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# Decadal change of benthic macroinvertebrates driven by multiple stresses in the Changjiang Estuary in summer

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**Abstract**

Both human activities and climate change have influenced benthic macroinvertebrates in the Changjiang Estuary since the Anthropocene. As a result, we investigated long-term variations in benthic macroinvertebrates and related them to changes in depth, salinity, temperature, pH and dissolved oxygen in bottom water off the Changjiang Estuary from 10 summer cruises during 2006–2021. The bi-monthly multivariate ENSO index and summer runoff rate of Changjiang were used to estimate the climate change during this period. The abundance and biomass of benthic macroinvertebrates increased significantly from 2006 to 2014 owing to a series of environmental protection measures. An intensive El Niño event, coupled with Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO), promoted diluted water discharge and hypoxia in summer in the Changjiang Estuary since 2015. We noted changes in the macrobenthic community following these events, including a dramatic decrease in abundance and biomass, alterations in dominant species and a decline in benthic diversity. Correlation analysis, canonical correspondence and redundancy analysis revealed that depth, salinity and dissolved oxygen were the main factors influencing the distribution of benthic macroinvertebrates. Owing to the ubiquitous pressure caused by human activities and climate change in estuaries, we make an appeal that international cooperation is required to protect estuarine ecosystems under the scenario of global climate change.

**Keywords**

Benthic macroinvertebrate; Large estuary; Diluted water; Anthropogenic activity; El Niño

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## 1. Introduction

Estuaries are the transition regions between continents and oceans, where the salty ocean mixes with a freshwater river. Estuaries are subject to marine influences, such as tides, waves, and the influx of saline water, and to fluvial influences such as flows of freshwater and sediment (Shou et al., 2013). A large amount of freshwater discharges into the ocean provides high levels of nutrients, both in the water column and sediment, making estuaries one of the most productive natural habitats in the world (Douglas et al., 2022).



The Changjiang Estuary (CE) is one of the most important estuaries in the world, located on the coast of the East China Sea (ECS) in the western North Pacific. Changjiang delivers approximately 470 million metric tons of suspended sediments and 924 billion cubic meters of freshwater, called Changjiang Diluted Water (CDW), into the ECS annually (Su and Yuan, 2005; Dai and Lu, 2014). Due to its large size, high river discharge, and relatively high suspended sediment concentration, the CE exerts significant influence on the ecosystem of the adjacent sea area (Zhu et al., 2018). Surrounded by the most intensive human activity regions in China, the expanding population and industrial aggregation in the Changjiang Basin have led to an increase in terrestrial contaminants such as heavy metals (Dong et al., 2012), hydrocarbons (Bouloubassi et al., 2001; Duan et al., 2015) and microplastics (Xu et al., 2018) accumulation in the water and sediments of the CE. In addition, the CE and adjacent ECS were under long-term intense fishing pressure from the 1990s to the early 2000s, resulting in a decline in living resources (Teh et al., 2020; Y. Xu et al., 2022). Fortunately, the Chinese government introduced a series of protective measures and policies, such as the summer fishing moratorium and developments in wastewater services infrastructure, to promote sustainable marine fishery development and improve the marine ecological environment in the Changjiang and ECS (L. Xu et al., 2022; Qi et al., 2022).

El Niño-Southern Oscillation (ENSO) can provide favorable hydrographic conditions for coastal hypoxia (DO $<3$ mg $L^{-1}$) off the CE (K. Wang et al., 2021). Hypoxia often intensifies during summer, which is associated with the nutrients brought in by the CDW and the subsequent algal blooms in this area (Jiang et al., 2014; Wang et al., 2017). Hypoxia of the CE was first reported in the late 1950s and has received more attention in the last two decades due to its extended spatial coverage and ecological risks (Ma et al., 2022). Grothe et al. (2020) suggested that El Niño has increased in recent decades. The intensity of change in El Niño under increased greenhouse warming is of great social concern. El Niño also strongly affects marine life off the Pacific Coast. Strong El Niño events during 1982–1983 and 1997–1998 have caused species shift, migration and mortality of benthic macroinvertebrates in the temperate oceans (Arntz et al., 2006). The CE is also under the influences of both the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO), which contribute to decadal variations in precipitation and sea surface temperature (W. Zhang et al., 2021). The PDO primarily affects ventilation conditions in eastern China, while the AMO impacts large-scale atmospheric circulation patterns (Ge et al., 2023). Together, these oscillations can alter regional precipitation regimes and have significant effects on marine ecosystems (Yu et al., 2021).

Benthic macroinvertebrates are small animals without backbones that inhabit the bottom substrates or sediments and are critical components of aquatic ecosystems. As key elements of the food web, they serve as a primary food source for fish and other organisms of higher trophic levels (Herman et al., 1999). The abundant benthic macroinvertebrates usually provide a high degree of secondary productivity and biological diversity. Benthic macroinvertebrates are sessile or slow-moving, with a relatively long life span, and some of them are sensitive to variations in their surroundings (Peng et al., 2014). Thus, they have been widely used as bioindicators to assess the health status of aquatic environments (Dauvin, 2007). Previous studies have shown that benthic macroinvertebrates can indicate the degree of disturbance to the ecosystem in areas characterized by hypoxia, industrial pollution, or aquaculture (Gammal et al., 2017; Ghribi et al., 2019; Liao et al., 2019; Pinto et al., 2021). There are great taxonomic and functional diversities of benthic macroinvertebrates in estuarine ecosystems, which allows the development of metrics for assessing the ecological status of estuaries.

Scientific research on benthic macroinvertebrates in the CE began in 1959 (Yan et al., 2017). However, only a few studies have been conducted until the 21 century (Rhoads et al., 1985; Aller and Aller, 1986). Recently, benthic macroinvertebrates have drawn increasing attention as environmental bioindicators (Pinto et al., 2021; Li et al., 2022). In the past two decades, many benthic macroinvertebrate studies have been reported in the CE (Meng et al., 2007; Chao et al., 2012; Shou et al., 2013; Liao et al., 2017; Yan et al., 2017). Previous studies have investigated the spatial and temporal distributions (Chao et al., 2012; Liao et al., 2017), as well as the taxonomic and functional diversity (Lv et al., 2018; Yan et al., 2020) of benthic macroinvertebrates. Interactions between these communities and anthropogenic stressors have also been increasingly explored (Cheung et al., 2019). However, long-term changes in benthic macroinvertebrates in the CE remain poorly documented, and the influence of global climate change has rarely been discussed. During June, July, and August, – the summer season in the ECS - significant physicochemical processes, such as large river discharge (Su and Yuan, 2005), algal blooms (Zhu et al., 2014) and bottom water hypoxia (K. Wang et al., 2021), occur in the ECS, which highlights the effect of regional and global changes on benthic macroinvertebrates.

Thus, this study focused on benthic macroinvertebrates associated with physical-chemical forcing in the CE during ten summers (July and August) from 2006 to 2021. The objective was to explore the long-term changes in benthic macroinvertebrates in the CE, driven by both anthropogenic activities and climate change. We examined the abundance, biomass, dominant species, taxonomic composition, community diversity, and associated environmental factors (summer runoff rate, ENSO index, depth, salinity, temperature, pH and dissolved oxygen).

## 2. Material and methods

### 2.1 Study area

The Changjiang, also known as the Yangtze River, is the largest river in Asia and the third-longest river in the world. It discharges approximately $9.24 \times 10^{11}$ $m^3$ of freshwater into the ECS annually (Milliman et al., 1985; Su and Yuan, 2005). This large freshwater flow causes significant shifts in various ecological and environmental parameters in the ECS. CDW flux always peaks in July and is usually lowest in November (Zhu et al., 2018). In summer, the low-salinity water plume extends northeastward to the Tsushima Strait due to the significant increase in discharge (Ni et al., 2017). CDW brings a large amount of freshwater and nutrients into the ECS (Jiang et al., 2014). Off the estuary, hydrologi-

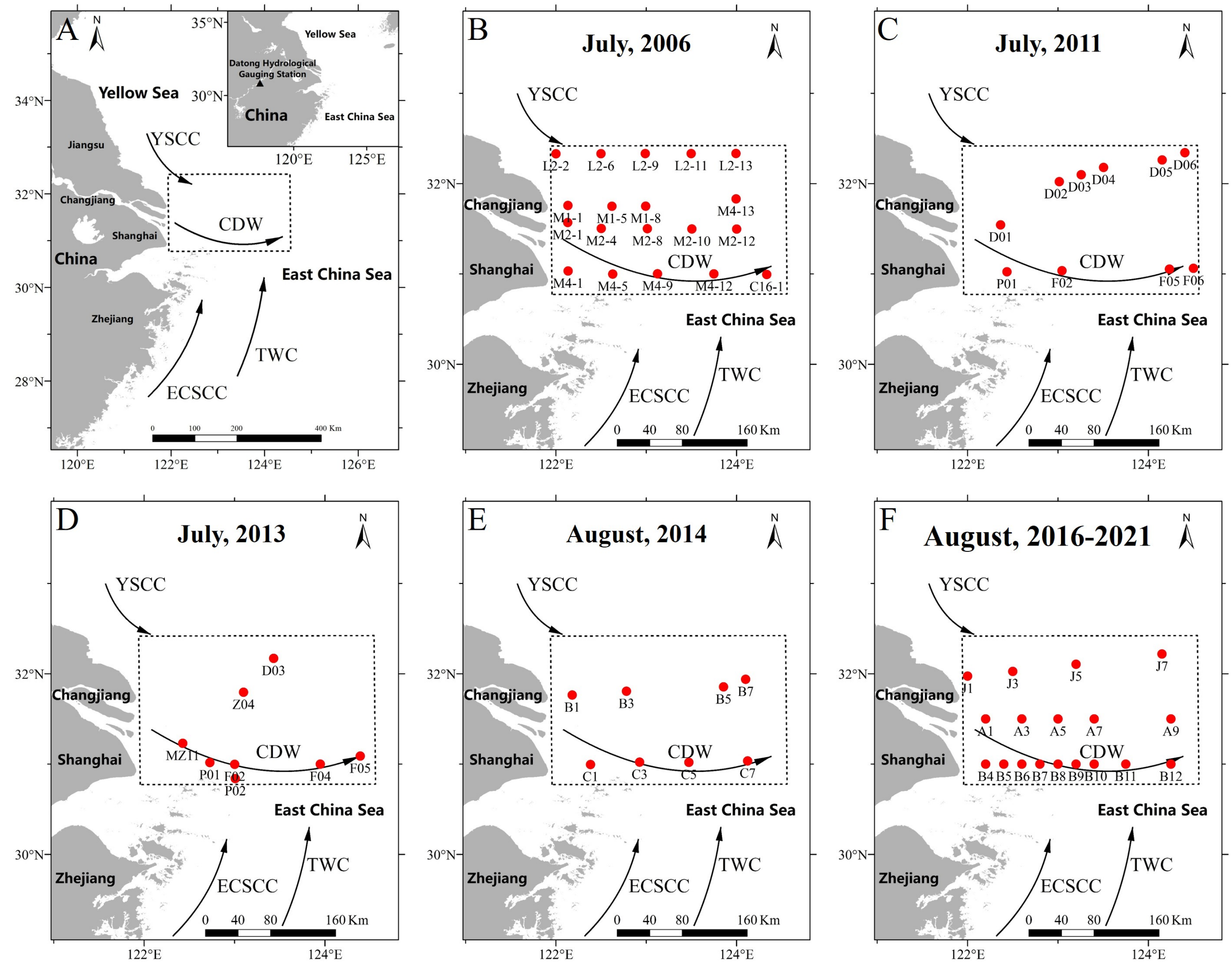

**Figure 1.** Map of the CE and the ECS (A) associated with the summer circulation pattern (after Su and Yuan, 2005) and sampling sites of the cruises during July 2006 (B), July 2011 (C), July 2013 (D), August 2014 (E) and August 2016–2021 (F). The dashed frame are the sampling regions of all cruises. The Datong Hydrological Gauging Station is marked as a triangle on the map. CDW: Changjiang Diluted Water; TWC: Taiwan Warm Current; YSCC: Yellow Sea Coastal Current; ECSCC: ECS Coastal Current.

cal conditions in summer are mainly controlled by the CDW, Taiwan Warm Current (TWC), Yellow Sea Coastal Current (YSCC), and ECS Coastal Current (ECSCC) (Figure 1).

## 2.2 Cruise data

Benthic macroinvertebrates and associated environmental factors, including depth, temperature, salinity, dissolved oxygen (DO), and pH of the bottom water, were surveyed from 10 cruises during July 2006, July 2011, July 2013, August 2014, and August 2016–2021. There were 19 sampling sites in 2006, 10 sites in 2011, 8 sites in both 2013 and 2014. From 2016 to 2021, 18 sites were consistently sampled at the same locations (Figure 1 and Supplementary Table 1). Although the sites from earlier cruises varied slightly, they were all located within the core area of the CE. All cruises were conducted in the summer (July or August) when the CDW was in its prime.

At each site, two sediment replicates were collected using a Van Veen grab with a surface area of 0.10 $m^2$. The sediments were washed through a 0.5 mm mesh sieve on the deck, and all residues retained on the sieve were fixed in a 10% formalin solution and transported to the laboratory for further analysis. Benthic macroinvertebrate specimens were sorted from the residues and identified to the highest taxonomic level (generally species) under a stereomicroscope in the laboratory. At each site, the water depth was determined by the ship echo sounder, after which seawater samples were collected using Niskin bottles on a CTD rosette from 2 m above the seafloor. The temperature and salinity were measured using a multiparameter monitor on the CTD. The pH of the bottom water was measured using a pH meter on the deck. DO was measured using the iodometric method.

### 2.3 Climatic indices and runoff data

The bi-monthly multivariate El Niño-Southern Oscillation index (MEI) combines oceanic and atmospheric variables and facilitates a single index to assess ENSO. The monthly PDO index is the time series of leading empirical orthogonal function of sea surface temperature anomalies over the North Pacific. The monthly AMO index is defined as the average anomalies of sea surface temperatures in the North Atlantic basin. The MEI, PDO and AMO index data from January 2006 to December 2021 were downloaded from NOAA (https://www.noaa.gov). Datong Hydrological Gauging Station is the nearest station in Changjiang to the CE that is not affected by the ocean. Therefore, we used measurements at Datong station to indicate runoff of the Changjiang Basin. The monthly average runoff rate data in summer (June–August) during 2006–2021 was collected from Datong Station.

### 2.4 Data analysis

For each cruise, total abundance and biomass, Shannon-Wiener diversity ($H'$) Pielou's evenness ($J'$), Margalef's richness ($d$), and the taxonomic composition of total abundance and biomass were calculated. The non-parametric Mann-Kendall test and Sen's method are widely used to detect monotonic trends in time series data without seasonal or cyclic patterns (Salmi et al., 2002), and have proven effective for identifying long-term trends (Xu et al., 2007). In this study, the Mann-Kendall test was conducted using the MAKESENS 1.0 application (Salmi et al., 2002) to assess monotonic increasing/decreasing trends in total abundance, total biomass, $H'$, $J'$, and $d$. Sen's non-parametric method was used to estimate the true slope of an existing trend. In addition, Pearson correlation analyses were conducted to determine the relationships between these biotic indices (abundance, biomass, $H'$, $J'$, and $d$) and the environmental variables (depth, temperature, salinity, DO and pH) using SPSS 20.0 (Pak and Oh, 2010). The dominant species of each cruise were identified based on their species dominance ($Y$) (Yan et al., 2017). The twenty species with the highest abundance in all cruises were selected to examine the relationship between benthic macroinvertebrate species and environmental variables. A detrended correspondence analysis (DCA) showed that the maximum gradient length of the axes of species was >3 SD. Therefore, canonical correspondence analysis (CCA) was used to assess the correlations between the environmental variables and species. DCA showed that the maximum gradient length of the axes of abundances of macrobenthic phyla was <3 SD. Therefore, redundancy analysis (RDA) was chosen to examine the relationship between the macrobenthic phyla and environmental variables (Yan et al., 2017). Monte Carlo permutations were used to test the significance of the ordination axes in both CCA and RDA. The DCA, CCA and RDA analysis were performed with Canoco 5.0.

## 3. Results

### 3.1 Climate change and runoff rate

The MEI provides real-time indications of the ENSO intensity. A higher MEI indicated a more intensive El Niño event. According to the MEI data from January 2006 to December 2021, a strong El Niño event occurred from October 2014 to June 2016, with the MEI ranging from 0.10 to 2.20 during this period. Another weak El Niño was observed from August 2018 to March 2020, during which the MEI ranged from 0.10 to 0.80. Positive values of the PDO index, ranging from 0.07 to 1.86, were recorded from July 2014 to July 2016, and ranged from 0.09 to 0.52 in 2019. Concurrently, negative values of the AMO index, ranging from −0.15 to −0.02, were observed, indicating periods characterized by warm PDO phases coupled with cold AMO phases (Figure 2).

The runoff rate of Changjiang in summer (June–August) increased from 2014 to 2016 under the influence of El Niño and then decreased from 2016 to 2018. During another El Niño event, the runoff rate increased again from 2018 to 2020 and reached a maximum of $71.70 \times 10^3$ $m^3$ $s^{-1}$ in July 2020 (Figure 3).

### 3.2 Environmental factors

Water depth at all sampling sites in the CE from 2006 to 2021 ranged from 6.13 m to 66.20 m, with an average depth of 32.17 m. Bottom-water temperature decreased from 23.00°C in 2006 to 17.15°C in 2011, increased to 24.87°C in 2018, and declinedagain in 2020. Salinity steadily increased from 29.75 in 2006 to a peak of 33.51 in 2013, followed by a decline to a minimum of 29.26 in 2016. pH value dropped to minima in 2016 (7.83) and 2020 (7.79), remaining relatively stable during other years. DO reached a minimum of 2.70 mg $L^{-1}$ in 2016, rose to 4.47 mg $L^{-1}$ in 2018, and then declined again to 3.11 mg $L^{-1}$ in 2020 (Figure 4).

### 3.3 Community structure

#### 3.3.1 Abundance and biomass

The abundance and biomass of benthic macroinvertebrates in CE showed the same trend (Figure 5). They increased significantly ($p < 0.05$) from 80 ind. $m^{-2}$ and 11.16 g $m^{-2}$ in 2006 to 1081 ind. $m^{-2}$ and 30.38 g $m^{-2}$ 2014 and then decreased significantly ($p < 0.05$) from 2014 to 218 ind. $m^{-2}$ and 4.85 g $m^{-2}$ in 2021 (Supplementary Table 2).

#### 3.3.2 Taxonomic composition

A total of 395 species belonging to nine phyla, including 167 Annelida, 93 Mollusca, 91 Crustacea, 18 Echinodermata, 11 Cnidaria, 5 Nemertea, 1 Platyelmia, 8 Sipuncula and 1 Echiura were collected during 2006–2021 (Supplementary Table 4). Annelida species were the main contrib-

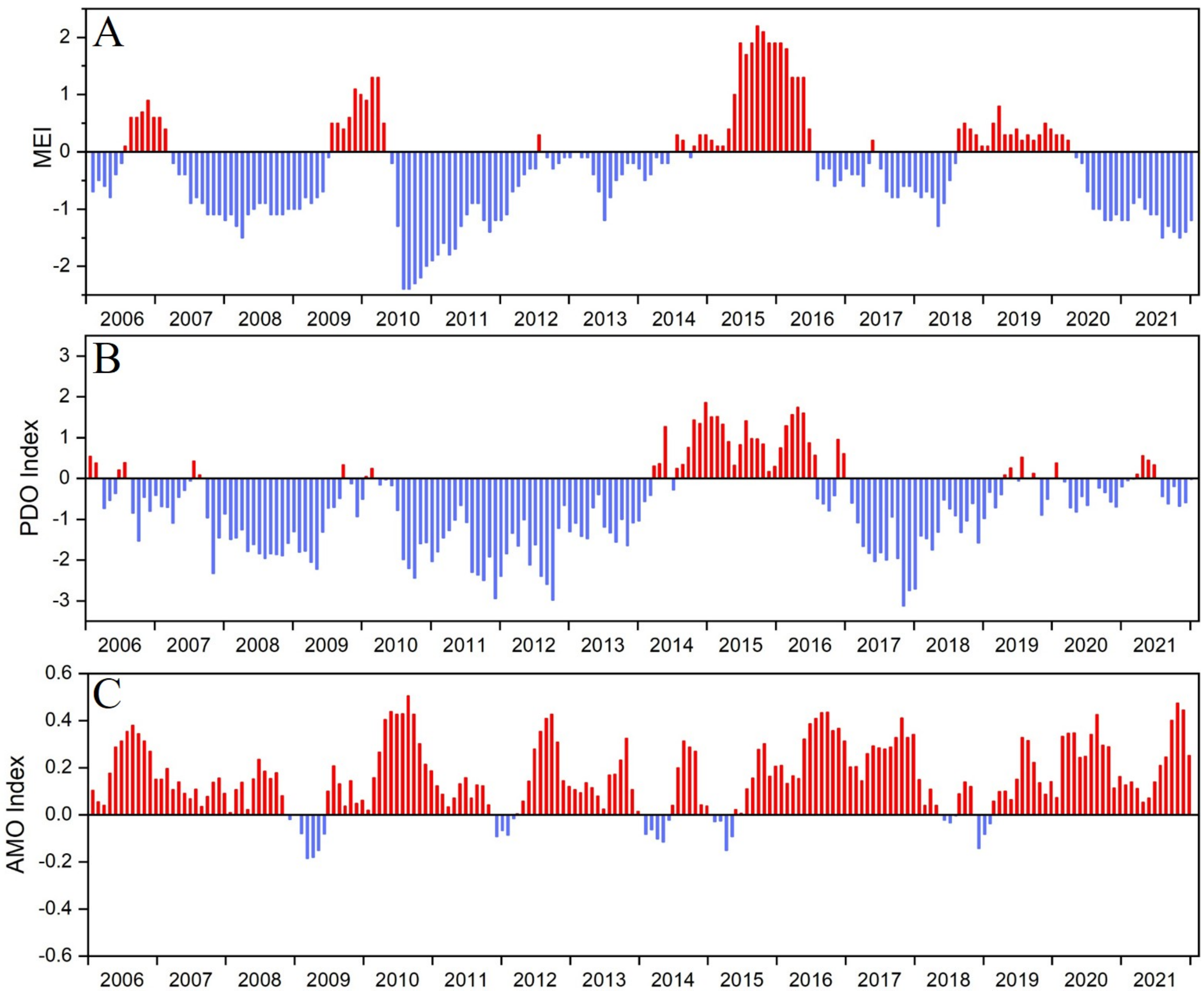


**Figure 2.** Time series of the bi-monthly Multivariate El Niño/Southern Oscillation (ENSO) index (MEI.v2) (A), monthly Pacific Decadal Oscillation (PDO) index (B), and Atlantic Multidecadal Oscillation (AMO) index (C) from January 2016 to December 2021.

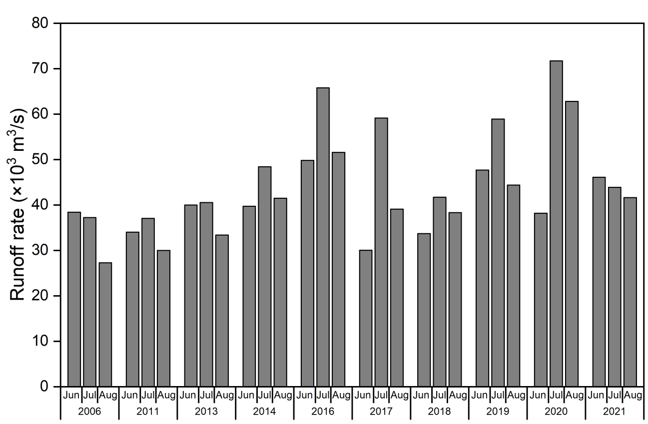


**Figure 3.** Monthly average runoff rate of the Changjiang during summer months (June, July and August) recorded at the Datong Hydrological Gauging Station.

utors to the total abundance and accounted for more than 50% over eight cruises (Figure 6). The relative abundance of Annelida increased from 45.54% in 2013 to 85.44% in 2018. In 2019, Annelida decreased to less than 40%, whereas Arthropoda increased to more than 45%. However, Annelida increased again from 32.95% in 2019 to 72.03% in 2021. The proportion of Annelida in the total biomass decreased from 84.84% in 2011 to 20.55% in 2018; meanwhile, Mollusca increased from 4.79% in 2011 to 62.60% in 2017. Annelida, in the proportion of total biomass, reached minima in 2014 (25.04%) and 2018 (20.55%).

### 3.3.3 Dominant species

Dominant species ($Y > 0.02$) identified in all ten cruises belonged to: Annelida, Arthropoda, Echinodermata, and Sipuncula based on the species dominance $Y$ (11, 4, 1, and 1, respectively). A dominant Annelida species occurred at least once, in each cruise except in 2019. *Photis longicau-*

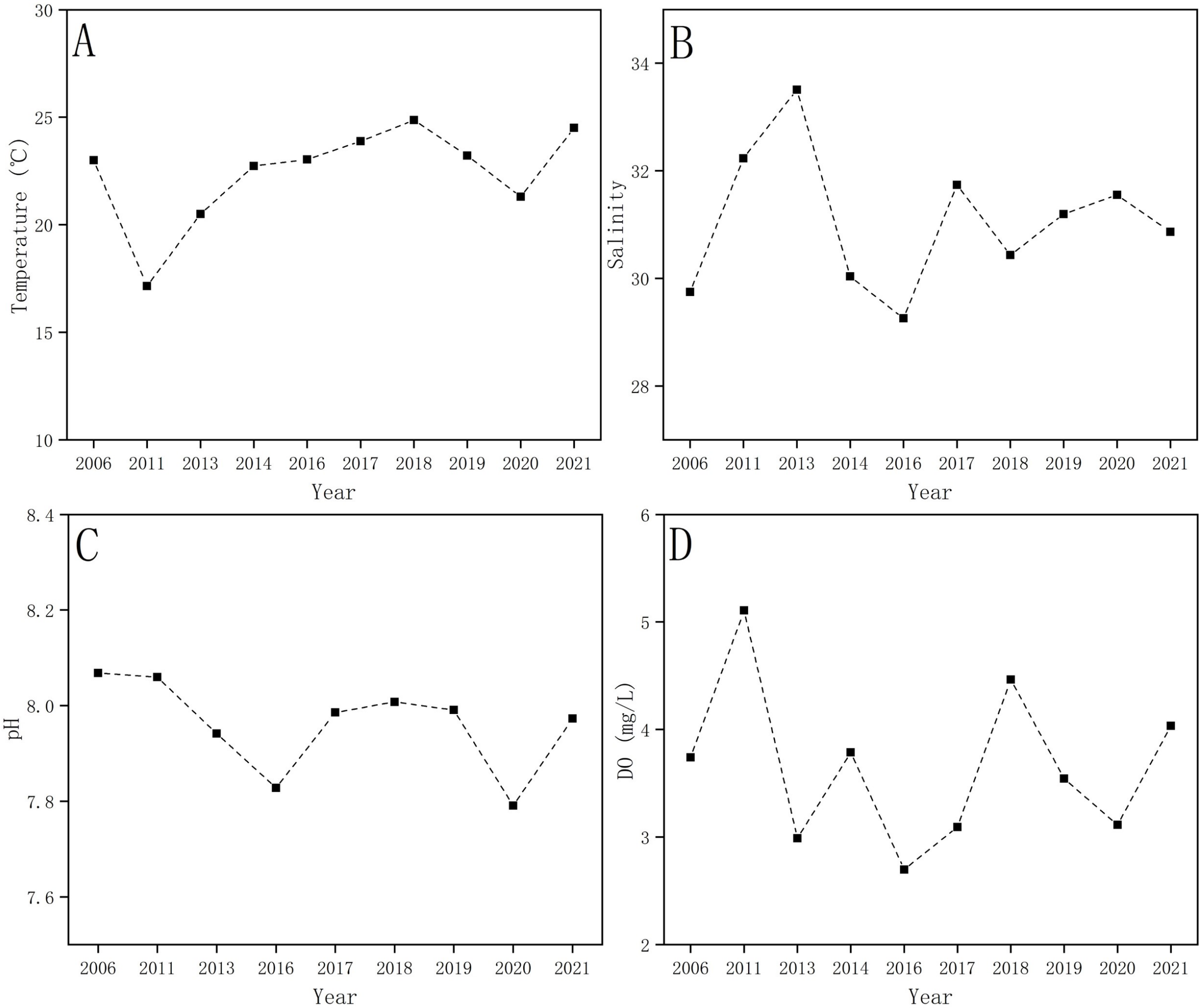


**Figure 4.** Changes in bottom water temperature (A), salinity (B), pH (C), and DO (D) in the CE during summer.

*data* was the only dominant species found in 2019. *Heteromastus filiformis* was dominant during the six cruises. Recently, more Annelida species have become dominant. Six dominant species that were dominant during 2006–2014, including three Annelida (*Praxillella affinis*, *Ophelina acuminate*, and *Terebellides stroemii*), two Arthropoda (*Byblis orientalis* and *Ampelisca miharaensis*), and one Sipuncula species (*Apionsoma (Apionsoma) trichocephalus*), were not dominant during 2016–2021. In contrast, five Annelida (*Glycinde bonhourei*, *Prionospio queenslandica*, *Cossura dimorpha*, *Aricidea (Acmira) simplex*, and *Lumbrineris latreilli*), two Arthropoda (*P. longicaudata* and *Xenophthalmus pinnotheroides*), and one Echinodermata (*Amphioplus (Lymanella) depressus*) have become dominant species since 2016 (Table 1).

#### 3.3.4 Community diversity

The Shannon-Wiener diversity $H'$, Pielou's evenness $J'$, and Margalef's richness $d$ all decreased in 2017 and then increased in 2020 but decreased again in 2021 (Figure 7). $J'$ decreased significantly from 0.88 in 2006 to 0.71 in 2017. $d$ increased significantly ($p > 0.05$) from 9. 42 in 2017 to 10.96 in 2021 (Supplementary Table 3); however, the average $d$ during 2017–2021 was still much lower than in 2006–2017.

### 3.4 Response to environmental factors

Abundance showed a positive correlation with both depth and salinity. Both $H'$ and $d$ were positively correlated with depth, salinity, and DO. Biomass and $J'$ did not show significant correlations with any of the environmental variables (Table 2).

For both CCA and RDA, the Monte Carlo test showed high significance for axis 1 and all canonical axes ($p < 0.05$), indicating that the ordination results were credible (Table 3). The CCA results showed that the five environmental variables explained 16.00% of the total variation in benthic macroinvertebrate species, while the RDA results showed that they explained 12.80% of the total variation in benthic macroinvertebrate abundances. The first two axes of CCA explained 78.31% of the species-environment relationship, and RDA explained 85.49%.

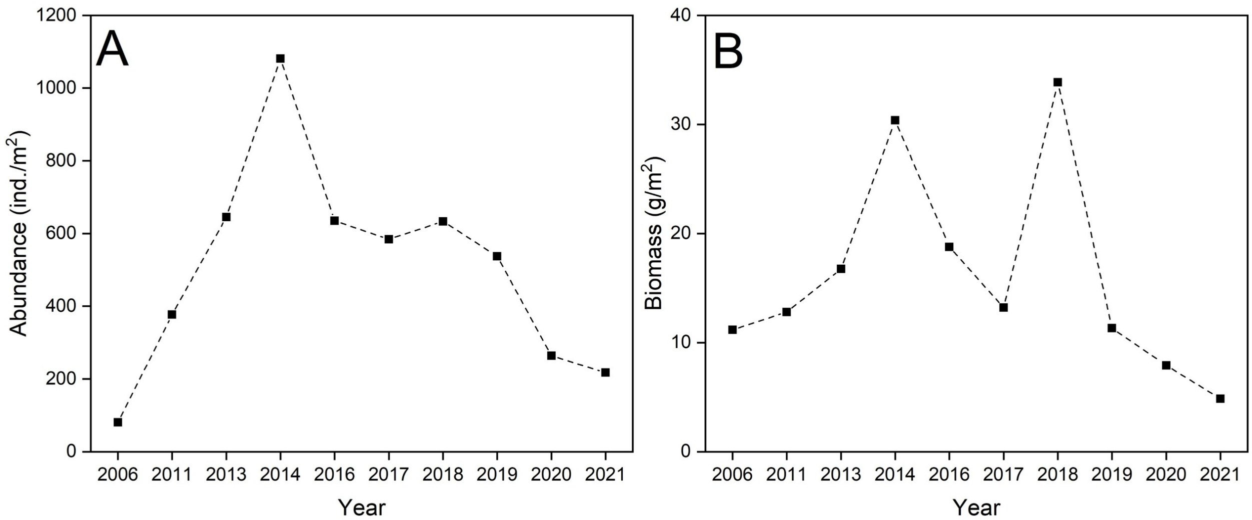


**Figure 5.** Changes in summer benthic macroinvertebrates abundance (A) and biomass (B) in the CE.

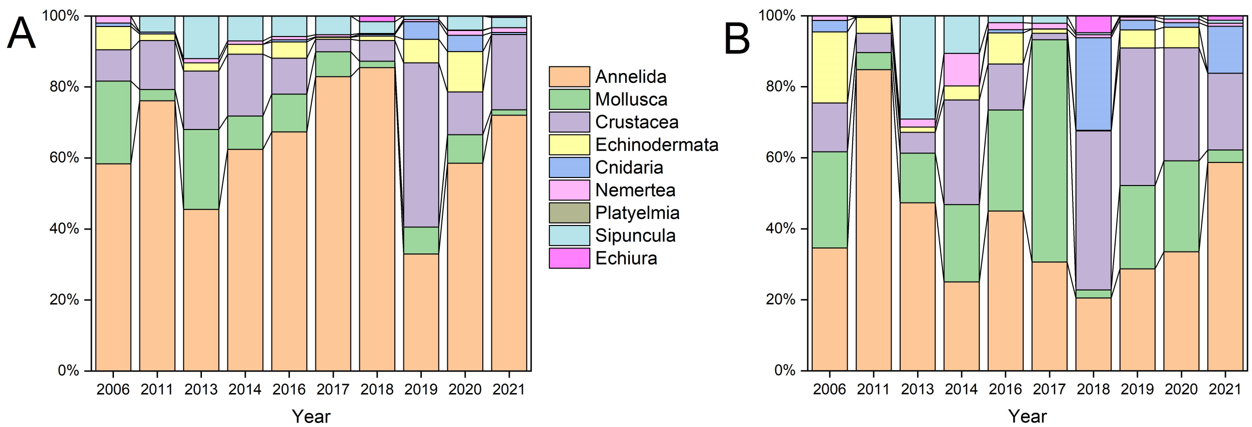


**Figure 6.** Changes in taxonomic composition of the total abundance (A) and biomass (B) of summer benthic macroinvertebrates in the CE.

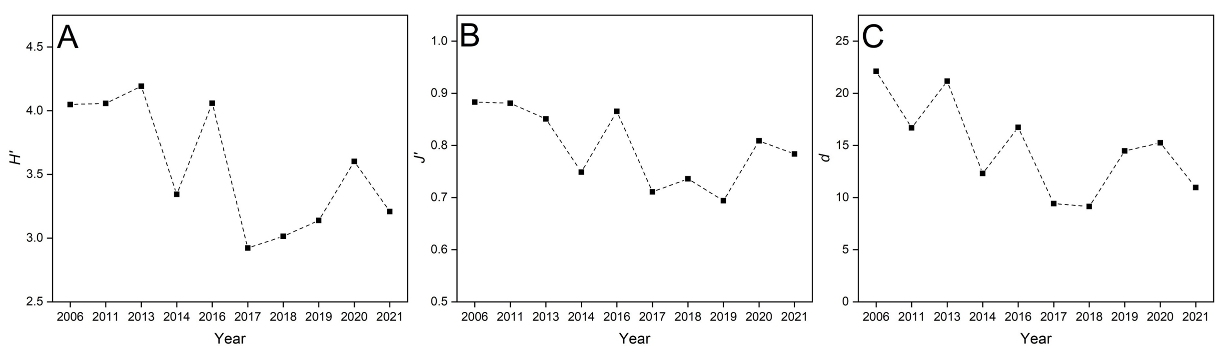


**Figure 7.** Changes in the (A) Shannon-Wiener diversity ($H'$), (B) Pielou's evenness ($J'$), and (C) Margalef's richness ($d$) of summer benthic macroinvertebrates in the CE.

Benthic macroinvertebrate species showed different distribution patterns depending on environmental factors (Figure 8). *Lumbrineris latreilli*, *Notomastus latericeus*, and *Apionsoma (Apionsoma) trichocephalus* preferred low DO and temperature conditions. Conversely, *Chaetozone setosa*, *Glycinde bonhourei* and*Aphelochaeta multifilis* preferred high DO and temperature conditions. *Paraprionospio pinnata*, *Cossura dimorpha*, *Sternaspis chinensis* and

**Table 1.** Dominant species (Y > 0.02) and species dominance (Y) of summer benthic macroinvertebrates in the CE in different years.

| Phylum | Species | Species dominance (Y) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2006 | 2011 | 2013 | 2014 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
| Annelida | *Glycinde bonhourei* | - | - | - | - | - | 0.04 | - | - | - | - |
| | *Prionospio queenslandica* | - | - | - | - | - | 0.09 | 0.02 | - | 0.06 | - |
| | *Cossura dimorpha* | - | - | - | - | - | - | 0.03 | - | - | - |
| | *Aricidea (Acmira) simplex* | - | - | - | - | - | - | 0.03 | - | - | - |
| | *Lumbrineris latreilli* | - | - | - | - | - | - | - | - | - | 0.05 |
| | *Heteromastus filiformis* | - | 0.03 | 0.02 | - | 0.04 | 0.07 | 0.05 | - | - | 0.16 |
| | *Chaetozone setosa* | - | - | - | - | - | - | 0.02 | - | - | - |
| | *Aphelochaeta multifilis* | - | - | - | 0.02 | - | 0.10 | 0.04 | - | - | - |
| | *Praxillella affinis* | 0.03 | 0.04 | - | 0.04 | - | - | - | - | - | - |
| | *Ophelina acuminata* | - | 0.02 | - | - | - | - | - | - | - | - |
| | *Terebellides stroemii* | - | - | - | 0.07 | - | - | - | - | - | - |
| Arthropoda | *Byblis orientalis* | - | - | 0.02 | - | - | - | - | - | - | - |
| | *Ampelisca miharaensis* | - | - | - | 0.04 | - | - | - | - | - | - |
| | *Photis longicaudata* | - | - | - | - | - | - | - | 0.03 | - | - |
| | *Xenophthalmus pinnotheroides* | - | - | - | - | - | - | - | - | - | 0.03 |
| Echinodermata | *Amphioplus (Lymanella) depressus* | - | - | - | - | - | - | - | - | 0.03 | - |
| Sipuncula | *Apionsoma (Apionsoma) trichocephalus* | - | 0.03 | 0.05 | 0.03 | - | - | - | - | - | - |

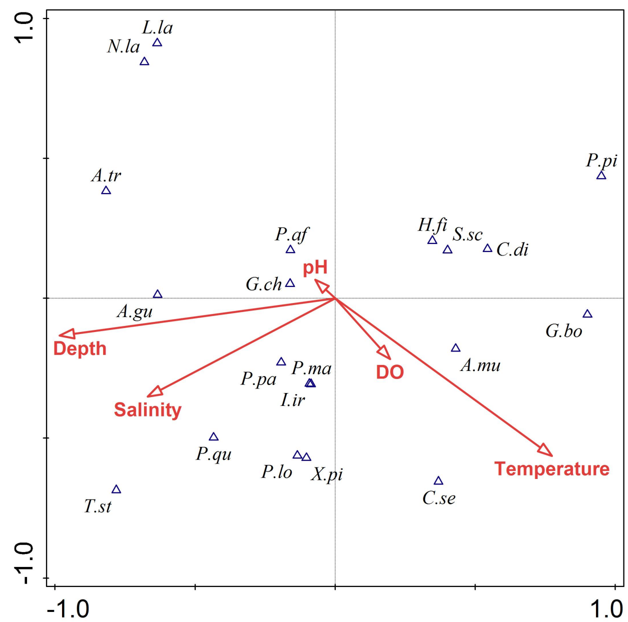


**Figure 8.** Canonical correspondence analysis ordination of the benthic macroinvertebrate species with environmental variables in the CE. *H.fi*: *Heteromastus filiformis*; *T.st*: *Terebellides stroemii*; *P.qu*: *Prionospio queenslandica*; *P.lo*: *Photis longicaudata*; *A.mu*: *Aphelochaeta multifilis*; *A.tr*: *Apionsoma (Apionsoma) trichocephalus*; *P.pi*: *Paraprionospio pinnata*; *C.se*: *Chaetozone setosa*; *C.di*: *Cossura dimorpha*; *P.pa*: *Paralacydonia paradoxa*; *I.ir*: *Iridona iridescens*; *P.af*: *Praxillella affinis*; *G.bo*: *Glycinde bonhourei*; *S.sc*: *Sternaspis chinensis*; *A.gu*: *Amphicteis gunneri*; *L.la*: *Lumbrineris latreilli*; *P.ma*: *Phyllodoce malmgreni*; *G.ch*: *Glycera chirori*; *X.pi*: *Xenophthalmus pinnotheroides*; *N.la*: *Notomastus latericeus*.

**Table 2.** Pearson correlation coefficient between biotic indices and environmental variables in the CE.

| Environmental variables | Abundance | Biomass | $H'$ | $J'$ | $d$ |
|---|---|---|---|---|---|
| Depth | 0.19* | 0.01 | 0.46** | 0.09 | 0.46** |
| Temperature | −0.07 | −0.05 | −0.05 | −0.14 | −0.09 |
| Salinity | 0.20* | 0.06 | 0.32** | −0.10 | 0.34** |
| DO | 0.10 | −0.10 | 0.43** | 0.10 | 0.43** |
| pH | −0.24 | −0.19 | 0.03 | 0.10 | 0.01 |

* $p < 0.05$

** $p < 0.01$

*Heteromastus filiformis* preferred shallow water and low salinity, whereas *Terebellides stroemii*, *P. queenslandica*, *Amphicteis gunneri*, *X. pinnotheroides* and *P. longicaudata* preferred deep water and high salinity. The distributions of most benthic macroinvertebrate phyla were positively correlated with depth, salinity, and dissolved oxygen (DO). Echinodermata, Annelida, Crustacea, Sipuncula, and Platyhelminthes preferred deeper waters and higher salinity.

**Table 3.** Summary of the canonical correspondence analysis and redundancy analysis on benthic macroinvertebrates community and bottom water environmental factors in summer in the CE.

| | CCA | | RDA | |
|---|---|---|---|---|
| | Axis 1 | Axis2 | Axis 1 | Axis2 |
| Eigenvalue | 0.30 | 0.18 | 0.08 | 0.03 |
| Species-environmental correlations | 0.80 | 0.70 | 0.42 | 0.46 |
| Cumulative percentage variance of species data | 7.93% | 12.50% | 8.37% | 10.92% |
| Cumulative percentage variance of species-environmental relation | 49.68% | 78.31% | 65.50% | 85.49% |
| Variance explained | 16.00% | – | 12.80% | – |
| Significance of first canonical axis | $2.00 \times 10^{-3}$ | – | $8.00 \times 10^{-3}$ | – |
| Significance of all canonical axes | $2.00 \times 10^{-3}$ | – | $4.00 \times 10^{-3}$ | – |

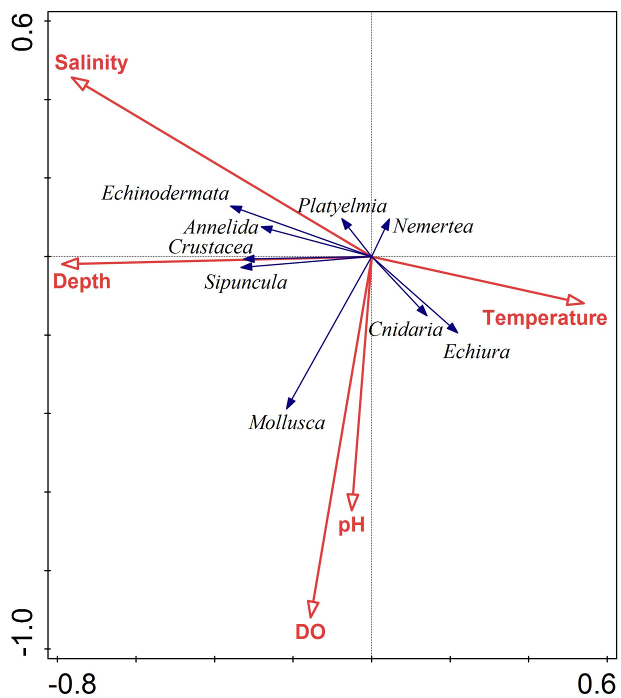


**Figure 9.** Redundancy analysis ordination of the benthic macroinvertebrate phyla with environmental variables in the CE.

Mollusca, Crustacea, Sipuncula, Cnidaria, and Echiura were more abundant under high DO conditions, and Mollusca also showed a preference for higher pH. Echinodermata, Annelida, and Crustacea tended to favor lower temperatures, while Cnidaria and Echiura preferred higher temperatures (Figure 9). Nemertea, which contributed only a small proportion to the total abundance, exhibited no clear preference for depth, salinity or DO.

## 4. Discussion

### 4.1 Long-term change of benthic macroinvertebrates

Changes in the macrobenthic community, including an increase in opportunistic species, a decrease in contaminant-sensitive species, and a reduction in diversity indices, revealed that benthic macroinvertebrates in the CE have been exposed to long-term disturbance (Rhoads et al., 1985; Luo and Shen, 1994; Shou et al., 2013; Liao et al., 2017; Yan et al., 2017). With a consistent increase in the abundances and biomasses from 2006 to 2014, the benthic macroinvertebrates appeared to show signs of slight recovery, but it was subsequently disturbed again during 2016–2021.

The dominant species and taxonomic compositions have changed since 2016 when Annelida has become the dominant species in the CE. Annelida accounted for approximately 40% of the total abundance in 1959 (Yan et al., 2017), but it increased to 77.5% in 1985 (Luo and Shen, 1994). In our study, Annelida was the phylum with the highest abundance among all benthic macroinvertebrates in all cruises except 2019. Echinodermata accounted for over 20% of the annual average abundance in 1959, which was lower than Annelida's (Yan et al., 2017). In 1985, it consisted of over 20% of the total biomass, which made it the second largest contributor to total biomass after Mollusca (Luo and Shen, 1994). However, it was less than 7% of the total abundance in all cruises except 2020 (11.38%) in our study and less than 6% of the total biomass, except in 2006 (20.04%). Besides, human activity and climate change are the two main factors that influence estuarine ecosystems (Jiang et al., 2014; Wang et al., 2021; Li et al., 2022). Their relationship with long-term changes in benthic macroinvertebrates in the CE is discussed below.

### 4.2 Variations of benthic macroinvertebrates driven by human activities

CE has been one of the most intensive areas of human activity in the last few decades worldwide. With the development of industrialization and urbanization along the Changjiang, anthropogenic contaminants such as heavy metals, hydrocarbons, and persistent organic pollutants have been discharged into the river (Dong et al., 2012; Adeleye et al., 2016; Zhao et al., 2017). Terrestrial contaminants are transported downstream of Changjiang and accumulate in the water and sediment of the CE (Zhu et al., 2018). With the rapid economic development of the Changjiang Basin, pollutant levels in the Changjiang Estuary have increased in recent decades (Li et al., 2014; Sun et al., 2019). Anthropogenic contamination, coupled with intensive fishery activity in the ECS, has deteriorated the ecosystem in the CE (Zhu et al., 2014; Duan et al., 2015; Cheung et al., 2019).

The benthic macroinvertebrates that responded to anthropogenic stress varied by phyla. Annelida species, for example, preferred low DO levels (Figure 8). Annelida are characterized by small body size and a high resistance to contamination (Rouse and Pleijel, 2001; Dafforn et al., 2013); therefore, they are considered opportunistic species that are usually dominant in the macrobenthic community under the influence of sedimental contaminations of heavy metals and petroleum hydrocarbons caused by anthropogenic activities (Tang et al., 2021). The proportion of Annelida in the total biomass varied with the cruises. Annelida accounted for less than 50% of the total biomass during most cruises. The abundance of Mollusca and Arthropoda was much lower than that of Annelida, but they were quite similar in biomass (Figure 6), implying that the body size of Annelida collected from the CE was smaller than that of Mollusca and Arthropoda. The proportion of Annelida in the total biomass decreased to minima in 2014 and 2018, while the biomass reached maxima in the same years. This means that the increase in biomass in 2014 and 2018 was mainly contributed by other phyla. Increases in the richness and abundance of Annelida have been reported in many contaminated estuaries (Elliott and Quintino, 2007; Dafforn et al., 2013) while other phyla typically decline (Dolbeth et al., 2011).

Historical data from 1959 and 1985 show that Echinodermata was an important component of the macrobenthic community (Luo and Shen, 1994; Yan et al., 2017). However, in our study, both its abundance and biomass were much lower than that in 1959 and 1985. Echinodermata are highly sensitive to various contaminants and are used as bioindicators to evaluate marine pollution (Sugni et al., 2007; de-la-Ossa-Carretero et al., 2016). The decreased abundance and biomass of Echinodermata may be caused by environmental deterioration in the CE.

Marine ecosystems in the ECS have been under strong fishing pressure from 1990s to the early 2000s. The Chinese government started an annual summer sea fishing moratorium in the ECS in 1995, which makes it illegal for vessels from any country to fish in this area in summer. Decades of fishing moratoriums promote sustainable marine fishery development and improve marine ecology in the ECS (L. Xu et al., 2022). Some species of Mollusca and Arthropoda are economically important species that were under fishing pressure from the 1990s to the 2000s (Xuan et al., 2014). As a result of national protective measures, macrobenthic communities have recently shown signs of recovery not only in the ECS (J. Zhang et al., 2021), but also in other marginal seas of China (Z. Wang et al., 2021; Shi et al., 2022; Zheng et al., 2025).

The damming in the Changjiang Basin over the past two decades, including the impoundment of the Three Gorges Dam in 2003, has significantly contributed to the reduction in both mean annual water discharge and sediment flux from the Changjiang River (Yang et al., 2018). Correlation analysis and RDA results indicated that the abundance of benthic macroinvertebrates in the CE was positively correlated with depth, salinity, and DO. Similarly, the Amazon River, which also discharges large volumes of freshwater, supports benthic macroinvertebrate communities that exhibit a distribution pattern analogous to that in the CE, with abundance and biomass increasing along the salinity gradient (Silva et al., 2011). Therefore, the reduced runoff resulting from damming may partly explain the observed increase in abundance and biomass of benthic macroinvertebrates from 2006 to 2014. Additionally, the initial stages of China's South-to-North Water Diversion Project, specifically the eastern and middle routes, were completed in 2013 and 2014, diverting 8.90 and $9.50 \times 10^9$ $m^3$ of water from the Changjiang annually (Jiang et al., 2014). However, summer runoff in 2016 was higher than in previous years (Figure 3), likely due to the strong El Niño event that occurred in 2015–2016.

The ecological environment has improved due to several protective measures and policies (Chen et al., 2020). The abundance and biomass of benthic macroinvertebrates increased significantly from 2006–2014. Nevertheless, with the occurrence of El Niño events in 2015–2016 and 2019–2020, the community structure of benthic macroinvertebrates in the CE was profoundly impacted. The regional protection efforts seem overshadowed by the effects of global climate changes during 2016–2021.

### 4.3 Variations of benthic macroinvertebrates driven by climate changes

The strong El Niño event and a warm PDO phase coupled with cold AMO phase during 2015–2016 promoted rainfalls in the Changjiang Basin during the summer of 2016 (Figures 2 and 3) (Sang et al., 2020). Large amounts of diluted water are discharged into the ECS, causing eutrophication and algal blooms (Zhu et al., 2014). When the deposited organic particles degrade, a large amount of DO in the bottom water is consumed, leading to hypoxia (Wang et al., 2017; Ma et al., 2022). The spatial distribution of benthic macroinvertebrates is positively associated with the DO in the bottom water. Therefore, large-scale bottom-water hypoxia caused by El Niño may reduce abundance and biomass. In our study, the abundance and biomass of benthic macroinvertebrates decreased significantly during 2016–2021 after the strong El Niño event, which implies negative impacts of global climate change on the macrobenthic community in the CE. Although long-term changes of benthic macroinvertebrates in estuaries have rarely been reported, some previous studies suggest that El Niño events play an important role in driving these changes (Currie and Small, 2005).

The dominant species and diversity index of benthic macroinvertebrates also changed after the strong El Niño during 2015–2016. Many Annelida species can tolerate hypoxia for a long time by reducing their metabolic activity and utilizing alternative respiratory pathways (Warren, 1981; Llansó, 1991; Abele et al., 1998). Therefore, they dominate the macrobenthic community when large-scale hypoxia occurs in the bottom water (Rouse and Pleijel, 2001). Similarly, due to the high nutrient input from the Pearl River and Mississippi River, seasonal hypoxia occurs in the Pearl River Estuary and the Mississippi Bight. During these hypoxic events, Annelida species have been reported to dominate the macrobenthic communities in both estuaries (Rakocinski and Menke, 2016; Tian et al., 2025). Nevertheless, persistent hypoxia can cause severe damage to all benthic macroinvertebrate phyla, including Annelida (Diaz and Rosenberg, 1995). In summer, the depth, salinity, and DO in the CE shared similar distribution patterns for hypoxia, which is highly associated with the CDW (Ma et al., 2022).

The near-shore area under the influence of CDW is characterized by shallow water, low salinity and low DO, where benthic macroinvertebrates are under pressure. In contrast, in open ocean, characterized by deep water, high salinity and high DO, most benthic macroinvertebrates prefer to live under such environmental conditions. Under the impact of El Niño, extreme rainfall occurred throughout the Chanjiang Basin (Bett et al., 2018). Thus, the CDW influenced a larger area of the CE during summer, resulting in large-scale hypoxia, which consequently reduced the abundance, biomass, and biodiversity of benthic macroinvertebrates.

Another El Niño event occurred during 2018–2019 (Fang et al., 2021) when abundance and biomass of benthic macroinvertebrates also decreased. The runoff rate during the summer of 2020 increased because of the summer rainfall caused by El Niño (Fang et al., 2021) and warm PDO (Sang et al., 2020). The proportion of Annelida in abundance and biomass increased from 2019 to 2021, whereas Arthropoda decreased in biomass simultaneously. Arthropoda species are susceptible to DO, and their mobility is relatively greater compared to other benthic macroinvertebrate species, so they may have emigrated from the hypoxic areas (de Lima et al., 2021). This suggests that they have great potential as bioindicators of bottom water hypoxia.

Benthic macroinvertebrates in the CE are vulnerable due to the increasing frequency of extreme El Niño events in the last decade. El Niño events influence the climate globally, so the consequences presented here may be a prelude to the future deterioration of global marine ecosystems if measures are not taken in time.

This study provides insights into the long-term dynamics of benthic macroinvertebrates in the CE. However, its exclusive reliance on summer cruise data may overlook seasonal variability in environmental conditions and biological communities. Besides, the duration of the time series may be insufficient to distinguish between short-term fluctuations and persistent shifts in community structure. To address these limitations, future research should incorporate year-round sampling to better reflect seasonal dynamics and extend the temporal coverage. Such approaches would allow for more accurate assessment of the temporal variability in macrobenthic communities and their responses to both anthropogenic pressures and climate variability, ultimately leading to more robust conclusions and management strategies for estuarine ecosystems.

## 5. Conclusion

The present study confirmed that long-term changes in benthic macroinvertebrates in the CE were highly associated with physicochemical stresses caused by human activities and climatic changes. The macrobenthic community in the CE recovered slightly from 2006 to 2014, likely due to regional protective measures for local ecosystems. However, under the influence of precipitation variations driven by ENSO, PDO and AMO over the last decade, the community structure of benthic macroinvertebrates has deteriorated rapidly. The effects of regional protection strategies seem to be limited, and more international cooperation measures are urgently required to conserve marine ecosystems. This study could be useful to local and international environmental managers because most estuaries suffer from human and climate driven global changes.

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## Supplementary material

Supplementary material associated with this article can be found here.

## Conflict of interest

None declared.

## References


Abele, D., Großpietsch, H., Pörtner, H.O., 1998. *Temporal fluctuations and spatial gradients of environmental P($O_2$), temperature, $H_2O_2$ and $H_2S$ in its intertidal habitat trigger enzymatic antioxidant protection in the capitellid worm Heteromastus filiformis*. Mar. Ecol. Prog. Ser. 163, 179–191. https://doi.org/10.3354/meps163179

Adeleye, A.O., Jin, H., Di, Y., Li, D., Chen, J., Ye, Y., 2016. *Distribution and ecological risk of organic pollutants in the sediments and seafood of Yangtze Estuary and Hangzhou Bay, East China Sea*. Sci. Total Environ. 541, 1540–1548. https://doi.org/10.1016/j.scitotenv.2015.09.124

Aller, J.Y., Aller, R.C., 1986. *General characteristics of benthic faunas on the Amazon inner continental shelf with comparison to the shelf off the Changjiang River, East China Sea*. Cont. Shelf Res. 6, 291–310. https://doi.org/10.1016/0278-4343(86)90065-8

Arntz, W.E., Gallardo, V.A., Gutiérrez, D., Isla, E., Levin, L.A., Mendo, J., Neira, C., Rowe, G.T., Tarazona, J., Wolff, M., 2006. *El Niño and similar perturbation effects on the benthos of the Humboldt, California, and Benguela Current upwelling ecosystems*. Adv. Geosci. 6, 243–265. https://doi.org/10.5194/adgeo-6-243-2006

Bett, P.E., Scaife, A.A., Li, C., Hewitt, C., Golding, N., Zhang, P., Dunstone, N., Smith, D.M., Thornton, H.E., Lu, R., Ren, H.L., 2018. *Seasonal forecasts of the summer 2016 Yangtze River basin rainfall*. Adv. Atmos. Sci. 35, 918–926. https://doi.org/10.1007/s00376-018-7210-y

Bouloubassi, I., Fillaux, J., Saliot, A., 2001. *Hydrocarbons in surface sediments from there Changjiang (Yangtze River) Estuary, East China Sea*. Mar. Pollut. Bull. 42, 1335–1346. https://doi.org/10.1016/S0025-326X(01)00149-7

Chao, M., Shi, Y., Quan, W., Shen, X., An, C., Yuan, Q., Huang, H., 2012. *Distribution of benthic macroinvertebrates in relation to environmental variables across the Yangtze River Estuary, China*. J. Coast. Res. 28, 1008–1019. https://doi.org/10.2112/JCOASTRES-D-11-00194.1

Chen, T., Wang, Y., Gardner, C., Wu, F., 2020. *Threats and protection policies of the aquatic biodiversity in the Yangtze River*. J. Nat. Conserv. 58, 125931. https://doi.org/10.1016/j.jnc.2020.125931

Cheung, R.C.W., Yasuhara, M., Iwatani, H., Wei, C.L., Dong, Y.W., 2019. *Benthic community history in the Changjiang (Yangtze River) mega-delta: Damming, urbanization, and environmental control*. Paleobiology 45, 469–483. https://doi.org/10.1017/pab.2019.21

Currie, D.R., Small, K.J., 2005. *Macrobenthic community responses to long-term environmental change in an east Australian sub-tropical estuary*. Estuar. Coast. Shelf Sci. 63, 315–331. https://doi.org/10.1016/j.ecss.2004.11.023

Dafforn, K.A., Kelaher, B.P., Simpson, S.L., Coleman, M.A., Hutchings, P.A., Clark, G.F., Knott, N.A., Doblin, M.A., Johnston, E.L., 2013. *Polychaete richness and abundance enhanced in anthropogenically modified estuaries despite high concentrations of toxic contaminants*. PLoS One 8, e77018. https://doi.org/10.1371/journal.pone.0077018

Dai, S.B., Lu, X.X., 2014. *Sediment load change in the Yangtze River (Changjiang): A review*. Geomorphology 215, 60–73. https://doi.org/10.1016/j.geomorph.2013.05.027

Dauvin, J.C., 2007. *Paradox of estuarine quality: Benthic indicators and indices, consensus or debate for the future*. Mar. Pollut. Bull. 55, 271–281. https://doi.org/10.1016/j.marpolbul.2006.08.017

de-la-Ossa-Carretero, J.A., Del-Pilar-Ruso, Y., Loya-Fernández, A., Ferrero-Vicente, L.M., Marco-Méndez, C., Martinez-Garcia, E., Giménez-Casalduero, F., Sánchez-Lizaso, J.L., 2016. *Bioindicators as metrics for environmental monitoring of desalination plant discharges*. Mar. Pollut. Bull. 103, 313–318. https://doi.org/10.1016/j.marpolbul.2015.12.023

de Lima, T.M., Nery, L.E.M., Maciel, F.E., Ngo-Vu, H., Kozma, M.T., Derby, C.D., 2021. *Oxygen sensing in crustaceans: functions and mechanisms*. J. Comp. Physiol. A Neuroethol. Sensory, Neural, Behav. Physiol. 207, 1–15. https://doi.org/10.1007/s00359-020-01457-z

Diaz, R.J., Rosenberg, R., 1995. *Marine benthic hypoxia: a review of its ecological effects and the behavioural responses of benthic macrofauna*. Oceanogr. Mar. Biol. Annu. Rev. 33, 245–303.

Dolbeth, M., Cardoso, P.G., Grilo, T.F., Bordalo, M.D., Raffaelli, D., Pardal, M.A., 2011. *Long-term changes in the production by estuarine macrobenthos affected by multiple stressors*. Estuar. Coast. Shelf Sci. 92, 10–18. https://doi.org/10.1016/j.ecss.2010.12.006

Dong, A., Zhai, S., Matthias, Z., Yu, Z., Zhang, H., Liu, F., 2012. *Heavy metals in Changjiang estuarine and offshore sediments: Responding to human activities*. Acta Oceanol. Sin. 31, 88–101. https://doi.org/10.1007/s13131-012-0195-y

Douglas, E.J., Bulmer, R.H., MacDonald, I.T., Lohrer, A.M., 2022. *Estuaries as coastal reactors: importance of shallow seafloor habitats for primary productivity and nutrient transformation, and impacts of sea level rise*. New Zeal. J. Mar. Freshw. Res. 56 (3), 553–569. https://doi.org/10.1080/00288330.2022.2107027

Duan, X., Liu, J., Zhang, D., Yin, P., Li, Y., Li, X., 2015. *An assessment of human influences on sources of polycyclic aromatic hydrocarbons in the estuarine and coastal sediments of China*. Mar. Pollut. Bull. 97, 309–318. https://doi.org/10.1016/j.marpolbul.2015.05.071

Elliott, M., Quintino, V., 2007. *The Estuarine Quality Paradox, Environmental Homeostasis and the difficulty of detecting anthropogenic stress in naturally stressed areas*. Mar. Pollut. Bull. 54, 640–645. https://doi.org/10.1016/j.marpolbul.2007.02.003

Fang, C., Liu, Y., Cai, Q., Song, H., 2021. *Why does extreme rainfall occur in central China during the summer of 2020 after a weak El Niño?* Adv. Atmos. Sci. 8, 2067–2081. https://doi.org/10.1007/s00376-021-1009-y

Gammal, J., Norkko, J., Pilditch, C.A., Norkko, A., 2017. *Coastal hypoxia and the importance of benthic macrofauna communities for ecosystem functioning*. Estuar. Coast. 40, 457–468. https://doi.org/10.1007/s12237-016-0152-7

Ge, Y., Miao, J., Lang, X., Si, D., Jiang, D., 2023. *Combined impacts of the Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation on summer precipitation in Eastern China during the Medieval Climate Anomaly and Little Ice Age*. J. Geophys. Res. Atmos. 128. https://doi.org/10.1029/2023JD038920

Ghribi, R., Correia, A.T., Elleuch, B., Nunes, B., 2019. *Toxicity assessment of impacted sediments from southeast coast of Tunisia using a biomarker approach with the polychaete Hediste diversicolor*. Arch. Environ. Contam. Toxicol. 76, 678–691. https://doi.org/10.1007/s00244-019-00611-2

Grothe, P.R., Cobb, K.M., Liguori, G., Di Lorenzo, E., Capotondi, A., Lu, Y., Cheng, H., Edwards, R.L., Southon, J.R., Santos, G.M., Deocampo, D.M., Lynch-Stieglitz, J., Chen, T., Sayani, H.R., Thompson, D.M., Conroy, J.L., Moore, A.L., Townsend, K., Hagos, M., O'Connor, G., Toth, L.T., 2020. *Enhanced El Niño–Southern Oscillation variability in recent decades*. Geophys. Res. Lett. 47, 1–8. https://doi.org/10.1029/2019GL083906

Herman, P.M.J., Middelburg, J.J., van de Koppel, J., Heip, C.H.R., 1999. *Ecology of estuarine macrobenthos*. Adv. Ecol. Res. 29, 195–240. https://doi.org/10.1016/S0065-2504(08)60194-4

Jiang, Z., Liu, J., Chen, J., Chen, Q., Yan, X., Xuan, J., Zeng, J., 2014. *Responses of summer phytoplankton community to drastic environmental changes in the Changjiang (Yangtze River) estuary during the past 50 years*. Water Res. 54, 1–11. https://doi.org/10.1016/j.watres.2014.01.032

Li, F., Ma, Y., Song, X., Li, S., Zhang, X., Wang, X., Wang, T., Sun, Z., 2022. *Community structure and ecological quality assessment of macrobenthos in the coastal sea areas of Northern Yantai, China*. Front. Mar. Sci. 9, 1–14. https://doi.org/10.3389/fmars.2022.989034

Li, H.M., Tang, H.J., Shi, X.Y., Zhang, C.S., Wang, X.L., 2014. *Increased nutrient loads from the Changjiang (Yangtze) River have led to increased Harmful Algal Blooms*. Harmful Algae 39, 92–101. https://doi.org/10.1016/j.hal.2014.07.002

Liao, Y., Shou, L., Jiang, Z., Tang, Y., Du, P., Zeng, J., Chen, Q., Yan, X., Chen, J., 2019. *Effects of fish cage culture and suspended oyster culture on macrobenthic communities in Xiangshan Bay, a semi-enclosed subtropical bay in eastern China*. Mar. Pollut. Bull. 142, 475–483. https://doi.org/10.1016/j.marpolbul.2019.03.065

Liao, Y., Shou, L., Tang, Y., Zeng, J., Gao, A., Chen, Q., Yan, X., 2017. *Macrobenthic assemblages of the Changjiang River estuary (Yangtze River, China) and adjacent continental shelf relative to mild summer hypoxia*. Chinese J. Oceanol. Limnol. 35, 481–488. https://doi.org/10.1007/s00343-017-5285-4

Llansó, R.J., 1991. *Tolerance of low dissolved oxygen and hydrogen sulfide by the polychaete Streblospio benedicti (Webster)*. J. Exp. Mar. Bio. Ecol. 153, 165–178. https://doi.org/10.1016/0022-0981(91)90223-J

Luo, B., Shen, H., 1994. *Three Gorges Project and Estuarine Ecological Environment*. Science Press, Beijing.

Lv, W., Zhou, W., Zhao, Y., 2018. *Macrobenthos functional groups as indicators of ecological restoration in reclaimed intertidal wetlands of China's Yangtze Estuary*. Reg. Stud. Mar. Sci. 22, 93–100. https://doi.org/10.1016/j.rsma.2018.06.003

Ma, X., Liu, A., Zhao, Q., Wang, B., Tian, D., Meng, Q., Zeng, D., Li, J., Huang, D., Zhou, F., 2022. *Temporal variation of summer hypoxia off Changjiang Estuary during 1997–2014 and its association with ENSO*. Front. Mar. Sci. 9, 1–14. https://doi.org/10.3389/fmars.2022.897063

Meng, W., Liu, L., Zheng, B., Li, X., Li, Z., 2007. *Macrobenthic community structure in the Changjiang Estuary and its adjacent waters in summer*. Acta Oceanol. Sin. 26, 62–71.

Milliman, J.D., Huang-ting, S., Zuo-sheng, Y., H. Mead, R., 1985. *Transport and deposition of river sediment in the Changjiang estuary and adjacent continental shelf*. Cont. Shelf Res. 4, 37–45. https://doi.org/10.1016/0278-4343(85)90020-2

Ni, G., Kern, E., Dong, Y.W., Li, Q., Park, J.K., 2017. *More than meets the eye: The barrier effect of the Yangtze River outflow*. Mol. Ecol. 26, 4591–4602. https://doi.org/10.1111/mec.14235

Pak, S. Il, Oh, T.H., 2010. *Correlation and simple linear regression*. J. Vet. Clin. 27, 427–434. https://doi.org/10.4324/9781003442011-24

Peng, S., Li, X., Wang, H., Zhang, B., 2014. *Macrobenthic community structure and species composition in the Yellow Sea and East China Sea in jellyfish bloom*. Chinese J. Oceanol. Limnol. 32, 576–594. https://doi.org/10.1007/s00343-014-3068-8

Pinto, I., Rodrigues, S., Antunes, S.C., 2021. *Assessment of the benthic macroinvertebrate communities in the evaluation of the water quality of portuguese reservoirs: An experimental approach*. Water (Switzerland) 13. https://doi.org/10.3390/w13233391

Qi, W., Wang, X., Kang, J., Bai, Y., Bian, R., Xue, H., Chen, L., Guan, A., Pan, Y.-R., Liu, H., Qu, J., 2022. *Improvement of the Yangtze River's water quality with substantial implementation of wastewater services infrastructure since 2013*. Engineering, 21, 135–142. https://doi.org/10.1016/j.eng.2022.03.014

Rakocinski, C.F., Menke, D.P., 2016. *Seasonal hypoxia regulates macrobenthic function and structure in the Mississippi Bight*. Mar. Pollut. Bull. 105, 299–309. https://doi.org/10.1016/j.marpolbul.2016.02.006

Rhoads, D.C., Boesch, D.F., Zhican, T., Fengshan, X., Liqiang, H., Nilsen, K.J., 1985. *Macrobenthos and sedimentary facies on the Changjiang delta platform and adjacent continental shelf, East China Sea*. Cont. Shelf Res. 4, 189–213. https://doi.org/10.1016/0278-4343(85)90029-9

Rouse, G.W., Pleijel, F., 2001. *Polychaetes*. Oxford University Press, Oxford.

Salmi, T., Maatta, A., Anttila, P., Ruoho-Airola, T., Amnell, T., 2002. *Detecting Trends of Annual Values of Atmospheric Pollutants by the Mann-Kendall Test and Sen's Solpe Estimates the Excel Template Application MAKESENS*. Air Quality Research, Finnish Meteorological Institute, Helsinki.

Sang, Y.F., Fu, Q., Singh, V.P., Sivakumar, B., Zhu, Y., Li, X., 2020. *Does summer precipitation in China exhibit significant periodicities?* J. Hydrol. 581, 124289. https://doi.org/10.1016/j.jhydrol.2019.124289

Shi, Y., Zhang, Guicheng, Zhang, Guodong, Wen, Y., Guo, Y., Peng, L., Xu, W., Sun, J., 2022. *Species and functional diversity of marine macrobenthic community and benthic habitat quality assessment in semi-enclosed waters upon recovering from eutrophication, Bohai Bay, China*. Mar. Pollut. Bull. 181. https://doi.org/10.1016/j.marpolbul.2022.113918

Shou, L., Zeng, J., Liao, Y., Xu, T., Gao, A., Chen, Z., Chen, Q., Yang, J., 2013. *Temporal and spatial variability of benthic macrofauna communities in the Yangtze River estuary and adjacent area*. Aquat. Ecosyst. Heal. Manag. 16, 31–39. https://doi.org/10.1080/14634988.2013.759497

Silva, R.F., Rosa Filho, J.S., Souza, S.R., Souza-Filho, P.W., 2011. *Spatial and temporal changes in the structure of soft-bottom benthic communities in an Amazon estuary (Caeté estuary, Brazil)*. J. Coast. Res. 440–444. https://doi.org/10.1007/s13131-024-0001-9

Su, J., Yuan, Y., 2005. *Coastal Hydrology of China*. Ocean Press, Beijing.

Sugni, M., Mozzi, D., Barbaglio, A., Bonasoro, F., Candia Carnevali, M.D., 2007. *Endocrine disrupting compounds and echinoderms: New ecotoxicological sentinels for the marine ecosystem*. Ecotoxicology 16, 95–108. https://doi.org/10.1007/s10646-006-0119-8

Sun, X., Fan, D., Liu, M., Liao, H., Tian, Y., 2019. *Persistent impact of human activities on trace metals in the Yangtze River Estuary and the East China Sea: Evidence from sedimentary records of the last 60 years*. Sci. Total Environ. 654, 878–889. https://doi.org/10.1016/j.scitotenv.2018.10.439

Tang, Y., Liu, Q., Liao, Y., Zhou, K., Shou, L., 2021. *Responses of macrobenthic communities to patchy distributions of heavy metals and petroleum hydrocarbons in sediments: A study in China's Zhoushan Archipelago*. Acta Oceanol. Sin. 40, 117–125. https://doi.org/10.1007/s13131-021-1892-1

Teh, L.S.L., Cashion, T., Cheung, W.W.L., Sumaila, U.R., 2020. *Taking stock: a Large Marine Ecosystem perspective of socio-economic and ecological trends in East China Sea fisheries*. Rev. Fish Biol. Fish. 30, 269–292. https://doi.org/10.1007/s11160-020-09599-8

Tian, J., Zhang, W., Wu, J., Chen, Q., Huang, J., 2025. *Effects of hypoxia on community structure of macrobenthos in the Pearl River Estuary*. Acta Oceanol. Sin. 44, 1–10. https://doi.org/10.1007/s13131-024-0001-9

Wang, B., Chen, J., Jin, H., Li, H., Huang, D., Cai, W.J., 2017. *Diatom bloom-derived bottom water hypoxia off the Changjiang estuary, with and without typhoon influence*. Limnol. Oceanogr. 62, 1552–1569. https://doi.org/10.1002/lno.10517

Wang, K., Cai, W.J., Chen, J., Kirchman, D., Wang, B., Fan, W., Huang, D., 2021. *Climate and human-driven variability of summer hypoxia on a large river-dominated shelf as revealed by a hypoxia index*. Front. Mar. Sci. 8, 1–12. https://doi.org/10.3389/fmars.2021.634184

Wang, Z., Leung, K.M.Y., Sung, Y.H., Dudgeon, D., Qiu, J.W., 2021. *Recovery of tropical marine benthos after a trawl ban demonstrates linkage between abiotic and biotic changes*. Commun. Biol. 4, 1–8. https://doi.org/10.1038/s42003-021-01732-y

Warren, L.M., 1981. *Respiratory adaptations to temporary hypoxia by the polychaete Cirriformia tentaculata*. Comp. Biochem. Physiol. Pt. A, 69, 321–324. https://doi.org/10.1016/0300-9629(81)90300-5

Xu, L., Song, P., Wang, Y., Xie, B., Huang, L., Li, Y., Zheng, X., Lin, L., 2022. *Estimating the impact of a seasonal fishing moratorium on the East China Sea ecosystem from 1997 to 2018*. Front. Mar. Sci. 9, 1–15. https://doi.org/10.3389/fmars.2022.865645

Xu, P., Peng, G., Su, L., Gao, Y., Gao, L., Li, D., 2018. *Microplastic risk assessment in surface waters: A case study in the Changjiang Estuary, China*. Mar. Pollut. Bull. 133, 647–654. https://doi.org/10.1016/j.marpolbul.2018.06.020

Xu, Y., Ma, L., Sui, J., Li, X., Wang, H., Zhang, B., 2022. *Potential effects of climate change on the habitat suitability* *of macrobenthos in the Yellow Sea and East China Sea*. Mar. Pollut. Bull. 174, 113238. https://doi.org/10.1016/j.marpolbul.2021.113238

Xu, Z.X., Li, J.Y., Takeuchi, K., Ishidaira, H., 2007. *Long-term trend of precipitation in China and its association with the El Niño-southern oscillation*. Hydrol. Process. 21, 61–71. https://doi.org/10.1002/hyp.6180

Xuan, F., Guan, W., Bao, C., Tang, F., Tang, B., Zhou, C., 2014. *Current fishing practices may induce low risk of sperm limitation in female swimming crab Portunus trituberculatus in the East China Sea*. Aquat. Biol. 20, 145–153. https://doi.org/10.3354/ab00555

Yan, J., Sui, J., Xu, Y., Li, X., Wang, H., Zhang, B., 2020. *Assessment of the benthic ecological status in adjacent areas of the Yangtze River Estuary, China, using AMBI, M-AMBI and BOPA biotic indices*. Mar. Pollut. Bull. 153, 111020. https://doi.org/10.1016/j.marpolbul.2020.111020

Yan, J., Xu, Y., Sui, J., Li, X., Wang, H., Zhang, B., 2017. *Long-term variation of the macrobenthic community and its relationship with environmental factors in the Yangtze River estuary and its adjacent area*. Mar. Pollut. Bull. 123, 339–348. https://doi.org/10.1016/j.marpolbul.2017.09.023

Yang, H.F., Yang, S.L., Xu, K.H., Milliman, J.D., Wang, H., Yang, Z., Chen, Z., Zhang, C.Y., 2018. *Human impacts on sediment in the Yangtze River: A review and new perspectives*. Glob. Planet. Change 162, 8–17. https://doi.org/10.1016/j.gloplacha.2018.01.001

Yu, W., Wen, J., Chen, X., Li, G., Li, Y., Zhang, Z., 2021. *Effects of climate variability on habitat range and distribution of chub mackerel in the East China Sea*. J. Ocean Univ. China 20, 1483–1494. https://doi.org/10.1007/s11802-021-4760-x

Zhang, J., Pei, Z., He, P., Shi, J., 2021. *Effect of escape vents on retention and size selectivity of crab pots for swimming crab Portunus trituberculatus in the East China Sea*. Aquac. Fish. 6, 340–347. https://doi.org/10.1016/j.aaf.2020.04.008

Zhang, W., Dong, X., Liu, Z., Lin, R., Luo, H., 2021. *Influence of decadal ocean signals on meteorological conditions associated with the winter haze over Eastern China*. Front. Environ. Sci. 9, 1–13. https://doi.org/10.3389/fenvs.2021.727180

Zhao, H., Cao, Z., Liu, X., Zhan, Y., Zhang, J., Xiao, X., Yang, Y., Zhou, J., Xu, J., 2017. *Seasonal variation, flux estimation, and source analysis of dissolved emerging organic contaminants in the Yangtze Estuary, China*. Mar. Pollut. Bull. 125, 208–215. https://doi.org/10.1016/j.marpolbul.2017.08.034

Zheng, W., Song, M., Wang, L., Zhang, W., Li, Z., Zhu, L., Xie, W., Liang, Z., Jiang, Z., 2025. *Improving costal marine habitats in the northern yellow sea: The role of artificial reefs on macrobenthic communities and eco-exergy*. Sci. Total Environ. 971, 179027. https://doi.org/10.1016/j.scitotenv.2025.179027

Zhu, J., Wu, H., Li, L., Qiu, C., 2018. *4 Changjiang Estuary*. [In:] Wang, X. (Ed.), *Sediment Dynamics of Chinese Muddy Coasts and Estuaries: Physics, Biology and Their Interactions*. Acad. Press, London, 51–75. https://doi.org/10.1016/B978-0-12-811977-8.00004-2

Zhu, Z.Y., Wu, Y., Zhang, J., Du, J.Z., Zhang, G. Sen, 2014. *Reconstruction of anthropogenic eutrophication in the region off the Changjiang Estuary and central Yellow Sea: From decades to centuries*. Cont. Shelf Res. 72, 152–162. https://doi.org/10.1016/j.csr.2013.10.018