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Oxygen Deficit Area Spatial-temporal Heterogeneity in the Bohai Sea: Formation and their Drivers

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In recent years, the oxygen deficit in coastal seas has seriously affected the marine ecological environment. Using a large number of observed data in May and August from 2015 to 2018, we obtain the vertical distribution of DO and related hydrological factors in the central section of the Bohai Sea by three-dimensional spatial interpolation to analyze the variation characteristics

and their potential changing drivers. The results show that there are two typical oxygen deficit regions in the bottom water of the central Bohai Sea in summer, which are located off Qinhuangdao (QHD) and off the Yellow River estuary (YRE). We analyze the main mechanisms for the formation of oxygen deficit regions: continuous strong stratification and high temperature in summer as well as the aerobic decomposition of organic matter produced after the death of the massive phytoplankton in spring and summer during the slow sedimentation process. In addition, the physical-biological mechanisms of QHD and YRE, the two oxygen deficit core regions, are obviously different. This comparison highlights the influence of the initiation time of stratification enhancement and phytoplankton species on the degree of oxygen deficit, which provides a new understanding for perfecting the formation mechanism of oxygen deficit. Finally, two oxygen deficit regions are simply predicted, which highlights the seriousness of the oxygen deficit in the Bohai Sea.

Dissolved oxygen (DO) is one of the important parameters of seawater chemistry and an important index of seawater quality. The occurrence of an oxygen deficit will have a serious impact on the survival of marine organisms; for example, the diversity, abundance and biomass of benthic communities will decline (Ekau et al., 2010). It also leads to the formation of greenhouse gases (such as nitrous oxide and methane) and toxic compounds (such as hydrogen sulfide) (Luther et al., 1991; Diaz and Rosenberg, 2008; Naqvi et al., 2010). When water bodies suffer from extreme hypoxia, ecosystem functions will be threatened or even destroyed (Naqvi et al.,

2010), resulting in large numbers of benthic organisms dying and forming dead zones, such as the Gulf of Mexico (Rabalais et al., 2002) and the Baltic Sea (Conley et al., 2009).

Increased eutrophication of the ocean brought on by rising human activity in recent years has increased the number of coastal regions with an oxygen deficiency. At present, it is known that there are more than 500 nearshore regions in the world with DO contents lower than 2 mg/L, and the area (volume) and degree of hypoxic areas are increasing (Breitburg et al., 2018). In addition, studies have also found that low-oxygen areas are often accompanied by the occurrence of seawater acidification (Matear and Hirst, 2003; Carstensen et al., 2014), which poses a threat to calcifications and causes serious loss of shellfish fisheries (Zhai et al., 2019).

Since the late 1950s, hypoxia and seawater acidification have occurred in the estuaries of large rivers, such as the Changjiang River (Wei et al., 2007; Lu et al., 2017; Wei et al., 2017; Zhou et al., 2017; Luo et al., 2018) and the Pearl River (Su et al., 2017; Qian et al., 2018), in coastal China. There have been many studies and analyses on the spatial and temporal distribution, variation and formation mechanism of hypoxia in these regions. The Bohai Sea has been a newly formed oxygen deficit area in the past two decades (Wei et al., 2019; Wei et al., 2021). Relevant research has demonstrated that the DO in the bottom layer of the Bohai Sea has a declining tendency in the summer since the early 1980s (Wei et al., 2019). In August 2011, the lowest DO value in the Bohai Sea was located near the northern shore of the Bohai

Sea, which was approximately 3.3-3.6 mg/L, and the pH value was 7.64-7.68 (Zhai et al., 2012). In August 2014, DO concentrations below 3 mg/L and pH values below 7.8 were observed in the central Bohai Sea, with a spatial distribution of south and north dual-core structures located offshore of Qinhuangdao (QHD) and the Yellow River Estuary (YRE), respectively. The hypoxia area and volume were 756 km^2 and 7820$\times$ 10^6 $m^{3,\ respectively}$ (Zhang et al., 2016; Zhao et al., 2017). In early September 2015, the lowest DO value of the bottom water in the Bohai Sea was observed, which was approximately 2.11 mg/L (Zhai et al., 2019). The seasonal oxygen deficit in the Bohai Sea is closely related to weak water exchange (Li et al., 2015), seasonal stratification (Zhao et al., 2019), eutrophication (Wang et al., 2019) and nutrient structure imbalance (Wei et al., 2021). At present, research on the control mechanism of vertical transport (including temperature and stratification) on oxygen deficit in the bottom layer of the Bohai Sea is still not complete, and there is a lack of relevant research and analysis on the differences between the two oxygen deficit regions in the Bohai Sea.

In this paper, the vertical distribution of DO and related hydrological factors in the central section of the Bohai Sea (from the Yellow River Estuary to northern Liaodong Bay) is obtained by three-dimensional spatial interpolation based on in situ observation data in spring (May) and summer (August) in the Bohai Sea from 2015 to 2018. On this foundation, we improve the effect of vertical transport on DO in the bottom layer by studying the influence mechanism of stratification and surface temperature. Meanwhile, a novel understanding of the formation mechanism of

oxygen deficit is attained by systematically comparing the causes of different oxygen deficits in YRE and QHD. Finally, the mean rate of respiratory oxygen consumption of YRE and QHD is calculated by a one-dimensional box model, which is convenient for the future prediction of oxygen deficit.

Data and methods

In situ observation

The Bohai Sea is a semi-enclosed shallow sea with an average depth of approximately 18 m (Shang et al., 2016) and a total area of 77,000 square kilometres, consisting of four regions: the central Bohai Sea, Liaodong Bay, Bohai Bay and Laizhou Bay (Figure 1). In summer, the Bohai Sea stratification starts to form in spring and decreases in October as a result of the combined effect of seasonal sea surface temperature and monsoon induction (Huang et al., 1999). Meanwhile, the residual vein of the Yellow Sea Warm Current enters the Bohai Sea through the northern part of the Bohai Strait and then gives rise to branches, one going west and the other going north along the eastern coast of Liaodong Bay. Cyclonic circulation is formed in the northern Bohai Sea, and anticyclonic circulation is formed in the central Bohai Sea. The northbound flow along the east coast of Liaodong Bay flows southward on the west bank and then flows southward along the coast after pooling with the coastal current. After passing through Laizhou Bay, the flow flows out of the Bohai Sea along the Bohai Strait, forming a counterclockwise flow ring (Zhou et al., 2017). This results in a weak water exchange capacity with the open sea, and the

average retention time of seawater is approximately 1.5 years (Li et al., 2015).

In this study, based on the in situ observation data of the Bohai Sea in May and August from 2015 to 2018, the linear radial basis function method was used to obtain the global three-dimensional spatial data of the Bohai Sea. Sampling locations are shown in Figure 1a and the number of observation points at different layers in each characteristic month from 2015 to 2018 is shown in Table 1. On this basis, the section from the Yellow River estuary to the top of Liaodong Bay (called the central section of the Bohai Sea) was selected for relevant research and analysis. There are 7 observation locations in the central section of the Bohai Sea, and the station distribution and sampling depth are shown in Figure 1. Sampling data are obtained from the National Marine Environment Monitoring. Among them, the temperature and salt are measured by the conductivity-temperature-depth (CTD). The fluorescence method is used to measure chlorophyll (Chl-*a*), and the Winkler titration method is used to quantify the dissolved oxygen (DO) on board. A pH meter was used on board to measure pH. Dissolved inorganic nitrogen (DIN), dissolved inorganic phosphate (DIP), and dissolved silicon (DSi) were analyzed manually by spectrophotometry onboard after filtering the samples using a cellulose acetate-fiber filter (Cui et al., 2010; Wei et al., 2019; Song et al., 2020). Element samples are transferred, stored and analyzed in accordance with the *Marine Monitoring Specifications* (2007).

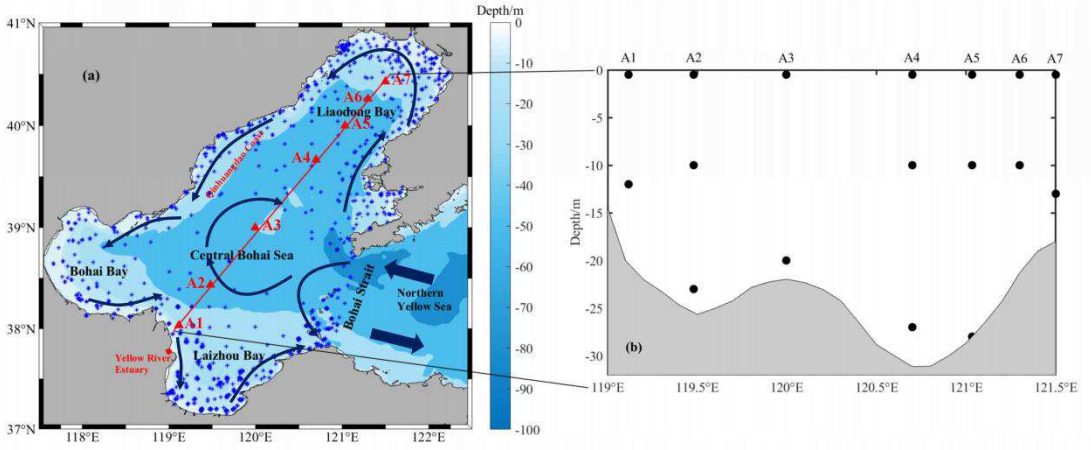

Figure 1. (a) Bathymetric survey of the Bohai Sea. The dark blue arrow is the circulation model of the Bohai Sea in summer (Zhou et al., 2017), and the blue star is the distribution of all observation locations. The solid red line and the red point are the section of the central Bohai Sea and the location of the observation points (A1-A7). (b) The bottom topography of the section in the central Bohai Sea and sampling depth of each location (black dots).

Table 1. The number of sampling points in the surface, middle and bottom layers in May and August from 2015 to 2018 in the Bohai Sea.

	Surface Layer		Middle Layer		Bottom Layer	
	May	August	May	August	May	August
2015	486	522	101	129	65	44
2016	392	391	70	78	50	55
2017	436	440	92	99	83	83
2018	482	507	106	100	81	87

Spatial interpolation method

Spatial interpolation of the data is necessary to improve the data visualization and make it more straightforward to calculate the buoyancy frequency and mean rate

of respiratory oxygen consumption. The radial basis function (RBF) method is not limited by dimensionality and has good scatter interpolation accuracy. It can produce continuous elevation and slope surfaces and limit the resulting surface bending to a minimum, so it is widely used in scatter data interpolation (Hardy, 1971; Franke, 1982; Vennell and Beatson, 2006; Ikechukwu et al., 2017; Nie et al., 2020).

The observed dataset is recorded as $D(xi, yi, zi)$, $i=1, 2..., n$, where (x_i, y_i) is obtained by converting the latitude and longitude of point i into a plane cartesian coordinate system (using Miller map projection). z_i is the depth, and n is the number of observation points. Assuming an isotropic distribution of ocean elements, the calculation formula of the interpolation point $\tilde{D}(x_j, y_j, z_j)$ is as follows:

$$\tilde{D}(x_j, y_j, z_j) = \sum_{i=1}^{n} \beta_{ij}\varphi(d_{ij}) + \lambda_1 + \lambda_2 x_i + \lambda_3 y_i + \lambda_4 z_i \tag{1}$$

where β_i, λ_1, λ_2, λ_3 and λ_4 are calculated according to the following formulas:

$$\begin{bmatrix} \beta \\ \lambda \end{bmatrix} = \begin{bmatrix} A & P \\ P^T & 0 \end{bmatrix}^{-1} \cdot \begin{bmatrix} D' \\ 0 \end{bmatrix} \tag{2}$$

where

$$\beta = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_n \end{bmatrix}, \quad \lambda = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \end{bmatrix}, \quad P = \begin{bmatrix} 1 & x_1 & y_1 & z_1 \\ 1 & x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_n & y_n & z_n \end{bmatrix}, \quad D' = \begin{bmatrix} D'(x_1, y_1, z_1) \\ D'(x_2, y_2, z_2) \\ \vdots \\ D'(x_n, y_n, z_n) \end{bmatrix} \tag{3}$$

$$A = \begin{bmatrix} 0 & \varphi(d_{12}) & \varphi(d_{13}) & \cdots & \varphi(d_{1n}) \\ \varphi(d_{21}) & 0 & \varphi(d_{23}) & \cdots & \varphi(d_{2n}) \\ \vdots & \vdots & \ddots & \cdots & \vdots \\ \varphi(d_{n1}) & \varphi(d_{n2}) & \varphi(d_{n3}) & \cdots & 0 \end{bmatrix} \tag{4}$$

where d_{ij} is the Euclidean distance between (x_i, y_i, z_i) and (x_j, y_j, z_j). $\varphi(d_{ij})$ is a basis function. The linear basis function $\varphi(d_{ij})=d_{ij}$ is employed in this paper (Nie et al., 2020). However, each element in the ocean has an anisotropic distribution, so after comparing the vertical and horizontal variability of each element, we add the weight of the vertical change rate ($z_i'=z_i/1000$) in the calculation process to keep the change rate of each dimension as consistent as possible to obtain better interpolation results.

Buoyant frequency

The strength of the water column stratification is usually represented by the square of the buoyancy frequency (N^2), when $N^2 >= 10^{-3}$ (unit per square second, s^{-2}), representing the presence of a strong density pycnocline in the water column (Song et al., 2020; Wei et al., 2021). The square of the buoyancy frequency is calculated as follows (Gill and Adrian, 1982):

$$N^2 = -\frac{g}{\rho}\frac{d\rho}{dz} \tag{5}$$

where g is the acceleration of gravity, ρ is the density of water, and $d\rho/dz$ is the rate of change of density ρ with depth z.

Apparent oxygen utilization

Apparent oxygen consumption (AOU) is generally considered to be related to community metabolism (Zhai et al., 2019), assuming that water starts from a fully saturated state and ignoring the effects of air-ocean exchange and water mixing. AOU >

0 indicates a dissolved oxygen deficit in the water column, and AOU < 0 indicates supersaturation of dissolved oxygen in the water column (Chen et al., 2022). AOU is calculated by Eq. (6) to show the deviation between the measured oxygen level and saturation concentration (Zhao et al., 2017):

$$AOU=[O_2]_{eq}-[O_2]_{mea} \tag{6}$$

where $[O_2]_{eq}$ and $[O_2]_{mea}$ are the solubility of DO in equilibrium with the atmosphere and DO concentration measured in the field, respectively.

$[O_2]_{eq}$ is calculated by the Weiss equation, and the DO solubility calculated by this method is only affected by temperature and salt. The specific formula is as follows (Weiss 1970; Garcia and Gordon, 1992):

$$\begin{aligned} DO(\%) = A1 + A2 \cdot \frac{100}{T+273.15} + A3 \cdot \log(\frac{T+273.15}{100}) + A4 \cdot \frac{T+273.15}{100} + \\ S \cdot (B1 + B2 \cdot \frac{T+273.15}{100} + B3 \cdot \frac{(T+273.15)\cdot(T+273.15)}{10000}) \end{aligned} \tag{7}$$

where DO(%) is the saturation of dissolved oxygen, and T and S are the corresponding temperature and salinity, respectively. A1 is -173.4292, A2 is 249.6339, A3 is 143.3483, A4 is -21.8492, B1 is -0.033096, B2 is 0.014259, and B3 is -0.0017. Eq. (7) only calculates DO saturation, and the concentration of DO corresponding to saturation should also be calculated according to $DO=e^{DO(\%)}$. Then, the unit is converted from ml/L to mg/L according to Eq. (8), and $[O_2]_{eq}$ is finally obtained.

$$DO_{(mg/L)} = DO_{(ml/L)} \cdot \frac{AirP}{T+273.15} \cdot 0.5513 \tag{8}$$

where *AirP* is set as a constant air pressure in millimeters of mercury (mmHg).

Mean rate of respiratory oxygen consumption

Nearshore oxygen deficit is usually considered to be the result of aerobic decomposition of organic matter in the bottom water or surface of sediments (Su et al., 2017), so estimating the oxygen consumption rate is of great significance for the analysis and prediction of oxygen deficit. A one-dimensional box model is designed to calculate the mean rate of respiratory oxygen consumption (MROC) below the pycnocline in the central section of the Bohai Sea. According to previous studies, oxygen deficits in the central section of the Bohai Sea mainly occur in the YRE and QHD. The effects of horizontal diffusion and convection on DO will be disregarded when estimating the MROC of the water column below the pycnocline because the bottom water in these two regions is located in the south and north grooves of the central Bohai Sea, where water exchange is weak and the change in DO concentration is local (Zhao et al., 2017; Wei et al., 2019). The calculation formula is as follows:

$$\frac{\partial DO}{\partial t} = \frac{\partial}{\partial z}(K_V \frac{\partial DO}{\partial z}) + Q \tag{9}$$

where $\frac{\partial DO}{\partial t}$ is the time variation term of DO in the water body, $\frac{\partial}{\partial z}(K_V \frac{\partial DO}{\partial z})$ is the vertical turbulent diffusion term of DO, K_V is the vertical turbulent diffusion coefficient, and Q is the DO consumption term caused by aerobic decomposition in the water body and sediment. Since the vertical turbulent diffusion coefficient is not observed, data from previous research literature are used. During weak stratification,

the vertical turbulent diffusion coefficient is set as 10^{-5} m^2/s. During strong stratification, the vertical turbulent diffusion coefficient is set as 10^{-6} m^2/s (Xu et al., 2020). By vertical integration of the water body from the seabed to the pycnocline in Eq. (9), the box model shown in Eq. (10) is obtained.

$$\int_{-h}^{-z_b} \frac{\partial DO}{\partial t} dz = (K_V \frac{\partial DO}{\partial z})_{-z_b} + \int_{-h}^{-z_b} Q dz \tag{10}$$

As there are only three layers of data in the observation data, it is necessary to use the three-dimensional spatial interpolation results for calculation. The DO deficit is calculated using the depth integral difference (from the bottom to the pycnocline) of the time variation terms $\frac{\partial DO}{\partial t}$ of the water below the pycnocline in May and August. In Equation (10), $(K_V \frac{\partial DO}{\partial z})_{-z_b}$ is the vertical diffusion flux (VDF) of DO through the pycnocline. After obtaining the DO deficit and the vertical DO diffusion flux across the pycnocline from May to August, the MROC $\int_{-h}^{-z_b} Q dz$ in the water and sediment below the pycnocline can be calculated.

Results

The complete three-dimensional spatial fields of DO and other hydrological factors in the Bohai Sea in May and August from 2015 to 2018 are obtained based on the linear basis function spatial interpolation method, and the vertical distribution results of each factor in the central section of the Bohai Sea are obtained.

Physical and biological environment of the central section of the Bohai Sea

The vertical distribution of temperature in the central section of the Bohai Sea is shown in Figure 2. In May, the temperature in the bottom layer is slightly lower than that in the surface layer, and the water column appears weakly stratified. In August, the thermocline appeared at stations A2 (YRE) and A4 (QHD), and the temperature difference between the surface and bottom layers could reach more than 7°C. The overall variation in salinity in the central section of the Bohai Sea is small, ranging from 29.42 to 32.98.

The buoyancy frequency N^2 of the central section of the Bohai Sea in May and August from 2015 to 2018 is calculated using temperature and salinity data. N^2 represents the stability of the water body; when $N^2 > 10^{-3}$ s^{-2}, it indicates that the water is stable and there is strong stratification (Song et al., 2020; Wei et al., 2021). The vertical distribution of $log_{10}(N^2)$ of the central section in the Bohai Sea (Figure 2) shows that the water is unstable in May and that mixing is a constant activity. In August, strong stratification appeared in the central section of the Bohai Sea, especially at stations A2 and A4, and the depth of the mixed layers was basically 9-13 m.

In summary, the central section of the Bohai Sea exhibits weak stratification in spring. Meanwhile, due to the similar vertical distribution of N^2 and temperature and the smaller variation in salinity compared with temperature, water stratification in the central section of the Bohai Sea is mainly controlled by temperature in summer.

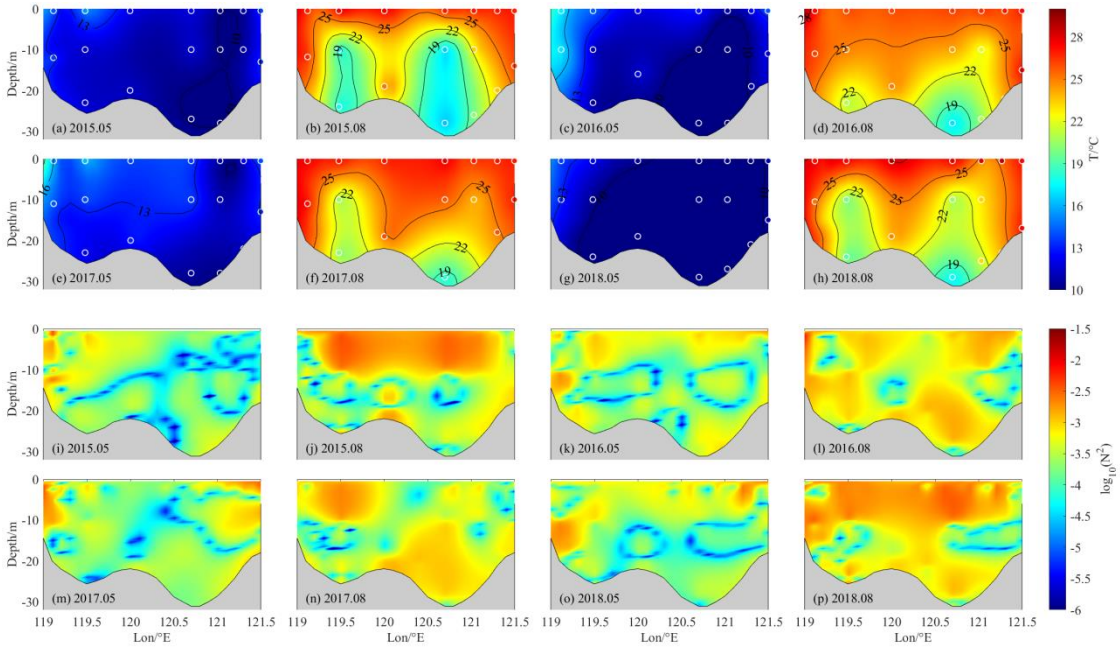

Figure 2. (a-h) The first and second rows show the vertical distribution of temperature in May and August from 2015 to 2018. (i-p) The third and fourth rows show the vertical distribution of the square logarithm ($log_{10}N^2$) of buoyancy frequency in May and August from 2015 to 2018. Scatter is the observed data.

The vertical distribution of Chl-*a* concentration in the central section of Bohai Sea (Figure 3) shows that the Chl-*a* concentration in May is generally higher than that in August, and the high Chl-*a* concentration regions are generally located in the coastal water, A2 and A4 stations, with the maximum value exceeding 5 μg/L. According to the spatial-temporal distribution of Chl-*a* concentrations, high phytoplankton biomass in the central section of the Bohai Sea mainly existed in the YRE and QHD regions in spring and summer.

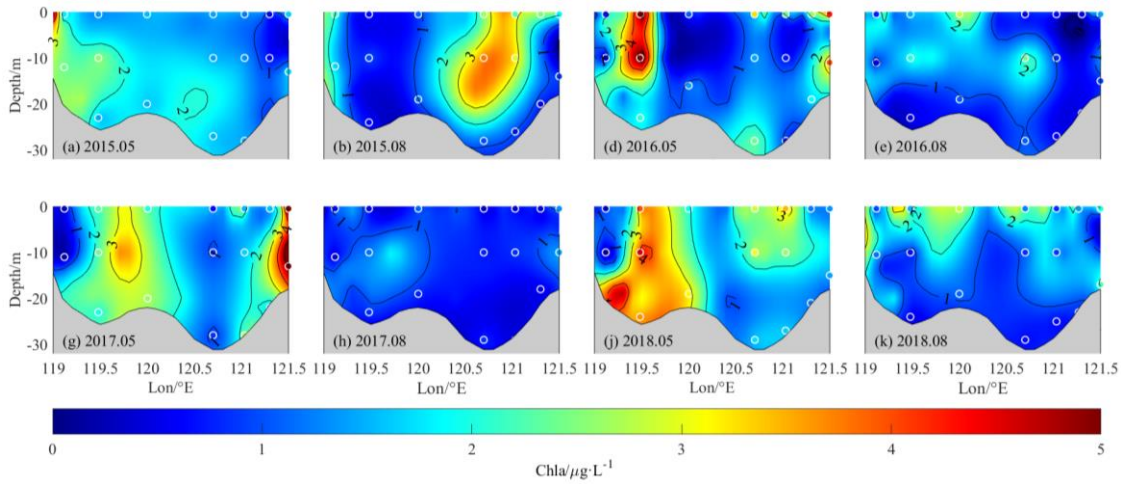

Figure 3. Vertical distribution of Chl-*a* concentrations in May and August from 2015 to 2018. Scatter is the observed data.

Analysis of DO and pH variation characteristics in the central section of the Bohai Sea

The vertical distributions of DO and AOU in the central section of the Bohai Sea are shown in Figure 4. The results show that in May, the DO of surface water and bottom water are basically the same, and the AOU is basically less than 0, which means that the whole water column of the central section of the Bohai Sea is in the state of supersaturation of DO in spring. In August, there is a clear stratification of DO concentration in the water column, and the DO in the bottom layer decreases rapidly. In the limited observations, the lowest DO concentration was found to be below 4 mg/L. Meanwhile, the AOU of the surface layer is close to or less than 0, while the AOU of the bottom layer is greater than 0, and the maximum value is higher than 3 mg/L. As can be observed, summertime DO in surface water is still saturated, while the bottom water experiences an oxygen deficiency.

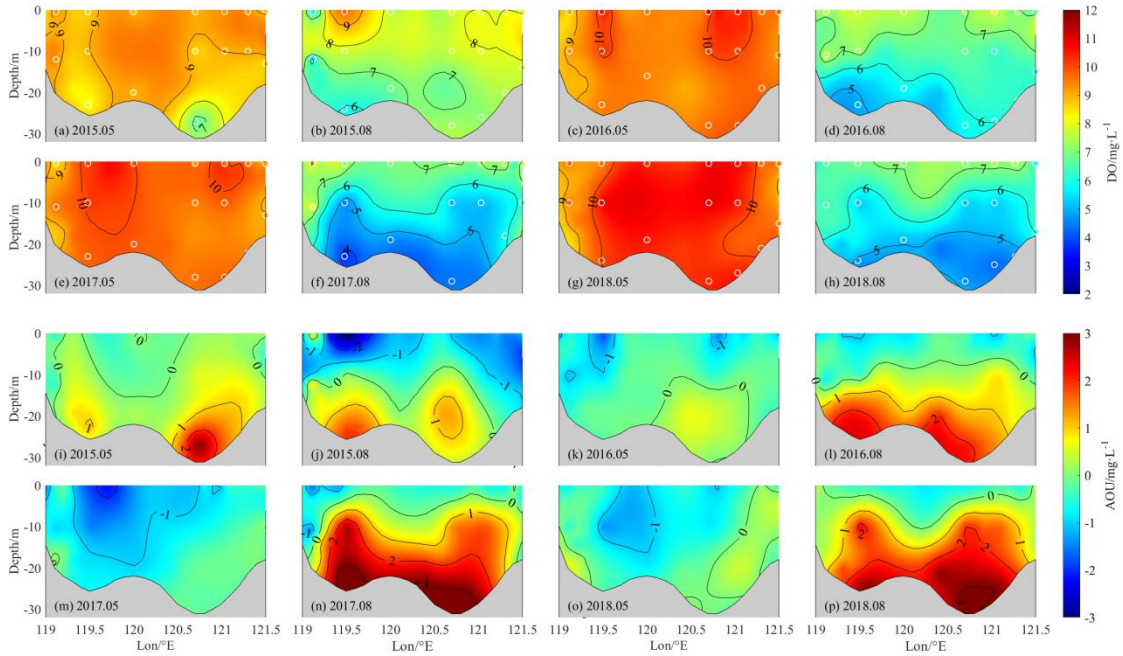

Figure 4. (a-h) The first and second rows show the vertical distribution of DO in May and August from 2015 to 2018. (i-p) The third and fourth rows show the vertical distribution of AOU in May and August from 2015 to 2018. Scatter is the observed data.

The vertical distribution of pH (Figure 5) is not completely consistent with that of DO, but there is a certain similarity. In May, the pH of the surface and bottom water is essentially the same. In August, the pH of the bottom water shows a significant decrease, and the pH of the A2 and A4 stations is the lowest, approximately 7.9. The same changes in DO and pH in the bottom layer in summer indicate that there is good coupling between them. When an oxygen deficit occurs in water, water acidification often occurs.

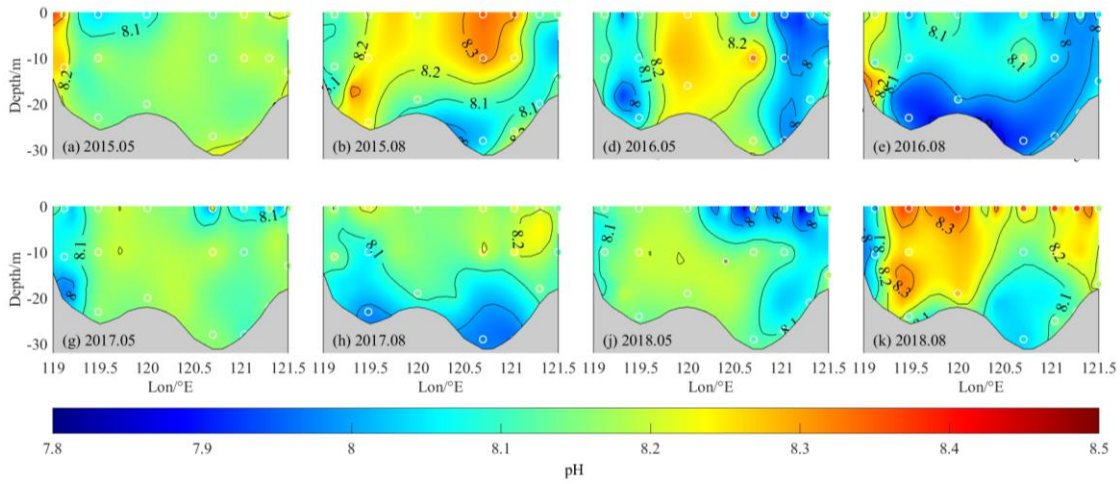

Figure 5. Vertical distribution of pH concentrations in May and August from 2015 to 2018.

Comparing the vertical distribution of DO, pH, and temperature in the central Bohai Sea reveals that, despite the water column's weak stratification in the spring, the overall mixing is intense, resulting in oxygen supersaturation and high pH values in the bottom layer of the water column. However, when stratification occurs in the water column in summer, the DO corresponding to the bottom cold water decreases significantly and is in an oxygen deficit state, and the pH also decreases, especially in the YRE and QHD regions. This suggests that oxygen deficiency in the bottom layer of the central region of the Bohai Sea is caused by stratification, which is a significant physical condition.

Meanwhile, compared with the vertical distribution of Chl-*a* concentration, it can be seen that the DO concentration in the area with high Chl-*a* concentration is usually higher, while the DO and pH in the corresponding bottom water are lower. The findings indicate that phytoplankton photosynthesis contributes to the DO of water in a certain way but that the aerobic decomposition of organic matter caused by

phytoplankton death would also deplete the DO in the water bodies and cause it to fall.

Later, we will further analyze and compare the formation mechanism of oxygen deficit between YRE and QHD to reveal the reasons for the difference in the degree of oxygen deficit between these two regions.

Discussion

The research in Section 3 indicates that temperature, stratification, and biological processes all work together to govern the incidence of oxygen deficit in the YRE and QHD in the summer. The generation mechanism of the oxygen deficit in the central Bohai Sea will then be further examined, as well as the differences between YRE and QHD's oxygen deficits.

Effects of stratification, temperature and salinity on DO in oxygen-depleted regions

According to the above analysis, stratification is an important physical condition for the occurrence of oxygen deficit in the bottom layer. Figure 6a shows that stratification in summer is stronger than that in spring, and the corresponding bottom DO is significantly lower than that in spring. Meanwhile, correlation analysis of DO concentration and stratification strength in the bottom water shows that they are negatively correlated, with a correlation coefficient of -0.67 ($p < 0.01$), indicating that DO concentration in the bottom water basically decreases with the enhancement of

water stratification, which is consistent with previous studies (Zhao et al., 2017; Wei et al., 2019). These results indicate that the occurrence of stratification impedes the vertical transport of DO from the surface to the bottom (Zhao et al., 2017). Moreover, previous studies have shown that water column stratification often occurs before hypoxia (Zhang et al., 2022). Therefore, the occurrence of stratification is not only an important physical condition but also a prerequisite for the occurrence of oxygen deficit.

In addition, the N^2 corresponding to DO in the bottom layer below 5 mg/L is approximately 0.001-0.004 s^{-2}, and the N^2 corresponding to the lowest DO concentration (3.58 mg/L) is approximately 0.002 s^{-2}. This means that when the degree of oxygen deficit is the highest, the corresponding stratification strength is not the strongest, which means that when the stratification strength reaches a certain strength, even though it continues to increase, the underlying oxygen deficit degree does not necessarily continue to decrease. In particular, Zhang et al. (2022) showed that the longer the duration of the pycnocline, the lower the DO concentration in the bottom layer.

Compared with previous studies, the control process of stratification on underlying DO is further improved. Before water stratification reaches a certain strength, the concentration of bottom DO decreases with increasing stratification, while after it reaches a certain strength, the influence of continuous enhancement of stratification strength on bottom DO will be weakened. In addition, the duration of

stratification may be an important factor in the continued decrease in bottom DO. With more observations in the future, this stratification intensity threshold can be defined to further understand the formation mechanism of oxygen-depleted regions.

In addition to stratification, surface DO concentration is another important factor affecting the vertical transport of DO from the surface to the bottom. Warming sea water and increasing salinity will decrease oxygen solubility, resulting in a decrease in DO concentration (Carstensen et al., 2014; Schmidtko et al., 2017). The T-S diagram of DO concentration drawn based on the observed data (Figure 6b) shows that, under a certain salinity, DO concentration in water decreases significantly with increasing temperature, while under a certain temperature, DO concentration changes little with increasing salinity. Therefore, the influence of temperature on DO is much greater than that of salinity. However, due to the aerobic decomposition of organic matter, the bottom water is extremely unsaturated (Zhao et al., 2017; Song et al., 2020), and the bottom temperature has shown a downward trend in recent decades (Wei et al., 2019), so the direct effect of temperature increase on bottom DO is small.

However, this does not mean that temperature increase has no indirect effect on bottom DO. Correlation analysis of the surface DO concentration and VDF at stations A2 and A4 shows that they are positively correlated (Figure 6c), indicating that the higher the surface DO concentration is, the greater the VDF of DO and the higher the supplementary amount of DO to the bottom. Therefore, when the surface water temperature increases in summer, the VDF of DO decreases with the decrease in

surface DO, which eventually leads to the decrease in DO transported from the surface to the bottom. At present, the global average surface temperature has increased by 2.0°C or more since preindustrial times (Hoegh-Guldberg et al., 2019), and it is predicted that global ocean temperatures are expected to rise by 1-4°C by 2100 (Alfonso et al., 2021). In the Bohai Sea, sea surface temperatures are sensitive to global warming because of its shallow depth, at almost twice the global average rate (Wei et al., 2020). According to the Weiss equation (Eq. 3), the influence of temperature and salinity changes on DO concentrations in surface water was quantified. The results show that DO decreases by 0.17 mg/L for every 1°C increase in temperature. For every 1 PSU increase in salinity, DO decreased by 0.05 mg/L. Therefore, under the future global warming scenario, the increase in water temperature in the Bohai Sea will lead to a decrease in surface DO concentrations by 0.34-1.36 mg/L. This will greatly reduce the amount of DO replenishment transported from the surface water to the bottom water, thus exacerbating the oxygen deficit in the bottom water of the Bohai Sea in summer.

At present, most studies on oxygen deficit in the Bohai Sea ignore the indirect effect of temperature on bottom layer DO. The study in this paper shows that with increasing surface temperature, the surface DO concentration decreases, and the VDF decreases, which eventually leads to a decrease in DO addition transported from the surface to the bottom water. This result improves the formation mechanism of the oxygen deficit in the Bohai Sea. On this basis, the influence of temperature on surface DO is quantified, which plays an important role in further predicting the degree of

bottom DO deficit.

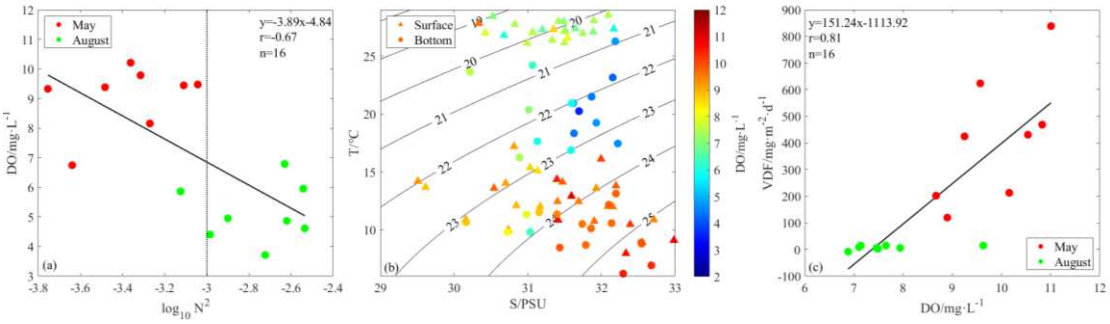

Figure 6. (a) Relationship between the log of buoyancy frequency ($\log_{10}(N^2)$) and bottom DO concentration of stations A2 and A4 in May and August from 2015 to 2018. Red circles represent May, and green circles represent August. The solid black line is the regression line. The black dashed line shows the value corresponding to the strong stratification. (b) T-S diagram relative to DO concentration. The triangle is the surface DO concentration of the central section of the Bohai Sea from 2015 to 2018, and the circle is the bottom DO concentration. (c) Correlation analysis between surface DO concentration and vertical diffusion flux. The solid black line is the regression line.

Influence of phytoplankton on DO

Phytoplankton influence DO in water through biological processes. AOU is considered to be closely related to biological activities in the ocean (Zhao et al., 2017; Zhai et al., 2019), so the influence of phytoplankton on DO in water is discussed by analyzing the relationship between AOU and Chl-*a*. The correlation analysis of Chl-*a* and AOU above the pycnocline (Figure 7a) shows that they are negatively correlated in May with a correlation coefficient of -0.55 ($p < 0.01$), indicating that if the

phytoplankton biomass is higher, the water body DO supersaturation degree is higher. However, in August, the correlation between AOU and Chl-*a* concentration was poor, which may be due to the lower biomass of phytoplankton in August than in May, resulting in the limited effect of phytoplankton photosynthesis on DO concentration in water. According to the correlation analysis of Chl-*a* concentrations above the pycnocline and AOU below the pycnocline (Figure 7b), the correlation between them is poor in May, with the correlation coefficient only being -0.36, while the correlation coefficient reaches -0.75 in August ($p < 0.01$). There may be a certain lag correlation between the two, which may be related to the time required for the death, settlement and decomposition of phytoplankton. At the same time, the negative correlation between them also indicates that aerobic decomposition of organic matter produced by phytoplankton death will consume a large amount of DO in the bottom water. The correlation between AOU and pH below the pycnocline (Figure 7c) shows that there is no obvious correlation between them in May, but there is a negative correlation in August, with a correlation coefficient of -0.48 ($p < 0.01$), indicating that acidification appears in water with the increase in oxygen deficit.

In conclusion, although phytoplankton can produce DO through photosynthesis, it has limited influence on DO in water in summer. After dying and settling, it will simultaneously consume a large amount of DO in the bottom water through aerobic bacterial decomposition and release a large amount of CO_2, which will reduce the pH of the water. These results are consistent with previous studies, which indicate that aerobic respiration of organic matter is the main process of DO consumption in the

bottom water of the Bohai Sea (Zhao et al., 2017; Zhai et al., 2019), and the organic matter is mainly derived from phytoplankton (Liu et al., 2015). At the same time, the dead and sinking times of phytoplankton may have an important influence on bottom DO consumption. Since the 21st century, the abundance ratio of dinoflagellates to diatoms in the Bohai Sea has increased and been miniaturized. The detrital new dominant species of dinoflagellates and microcellular and nanocellular algae have the characteristics of slow sinking speed and long residence time, which are conducive to the high oxygen consumption of water and finally lead to the enhancement of water oxygen consumption and a decrease in DO concentration (Wei et al., 2021).

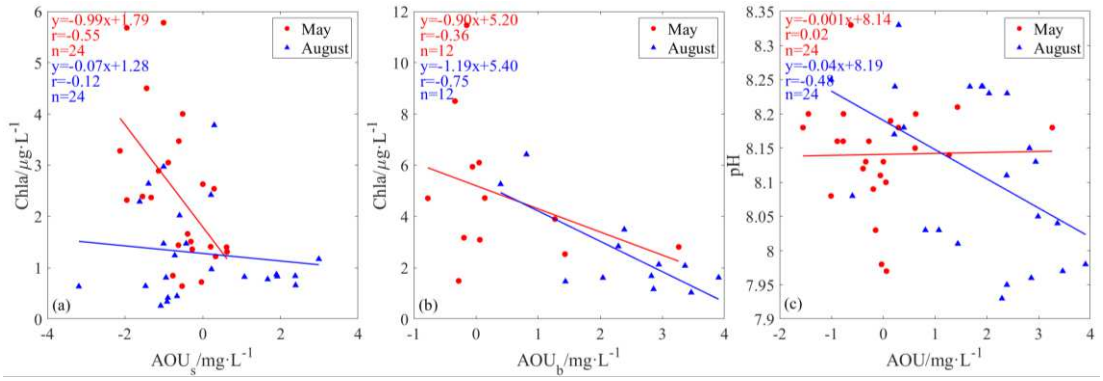

Figure 7. (a) Correlation analysis of AOU and Chl-*a* concentrations above the pycnocline. (b) Correlation analysis of AOU below the pycnocline and Chl-*a* concentration above the pycnocline. (c) Correlation analysis of AOU and pH below pycnocline.

Difference analysis of oxygen deficit in the central section of the Bohai Sea

There are two oxygen deficit regions in the central section of the Bohai Sea, namely, the YRE and QHD. There is a difference in the degree of oxygen deficit

between the two core areas. This section will analyze the reasons for the difference between the two core areas of oxygen deficit located in the same bay and make a simple prediction of the oxygen deficit in these two areas.

The change in DO at the bottom of stations A2 and A4 from August 2015 to August 2018 shows (Figure 8a) that the DO concentration at the bottom of station A2 was significantly lower than that at station A4 in the previous three years, while that at station A4 was lower than that at station A2 in 2018. The changes in VDF and bottom DO are not completely consistent, but MROC and bottom DO are completely consistent, which indicates that the bottom oxygen deficit degree of stations A2 and A4 is mainly controlled by MROC, and VDF is a secondary influencing factor.

The VDF represents the amount of DO that the surface water can add to the bottom water. Since the VDF in summer was significantly lower than that in spring (Figure 8b), the effect of the VDF in summer on the difference in the oxygen deficit in the bottom layer between the YRE and QHD was not considered. According to the change in the VDF over time, although the VDF of station A2 was lower than that of station A4 in 2015 and 2018, the two stations were comparable, while in 2016 and 2017, the VDF of station A4 was twice that of station A2. This suggests that the vertical transport capacity of station A4 is similar to or perhaps greater than that of station A2.

According to the above analysis, the VDF is mainly controlled by temperature and stratification. The changes in stratification and temperature over time show that

the stratification intensity at station A2 is higher than that at station A4 in May, while the increase in surface temperature at station A4 is higher than that at station A2 from May to August. The above results show that the effect of vertical transport on the oxygen deficit in the bottom layer is mainly affected by the initial time of stratification enhancement. The earlier the stratification enhancement is, the less DO is transported from the surface layer to the bottom layer, which will lead to the lower DO concentration in the bottom layer in summer. A change in surface temperature is a secondary factor.

Stratification is not only necessary for the formation and maintenance of oxygen deficits in the Bohai Sea but also plays an important role in low oxygen regions such as the Changjiang Estuary, Mississippi Estuary and Chesapeake Bay (Rabouille et al., 2008; Irby et al., 2016), so a comprehensive stratification analysis is needed. By comparing the effects of stratification on YRE and QHD, it can be seen that not only the intensity and duration of stratification should be considered when analysing the effects of stratification on oxygen-depleted regions (Zhao et al., 2017; Zhang et al., 2022), but the influence of the initial time of water stratification enhancement on the degree of oxygen deficit in different regions should also be taken into account.

According to the above analysis, MROC is the main factor leading to hypoxia at the bottom, which implies the importance of biological processes. By comparing the Chl-*a* concentration between stations A2 and A4 (Figure 8c), it can be seen that the Chl-*a* concentration at station A2 is basically higher than that at station A4, indicating

that the phytoplankton biomass at station A2 is higher than that at station A4. Meanwhile, previous studies have shown that phytoplankton species also influence the degree of oxygen depletion in the water column (Wei et al., 2021). The growth and competition of phytoplankton are related to nutrient structure. High DIN concentrations and high N/P ratios are favorable for dinoflagellate growth (Glibert et al. 2013; Xiao et al. 2018). The nutrient structure of stations A2 and A4 (Figure 8d) shows that the DIN/DIP at station A2 is higher than that at station A4, while the DSi/DIP values at both stations are similar, indicating that the dinoflagellate and diatom ratios at station A2 are higher than those at station A4.

Song et al. (2020) showed that water column respiration (> 60%) is higher than sediment respiration (< 40%), meaning that the longer the phytoplankton sinks in the water column, the more DO is consumed. In addition, due to the small size of some dominant species of dinoflagellates, the sinking speed is slow, so their massive reproduction will increase oxygen consumption in the water column (Wei et al., 2021). Based on previous studies, we analyzed the biological factors contributing to the difference in oxygen deficit between YRE and QHD. The result reveals that the phytoplankton biomass of the YRE is higher than that of the QHD, which would lead to higher oxygen consumption in the bottom water of the YRE than that of the QHD. Meanwhile, because the proportion of dinoflagellates with small sizes and slow sinking in the YRE may be higher than that in the QHD, the oxygen deficit in the YRE water column will be further aggravated than that in the QHD. Therefore, for the YRE area, it is necessary to further strengthen the control of water eutrophication in

the future.

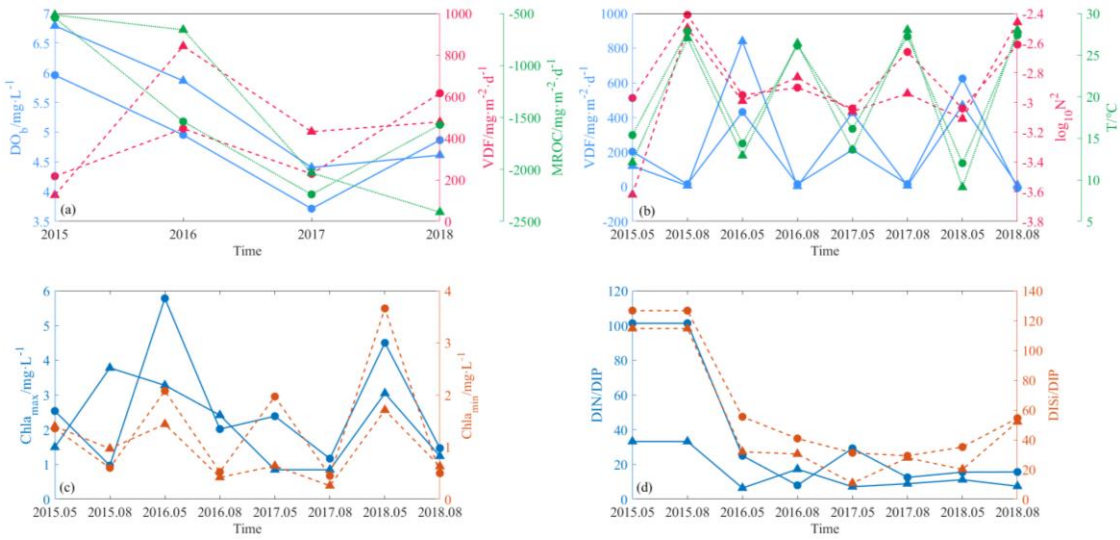

Figure 8. (a) The variation in DO in the bottom layer in August, the sum of vertical diffusive fluxes (unit: mg/m^2/d) in May and August, and the mean rate of respiratory oxygen consumption (unit: mg/m^2/d) from May to August from 2015 to 2018 at stations A2 and A4. (b) The variation in vertical diffusive fluxes, intensity of stratification $log_{10}N^2$ and temperature with time from 2015 to 2018 at stations A2 and A4. (c) Chl-*a* concentration changes with time at stations A2 and A4. (d) Changes in the DIN/DIP ratio and DISi/DIP ratio in water above the pycnocline at stations A2 and A4 over time. The circle and triangle in the figure are the data of stations A2 and A4, respectively.

According to the changes in bottom DO and MROC, the changes in bottom DO at stations A2 and A4 are consistent with MROC. Therefore, the oxygen deficit of stations A2 and A4 can be simply predicted by calculating the MROC. From 2015 to 2018, the MROC in the bottom water and sediment below the pycnocline at stations A2 and A4 from May to August basically increased year by year, except for a slight decrease at station A2 in 2018. At the same time, although the oxygen deficit degree

of station A4 was lower than that of station A2 from 2015 to 2017, the underlying oxygen deficit degree of station A4 exceeded that of station A2 with the increase in MROC in 2018. Compared with other hypoxic regions (Table 2), the magnitude of the MROC at stations A2 and A4 was consistent with the Changjiang Estuary, the Oregon Shelf, and the northern Gulf of Mexico (Lehrter et al., 2012; Reimers et al., 2012; Zhou et al., 2017). At present, the oxygen deficit degree of stations A2 and A4 is slightly lower than that of other hypoxic areas in the world, but if the current trend continues, the oxygen deficit degree of stations A2 and A4 will be further aggravated.

Table 2. Oxygen consumption rate of sediments in different areas ($mg/m^2/d$) and oxygen consumption rate of water column respiration below the pycnocline ($mg/m^3/d$).

Region	Oxygen consumption rate of the sediment	Rate of oxygen consumption in the water column below the pycnocline
Changjiang Estuary	432-768	120-3600
Oregon Continental Shelf	102-314	—
Northern Gulf of Mexico	352-832	1484-3344

Conclusion

Based on the observed data of temperature and salinity, Chl-*a*, nutrients, DO and pH in the Bohai Sea during May and August from 2015 to 2018, the linear radial basis function is used for three-dimensional spatial interpolation to obtain the vertical distribution of DO and related hydrological factors in the central section of the Bohai Sea. Two oxygen deficit regions in the central Bohai Sea in summer are located in the YRE and QHD. Analysis and research results show that the water column exhibits

weak stratification in spring, water mixing is strong, and the surface and bottom water are in a state of oxygen supersaturation. In summer, the stratification is enhanced, and the vertical transport is weakened. At the same time, the organic matter produced by the dead phytoplankton consumes a large amount of DO in the sedimentation process, which leads to the occurrence of an oxygen deficit in the bottom layer of the central section of the Bohai Sea.

Currently, both horizontal and vertical transport in the oxygen-depleted region of the Bohai Sea have been studied (Zhao et al., 2017; Zhang et al., 2022). This study further supplements the control mechanism of vertical transport on bottom layer DO, indicating that the intensity of stratification, the duration of stratification and the onset time of stratification enhancement jointly affect the oxygen deficit in the bottom layer. At the same time, biological influences on bottom DO are highlighted, showing that bottom oxygen consumption is significantly influenced by both phytoplankton biomass and its species. In addition, the discussion of the oxygen deficit degree in different regions can provide a certain reference value for the targeted improvement of water quality in different areas. Finally, the one-dimensional box model is used to calculate the mean rate of respiratory oxygen consumption, which is of great significance for the prediction of hypoxia in coastal areas.

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Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request, Zhang Shufang, Email: sfzhang@nmemc.org.cn.

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