Study on temporal-spatial distribution and changes of dissolved oxygen in the Yellow Sea from 1965 to 2014

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Multi-source and long-term sequenced data were used to analyse the temporal-spatial distribution and changes of Dissolved oxygen (DO) for the last 50a. Results show that the annual mean values of DO are mostly between 8 mg/L and 9 mg/L, which have varied within a slight trend of declination. The surface DO concentration is higher than the bottom in winter, with the similar distribution trend and the inshore waters overall higher than offshore areas. In summer, the surface DO concentration is lower than the bottom. The vertical distribution of the subsurface DO values are above 9 mg/L, significantly higher than the surface and bottom DO values in summer and autumn. In north Yellow Sea, the DO concentration tended to vertically uniform in spring, autumn, and winter. In south Yellow Sea, the maximum DO concentration zones are formed under the effects of thermocline in summer and autumn. According to the correlation analysis, in winter, the variation of DO is mainly influenced by the sea water temperature, and the effect of seawater salinity is increased in summer. This study was performed based on a large amount of historical data, and the research results would be of great significance for further learning about the physical and chemical processes of the Yellow Sea.

[Keywords: Yellow Sea; Dissolved oxygen; Temporal changes; Spatial distribution features; Sectional distribution; Vertical structure]

Introduction

As the typical marginal sea of China, the Yellow Sea is a north-south direction semi-enclosed continental shelf located between northern China and the Korean peninsula in the shape of a reverse-S. It is known as the large marine ecosystem of the Yellow Sea and listed as one of the “50 Large Marine Ecosystems”, which has intense interactions between terrestrial, oceanic and atmospheric processes. Dissolved oxygen (DO) is fundamental for the survival, reproduction, and growth of marine life. Its concentration can reflect the growth of marine life and the quality of the environment while playing an important role in the study of various physical, biological, and chemical processes in the sea.

Previous studies have been done on the DO distribution in Chinese key estuaries and related sea areas. This study on temporal-spatial DO distribution will help in learning about the marine ecological processes of the Yellow Sea and serve as a reference for studying the physical, chemical, and biological processes of the marine environment of the Yellow Sea.

In the Yellow Sea, Chinese oceanographers have conducted many investigations and studies on the changes of the DO distribution. Wei found that the major factors affecting the DO concentration in the southern Yellow Sea in spring were hydrology, phytoplankton photosynthesis, and the decomposition of organic matter in bottom water, and the distribution controlled by the circulation structure of the Yellow Sea. Song believed that the major factors affecting the DO distribution in offshore waters of the Yellow Sea in spring were temperature and salinity, and the inshore DO distribution was mainly controlled by temperature rather than salinity. In summer, the cold water mass area of the southern Yellow Sea had a significant DO cline in vertical distribution, the maximum DO value appeared below the thermocline (20-30 m), but this did not occur in the cold water mass area of the northern Yellow Sea. In autumn, the DO concentration at the bottom of the Yellow Sea Cold Water Mass area was significantly lower than that in summer. In winter, the horizontal distribution was mainly controlled by water temperature, and intense vertical mixing of the seawater contributes to the consistent DO distribution trended in different layers. However, most studies on the DO in the Yellow Sea focused on only one or a few
investigations with few reports on the distribution of long-term DO distribution features. In this paper, the temporal-spatial DO distribution in the Yellow Sea would be studied based on multi-source and long-term data regarding DO and relevant physical and chemical factors in the last 50 years from 1965 to 2014. The results would contribute to a more accurate understanding and analysis of the physical and chemical characteristics of DO changes in the Yellow Sea, and it has great significance in promoting the sustainable use of marine resources in the Yellow Sea.

Materials and Methods

As a marginal sea in the Western Pacific Ocean, the Yellow Sea is a semi-enclosed shallow sea in north-south direction between northern China and the Korean Peninsula. The Yellow Sea is part of the East Asian continental shelf, with an average depth of 44 m, which has a gentle seabed. Overall, the Yellow Sea’s circulating currents are mainly composed of the Yellow Sea Warm Current (YSWC)\(^{13}\) (and its offshoots) and the Yellow Sea Coastal Current (YSCC)\(^{14}\). The YSWC is a branch of the Tsushima Warm Current and the main source of offshore waters of the Yellow Sea, with high salinity (and high temperature in winter). The YSCC is characterized with low salinity (and low temperature in winter). The YSWC and the YSCC have stable basic flow directions all year round. Seasonal circulating currents of the Taiwan Warm Current (TWC) and the diluted water of the Chang jiang (CDW) driven by the summer monsoon enter the southern Yellow Sea from the northeast. The western part of the south Yellow Sea is affected by the Subei Coastal Current (SCC) and the Lubei Coastal Current (LCC) flowing southward all year round\(^{15}\). In addition, the eastern part is affected by the Korean Coastal Current (KCC). The study area and transect locations are presented below (Fig. 1).

The data collected included the following: (1) World Ocean Data (WOD) from May 1965 and September 2008; (2) Climate Variability and Predictability (CLIVAR) data in January 2006; (3) national marine environmental monitoring database between September 2000 and May 2015; (4) national environmental impact assessment database from November 2010 and June 2013; (5) the second pollution baseline investigation data in June and October of 1998; (6) national island resource investigation data from February 1990 to August 1991; (7) national economic zones and continent shelf survey data from October 1997 to September 2000; (8) national coastal integrated investigation and evaluation data from July 2006 to August 2008; and (9) marine monitoring data of transect stations from January 1960 to November 2013.

The above-mentioned data and information came from different countries and institutions, which is helpful for the supplement of 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. However, due to the considerable differences in sampling methods, laboratory analysis methods, and technical specifications, it resulted in varied data format, data structure, the number of valid parameters and measuring units. Therefore, we first unified all the basic information (including sampling time, longitude, latitude, and sample depth), then normalized the data format, measuring units, and significant digits.

After normalization, data quality was further controlled. The quality control mainly involved the
following: (1) delete repetitive records; (2) geographic information check (deleting missing or on land records); (3) time information check (delete missing records or those out of the starting-ending time); (4) sampling depth data check (delete missing data or that exceeding the water depth); (5) range check (screening unreasonable data of DO, water temperature and salinity based on climatology range and spatial statistics recommended by the World Ocean Atlas (WOA)); (6) outliers check by scatter diagram; and (7) identifying the cause of suspicious data screened in (5) and (6), verifying the availability with the help of experts’ experiences. After normalization and data quality control, about 127,000 data records were used to analyze the temporal-spatial distribution and changes of DO for the last 50a.

Objective analysis methods were used in this study to depict the spatial distribution of DO. Levitus used the successive correction method (one of the objective analysis methods) to analyze the global seawater temperature. The results have been widely applied all over the world, namely World Ocean Atlas (WOA). The key procedure of Levitus’ method is 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:

\[ G_{i,j} = F_{i,j} + C_{i,j} \]  \hspace{1cm} \ldots (1)

where \( i \) and \( j \) represent coordinates of analyzed grid point, \( G_{i,j} \) represents analyzed value, \( F_{i,j} \) represents guess value, and \( C_{i,j} \) represents correction value.

\[ C_{i,j} = \frac{\sum_{s=1}^{n} w_s Q_s}{\sum_{s=1}^{n} w_s} \]  \hspace{1cm} \ldots (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 \( s \) point, and \( w_s \) is the weight function. The expression for \( w_s \) is

\[ w_s = \exp(-4r^2R^{-2}), r \leq R \]  \hspace{1cm} \ldots (3)

where \( r \) represents the distance of the observation from the grid point, \( R \) represents the influence radius.

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

**Results and Discussion**

**Temporal distribution**

Annual average values of the DO concentration may display its overall variation trend. The changes of annual average values of the DO concentration in the surface and bottom layers of the Yellow Sea from 1965 to 2014 were shown in Fig. 2. In the last 50a, the annual mean values of DO have varied within a small range, showing a slight declination (Fig. 2). The annual mean value of the surface DO was little higher than that of the bottom DO, and their annual changes have remained consistent with that of the total annual

![Fig. 2 — Annual variation trend of DO in the Yellow Sea in 1965 to 2014](image-url)
mean value. The annual DO distribution was stable except in 1974. After 1992, the annual mean DO concentration only changed slightly.

The annual mean values of DO concentration mostly fell between 8 mg/L and 9 mg/L. The minimum (approximately 7 mg/L) appeared in 1974, and the maximum (approximately 9 mg/L) appeared in 1970 and 1976 to 1981. The annual mean values of surface DO concentration mostly fell between 7 mg/L and 9 mg/L. In 1970 to 1971 and 1976 to 1989, the annual mean value of surface DO concentration was approximately 9 mg/L, and stayed at a low level in 1991, 2009, and 2012, approximately 7.5 mg/L. The annual mean values of bottom DO concentration mostly fell between 7 mg/L and 9 mg/L, and stayed at a low level in 1974, 1991, and 1997, approximately 7 mg/L.

The seasonal variation of DO in the surface and bottom over the years was shown (Fig. 3). As shown in the figure, the average concentration in winter and spring was overall higher than that in summer and autumn at both surface and bottom. The surface DO concentration varied between 8.5 mg/L and 10.5 mg/L in winter and spring, meanwhile between 7 mg/L and 8 mg/L in summer and autumn. The bottom DO concentration varied between 8 mg/L and 10 mg/L in winter and spring, meanwhile between 6 mg/L and 8 mg/L in summer and autumn.

In terms of annual variation of the DO concentration in different seasons, the annual change of surface and bottom DO concentrations was reasonably big in 1965 to 1973 and in 1989 to 1999. Since then, they have been in the stable situation. Particularly, the greatest seasonal variation occurred in around 1991, and the smaller value of surface and bottom DO (approximately 7.5 mg/L) appeared in spring. In 1998, a larger value of surface and bottom DO (approximately 9 mg/L) appeared in autumn.

The monthly variation trend of surface and bottom DO over years was recorded (Fig. 4). The monthly variations of DO concentration in the last 50a showed that the values of bottom DO are approximate to those of surface DO. Except for a few months, the maximal monthly mean value of DO generally appeared in the surface layer, and the minimum appeared in the bottom layer. The monthly mean values of surface and bottom DO concentrations were rather similar, showing a sinusoidal trend. The maximum was 10.1 mg/L, which appeared in surface waters of the study area in March. The minimum was 7.12 mg/L, which appeared in surface waters of the study area in August.

The above research results indicate that the annual mean values of the DO concentration in the Yellow Sea have dropped slightly, responding to global warming. The changes in surface and bottom DO were similar. In summer and autumn, the DO concentration was generally smaller than that in winter and spring, and hypoxia was more likely to occur in summer and autumn. The maximum DO concentration usually appeared in the surface layer of the study area, and the minimum usually appeared in the

Fig. 3 — Seasonal variation trend of DO in the Yellow Sea in 1965 to 2014

Fig. 4 — Monthly variation trend of DO in the Yellow Sea in 1965 to 2014
bottom layer. The DO distribution in the Yellow Sea is mainly subject to the influence of water temperature, phytoplankton photosynthesis, and decomposition of organic matter. As the aforementioned factors remained all the time, DO variation exhibited a regular pattern to some extent in the time sequence.

Due to the rapid development around the Yellow Sea, the surface DO concentration is mainly affected by the runoff, CDW, and plankton breeding, meanwhile the bottom DO is mainly affected by the Yellow Sea currents, seasonal thermocline, and the decomposition of organic matter. Because of the thermocline, the DO at the bottom has a very limited supply but a high consumption, and the minimum of the DO concentration usually appears at the bottom. However, the changes of the surface and bottom DO are not completely the same. Subject to the influence of cold water mass and organic matter decomposition, the DO concentration in summer and autumn is usually lower than that in winter and spring. This is consistent with previous research.

Spatial distribution

The horizontal distribution of surface and bottom DO in the Yellow Sea was diagrammed in summer and winter (Fig. 5). In winter, the mean value of the surface DO was 9.39 mg/L, slightly higher than that of the bottom DO (9.24 mg/L). The DO concentration was higher in the north Yellow Sea, and the concentration inshore was higher than that offshore, same as the result of Dou. The horizontal distributions of surface and bottom DO in the north Yellow Sea were essentially consistent. The zones of high DO concentrations (as high as 12 mg/L) were mainly located near the Yalu River. In the south Yellow Sea, the horizontal distributions of surface

(a) Surface DO

(b) Bottom DO

Fig. 5 — Horizontal distribution of the DO in the Yellow Sea (Unit: mg/L)
and bottom DO were consistent, yet the values in the bottom significantly lower than the surface. In the vast central area of the south Yellow Sea, the DO concentration was relatively low (below 6 mg/L), showing certain stratification. Wei\textsuperscript{19} pointed out that this was mainly due to the effect of residual Yellow Sea Cold Water and high temperature YSWC, and it also was related to more severe organic degradation process since autumn.

In summer, the mean value of the surface DO in the study area was 7.33 mg/L, slightly lower than that of the bottom DO (7.39 mg/L). The DO concentration in the north Yellow Sea showed obvious stratification, and the bottom DO concentration was significantly higher than the surface’s. But in the south Yellow Sea, the bottom DO concentration was much lower than the surface. Subject to the influence of the Yellow Sea Cold Water Mass, there is a large low DO value (< 7 mg/L) area in the central part of the south Yellow Sea. When summer comes, seasonal thermocline and pycnocline hindered the transportation from upper layers of water to bottom, thus the consumption of oxygen induced by the decomposition of organic matter in bottom could not be replenished, eventually making for lower DO levels\textsuperscript{20}.

In addition, a low DO area appeared in the southeast waters of the study area between 122°E and 124°E as well as the south of 33°N, which was the extension of the hypoxic zone outside the Yangtze Estuary. In summer, the CDW and the TWC are strong and they gradually expand towards the northeast under the influence of the southwest monsoon. It was shown that the hypoxic zone could extend as far as the area near 33°N.

The relationship between the DO concentration and the water depth in the Yellow Sea in each month was shown by scatter diagrams (Fig. 6). As shown in the figure, in winter, the DO concentration decreased

Fig. 6 — Scatter diagrams of the DO and water depth in each month in the Yellow Sea
each month as the depth increased; as the same in spring. The variation ranges gradually increased within the depth of 100 m. It clearly appears from May to November that the DO concentration increased as the depth increased within the depth of 40 m and decreased as the depth increased below the depth of 40 m. This layer in the depth of around 40 m is called the maximum DO value layer (MDOVL). The DO concentration in the surface layer became lower from June. In the summer months, the variation range of surface DO concentration significantly increased until the maximum achieved in August. In July, August and September, there appeared hypoxia zones (DO < 3mg/L) within the depth of 40 m.

The above research results indicate that the DO concentration in the Yellow Sea and its adjacent areas shows strong seasonal changes, the low DO concentration mainly appears between July and September in summer and autumn, and the range of water depth is within 40 m. Between May and November, the maximum DO value layer (MDOVL) appears around the depth of 40 m. Above the MDOVL, the DO concentration increases as the depth increases, and below it, the DO concentration decreases as the depth increases. The maximum DO value in the Yellow Sea appears below the thermocline\textsuperscript{21}, and it is not kept from the maximum DO value in winter. It has significant correlation with the stratification of the seasonal Yellow Sea Cold Water Mass area, thermocline intensity, and phytoplankton photosynthesis. The DO concentration decreases above and below thermocline due to the temperature rise as well as the decomposition of organic matter. The seasonal Yellow Sea Cold Water Mass exists all year round. In winter, the northern monsoon strongly mixes the waters in the vertical direction, which makes the Yellow Sea waters from the surface to the bottom mix uniformly. With the further influence of the high temperature and salinity of the YSWC, the Yellow Sea Cold Water Mass cannot be formed and the maximum DO value does not exist either. The seasonal Yellow Sea Cold Water Mass appears at the end of spring and the beginning of summer and disappears in November\textsuperscript{22}, with the same time to the maximum DO value. Above the MDOVL, the DO concentration increases subject to the influence of phytoplankton photosynthesis; and below it, the DO concentration decreases due to the cold water mass hinder and the organic matter decomposition.

Three transects were selected in the Yellow Sea (Fig. 7). Transect B1 is located in the north Yellow

![Fig. 7 — Seasonal vertical distribution at each transect in the Yellow Sea (DO Unit: mg/L)](image)
Sea, running northeast-southwest direction. The DO concentration was uniform vertically in winter, spring, and autumn. In summer, the bottom DO concentration was slightly lower than that of the surface’s, forming a certain gradient. However, a zone with high DO concentration was formed in the surface and subsurface layers of the transect B1 in the western waters, and its depth could reach around 40 m.

Transects B2 and B3 are in the south Yellow Sea, located at 36°N and 34°N respectively. Under the strongly vertical eddy mixing in winter, the vertical DO distribution of the two transects was highly uniform, and the DO isolines were nearly perpendicular to the sea level. In spring, the surface DO concentration increased significantly, indicating the important contribution of the phytoplankton bloom to the DO supply, and the bottom DO concentration generally kept the same with the winter’s and the stratification of DO gradually formed. In summer, transects B2 and B3 showed obvious maximum DO value in the subsurface layer. The DO concentration in the subsurface layer with the depths from 10 m to 40 m was significantly higher than that in surface and bottom layers, and most DO values were above 9 mg/L and close to the DO concentration in spring. These results are in agreement with the vertical DO distributions described in the paragraphs above. In autumn, with the weakening of water stratification, the range of the zones with high DO concentrations gradually retreated to the deep waters, and tended to move eastwards horizontally.

As early as in 1966, Gu23 first discovered the maximum DO value in the vertical distribution in the Yellow Sea in summer. It was conducted by Zhang24 showed that the maximum DO value was in the intermediate and lower layer of the central Yellow Sea. Li25 pointed out that the maximum DO value mainly appeared in the areas of the south Yellow Sea affected by the Yellow Sea Cold Water Mass and the areas of the East China Sea affected by the northern bottom cold water and the sub-intermediate climbing water of the Kuroshio Current. Wang26 found that the layer with the maximum DO value was generally at the depth of 10-40 m and the maximum value generally appeared at the depth of 15-40 m. This was consistent with our results. Currently, the more accepted cause of the maximum DO concentration in the subsurface layer is the joint action of thermocline and biological activities. In summer, along with the thermocline formation, the Yellow Sea Cold Water Mass gradually grew in the southern Yellow Sea basin. In the upper thermocline, the DO concentration in waters decreased due to the temperature rise, while at the bottom, the DO concentration was lower due to the organic matter decomposition could not be replenished through the water exchange. In the euphotic layer of the thermocline, oxygen produced by photosynthesis of phytoplankton was stored in the water, forming zones with high DO concentrations. In summer, the stratification had the highest intensity and the zone with high DO concentrations was also the largest. Wang27 pointed out that the maximum DO concentration requires both low water temperature and good vertical stability of waters. If the thermocline is too weak or too thin, the waters will not be stable enough to maintain the maximum DO concentration.

The transect B2 was chosen to study the annual variation of the vertical distribution of the DO, temperature, and salinity in winter (February) and summer (August) from 1975 to 2014 (Fig. 8). In the last 40 years, the vertical distribution of various factors of the transect B2 were basically similar. In summer, clines appeared at the depth of 20 m, with low water temperature and salinity but high DO concentration. In addition, the comparison between the changes of the three factors showed that the variation of the DO concentration was closely related to the temperature and salinity in summer. The zones with high DO concentrations often corresponded to a low-temperature and low-salinity environment, while the zones with low DO concentration corresponded to a high-temperature and high-salinity environment.

The vertical distribution of the three factors in summer was significantly different from that in winter. Thermocline and halocline were obviously formed at the depths of 20-40 m, and this layer was also the zone with high DO concentrations. In terms of annual variations, the zone with high DO concentrations had tended to decrease over the past 40 years, which was consistent with the annual decrease of the annual mean values of DO described in the paragraphs above.

**Relationship of the DO concentration to temperature and salinity**

The temperature-salinity scatter diagram is the most intuitively way to describe water features by simultaneously considering two important hydrological factors, potential temperature (Θ) and absolute salinity (S_A). Through mapping the temperature-salinity values of multiple stations on the same temperature-salinity
plane, relatively dense points were corresponded to waters with similar properties, so that represented the characteristics of different water masses. Meanwhile, the set of points from the sea surface to the bottom also showed the vertical stratification characteristics of studied waters. This approach has been widely used by domestic and foreign oceanographers since created\textsuperscript{28,29}. In this paper, the Thermodynamic Equation of Seawater 2010 (TEOS-10) was adopted for the calculation of potential temperature and absolute salinity of seawater\textsuperscript{30}.

On the basis of the $\Theta$-S scatter diagram, the DO concentration and DO saturation were introduced in this paper to analyze the relationship among DO concentration, sea water temperature and salinity. The relationship of the DO concentration to seawater temperature and salinity in the Yellow Sea are shown below (Fig. 9).

In winter, the temperature and salinity scatter diagram of the Yellow Sea showed two densely dotted zones. One was the high-temperature and low-salinity zone, with the salinity of 20-24 that was mainly located in the coastal waters in the west of 120°E. The salinity of the rivers flowing into this zone was low, and the mean DO value is 7.03 mg/L. Most points were in the other densely dotted zones, with the water temperature of lower than 20°C and the salinity of above 27. In winter, the DO concentration in the Yellow Sea was mainly affected by the water temperature. The salinity gradually decreased, and the DO concentration increased as the temperature decreased. The linear regression analysis showed that there was a significant linear relationship between the seawater temperature and the DO concentration ($R^2 = 0.55$, $p < 0.05$) (Fig. 10). In terms of the DO saturation, the DO saturation was higher in the high-temperature zones (i.e. the upper seawater) and lower in the low-temperature zones (i.e. the bottom seawater). That was related to atmospheric reoxygenation of the upper water and the biological actions. The upper and lower waters were dominated by oxygen-supplying photosynthesis and oxygen-consuming respiration, respectively.

In summer, the ranges of seawater temperature and salinity were significantly expanded as compared with those in winter, with the water temperature and salinity ranging from 0 to 33.5 and 11.4 to 39.3, respectively. The water temperature still significantly

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig_8.png}
\caption{Annual variations of the vertical distribution at transect B2 of the Yellow Sea}
\end{figure}
Fig. 9 — Relationship of the DO concentration and the DO saturation to the seawater temperature and salinity

Fig. 10 — Linear regression of seawater temperature, salinity and DO concentration in the Yellow Sea in winter
influenced the DO concentration. The DO concentration gradually increased as the temperature decreased. In addition, the salinity also had a certain influence on the DO concentration. The DO concentration increased as the salinity increased (Fig. 11). As Fig. 8 shown, the effect of salinity on the DO concentration was significant in the intermediate and lower waters, and the distribution of surface and bottom DO concentrations was disorder. From the DO saturation, the supersaturated points mainly gathered in the upper waters, while the unsaturated points mainly gathered in the bottom layer of seawater and low-salinity zones (i.e. coastal areas).

Conclusions

Based on a large amount of historical data, during the study, the annual changes of the DO concentration in the Yellow Sea had been marginal in the past 50a, dropping slightly. Mean values of surface and bottom DO concentrations in winter and spring both were generally higher than those in summer and autumn. Monthly mean values of surface and bottom DO concentrations were rather similar, showing a sinusoidal trend. The DO concentration in the Yellow Sea showed strong seasonal changes, as the low DO concentration mainly appearing between July and September in summer and autumn with the water depths of 40 m. Between May and November, the maximum DO value appeared within the depth of 40 m. Above the waters with the maximum value, the DO concentration increased as the depth increased; and below it, the DO concentration decreased as the depth increased.

From the sectional distribution, the DO concentration at the transects of the north Yellow Sea was very uniform vertically in winter, spring, and autumn. Only in summer, the bottom DO concentration was slightly lower than the surface’s, forming a DO gradient. Sectional distribution in the south Yellow Sea showed significant seasonal changes, and the DO concentrations in winter and spring were uniform in vertical distribution, with weak water stratification. In summer and autumn, the subsurface (10-40 m) DO concentration was above 9 mg/L, which was significantly higher than the surface and bottom DO in the south Yellow Sea. Seawater temperature and salinity both had material effects on the DO concentration in the Yellow Sea. In winter, the DO concentration was mainly affected by water temperature. Salinity gradually decreased and the DO concentration increased as the temperature decreased. In summer, the water temperature still had important effects on DO concentration. In addition, salinity also had a certain effect on the DO concentration. The DO concentration increased as the salinity increased.

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References