Yearly variations in nutrient supply in the East China Sea due to the Zhejiang coastal upwelling and Kuroshio intrusion

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Purpose

Upwelling is a worldwide phenomenon that transports deep cold water to the upper layers and decreases sea surface temperature. Deep nutrient-rich water is pumped up to the euphotic layers, thereby promoting local primary production and the associated species interactions. The East China Sea (ECS) is a marginal sea in the northwestern Pacific Ocean, with high biological productivity, especially in summer. The southwest monsoon in summer creates favorable conditions for the northeastward alongshore current and the occurrence of the Zhejiang coastal upwelling (ZCU), which is believed to pump nutrients and induce large phytoplankton biomass. On the other hand, oceanic nutrients supplied by the Kuroshio intrusion (KI) onto continental ECS is also regarded as an important nutrient source for coastal region. The intensities of the ZCU and KI are both characterized by obvious yearly variations which are not consistent. Such inconsistency probably affects and complicates the yearly nutrient supply to the ECS shelf as well as coastal primary production. In this study, we hope to understand the contributions of ZCU and KI to the nutrient supplies, nutrient concentrations, and phytoplankton biomass in ECS as well as their yearly variations.

Methods

A three-dimensional physical-biochemical coupled model was used in this study, which consists of two modules. The physical module is based on the Princeton Ocean Model, and the biochemical module is based on the biological part of the NORWECOM. The horizontal resolution of the model was 1/18° (~6 km), and there were 21 terrain-following sigma layers in the vertical direction. The model domain is 117.5–131.5°E, 24.0–41.0°N, which covered the Bohai Sea, Yellow Sea, and ECS (Fig. 1a). The Zhejiang coastal (ZC) region is defined as the enclosed area surrounded by three open boundaries and the coastline of Zhejiang Province (Fig. 1b).

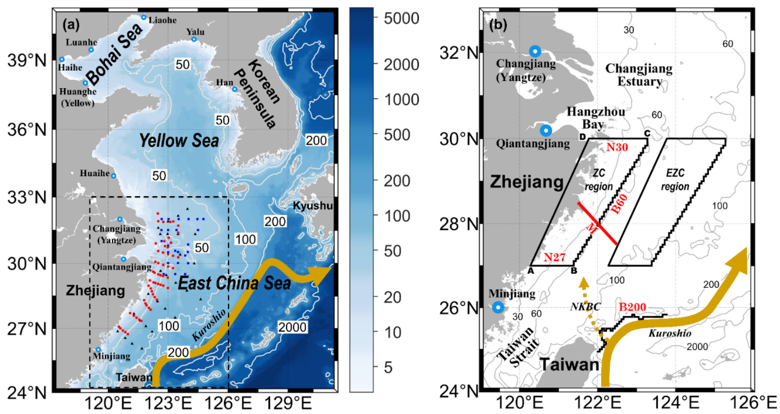

Figure 1. (a) Map of the model domain and (b) enlarged coastal East China Sea (ECS). Scatters in (a) denote coastal nutrient sampling sites in the summer of 2013 and 2018, among which red circles are the sites of this study, blue squares are the sites from Yu (2014), black triangles are the sites from Lyu et al. (2020). Blue-white dots in (a, b) are the positions of inflow from rivers. ZC region: Zhejiang coastal region, EZC region: East Zhejiang coastal region, NKBC: nearshore Kuroshio Branch Current. Sections N27, B60, and N30 are the open boundaries of the ZC region. A, B, C, and D represent the endpoints of the sections N27, B60, and N30. Section M is a cross-shelf section. Section B200 is the location where NKBC intrudes into the ECS. The gray lines represent the isobaths.

To quantitatively investigate the effects of the atmospheric forcing, river runoff from the Changjiang River, and KI on the nutrient supply and Chl-a concentration in the ZC region, four numerical experiments were carried out for the reference years 2013 and 2018. The details of each numerical experiment are listed in Table 1.

Table 1

Forcing conditions for the numerical experiments.

Experiment	Wind stress	Other atmospheric forcings except for wind stress	Southern open boundary conditions	Changjiang River runoff
WIND	2013	2018	2018	2018
OTHERS	2018	2013	2018	2018
KURO	2018	2018	2013	2018
RIVER	2018	2018	2018	2013

The ZCU intensity is defined as the mean vertical velocity of the ZC region in July. The KI intensity is defined as the DIP flux through section B200 from March to June.

Results

During 2010–2018, 2013 was a strong-ZCU-weak-KI year, while 2018 was a weak-ZCU-strong-KI year (Fig. 2). The coastal summer SST was obviously lower in 2013 than in 2018. And the SST difference between offshore region and coastal region is larger in 2013. Along the section, isotherms are upwelled higher. These results are induced by different upwelling intensities. The vertical velocity along the section in 2013 was 1.11 m/day, which was 5.2 times of that in 2018.

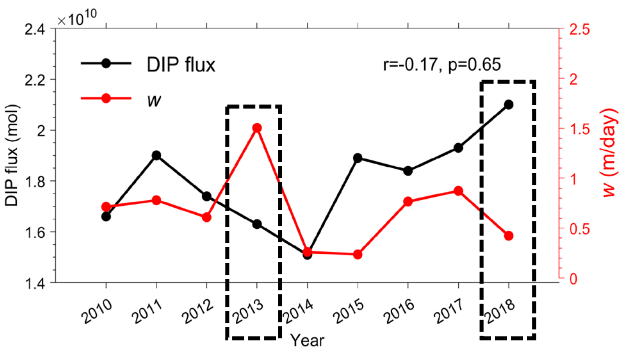

Figure 2. Yearly variations in ZCU and KI intensities.

At bottom, the DIP concentrations ranged from 0.4 and 1.0 $mmol/m^3$ (Fig. 3a, b). Interestingly, at bottom within 20-m isobath, DIP concentration was higher in 2013, but higher in 2018 out of 20-m isobath (Fig. 3c). This difference in yearly bottom DIP concentrations is caused by the co-effects of wind stress and open boundary conditions. Take the results of numerical experiments (WIND and KURO) minus the results of Control, we can get the influence of a single forcing. After strengthening wind stress and upwelling (Fig. 3d), coastal nutrient concentration increases. After weakening Kuroshio intrusion (Fig. 3e), nutrient concentrations decreased at sea bottom out of 20-m isobath.

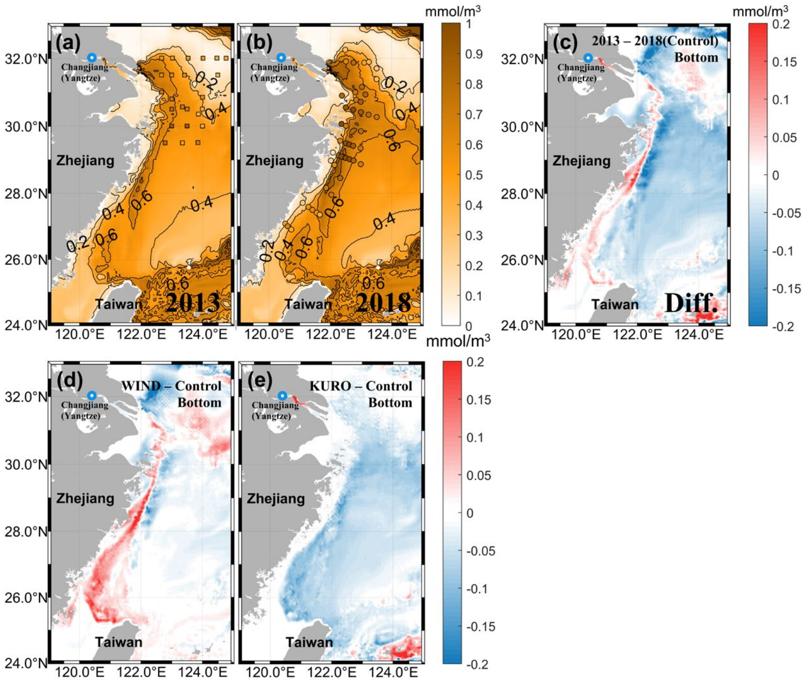

Figure 3. Bottom DIP concentrations in July of (a) 2013 and (b) 2018. Colored dots represent in situ observations in the summer of 2013 and 2018. (c) Difference between 2013 and 2018. (d) Difference between the numerical experiment WIND and 2018 (Control). (e) Difference between the numerical experiment KURO and 2018 (Control).

In the coastal region (Fig. 4a), phytoplankton is distributed in surface layers. Stronger wind-induced upwelling increases Chl-a concentration above 15-m in coastal region. The surface Chl-a concentrations were increased from around 2.3 mg/m^3 to around 4.0 mg/m^3. In the offshore region (Fig. 4b), phytoplankton is distributed in subsurface layers, and form Subsurface Chlorophyll Maximum. The stronger Kuroshio intrusion increases Subsurface Chlorophyll Maximum between 40-m and 60-m layers.

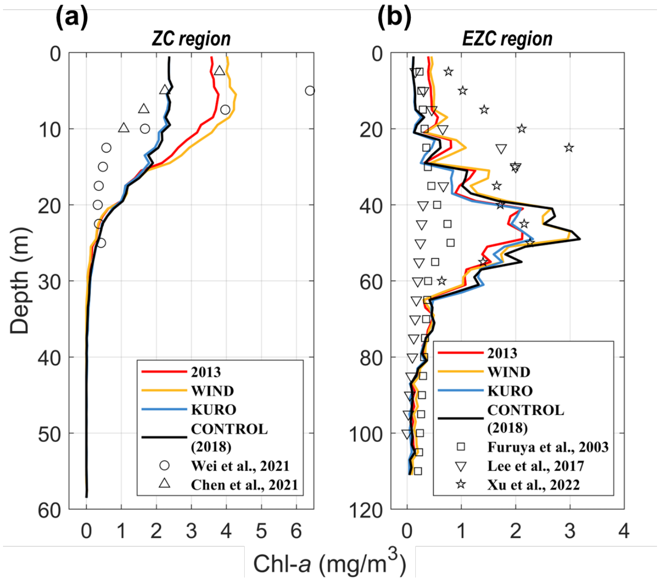

Figure 4. Vertical structures of Chl-a concentrations horizontally averaged in the (a) ZC and (b) EZC regions in July of the cases 2013, WIND, KURO, and CONTROL (2018). Scatters represent observed nearshore and offshore Chl-a concentration profiles in summer.

Future Challenges

In this study, the yearly variations in ZCU intensity mainly control coastal nutrient supply and primary production, while that in KI intensity mainly control offshore nutrient supply and subsurface chlorophyll maximum. The simulation span is from 2010 to 2018, in which a strong-ZCU-weak-KI year and a weak-ZCU-strong-KI year are selected. It is possible that there exists more extreme ZCU or KI intensities in other years. For example, in a year with extreme strong KI that is stronger than in 2018, could it transport enough nutrients to coastal region and substantially increase primary production even when upwelling intensity is weak? Therefore, it is recommended to extend simulation time span in future studies.