Journal of Environmental Management 351 (2024) 119901

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Unprecedented phytoplankton blooms in autumn/winter in the southern Bohai Sea (China) due to high Yellow River discharge: Implications of extreme rainfall events

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A R T I C L E I N F O

Keywords:
Phytoplankton
Abnormal blooms
Yellow River
Bohai Sea

A B S T R A C T

The occurrence of abnormal phytoplankton blooms is one of the significant changes in coastal ecosystems due to climate change. However, the underlying mechanism of such blooms remains poorly understood due to the complexity of the system. In this study, the data from numerous observations was used to elucidate the unprecedented phytoplankton blooms in the autumn and winter of 2021 in Laizhou Bay, a typical aquaculture bay in the southern Bohai Sea of China. The abundance of phytoplankton cells increased by more than tenfold in the southern waters compared to that in the same period from 2019 to 2020. The phytoplankton bloom was first observed in winter in the Bohai Sea, with the cell abundance in the southern bay exceeding 10^8 cells L^{-1} in December 2021. The diversity and evenness of phytoplankton communities decreased in the southern area. *Cerataulina pelagica* was the dominant algae, comprising 69 % of the total phytoplankton in October and 99 % in December. In autumn 2021, the largest flood of the Yellow River in recent decades occurred. This was attributed to extreme rainfall events within the river basin. The input of substantial riverine nutrients played a significant role in promoting phytoplankton blooms. Correlation analysis indicated the important cumulative impact of the Yellow River on phytoplankton blooms rather than a direct short-term effect. Numerical modeling results indicated that exceptionally high Yellow River discharge in autumn could significantly affect the entire bay from autumn to the following spring. This study may contribute to understanding the abnormal phytoplankton blooms in coastal waters and provide valuable insights for environmental management in river basins and coastal waters.

1. Introduction

Marine phytoplankton is responsible for nearly half of the global primary productivity and is essential in food webs and the geochemical cycle (Field et al., 1998; Thomas et al., 2012). Due to the abundant nutrient supply, phytoplankton concentration is higher in coastal seas than in the open ocean, which provides adequate food for many consumers. However, the phytoplankton blooms in coastal waters can lead to environmental problems including ocean hypoxia (Li et al., 2016). Phytoplankton blooms have become a subject of increasing attention in coastal ecosystem research (Dai et al., 2023).

Various factors, such as nutrients, light, and temperature, affect the phytoplankton biomass in coastal seas (Jakobsen and Markager, 2016; Ding et al., 2020). However, these environmental factors can exhibit significant discrepancies in different seas, resulting in regional characteristics in the timing of phytoplankton blooms. For example, strong convective mixing in the northwestern Mediterranean Sea causes spring blooms (Mayot et al., 2017), increased nitrogen supply induces autumn

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https://doi.org/10.1016/j.jenvman.2023.119901
Received 4 June 2023; Received in revised form 8 November 2023; Accepted 11 December 2023
Available online 25 December 2023

blooms in the eastern Seto Inland Sea (Yamaguchi et al., 2020), and modification of hydrography leads to summer blooms in the Ross Sea (Mangoni et al., 2017). Overall, phytoplankton blooms occur in a fixed season and do not change significantly in the short term.

In recent decades, drastic global climate change and increasing human activities have led to frequent non-periodic changes in the marine environment (Edwards and Richardson, 2004; Meng et al., 2021). These changes tend to induce significantly altered phytoplankton biomass and community structure in coastal seas compared to that in the previous conditions, which is commonly referred to as abnormal phytoplankton blooms. The abnormal phytoplankton blooms could disrupt the ecological balance and produce harmful effects on fish, shellfish, marine mammals, and humans (Wang et al., 2021). Clarifying the regulation mechanism of abnormal phytoplankton blooms would increase understanding of the marine biogeochemical cycle and prevent marine environmental disasters.

River input is widely recognized as one of the most important processes affecting coastal phytoplankton blooms (Zhu et al., 2009). Increased riverine nutrients due to human activities can substantially promote the phytoplankton blooms in coastal waters, especially in closed seas (Paczkowska et al., 2019). Moreover, the frequent occurrence of plume flow and the detachment of low-salinity water in river estuaries with high discharge can affect the coastal current in the short term (Wang et al., 2011). These aspects are crucial to the spatiotemporal scale of phytoplankton blooms by influencing the transport of materials in coastal seas (Wang et al., 2018). Extreme rainfall events in river basins may disrupt the natural seasonal variations in river discharge into the sea, leading to an abnormal spatiotemporal distribution of phytoplankton in coastal waters. However, few studies have reported the significant indirect impacts of extreme climate changes through their effects on rivers on coastal ecosystems.

Laizhou Bay (LZB) is a typical semi-enclosed bay in the southern Bohai Sea of China, in which the phytoplankton biomass is largely influenced by the Yellow River input (Ding et al., 2020; Wu et al., 2021). In the past ten years, significant progress has been achieved in the environmental pollution control of the Bohai Rim region, leading to decreases in nutrient concentrations in seawater (Ding et al., 2023). However, globally occurring extreme weather events, such as typhoons and extreme rainfall, can rapidly influx nutrients from rivers into the sea, which could trigger red tides in coastal waters (Jiang et al., 2022). This may emerge as one of the most pressing ecological risks faced by the Bohai Sea. Clarifying the impact of the extreme rainfall events on abnormal phytoplankton blooms in LZB could offer a reference for similar studies for coastal areas worldwide.

Evidence has shown that harmful algal blooms become more frequent during the summer in LZB, with a rare occurrence in the autumn (<5 %) (Song et al., 2016). Previously, phytoplankton blooms had never been reported in winter in the Bohai Sea. However, satellite images have shown that harmful algal blooms occurred frequently in the LZB from October to December of 2021, covering an area of approximately 1000 km^2 (reported by the Bulletin of China Marine Disaster in 2022). These blooms induced the unprecedentedly widespread death of farmed kelp, clams, and sea cucumber in autumn/winter by rapidly changing the physicochemical characteristics of seawater (http://www.moa.gov.cn/xw/bmdt/202201/t20220130_6388037.htm; Unpublished data). Although certain aspects of the abnormal phytoplankton blooms in the autumn/winter of 2021 are known, further details are still unavailable, as is the effect of extreme rainfall events on blooms.

In this study, we describe the unprecedented phytoplankton blooms in the autumn/winter of 2021 using the available observational data from the LZB. Furthermore, a three-dimensional hydrodynamic model was implemented to estimate the impact of high Yellow River discharge on the blooms. This study is the first report on the abnormal autumn/winter phytoplankton blooms in the Bohai Sea affected by the extreme climatic events within the river basins. The findings provide new insights into the hydrological management of river basins and environmental management in coastal waters.

2. Materials and methods

2.1. Study area

LZB has an area of approximately 7000 km^2 spanning from 37° N to 39° N and 118° E to 121° E (Fig. 1). LZB is a shallow bay with an average water depth of 11.2 m. The region has a continental climate, specifically a warm temperate semi-humid monsoon climate, where the highest temperatures and rainy season primarily occur in July and August. In recent decades, the bay has experienced increased eutrophication due to the influx of exogenous pollutants, resulting in severe environmental issues.

2.2. Sampling and analysis

Six field surveys were performed in the LZB in October and December 2019, October 2020, and January, October, and December 2021 (Fig. 1b). The October and December/January surveys were performed to represent the autumn and winter, respectively. Nutrient and phytoplankton enumeration analyses were performed on surface water samples collected at a depth of 0.5 m from 37 to 45 grid stations. Seawater samples from the bottom layers were collected to analyze in the six field surveys. Additionally, a small area located in the southern part of central LZB (Fig. 1b) was identified as the key observation area to study the temporal variations in the ecosystem affected by the Yellow River. The observed data in this key area can, to a certain extent, represent the conditions in LZB due to its distance from the coastline. Five stations were established in the key area, and continuous monthly observations of surface water were made from July 2021 to February 2022.

The identification and counting of phytoplankton and measurements of water temperature, salinity, and concentrations of dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), and dissolved inorganic silicon (DSi) are described in the supporting materials (Text S1).

To assess the composition and structure of phytoplankton communities, we calculated the indices of species diversity (H'), richness (D), evenness (J), and dominance (Y). The detailed calculations were provided in Text S1.

2.3. Data sources for the Yellow River

Data on monthly water discharge of the Yellow River between 2002 and 2021 were sourced from the China River Sediment Bulletin, while daily water discharge data for 2021 were retrieved from the Yellow River hydrological network (www.hwswj.gov.cn). The Yellow River discharge into the sea was defined as that from the Lijin hydrometric station. The concentrations of riverine DIN, DIP, DSi, dissolved organic nitrogen, and dissolved organic phosphorus in different seasons from 2001 to 2019 were collected from previous observations (Wu et al., 2021). Concentrations of particulate phosphorus were derived using the regression relationships between nutrient concentration and river discharge (Liu, 2015).

2.4. Correlation analysis

To investigate the impact of Yellow River discharge on phytoplankton blooms in autumn/winter, we performed correlation analysis between phytoplankton characteristics and various environmental factors. The Yellow River water has a mean age of 218 days in the LZB, indicating its significant cumulative effect on the ecosystem (Liu et al., 2012). Hence, we assessed the correlation between the environmental condition in the bay and the accumulated riverine discharge on different days before each seawater observation. In the latter correlation analysis,

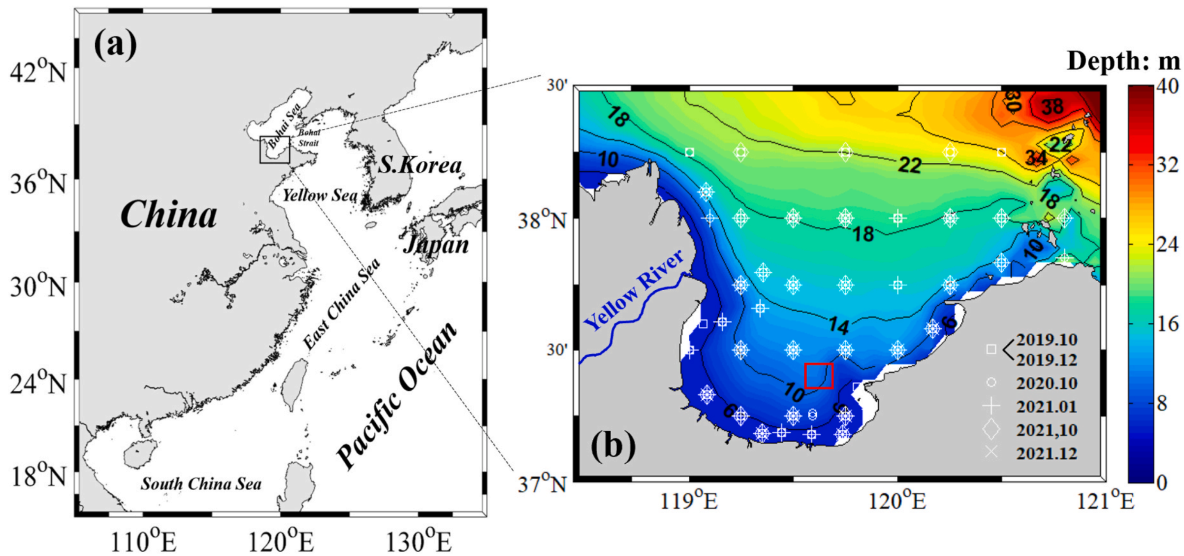

Fig. 1. (a) Location of Laizhou Bay and (b) sampling stations and bathymetry. The red box represents the key areas sampled each month from July 2021 to February 2022.

the observed data in the bay consists of continuous monthly observations in the key area from July 2021 to February 2022. The cumulative river discharge refers to the sum of the Yellow River inflow in the days leading up to each observation in the bay.

2.5. Hydrodynamic model

A hydrodynamic model was used to analyze the effects of increasing Yellow River discharge in the autumn of 2021 on the LZB ecosystem. The employed numerical model is based on a three-dimensional free-surface primitive equation ocean model known as the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987). Daily data for sea surface temperature, surface heat flux, evaporation, precipitation, and wind stress from January 2021 to August 2022 were obtained from the National Oceanic and Atmospheric Administration and were used to drive the model. This hydrodynamic model has been previously used in studies of the Bohai Sea (Wang et al., 2008; Liu et al., 2012). For model spin-up, it was integrated for five years, forced by daily surface forcing and riverine input in 2021. The model was then integrated from January 2021 to August 2022 (as the control group). The simulation results successfully replicated the spatiotemporal distributions of temperature and salinity in the LZB under the influence of the Yellow River (see Text S2 for details).

Another numerical experiment closing the Yellow River discharge during September–November 2021 was performed. The quantitative effect of the autumn floods in the Yellow River on the LZB ecosystem can be demonstrated by obtaining the difference between the two simulation results.

3. Results

3.1. Abnormal phytoplankton blooms in the autumn/winter from 2019 to 2021

Phytoplankton cell abundance in surface water during the autumn/winter significantly increased from 2019 to 2021. As shown in Fig. 2, the average abundances in October for 2019, 2020, and 2021 were 1.7×10^5, 1.0×10^5, and 4.2×10^5 cells L^{-1}, respectively. In October 2021, high abundances exceeding 1.0×10^6 cells L^{-1} were concentrated in the western and southern coastal areas. In contrast, the northeast areas showed lower abundances of less than 1.0×10^4 cells L^{-1}. The mean abundance continued to rise during winter 2021 to 5.0×10^6 cells L^{-1},

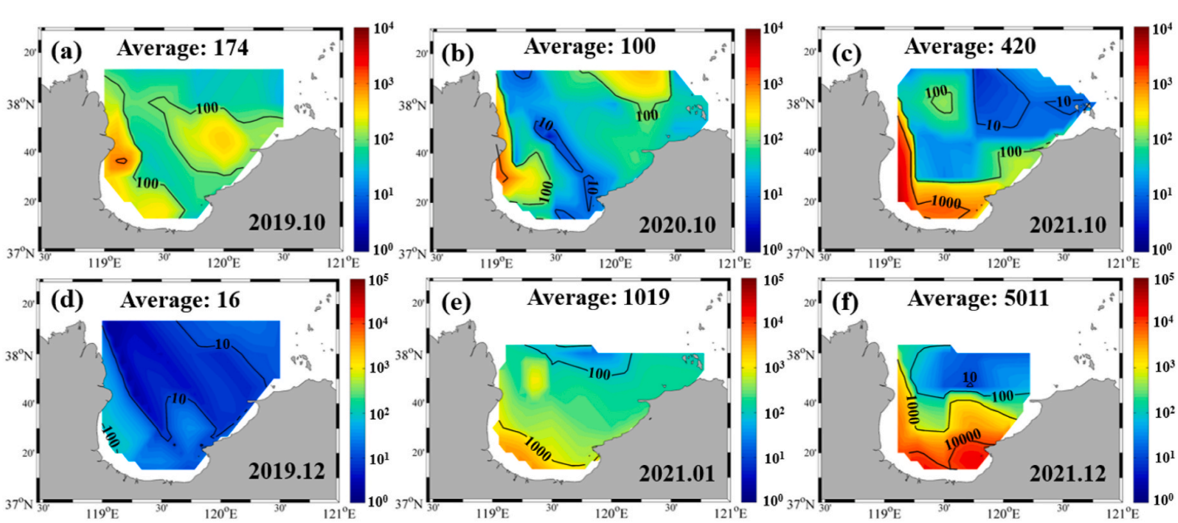

Fig. 2. Observed phytoplankton cell abundance in surface water in autumn/winter from 2019 to 2021 (unit: $\times 10^3$ cells L^{-1}).

which was higher than that in the preceding two years. By December 2021, the southern areas exhibited the highest abundance of >1.0 × 10^8 cells L^{-1}, while the abundance was lowest in the northern areas.

Compared to the previous two years, notable changes in phytoplankton communities were observed in the autumn/winter 2021. The average phytoplankton indices of H', D, and J were 3.1, 2.5, and 0.7 in October 2021, respectively (Figs. S1a–S1c). The low values of H' and J observed in the west and south areas indicate that the resident phytoplankton species were more uniform. By winter 2021, phytoplankton diversity decreased significantly with lower values of H', D, and J compared to October, particularly in the southern areas (Figs. S1d–S1f). The diversity and evenness of phytoplankton in the winter were notably lower in 2021 than in 2019 and 2020 (Figs. S2 and S3). However, no significant differences in phytoplankton community indices were observed in the autumn from 2019 to 2021.

The phytoplankton community in October 2021 was dominated by *Cerataulina pelagica*, *Chaetoceros* sp., and *Eucampia zodiacus*, with respective abundances of 66 %, 9 %, and 12 % (Table S1). By December 2021, *C. pelagica* had become the sole dominant species, contributing approximately 99 % of the total phytoplankton abundance. In contrast, multiple dominant species were observed in the autumn/winter of 2019–2020 (Tables S2 and S3), indicating a simpler phytoplankton community in the autumn/winter of 2021 than in the previous two years in the LZB.

3.2. Variations in hydrology-nutrient in autumn/winter from 2019 to 2021

3.2.1. Water discharge from the Yellow River

Climatological data demonstrated that the Yellow River discharged a substantial amount of freshwater during the summer months, with the highest value of 1.5 × 10^3 m^3 s^{-1} in July (Fig. 3). The water discharges from 2019 to 2021 were high during the summer. However, the seasonal variations in Yellow River discharge changed in 2021, when another peak with a value larger than the summer discharge appeared from late September to early November 2021. The highest water discharge in 2021 occurred in early October with a value of 5 × 10^3 m^3 s^{-1}. In 2021, the autumn runoff from September to November was 1.8 times greater than the summer runoff (June to August), constituting 48.6 % of the total annual runoff.

3.2.2. Sea surface temperature (SST) and salinity

The mean SSTs in autumn (October) were 16.9 °*C*, 16.5 °*C*, and 16.0 °*C* in 2019, 2020, and 2021, respectively. As shown in Fig. 4a–c, the SST in October 2021 was lower than that of the previous two years. The southern waters in the bay exhibited the lowest SST of 13.9 °*C* in October 2021, while the northern area had the highest SST of 17.5 °*C*.

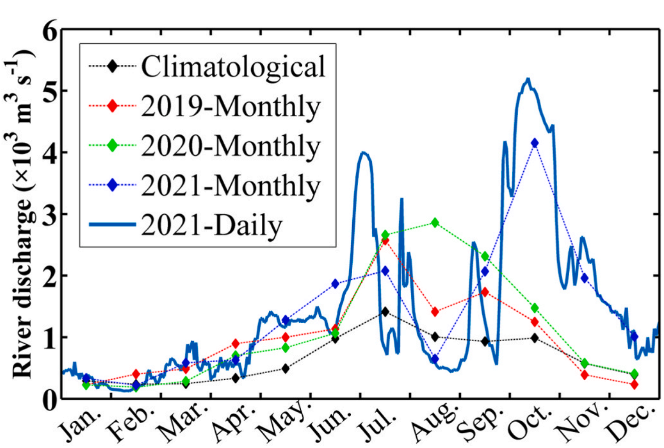

Fig. 3. Variations in water discharge of the Yellow River to the sea.

Such distribution results from the relation between water depth and water temperature in the cooling season (Xie et al., 2002). In winter (December/January), the SST remained low in the south and high in the north of the LZB from 2019 to 2021 (Fig. 4d and e). However, the mean SST in winter 2021 was 5.9 °*C*, which was higher than those of the previous two years. The SST of the nearshore south area in December 2021 was approximately 1 °*C* which was higher than that in 2019.

The average sea surface salinity in October and December 2021 was 24.5 and 24.8, respectively. Both values were lower than those during the same period from 2019 to 2020. Salinity in October 2021 showed the lowest value of <13 outside the Yellow River estuary (Fig. 4i). The southern regions recorded a decrease in salinity in October from approximately 25 in 2019–2020 to <20 in 2021 (Fig. 4g–i). However, the salinity levels in the northeast remained constant between 28 and 31 throughout these three years. In December 2021, the low salinity area in the bay shifted from the outer Yellow River estuary to the southern area with values of <23 (Fig. 4l). Furthermore, the highest salinity level of approximately 28 in the northern sea area was evidently lower than that observed in October 2021. Salinity levels from winter 2019 to 2021 exhibited a zonal distribution that gradually increased from south to north in the bay. However, it was relatively low in 2021. In addition, the salinity in bottom water showed a significant decrease in autumn/winter 2021 than in the previous two years (Fig. S4).

3.2.3. Nutrient concentrations and ratios

From October 2019 to 2020, the average concentration of DIN in surface water in the entire bay was approximately 15 μmol L^{-1}, with the highest value of approximately 40 μmol L^{-1} observed in the outer waters of the Yellow River estuary (Fig. 5a–b). However, in October 2021, the DIN concentration in the bay increased significantly, giving an average value of 49.5 μmol L^{-1} (Fig. 5c). Outside the Yellow River estuary, the DIN concentration over a large area exceeded 100 μmol L^{-1} in October 2021. During the winter months in 2019, 2020, and 2021, the respective average concentrations of DIN were 13.8, 27.1, and 36.6 μmol L^{-1}, respectively (Fig. 5d–f). In most areas of the bay, the winter DIN concentrations in surface water were higher in 2021 than in the previous two years, except for a high value observed outside the Yellow River estuary in 2020 (Fig. 5e). In December 2021, the northern part of the bay had a relatively low DIN concentration of <25 μmol L^{-1}, while the other areas showed a high DIN concentration of >35 μmol L^{-1} (Fig. 5f).

From 2019 to 2021, there was no obvious increase in DIP in surface water during the autumn/winter period. As shown in Fig. 5g–l, the mean DIP concentrations in each survey ranged between 0.1 and 0.3 μmol L^{-1}. In October 2019 and 2020, DIP concentrations were higher in the northern area than in the southern area, while a high DIP concentration was observed in the northeastern area and outside the Yellow River estuary in October 2021. During the winter of 2021, there was a relatively high DIP concentration in the central area whose value exceeded 2.5 μmol L^{-1} (Fig. 5l), which was not observed in the previous two years (Fig. 5j–l).

The DSi concentrations observed in surface water in autumn/winter were significantly higher in 2021 than in the previous two years (Fig. 5m–r), as described in detail in Text S3. DIN and DSi concentrations in bottom water also increased in autumn/winter from 2019 to 2021, whereas no obvious change in the bottom DIP appeared in this period (Fig. S5). Besides, the ratios of DIN to DIP and DSi to DIP in autumn/winter significantly increased from 2019 to 2021. Detailed explanations of variations in nutrient molecular ratios in autumn/winter from 2019 to 2021 can be found in Text S3 of the supplementary materials.

3.3. Temporal variation of the hydrodynamic ecosystem in 2021

The dynamic changes of abnormal phytoplankton blooms in autumn/winter 2021 and their relationships with various environmental factors were further analyzed using continuous monthly observations from July 2021 to February 2022.

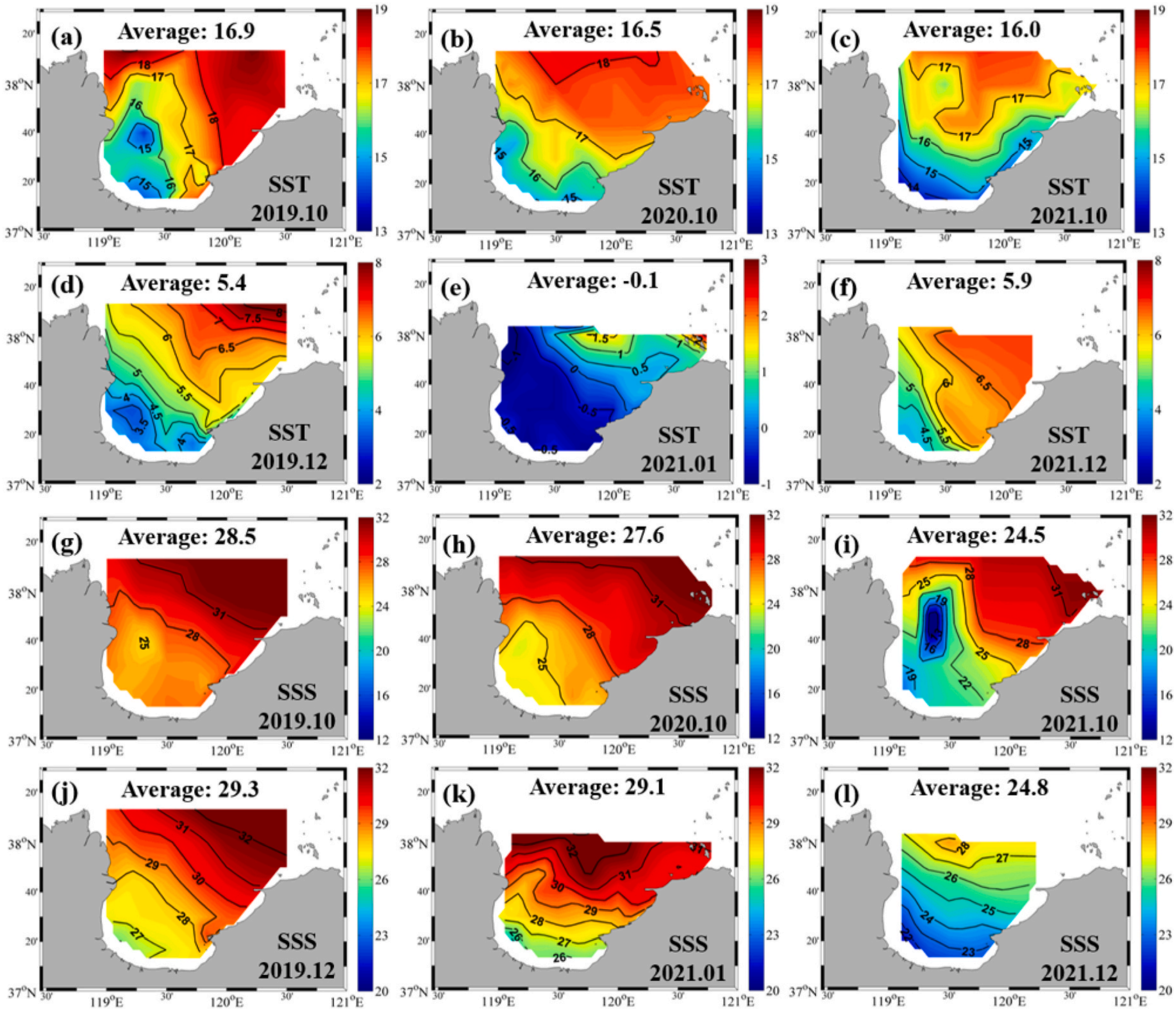

Fig. 4. Observed sea surface temperature (SST, in °C) and sea surface salinity (SSS) in autumn/winter from 2019 to 2021.

As shown in Fig. 6a, the surface sea temperature decreased from approximately 25 °*C* in July to approximately 2 °*C* in February. In contrast, the salinity had a high value of approximately 30 in July and August. However, it decreased significantly until November, reaching a low of approximately 23. The salinity remained below 25 from November to February, with a slight increase towards the end of this period.

DIN concentrations were below 9.5 μmol L^{-1} in July and August. However, they sharply increased to 63.8 μmol L^{-1} in October (Fig. 6b). After this peak, DIN concentration gradually declined and reached approximately 34.9 μmol L^{-1} in February 2022. DIP concentration increased from October 2021 to February 2022, rising from approximately 0.02 to 0.28 μmol L^{-1} (Fig. 6b). DSi showed no significant variation from July to February. Due to the high DIN and DSi values and low DIP levels in October, the DIN/DIP and DSi/DIP ratios reached exceptionally high values of approximately 4946 and 1792, respectively (Fig. 6d). The DSi/DIN ratio was highest in early August, reaching approximately 60.5. Moreover, the DIN/DIP ratios were higher after October compared with those before. In contrast, the DSi/DIP and DSi/DIN ratios significantly decreased after October.

In 2021, phytoplankton cell abundance increased significantly from summer to winter. Cell abundance was $<5.2 \times 10^6$ cells L^{-1} from July to October, but increased to $>8 \times 10^6$ cells L^{-1} in November and remained high until February 2022 (Fig. 6c). Additionally, the number of algal species increased significantly, with a severalfold increase beginning in November. However, phytoplankton diversity and evenness decreased substantially beginning in November. *H'* and *J* values were approximately 3.0 and 0.8, respectively, before October but decreased tenfold from November 2021 to January 2022 (Fig. 6e). In contrast, the richness index did not show a significant change from summer to winter 2021.

From July to October 2021, many algal species dominated (Fig. 6f). However, a new dominant species, *C. pelagica*, emerged in November 2021, increased to January 2022, and accounted for >99 % of the phytoplankton cell abundance. In February 2022, the dominant species shifted to *S. costatum* with the *C. pelagica* disappearing. Salinity and nutrients exhibited noteworthy changes in October. However, phytoplankton abundance and community did not change until November, indicating a lag in phytoplankton blooms in response to the altered environmental factors.

3.4. Correlation between phytoplankton characteristics and environmental factors

Correlations between phytoplankton characteristics and various environmental factors using continuous observations from July 2021 to February 2022 are described in Fig. 7a. Both phytoplankton cell abundance and community were significantly correlated with salinity, rather than nutrient concentrations and ratios. When considering one-month delays, phytoplankton characteristics was significantly related to DIN concentration and not other nutrients or nutrient ratios (Fig. S9). In addition, salinity, nutrient concentrations, and phytoplankton abundance were unrelated to Yellow River discharge at different times

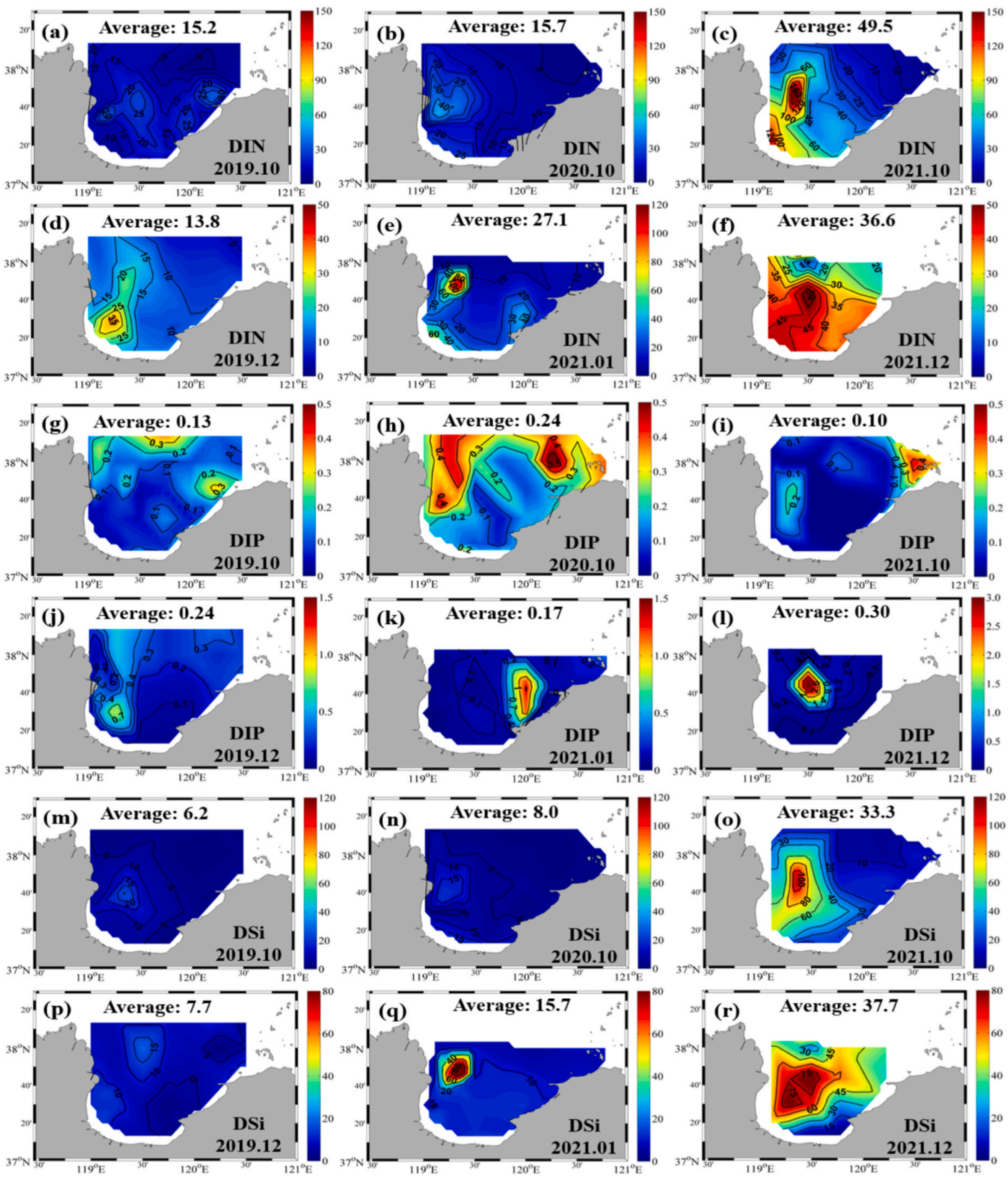

Fig. 5. Observed concentrations (μmol L^{-1}) of sea surface dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), and dissolved inorganic silicon (DSi) in autumn/winter from 2019 to 2021.

(Fig. 7a and S9). The time scale over which phytoplankton characteristics is influenced by environmental factors may have been less than one month. Data with a higher temporal resolution is required to confirm this.

The cumulative impact of Yellow River discharge on the LZB ecosystem is depicted in Fig. 7b. A negative correlation between salinity and accumulated freshwater was identified, starting at approximately 120 days and lasting up to 360 days. Nutrient concentration, phytoplankton abundance and community were significantly correlated with accumulated freshwater over different periods. However, the accumulated effect of the Yellow River on biochemical variables differed significantly over time from the effect on salinity. The highest correlation coefficient for DIN related to accumulated river discharge appeared at approximately 150 days, while it appeared at approximately 360 days for DIP. A positive correlation between phytoplankton cell abundance and accumulated river discharge was identified, starting at approximately 60 days and lasting up to 330 days. The accumulated effect of the Yellow River discharge on phytoplankton community structure persisted for more than half a year, with the highest correlation coefficient occurring at approximately 270 days. Overall, the correlation results indicate that the Yellow River discharge significantly impacts the LZB ecosystem (this is discussed in Section 4.2).

Finally, the relationships between phytoplankton abundance and the variations of meteorological factors, including SST, light intensity, wind speed, and precipitation, were estimated in the bay. No significant correlations were evident (Table S6).

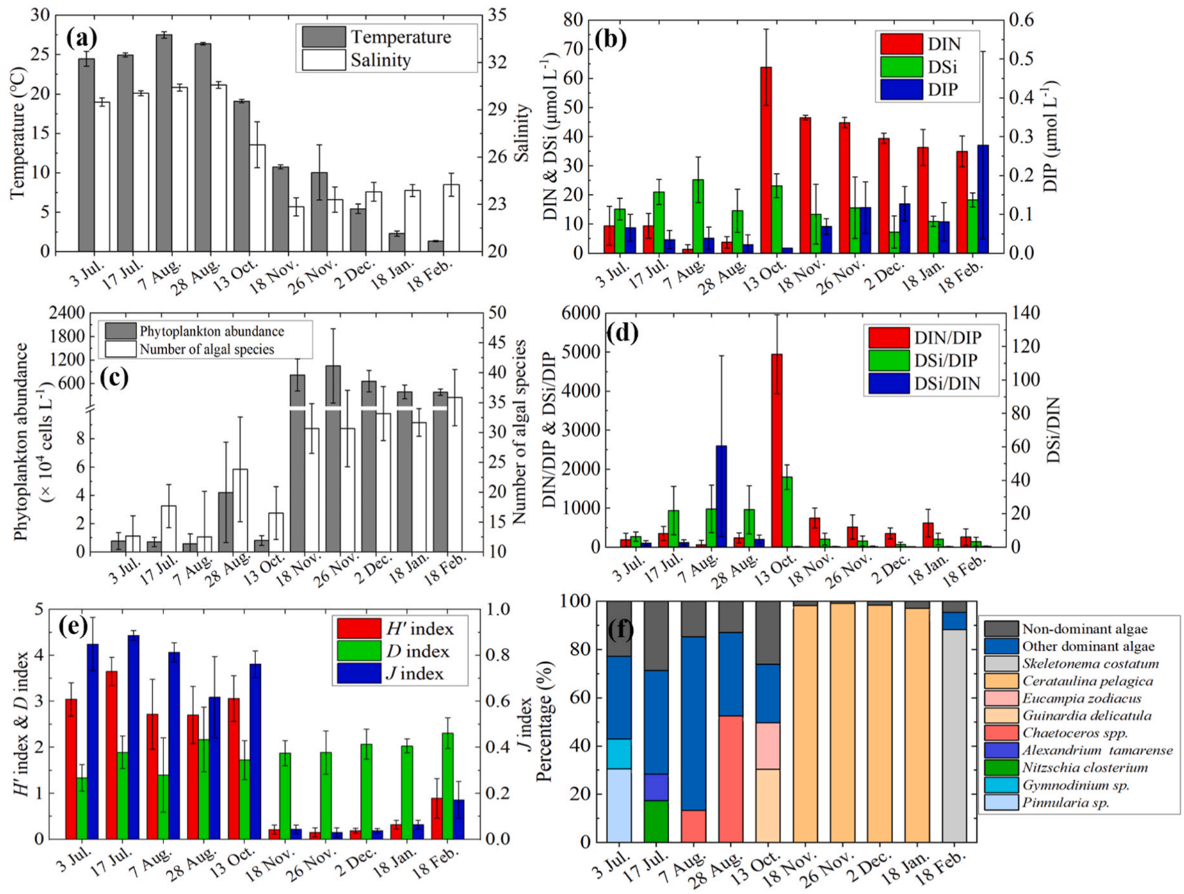

Fig. 6. Observed variations in hydrological and ecological states from July 2021 to February 2022. (a) Temperature and salinity, (b) nutrients concentrations, (c) phytoplankton cell abundance and the number of algal species, (d) nutrients ratio, (e) phytoplankton diversity (*H′*), richness (*D*), and evenness (*J*), (f) relative proportion of phytoplankton community. All the listed algae were dominant species with a dominance degree >0.1.

4. Discussion

4.1. Abnormally high discharge of the Yellow River in autumn 2021

The Yellow River is the second largest river in China, covering a basin area of 7.67×10^7 km^2 (Xu et al., 2021). Since the implementation of the Water Sediment Regulation Scheme in 2002, the flood peak of the Yellow River water into the sea has typically occurred during the summer months (Liu, 2015). However, the Yellow River discharge in autumn 2021 exceeded the summer peak (Fig. 3). The SST in the North Pacific was abnormally high in 2021, which led to increases in the area and intensity of the western Pacific subtropical high, causing it to extend north-westward (Gu et al., 2022; Liu et al., 2022). Consequently, the convergence of warm and cold air resulted in extreme autumn rain over the Yellow River Basin from late August to early October, with rainfall more than twice that in the same period of previous years (Liu et al., 2022; Sun et al., 2023). Monitoring data indicated that the downstream flood process with large flow lasted more than 20 days, resulting in the largest flood of the Yellow River since 1979.

Evidence suggests that the Yellow River discharge, under different scenarios, could significantly affect the LZB ecosystem and even the entire Bohai Sea by changing the hydrodynamic environment or supplying nutrients (Ding et al., 2020; Yu et al., 2021). Previous studies have mostly focused on the effects of summer flood peaks. The rare floods caused by extreme climate events in autumn 2021 may have substantially impacted the LZB ecosystem.

4.2. Significance of riverine nutrients supply for the LZB ecosystem

The Yellow River input constitutes a major part of the total riverine nutrient input in the LZB (Zhang et al., 2022). Previous studies have demonstrated the importance of the Yellow River nutrient supply on the LZB ecosystem and even the entire Bohai Sea (Ding et al., 2020). Since no significant correlations were evident between concentrations of riverine dissolved nutrients and Yellow River runoff (Liu, 2015), the fluxes of DIN, DIP, and DSi in October 2021 were determined to be 2.5×10^9, 1.0×10^6, and 7.4×10^8 mol month^{-1}, respectively, based on the measured concentrations of riverine nutrients in autumn (Wu et al., 2021) and water discharge. The calculated nutrient fluxes in October 2021 were several times higher than those of the previous autumn (Wu et al., 2021).

Phosphorus in the Yellow River is mainly in particulate form (He et al., 2010; Wang et al., 2019). The concentration of phosphorus is closely correlated with river discharge (Liu, 2015). Based on this relationship, the flux of particulate phosphorus from the river was calculated to be 1.5×10^9 mol month^{-1} in October 2021, which exceeded the highest monthly flux observed in the preceding 20 years (Ding et al., 2020). The calculation method for riverine phosphorus flux has been widely used in previous studies (Ding et al., 2020; Wu et al., 2021). In this study, the large nutrient input from the Yellow River in October 2021 resulted in high nutrient concentrations in the waters adjacent to the river estuary (Fig. 5c, i, and 5o).

The northwesterly winds during autumn in the LZB shift the surface currents southeastward, facilitating the transportation of riverine water throughout the bay (Wang et al., 2008). Accordingly, a substantial area of water with high nutrient concentrations appeared from October to

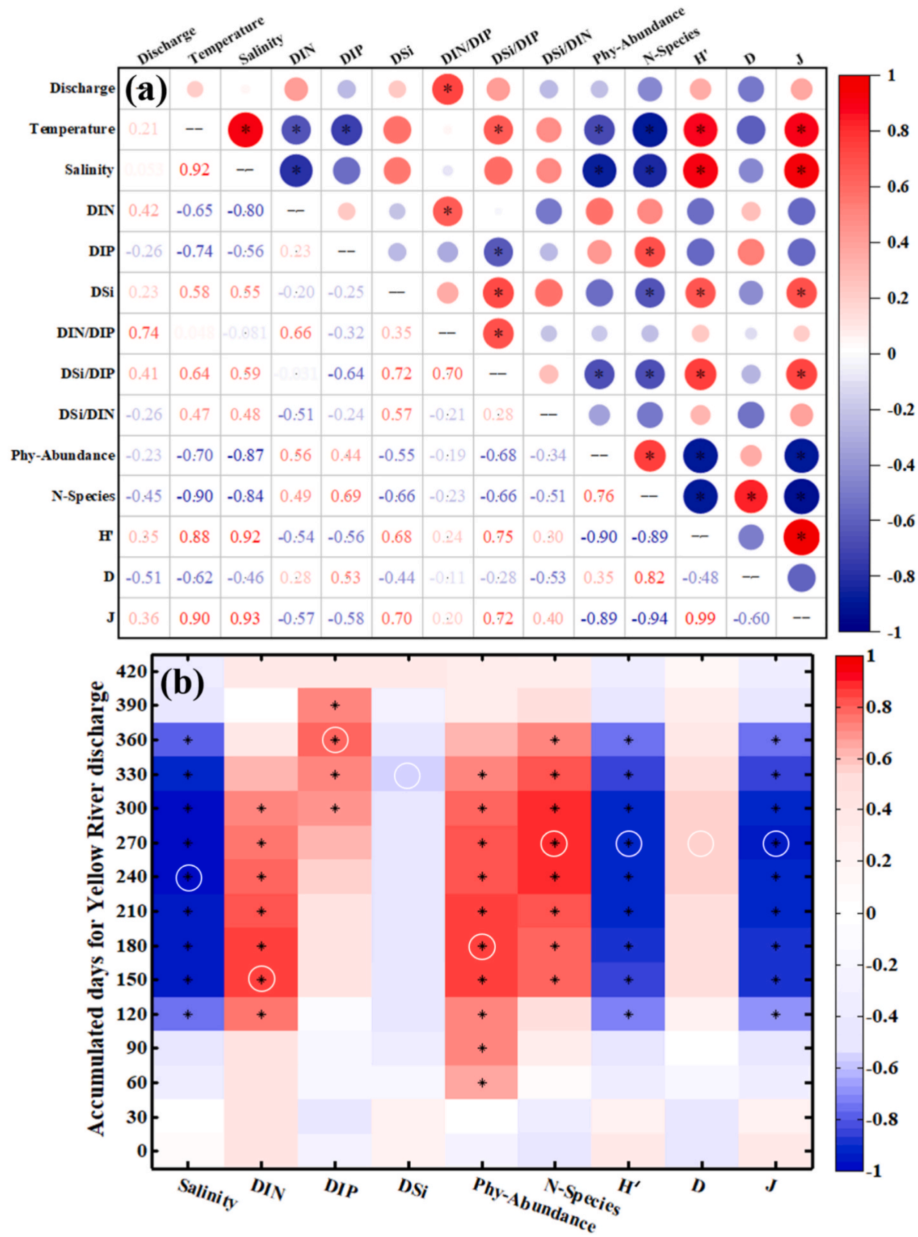

Fig. 7. (a) Correlations between observed phytoplankton growth and environmental variables from July 2021 to February 2022, including Yellow River discharge, temperature, salinity, nutrients concentrations and ratios, phytoplankton cell abundance (Phy-Abundance), number of species (N-Species), and phytoplankton diversity (*H′*), richness (*D*), and evenness (*J*). The numerical values are the correlation coefficients (*r*), and * denotes correlations with $p < 0.05$. (b) Correlations between ecological variables and the accumulated Yellow River discharge on different days before the observation in Laizhou Bay. The white circle represents the position of the maximum correlation coefficient. Abbreviations are: DIN, dissolved inorganic nitrogen; DIP, dissolved inorganic phosphorus; DSi, dissolved inorganic silicon.

December 2021 (Fig. 5). Since phytoplankton biomass is largely limited by the availability of phosphorus in this region (Xu et al., 2011; Zhang et al., 2022), the phosphorus supplied by the river is quickly utilized by phytoplankton. This explains the lack of a significant increase in DIP concentrations in the autumn/winter of 2021 compared with that in the previous year (Fig. 5g–l), despite the large influx of nutrients. This transport of riverine nutrients with the current led to the rapid and extensive phytoplankton blooms in the southern waters of the LZB during the autumn/winter period (Fig. 2c and f).

4.3. Effect of a changed hydrodynamic environment on phytoplankton blooms

The hydrodynamic environment of coastal waters can be altered by large rivers, which in turn affect nutrient distribution and phytoplankton biomass (MacCready and Geyer, 2010). With a significant amount of freshwater entering the sea, large plumes can appear in estuaries (Zhang et al., 2018). The wind can carry these surface-advected plumes to areas far from the estuary, during which low-salinity water may separate from the plume (Jurisa and Chant, 2012).

Evidence indicates that the Yellow River plume can flow downstream into the LZB along the coast under the northwesterly wind in autumn/winter (Wang et al., 2008). The large volume of river discharge can promote offshore movement of the Yellow River plume and detachment of low-salinity water (Yu et al., 2020, 2021), which transports nutrient-rich water and enhances the phytoplankton blooms over a large offshore area. Moreover, the input of freshwater from the Yellow River can affect the horizontal circulation and vertical mixing in the LZB by altering seawater density (Wang et al., 2011; Show et al., 2016), as reported in similar coastal seas worldwide (Zhang et al., 2018). The significant decrease in surface salinity in the LZB (Fig. 4i and l) could lead to a thinning of the mixed layer and the resulting potential for phytoplankton blooms because the whole community experiences sufficient light levels to support net growth (Ficher et al., 2014). Overall, during the autumn/winter of 2021, the high discharge of the Yellow River played a crucial role in nutrient transport and phytoplankton blooms by modifying the hydrodynamic conditions in the bay.

4.4. Duration of autumn flood impacts on LZB

Previous studies have shown that water exchange in the Bohai Sea is weak, with a renewal time of several years (1.1–5.2 years) (Li et al., 2015). The mean age of Yellow River water in the LZB is approximately 218 days (Liu et al., 2012). Our results demonstrate a strong correlation between the LZB ecosystem and the accumulated Yellow River discharge from 218 days before observations in the bay (Table S4). Further correlation analysis using the accumulated Yellow River discharge revealed a profound cumulative effect of the river discharge on the LZB ecosystem (Fig. 7b). The maximum correlation coefficient between salinity and accumulated freshwater occurred at approximately 240 days, similar to the 218 days calculated by Liu et al. (2012). Nutrients and phytoplankton are non-conservative substances affected by various biochemical processes, such as photosynthesis and organic matter decomposition. These processes led to temporal differences in the impact of the Yellow River on phytoplankton blooms and conserved salinity (Fig. 7b).

To trace the possible impact of the 2021 autumn floods on the LZB ecosystem, we compared the salinity change between the model results with and without the autumn Yellow River input. As shown in Fig. 8, the flood-affected region was limited to the estuary's adjacent area in September and October. From November to December, the offshore transport of river-diluted water led to a significant decrease in salinity over the entire bay, with a mean salinity decrease >2.7 in both months, particularly in the southwest area of approximately 8. The impact area shifted from the southwest to the southeast area, consistent with the surface current direction of the LZB (Wang et al., 2008). By May 2022, the salinity of most sea areas had decreased by over 1.0. However, the impact gradually declined over time and became almost negligible by August 2022 (Fig. 8l). Although salinity changes do not reflect the complexity of the nutrient cycle, they can still indicate the scope and duration of the Yellow River discharge on the LZB ecosystem to a certain extent.

In summary, the abnormal phytoplankton blooms observed between October 2021 and February 2022 (Figs. 2 and 6) were predominantly attributed to the elevated discharge of the Yellow River in autumn 2021, which aligns with earlier research, highlighting the significant, long-lasting impact of Yellow River input on chlorophyll-a levels in the Bohai Sea (Ding et al., 2020).

4.5. Adaptability of phytoplankton blooms to ambient changes

Various factors influence the phytoplankton blooms, and different

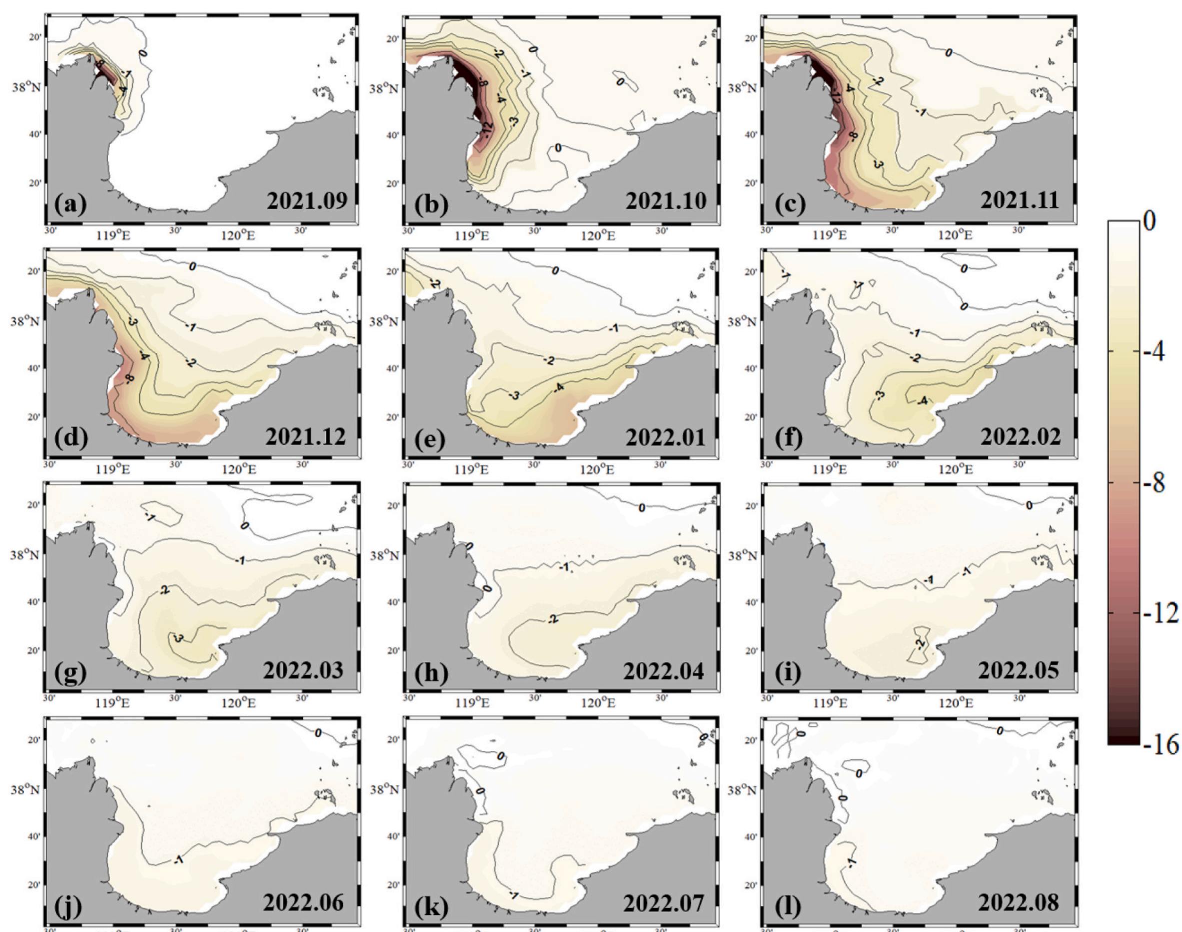

Fig. 8. Simulated continuous effects of the Yellow River discharge in autumn (September to November) 2021 on the sea surface salinity in Laizhou Bay. The value was calculated by subtracting the simulated salinity of no riverine autumn floods in the model from the simulated salinity of the control group. Negative values represent decreased salinity due to the river input.

species have individual adaptability to specific conditions (Zhu et al., 2009). High nutrient concentrations and a high DIN/DIP ratio are more likely to trigger phytoplankton blooms, particularly by diatoms, while reducing biodiversity (Zhang et al., 2020; Jiang et al., 2022). Therefore, the increased nutrient flux carried by the Yellow River during autumn 2021 played a critical role in the anomalous phytoplankton blooms observed in the LZB.

Temperature plays an important role in phytoplankton blooms by influencing enzyme activity in phytoplankton cells (Thomas et al., 2012). An increase in SST can stimulate the occurrence of phytoplankton blooms (Dai et al., 2023). A slight rise in SST was observed in winter 2021 in the LZB compared with that in the previous period (Fig. 4f). The satellite data showed that the mean SST in December was approximately 2.0 $^{\circ}C$ higher in 2021 than the climatological value in the LZB (Table S5). The SST also increased by $> 0.5\ ^{\circ}C$ in January and February 2022 compared with the climatological value. Therefore, the obvious increase in SST in winter 2021 may have contributed to the phytoplankton blooms at this time. Despite a decrease in water temperature in the southern bay in October 2021, compared with that in the previous two years (Fig. 4c, Table S5), high levels of phytoplankton abundance were still observed during this period (Fig. 2c). The finding suggests that the inhibitory effect of decreasing temperature on phytoplankton blooms may have been overshadowed by the positive effect of nutrient supplementation and the thinning mixed layer due to the Yellow River discharge. In addition, changes in other meteorological factors in LZB, such as light, wind speed, and precipitation, may have minimal impact on the abnormal phytoplankton blooms in autumn/winter 2021 (see Text S4 for details).

Diatoms possess strong adaptability to changes in environmental factors (Sun et al., 2017). This is consistent with our observations of the absolute dominance of *C. pelagica* during the autumn/winter of 2021 (Table S1, Fig. 6f). Before 2021, no winter phytoplankton blooms had ever been recorded in the Bohai Sea (Song et al., 2016). The extensive blooms of *C. pelagica* observed during winter 2021 in the LZB could indicate an important adaptation of phytoplankton to the extreme rainfall events in the river basin. However, a clear explanation for why *C. pelagica*, a warm-water coastal diatom (Carstensen et al., 2015), establishes absolute dominance in winter algal competition remains elusive. The specific physiological response of different algal species to complex environmental factors continues to challenge current algal research (Glibert et al., 2018).

The occurrence of abnormal phytoplankton blooms in LZB resulting from extreme rainfall is intricately linked to local regional factors (see Text S5 for details). A comparison of abnormal phytoplankton blooms worldwide was also conducted to enhance our understanding of such blooms in coastal waters (Text S5).

4.6. Implications for environmental management

Many rivers worldwide have been equipped with hydraulic engineering structures such as large reservoirs, which significantly affect the ecosystem in river basins and coastal waters (Humborg et al., 1997; Roy et al., 2013). The Water Sediment Regulation Scheme on the Yellow River shifted the seasonal variation of chlorophyll-a concentration in the Bohai Sea by altering the temporal rhythm of river flow into the sea (Ding et al., 2020). In this study, extreme rainfall in the Yellow River Basin led to a remarkable surge in water discharge. This could potentially disrupt the existing storage and discharge plans of reservoirs within the basin, potentially resulting in abnormal effects on the performance of these hydraulic projects and the coastal ecosystem. Evidence indicates that global warming will increase the frequency of extreme rainfall events on land (Seneviratne et al., 2021; Gu et al., 2022). These abnormal events could occur at any time, causing significant responses in land hydrological characteristics and coastal ecosystems. These findings support the recommendation that water authorities proactively assess the impact of extreme rainfall within river basins. These authorities should adjust reservoir plans based on weather conditions to enhance project efficiency and prevent marine disasters. In addition, the rapid influx of nutrients from rivers into the sea could easily trigger harmful algal blooms as discussed above, which may emerge as one of the most pressing ecological risks currently faced by coastal waters. Therefore, marine management authorities should pay more attention to extreme weather events in river basins flowing into the sea to promptly formulate response measures.

5. Conclusions

This study consisted of six field surveys conducted in autumn/winter from 2019 to 2021 and continuous monthly observations in the key area from July 2021 to February 2022 in LZB. Phytoplankton cell abundance increased severely in the autumn/winter of 2021, especially by more than tenfold in the southern bay compared to the findings in the previous two years. Phytoplankton blooms were observed for the first time in winter in the Bohai Sea. The abnormal blooms were characterized by a decrease in phytoplankton diversity and evenness. *C. pelagica* was the dominant algae, approximately >90 % of total phytoplankton cell abundance from November 2021 to January 2022. The largest flood of the Yellow River in recent decades occurred in autumn 2021. This flood led to the influx of freshwater and nutrients into the sea and was responsible for the abnormal phytoplankton blooms in the LZB. A three-dimensional hydrodynamic model was used to assess the impact of the increasing Yellow River discharge on the LZB ecosystem. The simulation results showed that the high Yellow River discharge in autumn could affect the entire bay ecosystem for at least half a year. The present findings will deepen our understanding of the abnormal blooms of phytoplankton in coastal waters and provide valuable insights for environmental management in river basins and coastal waters.

CRediT authorship contribution statement

Xiaokun Ding: Writing – original draft. **Xiangyang Li:** Review & writing. **Aobo Wang:** Methodology. **Xinyu Guo:** Writing – review & editing. **Xiaotao Xu:** Data curation. **Chenglei Liu:** Data curation. **Xiaohan Qin:** Data curation. **Yixuan Xie:** Resources. **Yuqiu Wei:** Review. **Zhengguo Cui:** Writing – review & editing. **Tao Jiang:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

This study was funded by the National Natural Science Foundation of China (42176206; 42306034), Natural Science Foundation of Shandong Province (ZR2021MD071; ZR2023QD011). X. Guo thanks the support from the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT) for a project on Joint Usage/Research Center, Leading Academia in Marine and Environmental Research (LaMer).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119901.

References

Blumberg, A.F., Mellor, G.L. (Eds.), 1987. A description of a three-dimensional coastal ocean circulation model, in Three-Dimensional Coastal Ocean Models. AGU, Washington, D. C, pp. 1–16.

Carstensen, J., Klais, R., Cloern, J.E., 2015. Phytoplankton blooms in estuarine and coastal waters: seasonal patterns and key species, Estuarine. Coastal and Shelf Science 162, 98–109.

Dai, Y., Yang, S., Zhao, D., Hu, C., Xu, W., Anderson, D.M., Li, Y., Song, X., Boyce, D.G., Gibson, L., Zheng, C., Feng, L., 2023. Coastal phytoplankton blooms expand and intensify in the 21st century. Nature.

Ding, X.K., Guo, X.Y., Zhang, C., Yao, X.H., Liu, S.M., Shi, J., Luo, C.X., Yu, X.J., Yu, Y., Gao, H.W., 2020. Water conservancy project on the Yellow River modifies the seasonal variation of chlorophyll-a in the Bohai Sea. Chemosphere 254, 126846.

Ding, X.K., Shi, J., Guo, X.Y., Gao, H.W., Liu, S.M., Guo, W., 2023. Interannual variations in the nutrient cycle in the central Bohai Sea in response to anthropogenic inputs. Chemosphere 313, 137620.

Edwards, M., Richardson, A.J., 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. Nature 430, 881.

Field, C.B., Behrenfeld, M.J., Randerson, J.T., Falkowski, P., 1998. Primary production of the biosphere: integrating terrestrial and oceanic components. Science 281 (5374), 237–240.

Glibert, P.M., Al-Azri, A., Icarus Allen, J., Bouwman, A.F., Beusen, A.H.W., Burford, M. A., Harrison, P.J., Zhou, M., 2018. Key questions and recent research advances on harmful algal blooms in relation to nutrients and eutrophication. In: Glibert, P.M., et al. (Eds.), Global Ecology and Oceanography of Harmful Algal Blooms. Springer International Publishing, Cham, pp. 229–259.

Gu, W., Chen, L., Wang, Y., Gao, H., Wang, L., Liu, Y., 2022. Extreme precipitation over northern China in autumn 2021 and joint contributions of tropical and mid-latitude factors. Adv. Clim. Change Res. 13 (6), 835–842.

He, H.J., Yu, Z.G., Yao, Q.Z., Chen, H.T., Mi, T.Z., 2010. The hydrological regime and particulate size control phosphorus form in the suspended solid fraction in the dammed Huanghe (Yellow River). Hydrobiologia 638 (1), 203–211.

Humborg, C., Ittekkot, V., Cociasu, A., Bodungen, B.V., 1997. Effect of danube river dam on black sea biogeochemistry and ecosystem structure. Nature 386 (6623), 385–388.

Jakobsen, H.H., Markager, S., 2016. Carbon-to-chlorophyll ratio for phytoplankton in temperate coastal waters: seasonal patterns and relationship to nutrients. Limnol. Oceanogr. 61 (5), 1853–1868.

Jiang, T., Wu, G.N., Niu, P.L., Cui, Z.G., Bian, X.D., Xie, Y.X., Shi, H.H., Xu, X.T., Qu, K. M., 2022. Short-term changes in algal blooms and phytoplankton community after the passage of Super Typhoon Lekima in a temperate and inner sea (Bohai Sea) in China. Ecotoxicol. Environ. Saf. 232, 113223.

Jurisa, J.T., Chant, R., 2012. The coupled Hudson River estuarine-plume response to variable wind and river forcings. Ocean Dynam. 62 (5), 771–784.

Li, Y.F., Wolanski, E., Zhang, H., 2015. What processes control the net currents through shallow straits? A review with application to the Bohai Strait, China, Estuarine. Coastal and Shelf Science 158, 1–11.

Li, M., Lee, Y.J., Testa, J.M., Li, Y., Ni, W., Kemp, W.M., Di Toro, D.M., 2016. What drives interannual variability of hypoxia in Chesapeake Bay: climate forcing versus nutrient loading? Geophys. Res. Lett. 43 (5), 2127–2134.

Liu, S.M., 2015. Response of nutrient transports to water–sediment regulation events in the Huanghe basin and its impact on the biogeochemistry of the Bohai. J. Mar. Syst. 141, 59–70.

Liu, Z., Wang, H., Guo, X., Wang, Q., Gao, H., 2012. The age of Yellow River water in the Bohai Sea. J. Geophys. Res.: Oceans 117 (C11).

Liu, J., Jin, L.J., Wang, P., 2022. Relationship between extreme autumn rainfall, atmospheric circulation and sea surface temperature in the Yellow River Basin in 2021. Joural of Water Resources & Water Engimeering 33 (5), 36–44 (In Chinese with English abstract).

MacCready, P., Geyer, W.R., 2010. Advances in estuarine physics. Ann. Rev. Mar. Sci 2 (1), 35–58.

Mangoni, O., Saggiomo, V., Bolinesi, F., Margiotta, F., Budillon, G., Cotroneo, Y., Misic, C., Rivaro, P., Saggiomo, M., 2017. Phytoplankton blooms during austral summer in the Ross Sea, Antarctica: driving factors and trophic implications. PLoS One 12 (4), e176033.

Mayot, N., D'Ortenzio, F., Taillandier, V., Prieur, L., de Fommervault, O.P., Claustre, H., Bosse, A., Testor, P., Conan, P., 2017. Physical and biogeochemical controls of the phytoplankton blooms in north western Mediterranean Sea: a multiplatform approach over a complete annual cycle (2012–2013 dewex experiment). J. Geophys. Res.: Oceans 122 (12), 9999–10019.

Meng, S.Y., Gong, X., Yu, Y., Yao, X.H., Gong, X., Lu, K.Y., Zhang, C., Shi, J., Yu, X.J., Gao, H.W., 2021. Strengthened ocean-desert process in the North Pacific over the past two decades. Environ. Res. Lett. 16 (2), 24034.

Paczkowska, J., Rowe, O.F., Figueroa, D., Andersson, A., 2019. Drivers of phytoplankton production and community structure in nutrient-poor estuaries receiving terrestrial organic inflow. Mar. Environ. Res. 151, 104778.

Roy, E.D., White, J.R., Smith, E.A., Bargu, S., Li, C., 2013. Estuarine ecosystem response to three large-scale Mississippi River flood diversion events. Sci. Total Environ. 458–460, 374–387.

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S.M., Wehner, M., Zhou, B., 2021. Weather and climate extreme events in a changing climate. In: Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766.

Show, W.W., Zong, H.B., Ding, P.X., 2016. Numerical study of the circulation influenced by runoff input in the Huanghe (Yellow) River Estuary and adjacent waters in summer. Hai Yang Xue Bao 38 (7), 1–13 (In Chinese with English abstract).

Song, N.Q., Wang, N., Lu, Y., Zhang, J.R., 2016. Temporal and spatial characteristics of harmful algal blooms in the Bohai Sea during 1952–2014. Continent. Shelf Res. 122, 77–84.

Sun, Y., Li, J.P., Wang, H., Li, R., Tang, X.X., 2023. Extreme rainfall in Northern China in September 2021 tied to air–sea multi-factors. Clim. Dynam. 60 (7), 1987–2001.

Sun, H.H., Liu, X.H., Sun, X.Y., Wang, Y.J., Liu, D.Y., 2017. Temporal and spatial variations of phytoplankton community and environmental factors in Laizhou bay. Mar. Environ. Sci. 36 (5), 662–669 (In Chinese with English abstract).

Thomas, M.K., Kremer, C.T., Klausmeier, C.A., Litchman, E., 2012. A global pattern of thermal adaptation in marine phytoplankton. Science 338 (6110), 1085–1088.

Wang, Q., Guo, X.Y., Takeoka, H., 2008. Seasonal variations of the Yellow River plume in the Bohai Sea: a model study. J. Geophys. Res.: Oceans 113 (C8).

Wang, Y.C., Liu, Z., Gao, H.W., Ju, L., Guo, X.Y., 2011. Response of salinity distribution around the Yellow River mouth to abrupt changes in river discharge. Continent. Shelf Res. 31 (6), 685–694.

Wang, Y.C., Guo, X.Y., Zhao, L., 2018. Simulating the responses of a low-trophic ecosystem in the East China Sea to decadal changes in nutrient load from the Changjiang (Yangtze) River. Journal of Oceanology and Limnology 36 (1), 48–61.

Wang, J.J., Yu, Z.G., Wei, Q.S., Yao, Q.Z., 2019. Long-term nutrient variations in the Bohai Sea over the past 40 years. J. Geophys. Res.: Oceans 124 (1), 703–722.

Wang, J., Bouwman, A.F., Liu, X., Beusen, A.H.W., Van Dingenen, R., Dentener, F., Yao, Y., Glibert, P.M., Ran, X., Yao, Q., Xu, B., Yu, R., Middelburg, J.J., Yu, Z., 2021. Harmful algal blooms in Chinese coastal waters will persist due to perturbed nutrient ratios. Environ. Sci. Technol. Lett. 8 (3), 276–284.

Wu, N., Liu, S.M., Zhang, G.L., Zhang, H.M., 2021. Anthropogenic impacts on nutrient variability in the lower Yellow River. Sci. Total Environ. 755, 142488.

Xie, S., Hafner, J., Tanimoto, Y., Liu, W.T., Tokinaga, H., Xu, H., 2002. Bathymetric effect on the winter sea surface temperature and climate of the Yellow and East China Seas. Geophys. Res. Lett. 29 (24), 81.

Xu, S.S., Song, J.M., Yuan, H.M., Li, X.G., Li, N., Duan, L.Q., Yu, Y., 2011. Petroleum hydrocarbons and their effects on fishery species in the Bohai Sea, North China. J. Environ. Sci. 23 (4), 553–559.

Xu, Z., Zhang, S., Yang, X., 2021. Water and sediment yield response to extreme rainfall events in a complex large river basin: a case study of the Yellow River Basin, China. J. Hydrol. 597, 126183.

Yamaguchi, H., Koga, N., Ichimi, K., Tada, K., 2020. Seasonal variations in phytoplankton productivity in a shallow cove in the eastern Seto Inland Sea, Japan. Fish. Sci. 86 (6), 1067–1078.

Yu, X.J., Guo, X.Y., Gao, H.W., 2020. Detachment of low-salinity water from the Yellow River plume in summer. J. Geophys. Res.: Oceans 125 (10).

Yu, X.J., Guo, X.Y., Gao, H.W., Zou, T., 2021. Upstream extension of a bottom-advected plume and its mechanism: the case of the Yellow River. J. Phys. Oceanogr. 51 (7), 2351–2371.

Zhang, Z.W., Wu, H., Yin, X.Q., Qiao, F.L., 2018. Dynamical response of changjiang River plume to a severe typhoon with the surface wave-induced mixing. J. Geophys. Res.: Oceans 123 (12), 9369–9388.

Zhang, X., Wang, J., Ma, W., Wang, H., Gao, Y., Liu, K.F., 2020. The net-phytoplankton community structure in the Bohai Sea in autumn 2014. Hai Yang Xue Bao 42 (8), 89–100 (In Chinese with English abstract).

Zhang, M., Lu, Q., Wang, D., Ding, D., Cui, Z., Shi, H., 2022. Spatiotemporal evolution of nutrients and the influencing factors in Laizhou Bay over the past 40 years. Mar. Pollut. Bull. 184, 114186.

Zhu, Z.Y., Ng, W.M., Liu, S.M., Zhang, J., Chen, J.C., Wu, Y., 2009. Estuarine phytoplankton dynamics and shift of limiting factors: a study in the Changjiang (Yangtze River) Estuary and adjacent area, Estuarine. Coastal and Shelf Science 84 (3), 393–401.