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Coastal hypoxia response to the coupling of catastrophic flood, extreme marine heatwave and typhoon: a case study off the Changjiang River Estuary in summer 2020

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Abstract

Massive bodies of low-oxygen bottom waters are found in coastal areas worldwide, which are detrimental to coastal ecosystems. In summer 2020, the response of coastal hypoxia to extreme weather events, including a catastrophic flooding, an extreme marine heatwave, and Typhoon Bavi, is investigated based on multiple satellite, four cruises, and mooring observations. The extensive fan-shaped hypoxia zone presents significant northward extension during July–September 2020, and is estimated as large as 13 000 km^2 with rather low oxygen minimum (0.42 mg/L) during its peak in 28–30 August. This severe hypoxia is attributed to the persistent strong stratification, which is indicated by flood-induced larger amount of riverine freshwater input and subsequent marine heatwave off the Changjiang River Estuary. Moreover, the Typhoon Bavi has limited effect on the marine heatwave and coastal hypoxia in summer 2020.

Key words: coastal hypoxia, Changjiang River Estuary, extreme weather events, seasonal evolution

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1 Introduction

Dissolved oxygen (DO) functions as an important parameter for the survival of most marine organisms (Diaz and Rosenberg, 2008; Wishner et al., 2018). DO concentration below 2 mg/L (or 62.5 μmol/L) is usually defined as hypoxia water (Diaz, 2001; Zhu et al., 2011), which is much lower than the DO threshold required for many fishery organisms (Vaquer-Sunyerand and Duarte, 2008). Compared with permanent oxygen minimum zones (OMZs) in open ocean, the coastal hypoxia has attracted considerable concern recently due to its rapid increase in the extent, frequency, and duration period during the past several decades (Diaz and Rosenberg, 2008; Diaz et al., 2019). Associated with global warming condition and increasing anthropogenic nutrient loading, the coastal hypoxia waters have been recorded to be over 700 sites worldwide (Diaz et al., 2019).

Currently, the Changjiang River Estuary has been regarded as one of the largest coastal hypoxia areas around the world (Chen et al., 2007, 2020). Many observation studies have clearly examined its spatial-temporal variation and underlying mechanism. For most years, the hypoxia water initially appears near the Zhe-Min (Zhejiang-Fujian) coast in late-spring, extends northward to the Changjiang River Estuary during mid-summer and early-autumn, and finally disappeared from north to south in mid- or late-autumn. Besides, the hypoxia water was sometimes advected offshore, forming hypoxia patches in the outer shelf of East China Sea (ECS) (Zhou et al., 2017; Zhu et al., 2017). Statistically, there are two hypoxia cores, which are distributed near the Changjiang River Estuary and along the Zhe-Min coast, separately (Wang et al., 2012; Zhou et al., 2020). The coastal hypoxia off the Changjiang River Estuary is highly variable in multi-time

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scales (synoptic: Ni et al. (2016); intraseasonal: Zhang et al., (2020); seasonal: Chi et al. (2020); year to year: Zhou et al. (2010); interannual: Chen et al. (2020); decadal and long-term trend: Lu et al. (2017), Ning et al. (2011), caused by complicated physical environments and biogeochemical processes (Zhou et al., 2020; Zhu et al., 2011). For spatial scale, the seaward and shoreward limits of hypoxia zone is determined by several coastal physical-biochemical fronts [turbidity front and Changjiang River diluted water (CDW) plume front; Wei et al., 2015, 2022]. Previous hypoxia observations indicate the coastal hypoxia zone mainly distributes between the surface-suspended sediment front and the 50-m isobath alongshore (Fig. 1b). It is generally agreed that sustainable vertical stratification and organic matter degradation are two main causes for the hypoxia formation off the Changjiang River Estuary (Chen et al., 2020; Fennel and Testa, 2019; Wei et al., 2017).

The climate change (such as flood, typhoon, and global warming) may complicate the natural and human-caused hypoxia dynamics in many coastal regions (Boesch, 2008; Rabalais et al., 2010), such as Baltic Sea (Bendtsen and Hansen, 2013; Meier et al., 2011), Chesapeake Bay (Hagy et al., 2004), and Gulf of Mexico (Justić et al., 2005). There are also studies that address the response of coastal hypoxia to climate change in the Changjiang River Estuary area. Zhou et al. (2017) explored the response of coastal hypoxia to three typhoons in drought 2006. Ni et al. (2016) reported the hypoxia reoccurrence phenomenon after strong wind in summer 2019. Combined *in situ* observation with flood numerical model, Ge et al. (2021) analyzed the impacts of fluvial flood on physical and biogeochemical environments in estuary–shelf continuum in the ECS. Gong et al. (2011) reported the chlorophyll bloom subsequent to flooding occurrence during the summers of 1998 and 2010. Song et al. (2023) indicated the huge nutrient flux after flooding in summer 2020. Similarly, Sun et al. (2023) detected the prodigious nutrient discharge near the Changjiang River Estuary following flooding events in the summers of 2016 and 2020. However, these previous studies are mainly focused on transitory weather events, and the temporal scope of their examination is limited to a duration of less than one month. The comprehensive study of periodic evolution of coastal hypoxia under extreme weather events has not been fully understood and the continuous observation data are comparatively infrequent off the Changjiang River Estuary.

The extreme weather events occurred in the ECS in summer 2020. First, the southern China suffered from catastrophic flooding during June–July 2020, which is the severest flood year in the past 60 a (Wei et al., 2020). This record-breaking flood event can be attributed to numerous distant atmospheric influences, including abnormal position and intensity of the western Pacific subtropical high (Ding et al., 2021), warming phase of equatorial Indian Ocean (Tang et al., 2021; Zhou et al., 2021), and North Atlantic Oscillation (NAO; Liu et al., 2020). Second, the western North Pacific typhoon season started slowly, and no typhoon passes by Chinese mainland in the entirely July 2020 (Wang et al., 2021). The fair weather, with enhanced solar radiation and weakened wind field, contributed to the extreme marine heatwave in the Yellow Sea and ECS in August 2020 (Pun et al., 2023). Third, a rare Typhoon Bavi, as the strongest typhoon in the ECS in past decade, has been proved to modulate the coastal current and surface warm water redistribution off the Changjiang River Estuary in August 2020. The modelling result indicated that Typhoon Bavi hardly obliterate the coastal hypoxia (Meng et al., 2022). Furthermore, another mooring study conducted by Pun et al. (2023) affirmed that the Typhoon Bavi, due in part to an intense salinity stratification, is incapable to abolish the marine heatwave in the outer shelf of the ECS. Until now, the coastal hypoxia response to these extreme weather conditions (a catastrophic flooding, an extreme marine heatwave, and Typhoon Bavi) in summer 2020 is still unknown.

Recently, an interdisciplinary marine investigation program combined with four cruises and a mooring site was conducted off the Changjiang River Estuary during July–September 2020. It provides an opportunity to investigate the coastal hypoxia variation under extreme weather conditions. This study focuses on the seasonal evolution of coastal hypoxia event and analyzes the response of coastal hypoxia to related extreme weather events during July–September 2020.

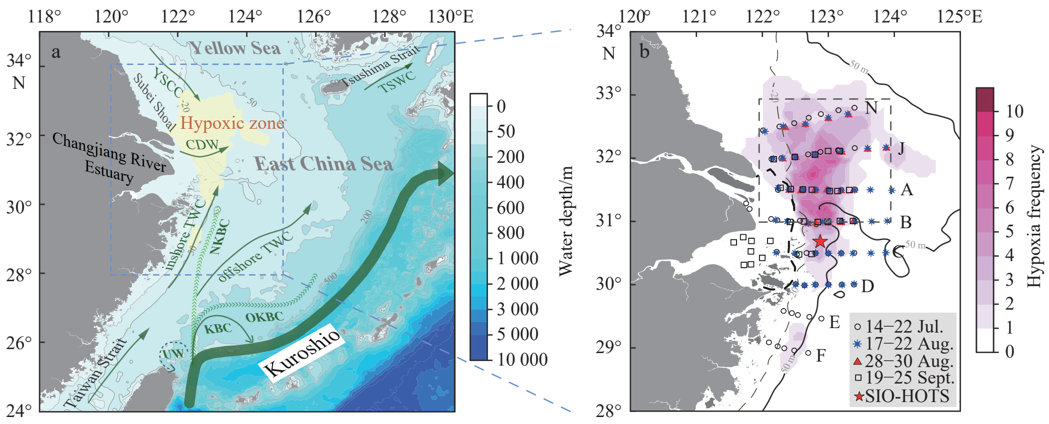

Fig. 1. a. Schematic of the summer time circulation in the East China Sea [modified from Yang et al. (2012, 2013) and Tian et al. (2022)]. CDW: Changjiang River Diluted Water; YSCC: Yellow Sea Coastal Current; TWC: Taiwan Warm Current. Four Kuroshio intrusion branches in summer are also represented (Yang et al., 2012): Kuroshio Branch Current (KBC), Offshore Kuroshio Branch Current (OKBC), Nearshore Kuroshio Branch Current (NKBC) and the westward Kuroshio branch (upwelling, UW). b. Historical bottom hypoxia frequency (1998–2020; shading, hypoxia records are listed in Table 1), cruise and mooring sampling stations (marked), and seabed topography (thin contour) off the Changjiang River Estuary. The black cycles, blue stars, red rectangles, and black rectangles indicate sampling stations observed during 14–22 July, 17–22 August, 28–30 August, and 19–25 September, respectively. The red star denotes SIO-HOTS mooring. The dashed curve indicates surface suspended sediment front off the Changjiang River Estuary (redrawn by Li et al., 2021). The dashed gray box indicates the domain average area for the climatic and hydrographic factors.

2 Data

2.1 *Shipboard and mooring observations*

Four shipboard surveys were conducted off the Changjiang River Estuary during July to September 2020. The cruise period is 14–22 July, 17–22 August, 28–30 August and 19–25 September, respectively. The sampling stations cover the northern component of historical hypoxia area off the Changjiang River Estuary, which were mainly located in the shelf waters with depths <50 m (Fig. 1b). Specially, six repeating hydrographic sections (N, J, A, B, C, and D) were conducted to better detect the seasonal evolution of coastal hypoxia, within the latitude range from 30°N to 32.5°N.

At all stations in four cruises, vertical profiles of temperature, salinity and DO were recorded by a Seabird Electronics (SBE 9plus) Conductivity-Temperature-Depth profiler (CTD) with DO sensor (SBE 43). The DO measurements were calibrated against water sample analyses conducted by the Winkler titration method for each station and layer. Linear regressions between sensor and sample DO concentration data during summer 2020 were analyzed: $DO_{LAB} = DO_{CTD} \times 1.01 - 0.27$ ($r^2 = 0.97$, $n = 191$), where DO_{LAB} is the dissolved oxygen concentration collected by water sampling bottles and DO_{CTD} is the dissolved oxygen concentration recorded by the SBE 43 sensor. According to conventional definition in literatures, the hypoxia status is defined as DO value <2 mg/L, and the low-DO status is defined as DO value <3 mg/L (Diaz, 2001; Zhu et al., 2011).

For continuous observation, a 3-m buoy combined with seabed mooring (named Second Institute of Oceanography Hypoxia Observation System, SIO-HOTS) was deployed from 3 July to 31 September 2020 at site (30.68°N, 122.88°E; 38 m depth), near Shengshan Island (Fig. 1b). This is a site near Zhoushan fishing ground and where the multi-scale variations of coastal hypoxia are clearly detected (Ni et al., 2016; Wang et al., 2017). Several bottom hydrographic parameters, including temperature, salinity, and DO (Seabird sensors integrated in water quality meter) are measured by a seabed mooring and used in this study. The DO sensor was also calibrated using the Winkler titration method.

Besides, discharge data of Datong station during 1998–2020 are used to evaluate riverine freshwater input from the report of the Changjiang Water Resources Commission of the Ministry of Water Resources of China. This hydrological gauging station has no tidal influence, with ~625 km upstream from the river mouth.

Table 1. Hypoxia area and dissolved oxygen minimum off the Changjiang River Estuary reported in literatures

Investigation period	Hypoxia extent (2 mg/L threshold)/km²	Dissolved oxygen minimum/ (mg·L⁻¹)	Reference
August 1998	600	1.44	Wang and Wang (2007)
August 1999	13 700	1.00	Li et al. (2002)
August 2002	579[a]	1.73	Wang (2009)
August 2003	100[a]	1.8	Chen et al. (2007)
August 2004	no data	2.30	Li et al. (2011)
August 2005	45[a]	1.56	Li et al. (2011)
August 2006	19 600	0.98	Zhou et al. (2010)
August 2007	7 600[a]	0.90	Li (2015)
August 2008	3 000[a]	1.40	Liu et al. (2012)
August 2009	2 800[a]	1.79	Liu et al. (2012)
August 2010	1 968	1.20	Liu et al. (2021)
August 2011	no data	2.10	Zhu et al. (2017)
August 2012	4 162	1.54	Luo et al. (2018)
August 2013	11 150	0.73	Zhu et al. (2017)
August 2014	1 000[a]	0.85	Zhou et al. (2020)
August 2015	no data	1.92[b]	Chi et al. (2017)
August 2016	22 800	0.08	Chen et al. (2020)
August 2017	10 071	0.33	Chen et al. (2020)
August 2020	13 000	0.42	this study

Note: a. The hypoxia areas are digitized from the listed references; b. the dissolved oxygen minimum appears in the subsurface layer.

2.2 *Satellite data*

Multiple-satellite remotely sensed observations are used to diagnose the climatic and hydrographic conditions associated with coastal hypoxia off the Changjiang River Estuary, such as sea surface temperature (SST), sea surface salinity (SSS), and sea surface wind. The daily temperature datasets of Optimum Interpolation Sea Surface Temperature (OISST Version 2; Huang et al., 2021), with spatial resolution of 0.25° × 0.25° during 1998–2020, are used to illustrate the ECS marine heatwaves. The daily salinity dataset of Soil Moisture Active Passive (SMAP Version 5.0; Entekhabi et al., 2010), with spatial resolution of 4 km × 4 km during 2015–2020, is used to illustrate the spreading pattern of CDW. The 6-hour Cross-Calibrated Multi-Platform (CCMP Version 3.1) wind data (Mears et al., 2022), with spatial resolution of 0.25° × 0.25° during 1998–2020, are used to analyze ECS wind field.

These three satellite products (SST, SSS, and sea wind) have been widely applied in the physical and biogeochemical studies in the Changjiang River Estuary and adjacent ECS, such as marine heatwaves (Yan et al., 2020), CDW variation (Wu et al., 2020), and ECS wind energy (Zheng et al., 2012).

2.3 *Extreme weather events in summer 2020*

Observed extreme weather events and associated hydrographic variations in summer 2020 are illustrated as follows (Fig. 2). The catastrophic flooding in the middle and lower reaches of Changjiang River during June–July 2020 induced large river discharge, and the flood peak (>8 × 10⁴ m³/s) occurs in 13 July according to Datong station records (Fig. 2a). The river discharge is about 50% greater than the climatology mean (1998–2020) and the high value lasts from mid–July to late-September 2020. Influenced by the huge fresh water input, the domain-average SSS is lower than 30 off the Changjiang River Estuary during July–September 2020. The salinity minimum occurred in 28 July, which is about two weeks later than the flood peak (Figs 2a and c). The Typhoon Bavi also can be detected from satellite wind field during 24–27 August. The surface wind direction shifts from southwestward to northwestward during typhoon passage period (Fig. 2b), however wind speed remains below 10 m/s because of the trajectory of Typhoon Bavi, which bypasses the Changjiang River Estuary and move northeastward (Pun et al., 2023). Significant marine heatwave appeared in the mid- and late-August, and the domain averaged SST can reaches 29℃ in 25–28 August (Fig. 2d). The SST decreased by 1.5℃ after the Typhoon Bavi passage, and rapidly increased to 28℃ subsequently, which agrees with the mooring observation in Pun et al. (2023). The relative warmer water sustained until 25 September off the Changjiang River Estuary.

3 Results

Figure 3 shows the coastal hypoxia evolution off the Changjiang River Estuary during July to September 2020. The hypoxia event has firstly appeared in the middle component off the Zhejiang coast in July 2020. Low DO water is distributed off the Changjiang River Estuary, and extends northward to approximately 32°N. The hypoxia area is estimated as ~700 km² and low DO area is ~21 000 km², respectively. The oxygen minimum is measured as ~1.6 mg/L at station F4 along the south most section.

Our survey in August 2020 is divided into two legs by a passing Typhoon Bavi. The post-typhoon cruise is conducted during 17–22 August and the past-typhoon cruise is conducted during 28–30 August. For the post-typhoon cruise, two hypoxia patches are distributed near the river mouth and offshore area separately, with hypoxia areas of 5 700 km² and 3 100 km² and oxygen minimum of 1.05 mg/L and 1.78 mg/L, respectively. In total, the hypoxia area is estimated as ~8 800 km² and low DO area is more than 25 000 km². After the Typhoon Bavi passage,

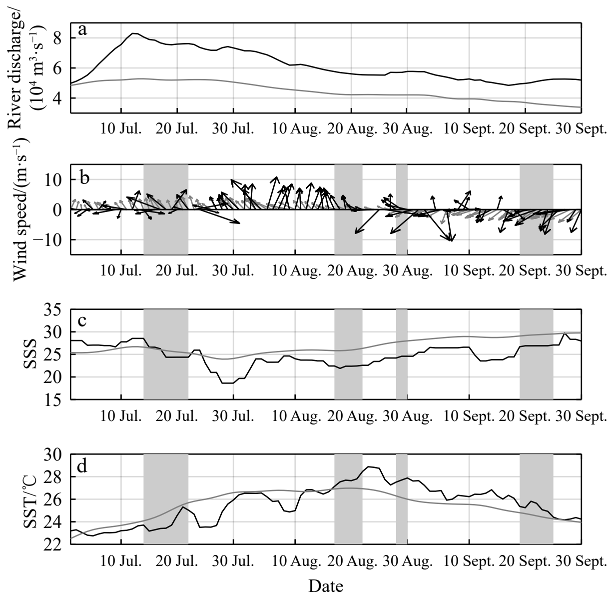

Fig. 2. The time series of Changjiang River discharge (a), CCMP wind vector (b), SMAP salinity (c), and OISST temperature (d) during July–September 2020. Gray lines in a–d denote the climatology mean. The average period is 1998–2020 for river discharge, wind, and sea surface temperature (SST), and 2015–2020 for sea surface salinity (SSS). The average domain for wind, SST, and SSS is shown in Fig. 1b. Gray shading areas indicate four cruise periods during July–September 2020.

the hypoxia area increased to 13 000 km², with rather low DO value (0.42 mg/L). It seems that typhoon does not eliminate coastal hypoxia in August 2020.

In 19–25 September, the hypoxia extent is decayed gradually, with similar pattern as that observed in 28–30 August (Figs 3c, d). The hypoxia core is still located near (31.5°N, 122.5°E), to the west of surface suspended sediment front. However, the associated hypoxia and low-DO areas are decreased to ~1 800 km² and ~9 700 km², respectively. Meanwhile, the measured DO minimum increases to 1.26 mg/L.

The bottom DO measured by continuous four cruises supports the traditional understanding about the seasonal evolution of coastal hypoxia in previous studies. Significant northward extension can be detected off the Changjiang River Estuary during July–September 2020. It is worth noting that the main body of bottom hypoxia water located north of the Changjiang River's mouth in August 2020 and sustained to the north of 31°N until late-September, which distributed farther north relative to the climatology mean (31°N, 123°E) (Wang, 2009). Since the investigated area limitation by cruise route, the northern and southern boundaries of the hypoxia zone could not be determined accurately in this study. Thus, the actual hypoxia region in summer 2020 was likely much larger than our estimates (Table 2).

As stated in Table 1, the hypoxia in summer 2020 is rather severe compared with historical records in literatures. (1) Although the 2020 hypoxia area is underestimated due to cruise plan, the maximum hypoxia area in 28–30 August 2020 is the fourth largest in records, which is comparable to those reported in summers of 1999, 2006, and 2016 (Chen et al., 2020; Zhou et al., 2010). (2) The DO minimum 0.42 mg/L observed in 28–30 August is the secondary lowest value reported in literatures, only larger than that of 2016 hypoxia.

To better illustrate the seasonal evolution of 2020 hypoxia event, we directly compare the DO distribution along repeated section 31.5°N (Fig. 4). As shown in Fig. 3, the hypoxia core mainly exists along this transection in August 2020. The seasonal evolution of coastal hypoxia is described as follows: on 20 July, the surface DO increases offshore with the range of 4–8 mg/L. For most stations, the DO value decreases with depth. And the subsurface DO value is lower than 3 mg/L for the longitude range of 122.3°–122.7°E, presenting low DO pattern in the coastal area. On 19 August, the surface DO is over saturated east of 122.6°E while apparent bottom hypoxia appears at nearshore sites, with the longitude range of 122.3°–122.7°E for the 10–20 m layer. The oxygen minimum is measured as 1.73 mg/L. After the passing of

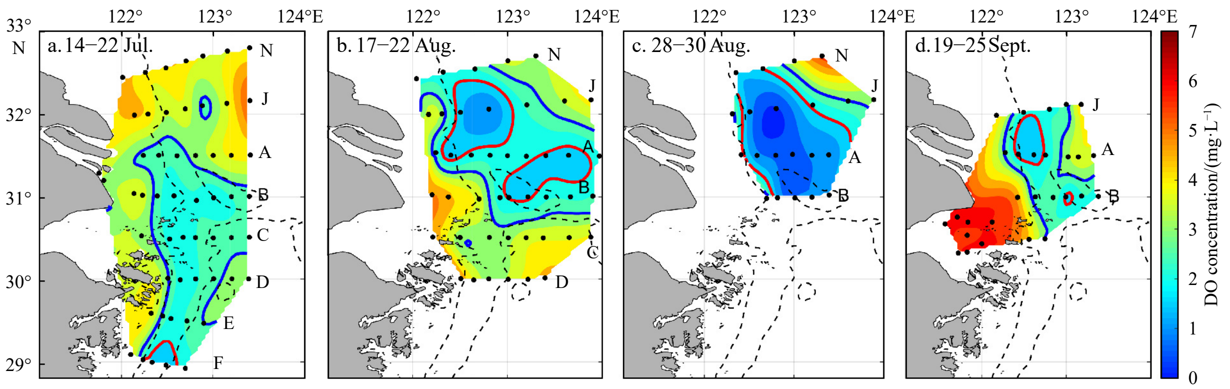

Fig. 3. Hypoxia events observed off the Changjiang River Estuary during July–September 2020. The observed periods is 14–22 July (a), 17–22 August (b), 28–30 August (c) and 19–25 September (d), respectively. Red and blue curves denote the hypoxia and low DO thresholds (2 mg/L and 3 mg/L, respectively).

Table 2. Hypoxia and low DO status observed off the Changjiang River Estuary during July–September 2020

Cruise period	14–22 July	17–22 August	28–30 August	19–25 September
Low DO area/km^2 (DO < 3 mg/L)	21 000	25 000	18 000	9 700
Hypoxia area/km^2 (DO < 2 mg/L)	700	8 800	13 000	1 800
DO concentration minimum/(mg·L^{-1})	1.60	1.05	0.42	1.26

Typhoon Bavi, we found coastal hypoxia becomes much severer off the Changjiang River Estuary. The hypoxia extent extends along the transection, with the longitude range of 122.4°–123.4°E below 20 m. Meanwhile, the observed DO minimum decreases to 0.72 mg/L on 29 August. Hypoxia waters still exist on 21 September, though the extent has retracted to the nearshore area, within the longitude range of 122.35°–122.75°E below 10 m depth.

The seabed mooring of SIO-HOTS also captures the seasonal evolution of coastal hypoxia near Shengshan Island during August–September 2020 (Fig. 5). During the period of Typhoon Bavi passage, mooring observation indicates that coastal hypoxia is retarded during 22–27 August and subsequently re-occurred on 30 August. This result agrees with above mentioned cruise observation. The bottom hypoxia near Shengshan Island is rather severe in September 2020, and eventually disappears until 19 September.

4 Discussion

4.1 *Linking the 2020 severe hypoxia with climatic and hydrographic conditions*

In addition to the important role of terrestrial and oceanic nutrient supplies to hypoxia formation, previous studies also demonstrated that physical conditions (such as slow advection, weak tidal mixing, or calm wind) can significantly affect the development of hypoxia (Wang, 2009; Zhou et al., 2017). Impacts of climatic and hydrographic factors on hypoxia are examined here based on cruise and multi-satellite data, with a focus on the seasonal evolution of 2020 hypoxia event.

In general, coastal hypoxia is strongly influenced by watershed in many estuaries (Breitburg et al., 2018). As shown in Fig. 2a, large river discharge typically occurs during June–September and peaks in July, which carries a large amount of terrestrial materials (nutrients and organic matters) from the drainage basin into the estuary and the adjacent ECS. The discharge in flooding season of 2020 was generally higher than the multi-year average (1998–2020), especially in July (~150%) and August (~147%).

It is likely that the northeastward spreading of the CDW in summer (Beardsley et al., 1985; Wu et al., 2011; Zhu et al., 2003) is responsible for the huge 200-km meridional scale of the observed low-salinity water off the Changjiang River Estuary. As shown in Fig. 6, a significant amount of freshwater gathered off the Changjiang River Estuary, creating a salinity front in the middle and outer shelves. During 14–22 July, massive freshwater spread offshore, with two low-salinity cores (SSS < 15) distributing near the river mouth and 100 km offshore. This offshore low-salinity water seems to be detached from the CDW (Xuan et al., 2012), which is favorable for nutrient offshore transport and subsequent coastal hypoxia extension (Wei et al., 2021; Sun et al., 2023). In the north the Subei coastal water inhibits the northern extension of CDW at 32°N. During 17–22 August, the CDW mainly spreads northeastward and more fresh water (S < 20) has been transported to the ECS middle shelf. The high-salinity oceanic water can be detected south of 30.5°N, forming strong salinity front in the upper layer. During 28–30 August, the CDW extension area is decayed compared to that in post-typhoon period. The offshore low-salinity plume (S < 20) disappears possibly caused by the vertical mixing process of Typhoon Bavi (Meng et al., 2022). During 19–25 September, the CDW spreading area has recovered to a certain extent, and the low-salinity tongue extends northeastward. It is worth noting that CDW always exist above the hypoxia water for all four cruises, even during the passage of Typhoon Bavi.

In fact, the Changjiang River plume is extremely mobile due to changes in wind magnitude and direction (Zhang et al., 2018). However, the hypoxia area was always located in the domain of CDW during July–September 2020 (Fig. 6). In this case, low-salinity and warm water can stay around the upper layer of the hypox-

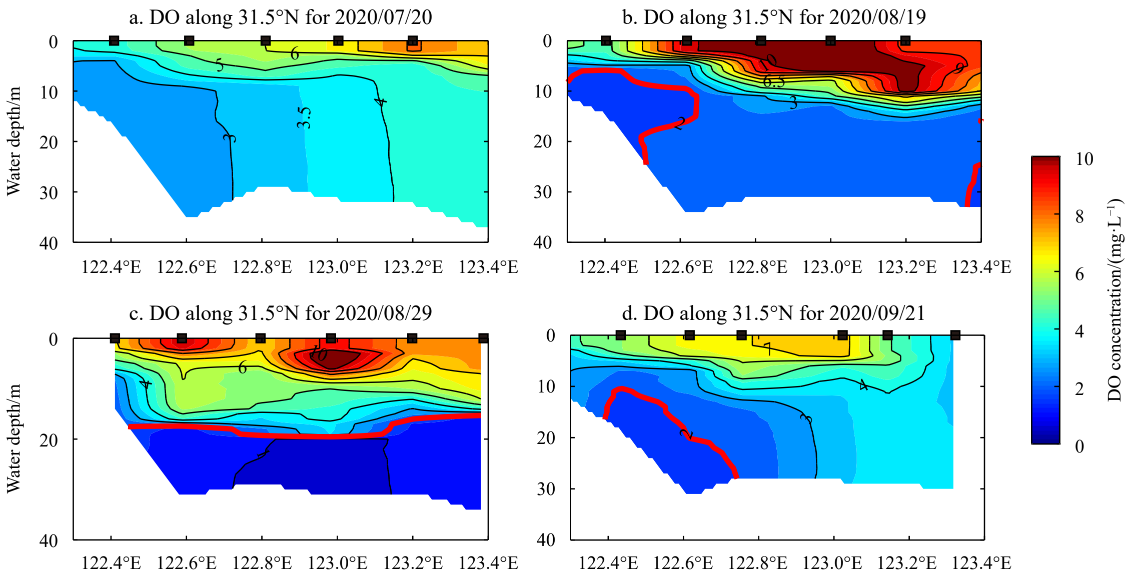

Fig. 4. DO value (with unit of mg/L) along the repeated Section A (~31.5°N) in 20 July (a), 19 August (b), 29 August (c) and 21 September (d), respectively. Red curves denote the hypoxia threshold (2 mg/L).

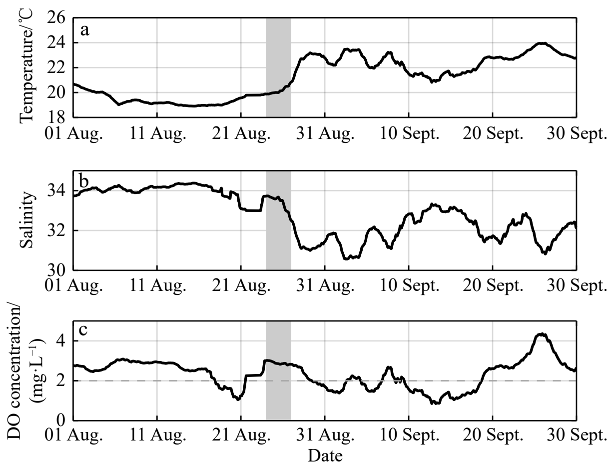

Fig. 5. Bottom hydrographic parameters observed by SIO-HOTS during 1 August–30 September 2020. The bold curves denote daily mean time series. a. Bottom temperature; b. bottom salinity; c. bottom DO value. Shading area denotes the passage period 24–27 August of Typhoon Bavi.

ia area and help provide a sustained stratification, which is favorable for the bottom oxygen depletion.

The cruise observed SST also present significant seasonal variation during July–September 2020 (Fig. 6). The SST is distributed rather homogenously during 14–22 July, with value ranges from 23℃ to 25℃. During 17–22 August, the SST pattern can be separated into two components by significant temperature front along 123°E. Coastal upwelling (SST < 26℃) can be clearly detected near Zhoushan Archipelago, and amount of warm water gathers offshore and forms marine heat wave. The average-mean SST is mostly over 28℃ in coastal hypoxia area. After the passage of Typhoon Bavi, the meridional temperature front near 123°E has disappeared during 28–30 August. There is good correlation between SST and SSS patterns. It is clearly to identify the warm and fresh CDW plume off the Changjiang River Estuary. The SST pattern is rather homogenously during 19–25 September, with value ranges from 23℃ to 25℃. And the marine heat wave disappears.

Many studies discussed the good correlation between vertical stratification and hypoxia extent (or bottom DO concentration) off the Changjiang River Estuary (Zhou et al., 2010; Ni et al., 2016; Zhu et al., 2016; Chi et al., 2017). The surface CDW overlying the saline oceanic bottom water enhances the stratification off the estuary, providing favorable condition for hypoxia formation. $\Delta\delta/\Delta z$ is used to quantitatively represent the intensity of stratification [pycnocline is defined as the water column where the density vertical gradient greater than 1 kg/m^4 for shallow waters (Sun, 2006), $\Delta\delta$ is the density difference between the upper and lower layers of the pycnocline, and Δz is the thickness of the pycnocline]. For July–September 2020, the pycnocline intensity presents tongue-like structure off the Changjiang River Estuary (Fig. 7). The value is greater than 2 kg/m^4 near the Changjiang River's mouth and relatively small in the other regions. This pattern is similar to that of SSS distribution (Fig. 6) because of the dominant contribution of salinity to surface density off the Changjiang River Estuary (Zhu et al., 2016).

The seasonal evolution of pycnocline is similar to that of hypoxia. Strong pycnocline appears off the Changjiang River Estuary during 14–22 July, although the DO value is not rather low. During 17–22 August, the pycnocline becomes rather stronger. Larger values (>0.5 kg/m^4) appears in the northern component of

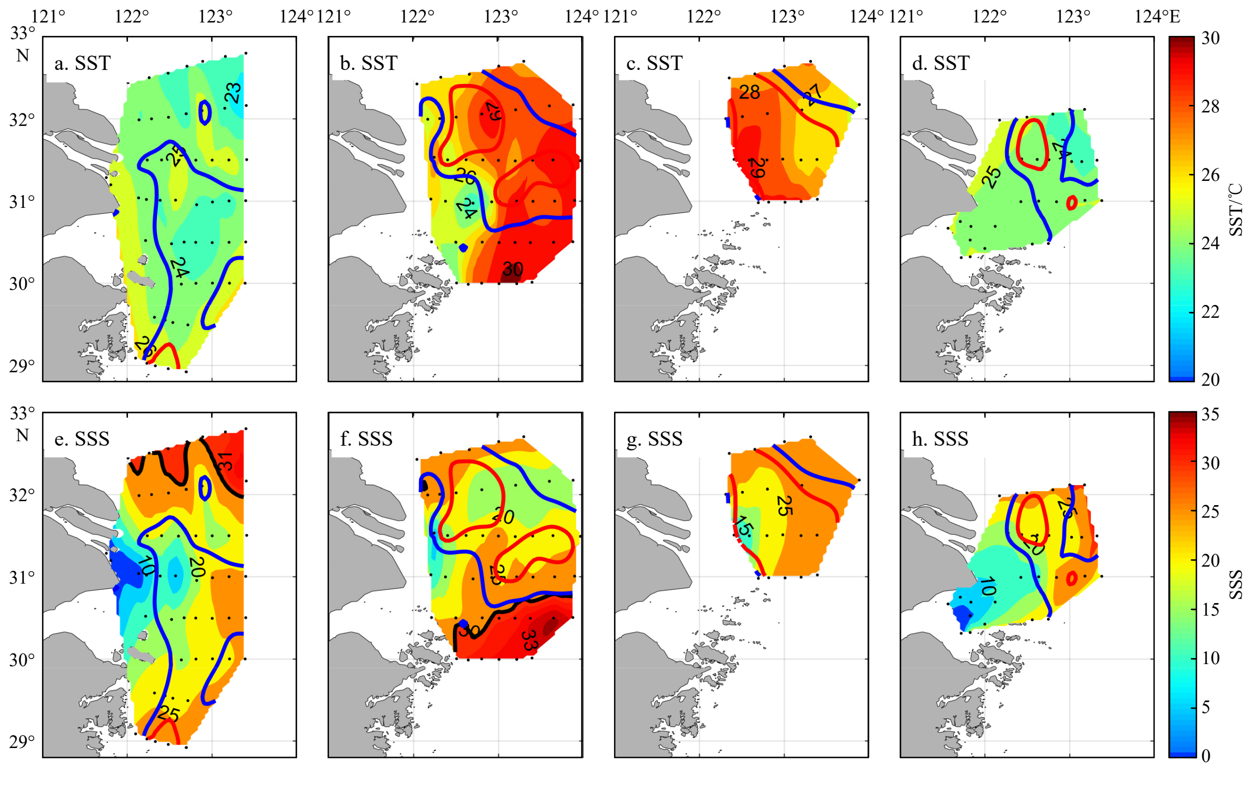

Fig. 6. SST and SSS off the Changjiang River Estuary during July to September 2020. The observed periods are 14–22 July (a, e), 17–22 August (b, f), 28–30 August (c, g), and 19–25 September (d, h), respectively. Solid contour in e–h denotes the isoline of CDW (S = 30). Red and blue curves denote bottom hypoxia and low-DO areas (blue: 3 mg/L; red: 2 mg/L).

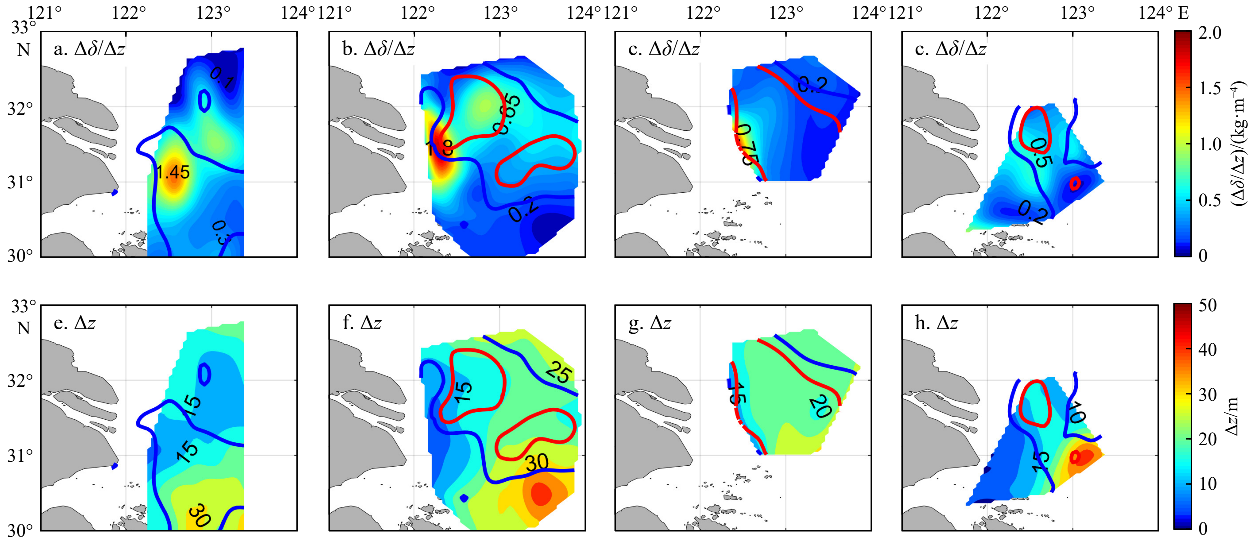

Fig. 7. Pycnocline intensity ($\Delta\delta/\Delta z$) and pycnocline layer thickness (Δz) during 14–22 July (a, e), 17–22 August, (b, f), 28–30 August (c, g) and 19–25 September (d, f), respectively. The solid contours indicate bottom hypoxia and low-DO areas (blue: 3 mg/L; red: 2 mg/L). The contour interval is 0.05 kg/m^4 in a–d and 5 m in e–h.

the study area, which coincides with the bottom hypoxia distribution. After the Typhoon Bavi, the pycnocline becomes weaker, with smaller intensity and much thicker layer. The thicker pycnocline forms much adequate and hermetic circumstance for oxygen depletion in bottom waters and further enhances the hypoxia extent in 28–30 August 2020. During 19–25 September, relative strong pycnoline sustains the oxygen depletion in bottom waters.

There are several observation studies about seasonal evolution of coastal hypoxia based on continuous cruise data, such as May–October 2006 (Wei et al., 2015; Zhou et al., 2010), June–September 2013 (Luo et al., 2018), and June–October 2015 (Chi et al., 2020). In these studies, the consecutive process of hypoxia (northward development and southward dissipation) is associated with the movements of several key water masses, such as CDW, TWC subsurface water, and even YSCC. Our results are consistent with this view. As is shown in Figs 6 and 7, the northern excursion of hypoxia area is associated with the advancement and recession of the CDW and related stratification pattern during July–September 2020.

To clearly describe the seasonal evolution of stratification observed during July–September 2020, we compare distributions of hydrographic parameters across the Changjiang River Estuary (31.5°N) among different periods (Fig. 8). On 20 July, warm and fresh water ($T > 25$℃, $S < 30$) sits in the upper layer, jointly contributing to the vertical density gradient. The vertical stratification becomes much stronger on 19 August. The bottom hypoxia seems to be blocked by high-saline subsurface water ($S = 34$) because of the prohibition of Kuroshio subsurface water to coastal

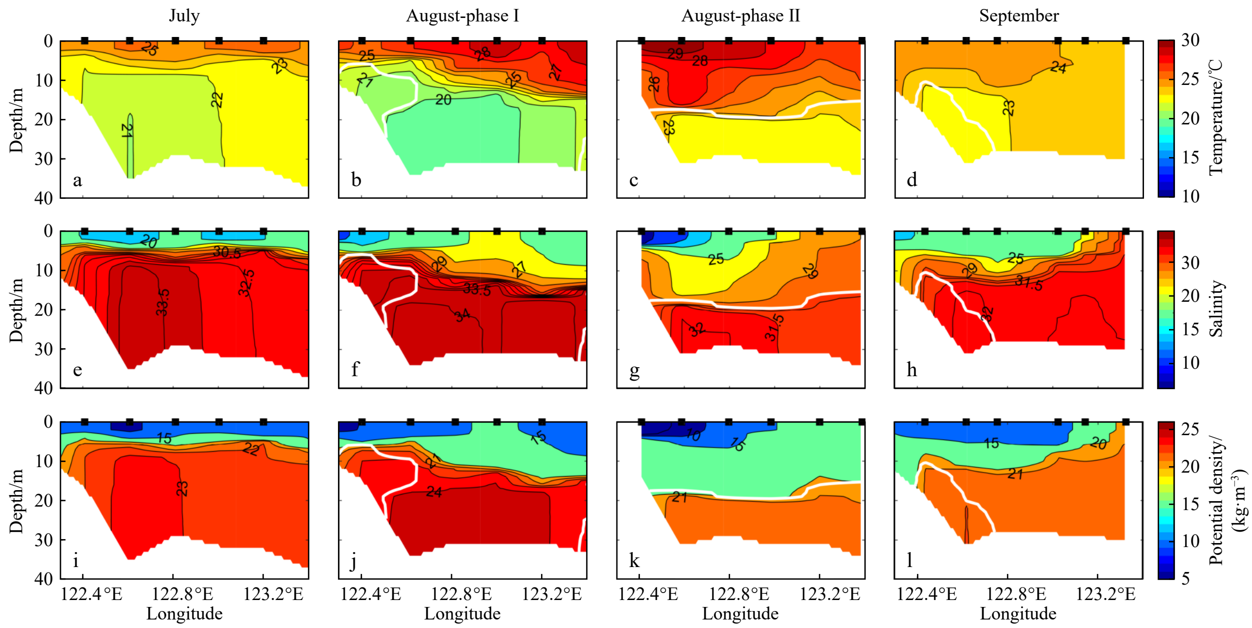

Fig. 8. Cross-shelf distributions of water properties measured along Section A (~31.5°N) in 20 July (a), 19 August (b), 29 August (c) and 21 September (d), respectively: temperature (a–d); salinity (e–h); and potential density (i–l). White contour indicates bottom hypoxia water (DO < 2 mg/L).

hypoxia (Luo et al., 2018). After the Typhoon Bavi, the upper layer water column was replaced by much warmer and fresher water ($T > 28$℃, $S < 26$). Meanwhile, the subsurface water becomes much warmer and fresher ($T > 23$℃, $S < 32.5$). Related stratification becomes weaker but not destroyed by Typhoon Bavi. Thus, oxygen deficit continues, and coastal hypoxia becomes much severer. On 21 September, the coastal hypoxia still exists west of 122.8°E, which coincides with the location of cold and saline bottom water.

Overall, the severe hypoxia during July–September 2020 is strongly controlled by the climatic and hydrographic conditions off the Changjiang River Estuary, especially for the strong vertical stratification. From both cruise observation and satellite data, the extensive freshwater distribution is well detected, and always stay in the domain of hypoxia waters during July–September 2020 (Fig. 6). For the stratification, the heavy rainfall and subsequent amount of river discharge is responsible. The river discharge is ~40% larger than climatology mean and the subsequently SST maximum in August is ~1℃ higher than climatology mean. Basically, the coastal hypoxia off the Changjiang River Estuary is river dominated, and the fair weather (typhoon absent) provides favorable condition for the accumulation of marine heatwave and subsequently DO deficit during July–August 2020. Besides, the Typhoon Bavi did not have a substantial impact on the hypoxia area off the Changjiang River Estuary, which may be related to the truth that typhoon not passing through the hypoxia area directly. Using the ROMS-CoSiNE physical-biochemical model, Meng et al. (2022) has found the advection induced by Typhoon Bavi caused coastal warming and changed the spatial distribution of bottom hypoxia water. However, the bottom hypoxia is not eliminated and becomes much severer after the typhoon passage.

4.2 *Comparison with literature results*

The extreme weather events, including a catastrophic flood, an extreme marine heatwave and typhoon activity in summer 2020, strongly affect the ECS hydrography and eventually impact the bottom DO depletion off the Changjiang River Estuary. In this subsection, comparison study will be conducted for 19 historical hypoxia events and associated meteorological and hydrographic conditions during 1998–2020, in order to verify the above-mentioned climate effect on coastal hypoxia in statistical sense.

Among the years from 1998 to 2020, there were six years with severe hypoxia 1999, 2006, 2013, 2016, 2017, and 2020. These years exhibited both an extended hypoxia area and extremely low dissolved oxygen levels (hypoxia areas greater than 1×10^4 km^2 and minimum dissolved oxygen values less than 1 mg/L). It is worth noting severe hypoxia appears much frequently for the past two decades. It can be observed that four years experienced pronounced hypoxia during the past decade (2011–2020), whereas only two years encountered extreme hypoxia events during 1998–2010. This seems to imply a rising frequency of hypoxia events off the Changjiang River Estuary under the influence of climate change and human activities (Zhu et al., 2017; Chen et al., 2020).

Further analysis of the Changjiang River discharge and SST near the hypoxia area in six severe hypoxia years revealed the following: in most of these years, four of them had a discharge exceeding the long-term average, except for 2006 and 2013. In terms of temperature, except for 1999, the other five severe hypoxia years were associated with positive SST anomalies and associated marine heatwaves. Further analysis indicates that the hypoxia core in summer 1999 also aligns well with the positive SST anomaly (SSTA) region (Fig. 10a), highlighting the potential impact of marine heatwaves on hypoxia. Park et al. (2011) speculated that the presence of the CDW can cause the formation of warm water in the estuary. However, in reality, the core of marine heatwaves in certain years is not located off the Changjiang River Estuary, and it is not solely influenced by river discharge, but rather more apparent in the ocean-atmosphere interactions (Yan et al., 2020). We calculated the correlation between July river discharge and August SST mean value (or SST maximum), and the results were found to be insignificant.

The impact of typhoons on ECS hydrography is largely determined by typhoon intensity, the influence extent of strong wind, and its passage speed (Cong et al., 2021; Li et al., 2024). Ni et al. (2016) posits that on one hand, typhoons can disrupt vertical stratification, facilitating vertical exchange of dissolved oxygen and thus alleviating hypoxia. On the other hand, however, subsurface excessive nutrient influx into surface waters through mixing can lead to algal blooms and the recurrence of hypoxia. In six severe hypoxia years, the number of passage typhoons is relatively low, and most of them are of lower intensity. Specifically, in summers of 2006, 2016, and 2017, no typhoons passed through the Changjiang River Estuary. Although typhoons were present near the hypoxia area in 1999 and 2013, they were also relatively weak (weaker than Category 3). The only exception is the powerful Typhoon Bavi during summer 2020. However, it has been indicated in previous studies that despite the significant vertical exchange of heat caused by Typhoon Bavi due to the excessively strong ocean stratification.

The Changjiang River discharge, marine heatwaves, and typhoons are modulated by different atmospheric and oceanic signals, and the underlying mechanisms behind them may be relatively independent. At least from a statistical perspective, no correlation has been found among them. However, the combined effect of these three factors creates favorable conditions for the occurrence of hypoxia. During the previous two decades, two

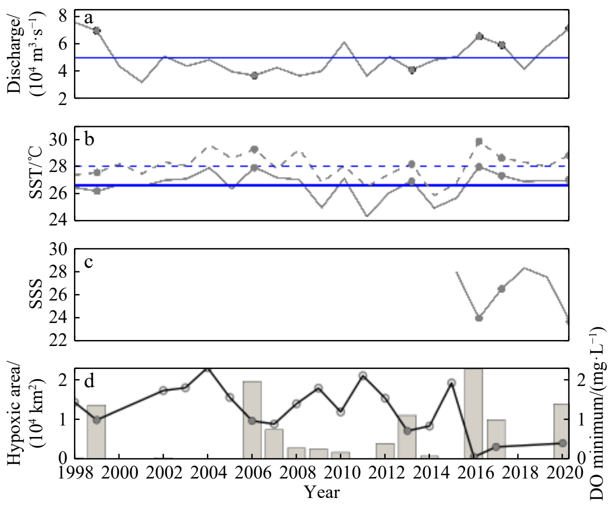

Fig. 9. a. Changjiang River discharge in July during 1998 to 2020; b. domain averaged SST and SST maxima in August off the Changjiang River Estuary during 1998 to 2020; c. domain averaged SSS in August off the Changjiang River Estuary during 2015–2020; d. historical records about the hypoxia area (histogram) and DO minimum (dotted; mg/L) during 1998 to 2020. The statistical rectangle area for b and c is shown in Fig. 1b. Solid cycles denote the severe hypoxia events happened in summers of 1999, 2006, 2013, 2016, 2017 and 2020. The climatology mean values for river discharge and SST are also given in a and b.

noteworthy years, specifically 2016 and 2017, have witnessed the occurrence of three favorable conditions conducive to hypoxia. In reality, hypoxia was particularly severe during both years, with the minimum dissolved oxygen (DO) values reported being merely 0.08 mg/L and 0.33 mg/L, respectively. These two years also represent the lowest recorded levels to date. There are some similarities between two severe hypoxia events occurred in summers of 2016 and 2017. The hypoxia centers are both located to the north of Changjiang River mouth, and observed bottom DO value are nearly nil (Chen et al., 2020). It is coincidental that two hypoxia events are both related to catastrophic flooding events in July (Bi et al., 2017; Yang et al., 2021) and extreme marine heatwaves in August (Yan et al., 2020; Pun et al., 2023). As shown in Fig. 9, the river discharge is relatively large (> 6 ×10^4 m^3/s) in July and the domain-average SST is rather high in August for both 2016 and 2017. It is undoubtable that these physical environments are important for the severe hypoxia in these two years.

It may be difficult to form a very severe hypoxia event with only one typical factor (flooding, marine heatwave, and less typhoon). For example, in terms of the discharge of the Changjiang River, 1998 was the second largest flood after 2020. However, as stated by Ma et al. (2022), due to unfavorable conditions for algal bloom growth before the construction of Three Gorges Dam and the absence of other contributing factors, the hypoxia in summer 1998 was not very significant. Although there may be a hypoxia situation with very low DO levels along certain section (Ma et al., 2022), another survey data from the same period indicate that the hypoxia area was only 600 km^2 (Wang and Wang, 2007), suggesting that the duration of hypoxia in 1998 was not so robust.

Another example happened in summer 2004. Based on satellite records, significant marine heatwaves have manifested in the summers of 2004, 2006, and 2016 (Yan et al., 2020). However, the river discharge is normal in summer 2004 (Fig. 9a), unable to support abundant nutrient for hypoxia development. As depicted in Fig. 9b, severe hypoxia events transpire during these years (2006 and 2016), except for 2004, denoting the correlation between coastal hypoxia and extreme ECS warming. However, the global warming effect on coastal hypoxia can not be ignored in future study. Synoptic extreme SST events (marine heatwaves) happened frequently and exert a profound impact on the ECS hydrology during the past decades (Cai et al., 2017; Wang et al., 2023). Recent modelling study also suggests that the ECS coastal hypoxia will be aggravated by the end of the 21st century under

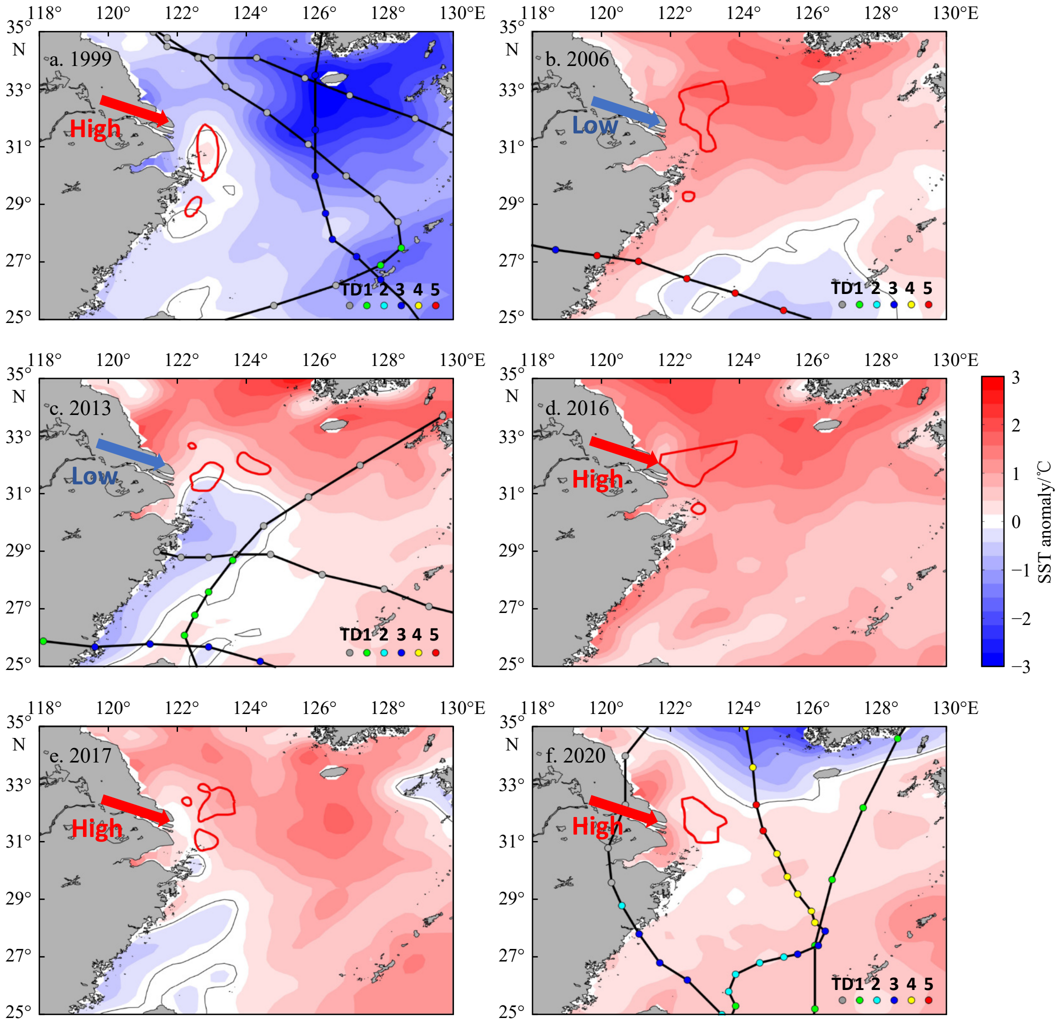

Fig. 10. The SST anomaly (℃) and summer typhoon activities in summers of six severe hypoxia years: August 1999 (a), August 2006 (b), August 2013 (c), August 2016 (d), August 2017 (e), and August 2020 (f). Red curves indicate observed hypoxia area in literatures. The colors of the typhoon dots (within the interval of 6-hours) indicate the “Saffir-Simpson” wind scale. The typhoon data are provided by Joint Typhoon Warning Center.

projected future warming trend, with an elongated duration period (~one month) and expansion area exceeding 200% (Zhang et al., 2022).

In statistical terms, the impact of three factors on hypoxia in the Changjiang River Estuary is expound quantitatively (Table 3). First, six severe hypoxia years correspond to a discharge volume of 115% compared with multi-year average, while the discharge in normal hypoxia years is similar to the mean (95%). Second, the severe hypoxia years exhibits an SST pattern that is 0.6℃ higher than the multi-year average, whereas the normal hypoxia years is approximately 0.2℃ lower than the multi-year average. Additionally, the maximum SST is 0.6℃ higher in the severe hypoxia years, while it is 0.9℃ lower in the normal hypoxia years. Looking specifically at the year 2020, we observe a 40% increase in discharge volume and a 0.8℃ rise under flooding and extreme marine heatwave condition.

Table 3. Indices for coastal hypoxia and the associated hydrographic factors for 2020, climatology mean, severe hypoxia years, and normal hypoxia years

	Factor	2020	Climatology (1998–2020)	Severe hypoxia year	Normal hypoxia year
Hypoxia	Area/(10^3 km^2)	13 000	5 900	15 200	1 680
	Minimum oxygen/(mg·L^{-1})	0.42	1.27	0.59	1.58
River discharge	Transport in July/(m^3·s^{-1})	71 500	50 000	57 400	47 300
SST^a	August mean SST/℃	27.0	26.7	27.3	26.5
	August maximum SST/℃	28.9	28.1	28.7	27.8

Note: a. The statistical rectangle area is shown in Fig. 1b; b. severe hypoxia years: 1999, 2006, 2013, 2016, 2017, and 2020; c.normal hypoxia years: 1998, 2002, 2003, 2004, 2005, 2007, 2008, 2009, 2010, 2011, 2012, 2014, and 2015.

5 Conclusions

The Changjiang River Estuary is a quite essential domain under strong natural forces and anthropogenic influences, resulting in frequent instances of coastal hypoxia over the past few decades. Based on multiple cruise and mooring observations, the evolution of coastal hypoxia off the Changjiang River Estuary during the period of July to September 2020 has been identified. Severe bottom hypoxia is characterized by a large hypoxia zone of 13 000 km^2 (using DO < 2 mg/L), minimum DO of 0.42 mg/L, and duration period of over 40 days.

The extreme weather events in summer 2020, including a catastrophic flooding, a marine heatwave, and strong Typhoon Bavi, had distinct impacts on the seasonal evolution of coastal hypoxia off the Changjiang River Estuary. The unprecedented heavy rainfall experienced in the lower Changjiang River valley during June–July, facilitated an ample river discharge and ensured the extensive expansion of CDW. Simultaneously, warm water accumulated and formed marine heatwave in August. These physical conditions intensified vertical stratification and lead to bottom hypoxia development. Additionally, the Typhoon Bavi had limited cooling effects that were insufficient to disrupt the vertical stratification. In statistical sense, the climate effects (including flood, marine heatwave, and typhoon) on coastal hypoxia also confirmed by historical records off the Changjiang River Estuary during 1998–2020.

This work focuses on the physical conditions affecting coastal hypoxia. The superimposed effects of flooding, marine heatwave, and typhoon should be paid much attention. Besides, other important biogeochemical factors, such as the distinct contributions of terrestrial and oceanic nutrient sources and the N-P ratio alteration off the Changjiang River Estuary, should be considered in future coastal hypoxia studies.

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