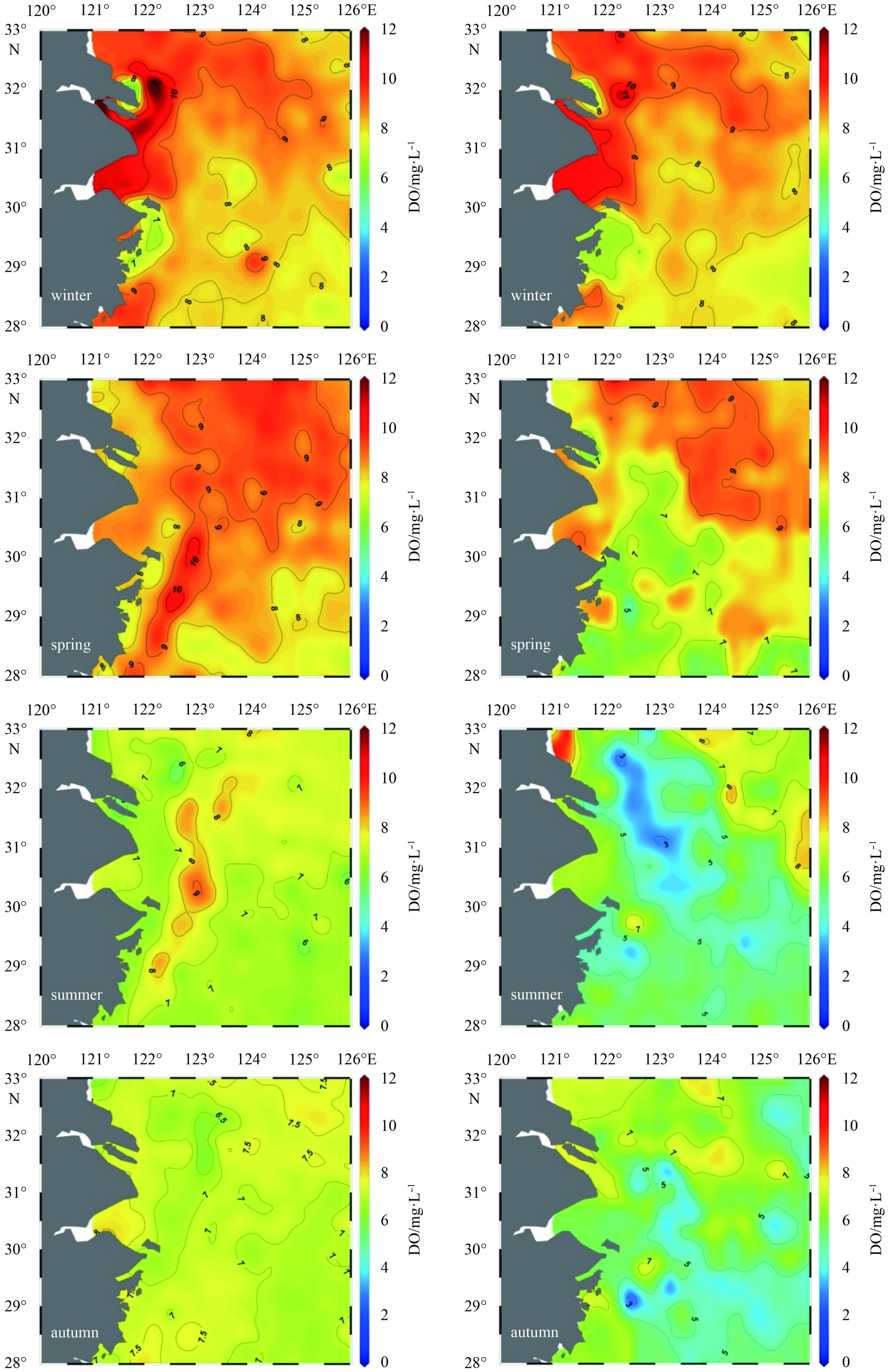
The relationship between the DO concentration in each month and the water depth were displayed by scatter diagrams (Fig. 5). As shown in the figure, in winter, the variation ranges of the DO concentration were relatively small, as the same in spring. Low value (<3 mg/L) of DO concentration first appeared in the middle layer in May. In summer, the ranges at different depths significantly increased, and the maximum was achieved in August. In July and August, the hypoxic values were widely distributed within the depth of 60 m. When autumn came, the variation ranges decreased within the depth of 120 m, but hypoxic values stayed still. In October, hypoxia values gradually decreased above 60 m, yet still present between 60 and 80 m. In November, within the depth of 60 m, there is little distribution of low DO concentration values, and the DO concentration values mainly varied from 6.5 to 8.0 mg/L.

The above results show that the DO concentration in the Changjiang Estuary and its adjacent waters displays strong seasonal variations. Low DO concentration values mainly appears between July and October (summer and autumn), and the water depth is above 80 m. These are all consistent with the conclusions made by Zhang et al. (2012), namely, July to September is a period with severe hypoxia when the intensity, total areas and spring layers' thickness reached their maximums. Meanwhile, the results are also in line with the seasonal variation characteristics described above (Ma et al., 2013; Zhang et al., 2012; Zhu, 2007).

3.3.3 *Sectional distribution*

The DO concentration distributions of each season at transects 32°N, 31°N and 30°N were displayed (Fig. 6). In winter, convective mixing could reach the bottom, and the vertical distribution of the DO concentration at the three transects was all quite uniform. The average DO concentration gradually decreased from the northern transect to the southern transect, 8.96, 8.50, and 8.17 mg/L, respectively. The high values of the DO concentration at transects 32°N and 31°N mainly concentrated in the inshore areas of the Changjiang Estuary, while the DO concentration values at transect 30°N displayed a rising trend from inshore to offshore areas.

In spring, the DO concentration variation remained a decreasing trend from north to south with DO mean values 9.13, 8.70 and 8.26 mg/L, respectively. Apart from transect 32°N which showed little difference from winter value, the bottom DO concentration near the shore significantly dropped as compared with winter. The isolines for the low DO concentration values inshore gradually became parallel to the sea level, consequently forming stratification. As Wei et al. (2015) pointed out, the stratification in the Changjiang Estuary started as early as April. In May, along with the increase of diluted water flow and affecting areas, the seawater temperature on the surface increased remarkably, thus facilitating the formation of strong thermocline and halocline. The formation of the thermocline and the halocline was regarded as the necessary hydrological conditions of hypoxia. As



a. Surface

b. Bottom

Fig. 4. Horizontal distribution of DO concentration in the Changjiang Estuary and its adjacent waters over years.

the temperature rise, microorganism activities turned more active, however, the leaping layers impeded the water exchange from the surface to the bottom, therefore resulting in the decrease of DO concentration values on the bottom. Besides, by comparing all three transects, the hypoxic areas on the bottom could be found to be gradually increasing from north to south. Notably, a vertical zone of low DO concentration (<6 mg/L) was observed at 126°E of 30°N transect. In spring, the northward force of the Taiwan Warm Current grew stronger, which was characterized by the high temperature, high salinity and low DO concen-

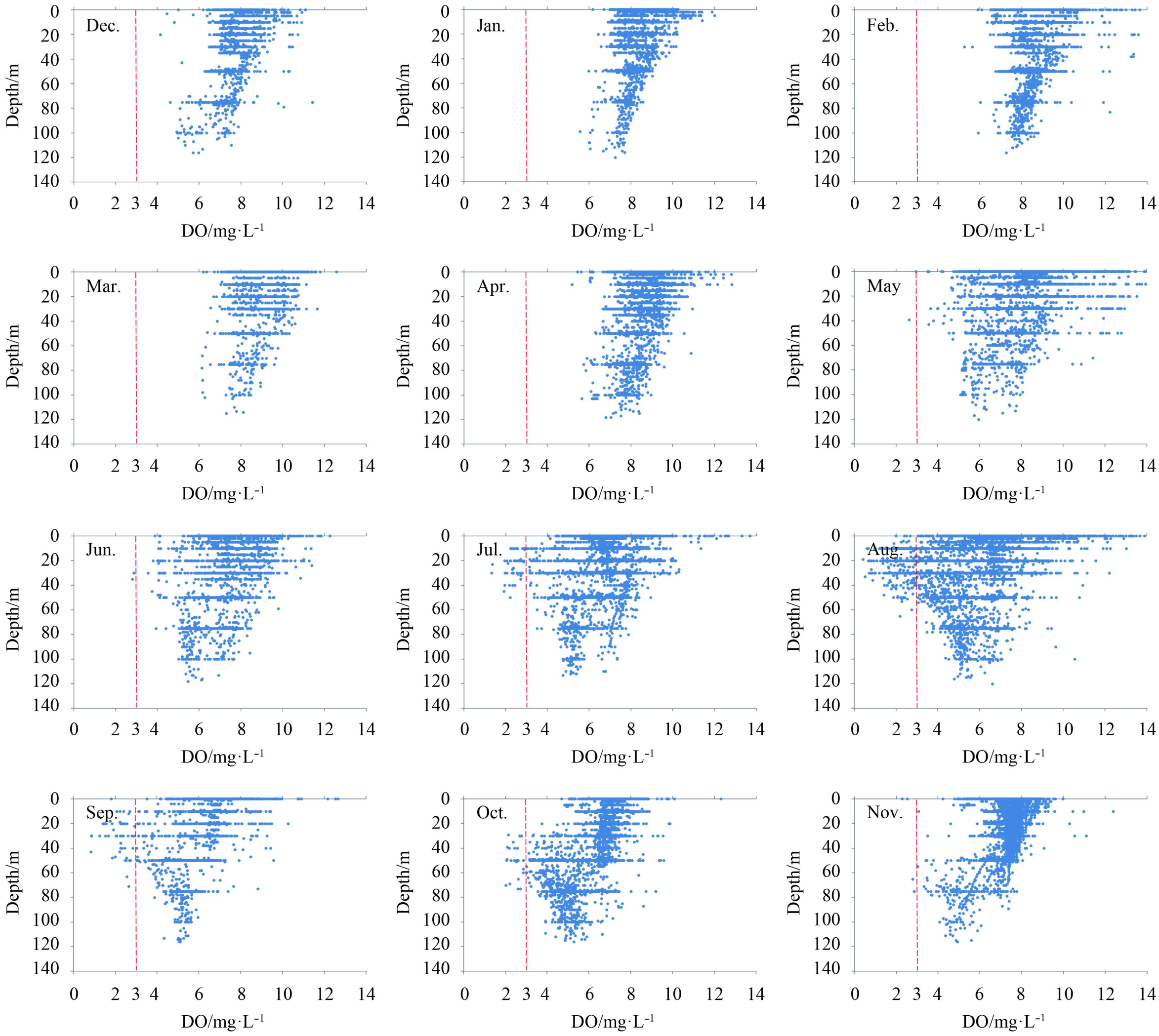


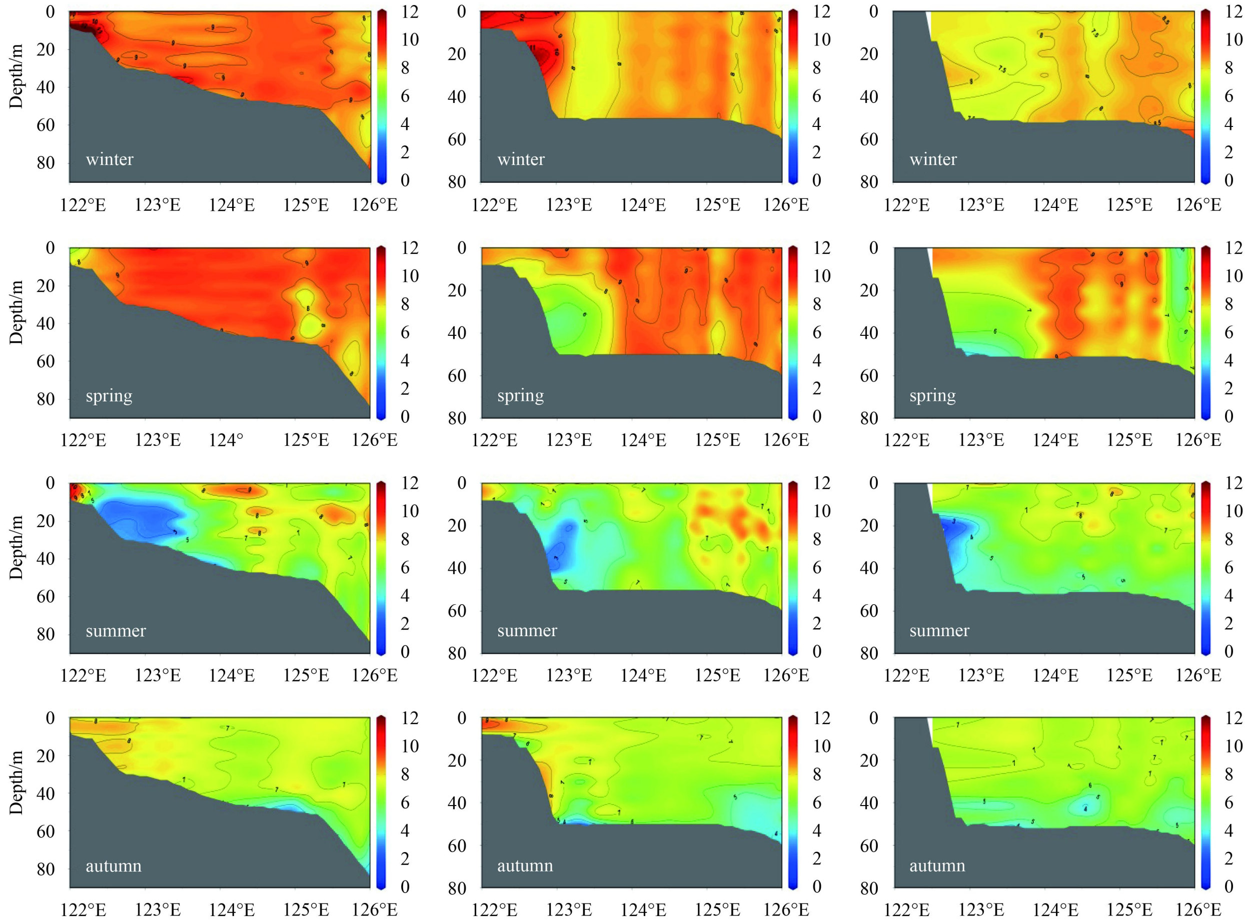
Fig. 5. Scatter diagrams of DO concentration and water depth in each month in the Changjiang Estuary and its adjacent waters.

tration. This may be a key reason for the formation of this low DO concentration zone (Fu, 1992; Wang, 2009).

In summer, the DO concentration dramatically decreased as compared with spring, with an average drop of approximately 3.3 mg/L. At 122.5°–124°E of transect 32°N, the DO concentration values dramatically dropped to from 9 to 7 mg/L, and typical hypoxia zones (<3 mg/L) were formed at a depth of 20–40 m. the hypoxia zones were also observed at the transects of 31°N and 30°N, but the intensity gradually weakened from north to south. At transect 30°N, the hypoxic areas were distributed in 122.5°–123.0°E, and the thickness was about 10 m. During this period, the stratification achieved the peak. On one hand, the Changjiang River runoff reached the maximum and formed the northeastern oriented diluted water mass under the influence of southwest monsoon. On the other hand, the Taiwan Warm Current of high salinity continued to move north and mixed with the low salinity diluted water off the Changjiang Estuary, therefore significantly reinforced the water stratification of the study area.

In autumn, the intensity of the water stratification started to decrease. The mean values remained at a low level and the highest DO concentration mean values at the transect 32°N was 7.01 mg/L. The hypoxia zones at transect 32°N completely disappeared and the low-DO concentration areas were below 60 m. The hypoxia residual remained at transects 31°N and 30°N, yet mainly on the bottom with the average values of 5 mg/L or so. At this time, the diluted Changjiang River water and Zhejiang–Fujian coastal currents moved southward and the invasion of Yellow Sea coastal water became strengthened, therefore driving the hypoxic zones moving southward (Su, 2005).

By comparing the vertical distribution of transects 32°N, 31°N, and 30°N in each season, the hypoxia zones in the Changjiang Estuary and its adjacent waters show distinctive seasonal variation. The decrease of the DO concentration first occurred at transects 31°N and 30°N in spring, with the concentration lower than 6 mg/L, and the area of the hypoxia zones gradually increased from the north to the south. In summer, the hypoxia zones pushed on to the northwest. The areas of the hypoxia zones reached the largest around 122°–123°E of 32°N, displaying way greater hypoxic intensity and spring layer thickness than the southern transects. Then, the hypoxia zones gradually faded away in autumn. At transect 32°N, the hypoxia zones completely disappeared, with the DO concentration values picking up quickly. While at transects 31°N and 30°N, hypoxic residuals were still observed. It was not until winter that the hypoxia zones at each transect fully disappeared and produced even vertical distribution of the entire water body. A research by Liu (2011) found that the hypoxia zones in the Changjiang Estuary exhibited such seasonal variation as "expanding from the south to the north and fading away



a. Transect 32°N b. Transect 31°N c. Transect 30°N

Fig. 6. Seasonal vertical distributions of the DO concentration (mg/L) at each transect in the Changjiang Estuary and its adjacent waters.

from the north to the south", which was highly consistent with the conclusion contained herein. In terms of its driving factors, as Wang (2009) pointed out, the northward strengthening of the Taiwan Warm Current in spring and summer, and its weakening in autumn kept in line with the variation trend of the hypoxia zones. At the same time, the diversion of Changjiang Diluted Water in summer and autumn was also one of the contributing factors.

3.3.4 *Variation trend of vertical distribution in hypoxia zones*

To explore the dynamic change of the hypoxia zones in the Changjiang Estuary and its adjacent waters for the last 50 a, the area of 29°–32°N, 122°–123°E was selected to study the variation trend of DO vertical structure (Fig. 7).

The monthly variation trend of the DO concentration in 1965–2014 is shown in Fig. 7a. High DO concentration values (>9 mg/L) decreased year after year, and were distributed more and more close to the seawater surface. Before 1985, high-DO concentration value zones were distributed above 30 m, while after the year 2000 high DO concentration values could only be observed above 20 m or less. On the contrary, the hypoxia zones occurred in 1985, and have gradually expanded to subsurface waters since 2000. The distribution layer of the hypoxia zones turned from the bottom layer to a depth of 10–50 m. Ning et al. (2011) reported that severe hypoxia was observed in 1976, 1986 and 1990. The hypoxia in 1976 and 1986 could be verified in this study as well. Besides, a clear trend of acceleration has been observed since the 1990s. As Wang (2009) pointed out, in the last 50 a, the probability of hypoxia in the Changjiang Estuary in summer was 60%, but after the 1990s the probability rapidly increased to 90%. With the China economic reform policy and rapid development, the human activities around the Changjiang River have been constantly increasing, so was the supply of organic nutrient, which all resulted in the acceleration of the hypoxic intensity.

Besides, the variation trend of the DO concentratioin vertical structure in August was examined, which was the severe period of hypoxia (Fig. 7b). The results show that within the last 50 a, severe hypoxia was observed during 1985–1990, during 1990–1997 there was a little recovery, but since then, the hypoxia stayed in a serious level.

4 Conclusions

On the basis of multi source and long-term data, the temporal-spatial distribution features of dissolved oxygen (DO) for the past 50 a were examined in the Changjiang Estuary and its adjacent waters.

(1) For the last 50 a, DO concentration on the surface of different seasons generally stayed stable, while the DO concentration in winter displayed a slight increase. In general, the average DO concentration in winter and spring was higher than that in summer and autumn. The DO average concentration in winter and spring varied between 7 and 11 mg/L, and in summer and autumn between 6 and 8 mg/L.

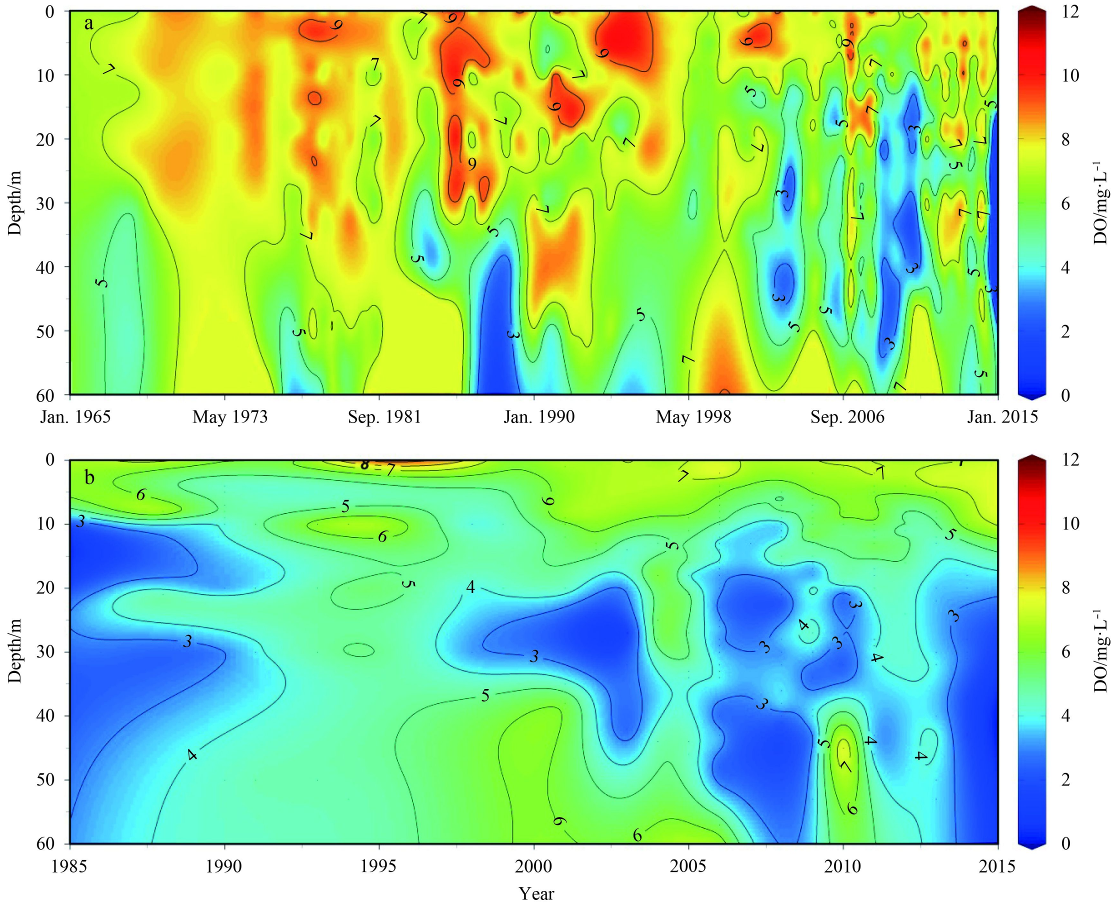


Fig. 7. Vertical variation trends in the hypoxia zones in the Changjiang Estuary and its adjacent waters. a. Monthly vertical variation trends of the hypoxia zones in 1965–2014, and b. vertical variation trends of the hypoxia zones in August from 1985 to 2014.

(2) According to horizontal distribution of DO, the distribution on the surface and the bottom varied throughout the year, with the most similar in winter and the least similar in summer. In spring, a north oriented low-DO concentration value plume was observed on the bottom along the coastal areas of Zhejiang and Fujian. It began to move northward in summer, with DO concentration decreasing below 5 mg/L. When autumn came, the low DO plume started to fade away to the northeast.

(3) DO concentration variation with the water depth in the Changjiang Estuary displayed strong seasonal changes. In winter and spring, DO concentration varied in a relatively small range and low DO concentration values (<3 mg/L) first occurred in May. In summer, the ranges dramatically expanded and the maximal range was reached in August. In autumn, the ranges gradually decreased in general while the distribution of the hypoxic values was still wide. Low DO concentration values appeared from May to November, and mostly distributed from July to October.

(4) In terms of the vertical distribution, the decrease of the DO concentration first appeared at transects 31°N and 30°N in spring. Then in summer, the hypoxia zones advanced to the northwest, and reached its highest coverage around 122°–123°E of 32°N. Moreover, the hypoxic intensity and thickness of its spring layer were much higher than those of the southern transects. After that, the area of hypoxia faded away little by little in autumn, and completely disappeared in winter.

(5) Within the last 50 a, hypoxia in the Changjiang Estuary and its adjacent waters started to appear in the 1980s. Since 2000, the degree of hypoxia has increased seriously and the distribution depth has become smaller.

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