The impact of Kuroshio intrusion, coastal upwelling, and Changjiang on the interannual variation of nutrients on the East China Sea

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1 Purposes

In summer, the East China Sea (ECS) faces significant ecological challenges, such as harmful algal blooms (Wang et al., 2023), hypoxia events (Li et al., 2024) and jellyfish blooms (Xu et al., 2013), which are linked to the distributions of nutrients. The distributions of nutrients in the ECS during summer are influenced by the Changjiang Diluted Water (CDW), Kuroshio intrusion, and the Zhejiang Coastal Upwelling (ZCU). However, the interannual variations of these three processes are not consistent, which makes the distributions of nutrients complicated in the ECS. In this study, the temporal and spatial variations of the dissolved inorganic nitrogen (DIN) and phosphorus (DIP) concentrations in the ECS during summer from 1993 to 2022 were analyzed using the Empirical Orthogonal Function (EOF) analysis.

2 Methods

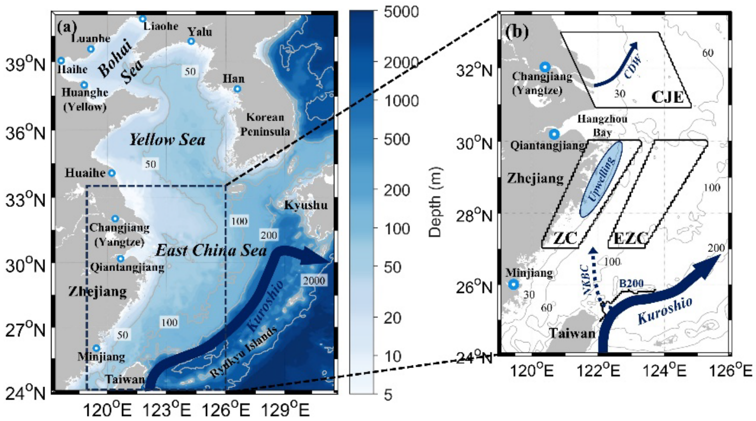

Fig. 1. The model domain (a) and the study area (b). In (a) and (b), bule-white dots are the positions of inflow from rivers, the dark blue thick arrows indicate the path of Kuroshio, and the gray lines represent the isobaths. In (b), the ZC, EZC, CJE, CDW and NKBC represent the Zhejiang coastal region, the East Zhejiang coastal region, the Changjiang Estuary, the Changjiang Diluted Water, and the Nearshore Kuroshio Branch Current. Section B200 is the location where NKBC intrudes into the ECS.

The three-dimensional low-tropic biophysical model used in this study consists of two modules (Zhao & Guo, 2011). The physical module is based on the Princeton Ocean Modules. This module provides water temperatures, current velocities, and turbulent viscosity coefficient to the biochemical module. The biochemical module is based on the biological part of the NORWECOM. There are seven state variables in the biochemical module: DIN, DIP, silicate, diatom, flagellate, detritus, and biogenic silica. As shown in Fig. 1a, the model domain was 117.5°E–131.5°E, 24°N–41°N, covering the Bohai Sea, YS, ECS, and part of the Sea of Japan. The model has a horizontal resolution of 1/18° (~ 6 km) and is vertically divided into 21 sigma layers. In this study, the ECS was the main research area (Fig. 1b).

3 Results

3.1 Interannual variations in DIN concentrations in summer

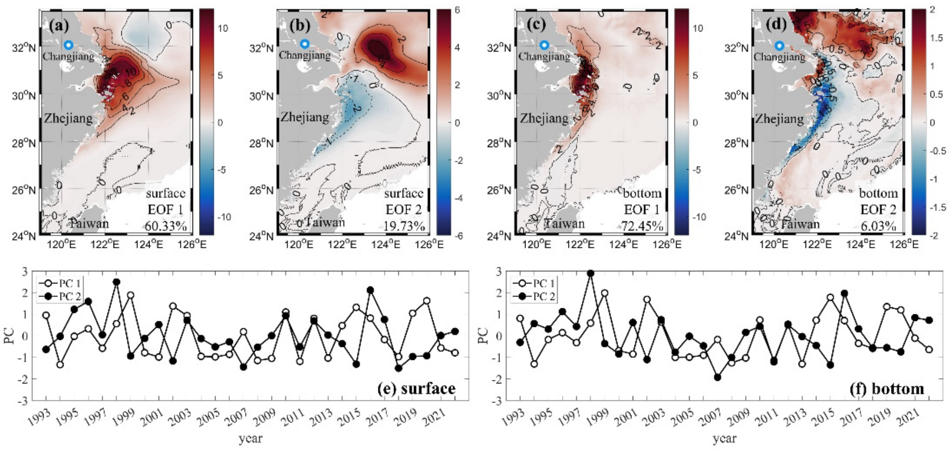

Fig. 2. The EOF1 and EOF2 of DIN concentrations at surface (a, b) and bottom (c, d) layer in summer, and their corresponding normalized PC1 and PC2 time series during 1993–2022 (e, f).

The spatial pattern of EOF1 (Fig. 2a) suggested an in-phase temporal variation in the surface DIN concentrations with the strongest positive values concentrated near the Changjiang Estuary and Hangzhou Bay. These strongest positive values extended southward along the coastline, forming a high-value band along the Zhejiang coast. The time series of principal component of EOF1 (PC1) revealed that the surface DIN concentrations within this high-value area were significantly higher in 1999, 2002, 2010, 2015, and 2020 compared to those in other years (Fig. 2e).

The spatial pattern of EOF2 suggested a horizontally reversed temporal variation in the surface DIN concentrations (Fig. 2b). There were the larger positive values east of the Changjiang Estuary, while there were obviously negative values along the Zhejiang coast. The time series of principal component of EOF2 (PC2) indicated that the surface DIN concentrations were significantly higher in 1995, 1996, 1998, 2010 and 2016 in the offshore area near the Changjiang Estuary than those in other years, while they were significantly lower in the Zhejiang coast in the same years (Fig. 2e).

At bottom, these first two modes of the DIN concentrations were similar to those of surface DIN concentrations in spatial pattern and the time series of PC (Fig. 2c and Fig. 2d). The correlation coefficients of the time series of PC1 and PC2 between surface and bottom reached up to 0.97 and 0.88, respectively. It indicated that the interannual variations in DIN concentrations at surface and bottom layer were the same during summer.

3.2 Processes influencing the interannual variations in DIN concentrations

To understand nutrient variations revealed by EOF analysis, composite maps of physical and biochemical variables (DIN, DIP, Chl-a, temperature, salinity) were averaged from summer model results. When nutrient PC values exceeded (or fell below) the mean ± one standard deviation, variables were averaged into High (Low) Maps. Differences between High and Low Maps, named Diff Maps, were used to analyze interannual variations.

For EOF1 of surface DIN, positive differences in DIN were observed along the Zhejiang coast south of 31°N (Fig. 3a). This region showed positive temperature and negative salinity differences, linked to the ZCU (Fig. 3b and Fig. 3c). The ZCU intensity time series (1993–2022) was derived from July vertical velocities in the ZC region (Luo et al., 2023). A negative correlation ($r = -0.51$) between ZCU intensity and PC1 indicated weaker ZCU in High Maps, reducing nutrient upwelling. However, higher DIN concentrations in High Maps (Fig. 3a) suggested weaker biological activity, as lower Chl-a concentrations (Fig. 3d) implied reduced DIN consumption. Thus, weaker ZCU and biological activity caused higher DIN along the Zhejiang coast.

North of 31°N, positive DIN differences corresponded to negative salinity differences (Fig. 3a, 3c), influenced by the Changjiang estuary and CDW rather than ZCU. The surplus DIN in this region was not from ZCU but correlated strongly with Changjiang discharges ($r = 0.74$, Fig. 4a). Southerly winds, quantified as July meridional winds in the CJE region, negatively correlated with

PC1 (r = -0.61), concentrating CDW nearshore. Thus, higher DIN nearshore in the north resulted from stronger Changjiang discharges and weaker southerly winds.

For EOF2 of surface DIN, negative DIN differences along the Zhejiang coast (Fig. 3e) aligned with negative temperature and positive salinity differences (Fig. 3f and Fig. 3g). A positive correlation (r = 0.39) between PC2 and ZCU intensity indicated stronger ZCU in High Maps, contrasting EOF1. Higher Chl-a concentrations (Fig. 3h) suggested greater DIN consumption, linking negative DIN differences to stronger ZCU and biological activity.

North of 31°N, High Maps showed positive DIN and negative salinity differences offshore (Fig. 3e and Fig. 3g), reflecting CDW influence. PC2 correlated positively with Changjiang discharges (r = 0.46) and southerly winds (r = 0.50), indicating stronger winds expanded CDW offshore. Thus, higher DIN offshore in the north was driven by stronger Changjiang discharges and southerly winds.

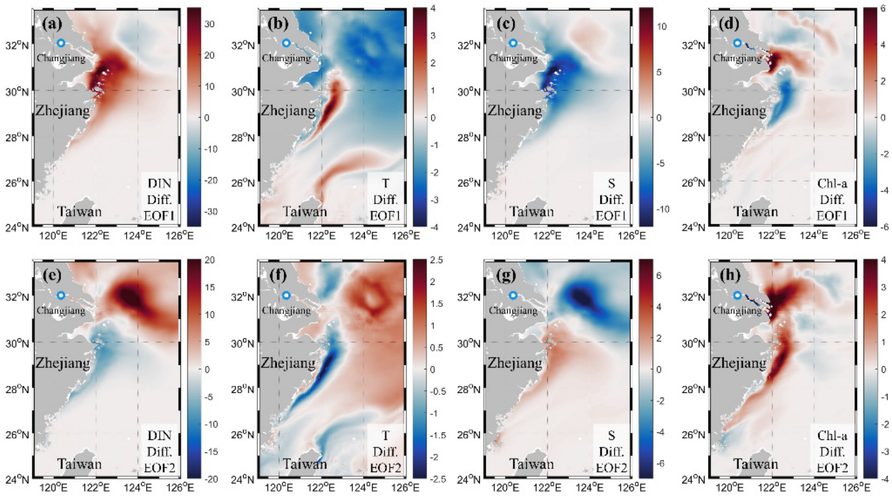

Fig. 3. The Diff Maps of surface DIN concentrations, temperature (T), salinity (S), Chl-a concentrations for the EOF1 (a–d) and EOF2 (e–h) of surface DIN concentrations.

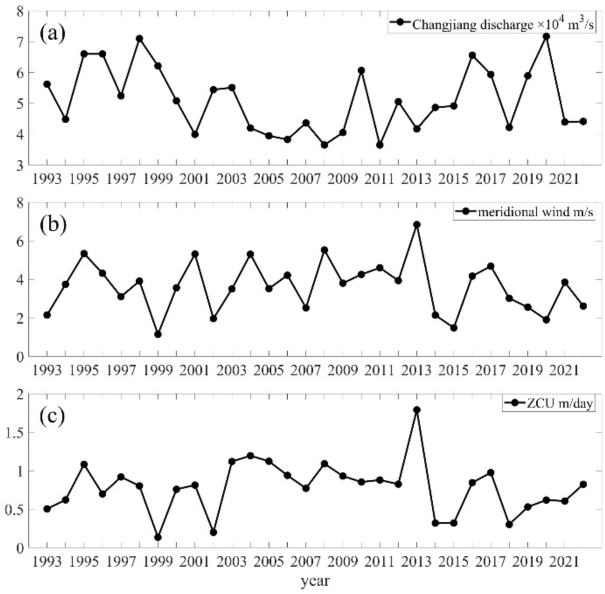

Fig. 4. The interannual variations in (a) Changjiang discharges in July, (b) the average meridional wind in the CJE region in July, and (c) the average vertical velocity in the ZC region in July (the ZCU intensity).

4 Future Challenges

In future studies, the interannual variations of DIP concentrations can be analyzed. In addition, the impact of CDW, ZCU and Kuroshio invasion on the interannual variation in DIP concentrations will be discussion.

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