Seasonal and spatial variations of nutrient exchange between the Yellow Sea and the East China Sea

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1 Purposes

The Yellow Sea (YS) (Fig.1), a semi-enclosed sea in China, is one of the Large Marine Ecosystems in the world and an important fishery. However, various marine ecological problems have occurred here. The health and function of the ecosystem in the YS depend on the nutrient cycling, which is closely related to nutrient transport through open boundaries. The YS has three open boundaries, i.e., the Bohai Strait (BS), the Cheju Strait (CS), and the section separating the YS and East China Sea (ECS) (YE) (Fig. 1). Spatial and seasonal variations in the material exchange across the BS and CS have been quantified using both observations and models (Liu et al., 2021; Shin et al., 2022). Nutrient exchange with the East China Sea (ECS) plays an important role in the primary production in the Yellow Sea (YS). Owing to the lack of simultaneous observations, spatiotemporal nutrient exchanges across the interface between the YS and ECS (YE) remain unclear. In this study, a three-dimensional physical-biochemical coupled model was used to determine the flux of the dissolved inorganic nitrogen (DIN) across the YE. And the spatiotemporal variations in DIN fluxes across the YE were calculated.

2 Methods

The 3-D model used in this study consisted of both a physical module and biochemical module. The physical module is based on the Princeton Ocean Model (POM), and the biochemical module is based on the biological part of NORWECOM. The physical module provides the water temperature, current velocity and turbulent viscosity coefficient for the biochemical part. The biochemical module includes three types of nutrients (DIN, dissolved inorganic phosphorus, and silicate), two groups of phytoplankton (diatoms and flagellates), and two types of detritus.

As shown in Fig. 1, 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 YE section was defined as the section connecting the Changjiang Estuary (Station A: 121.82°E, 31.91°N) to the southwest of Cheju Island (Station B: 126.15°E, 33.31°N) (black line AB in Fig. 1).

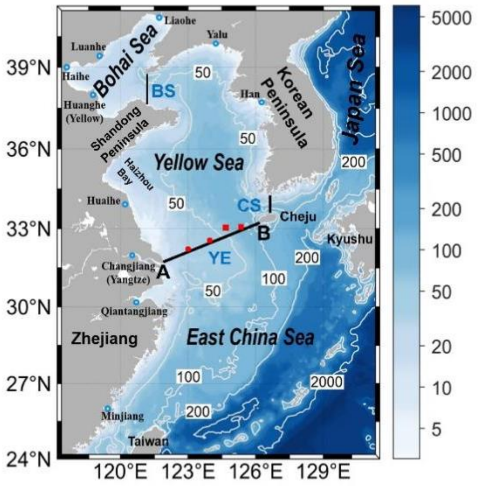

Fig. 1. Model domain and bathymetry (unit: m). Scatters denote nutrient sampling sites in the summer and winter; red circles are the sites from Wei et al. (2016), and red squares are the sites from the National Institute of Fisheries Science (NIFS). The three lines represent the location of the section of BS, YE, and CS, respectively.

3 Results

3.1 Seasonal variations of DIN concentration along the YE

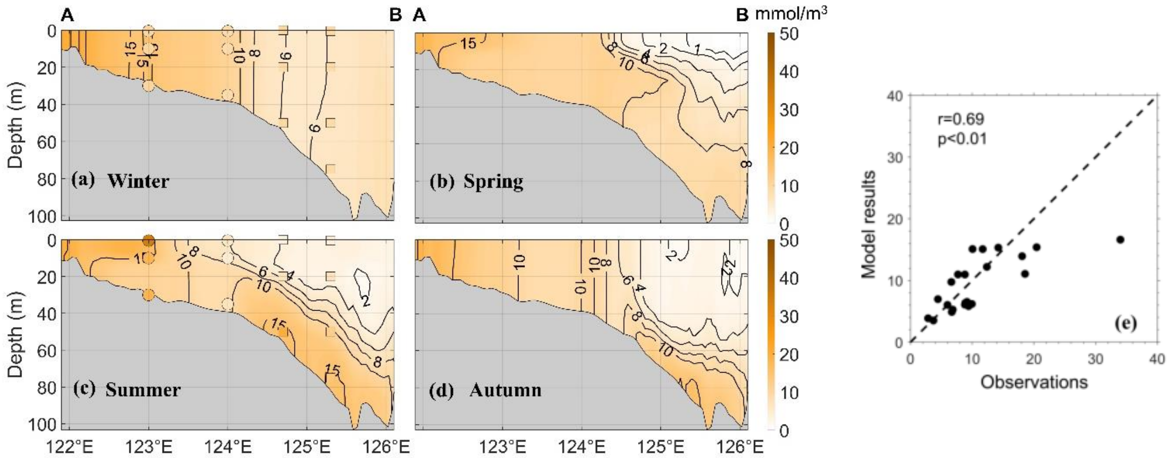

Fig. 2. Seasonal variations of DIN concentration (unit: mmol/m^3) along the YE in (a) winter, (b) spring, (c) summer, and (d) autumn. The colored circles and squares represent the observations from Wei et al. (2016) and NIFS, respectively. (e) represents the scatter plots of observations and corresponding model results in summer and winter.

The modelled distributions of the DIN concentration along the YE overlapped with the available published observational data (Fig. 2a and c). The model results agreed well with the observations, with a correlation coefficient of 0.69 (Fig. 2e). In winter (Fig. 2a), the distributions of DIN concentrations along the YE were vertically uniform owing to the strong vertical mixing induced by both strong winter monsoons and the loss of heat from the sea surface. The DIN concentrations near the Changjiang Estuary were high, with a maximum value of over 20 mmol/m^3, and then decreased seaward to the value below 6 mmol/m^3 near southwest Cheju Island. In spring (Fig. 2b), the average DIN concentration along the YE was lower than that in winter because of absorption by phytoplankton growth. Owing to the Changjiang River input, the DIN concentrations in the southwestern region of YE, with water depths shallower than 40 m, were high (>10 mmol/m^3) with a uniform vertical distribution. Stratification gradually occurred in the deeper region east of 124°E. In summer (Fig. 2c), the high-concentration area in the southwestern part of YE represents the extension of the CDW. In the deeper regions, the DIN concentrations in the upper layers increased slightly, and the area with DIN concentrations lower than 2 mmol/m^3 became smaller than that in spring. This was because the growth of phytoplankton was limited by phosphate, therefore, DIN consumption decreased. However, the stratification became the strongest throughout the year because of the increase in DIN concentrations in the lower layers caused by the successive supply of mineralization. The concentration at the bottom of the deeper region is approximately 15 mmol/m^3. Autumn is the transitional season from summer to winter, and the water body was transformed from a stratified structure in summer to a mixed homogeneous structure in winter.

3.2 Seasonal variations of DIN flux across the YE

The monthly average DIN flux across YE was calculated based on the model results (Fig. 3). The inflow, outflow, and net transport of DIN across the YE exhibited clear seasonal variations. The inflow of DIN had a minimum value of 3.26×10^6 mmol/s in January, increased until summer, with a maximum value of 6.37×10^6 mmol/s in July, and then, decreased until the end of the year. The annual mean inflow of DIN was 4.91×10^6 mmol/s. Seasonal variations in the outflow of DIN were different from those in the inflow. The largest outflow of DIN occurred in winter with a value of 2.84×10^6 mmol/s in

December, which was approximately twice its minimum value of 1.53×10^6 mmol/s in summer (June). The seasonal differences in DIN outflow were not as evident as those in the inflow, and the outflow was significantly weaker than the inflow. Therefore, the net transport of DIN was estimated to be the inflow into the YS throughout the year. Net transport followed similar seasonal variations in the inflow of DIN, with a maximum value of 4.44×10^6 mmol/s in June and a minimum value of 0.95×10^6 mmol/s in January. The annual transport of DIN across the YE from the ECS to the YS was 8.83×10^{10} mol. The inflow of DIN in summer was the largest, accounting for 38% of the total annual amount, whereas the value in winter was the smallest, only accounting for 10%.

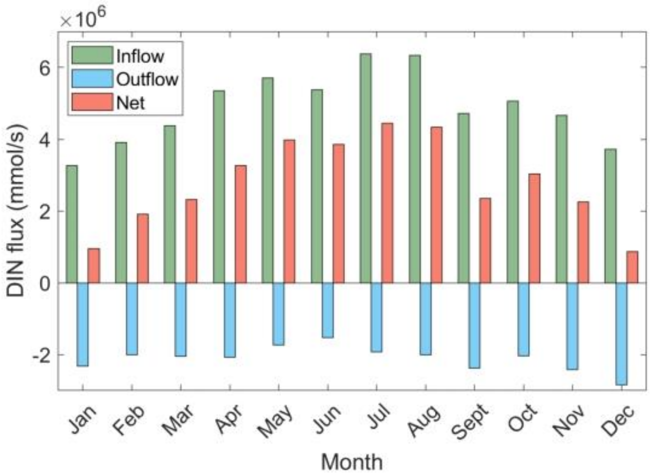

Fig. 3. Monthly mean DIN fluxes (unit: mmol/s) across the YE. The green bars are the inflow of DIN; the blue bars are the outflow of DIN; and the red bars are the net DIN flux. The positive values indicate DIN flux transport from the ECS to the YS across the YE, and the negative values indicate that transport from the YS to the ECS.

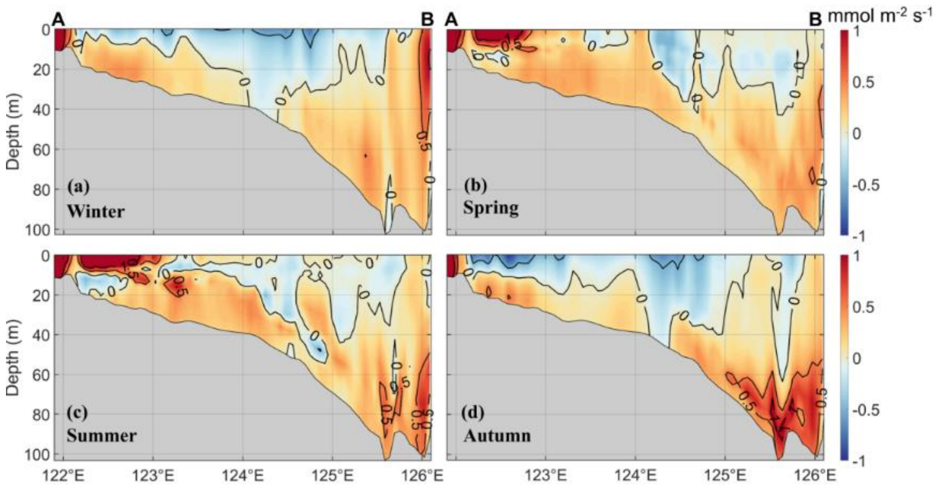

Fig. 4. Seasonal variations of DIN flux (unit: mmol m^{-2} s^{-1}) across the YE in (a) winter, (b) spring, (c) summer, and (d) autumn. Red and blue indicate inflow and outflow for the YS, respectively.

Fig. 4 shows the vertical distribution of DIN fluxes across YE during the four seasons. In winter (Fig. 4a), there was an area with a strong inflow of DIN near 122°E in the southeastern coastal region of YE. The inflow of DIN reached 1 mmol m^{-2} s^{-1} owing to the high DIN concentration near the mouth of the Changjiang River and northward coastal currents in winter. The outflows of DIN occupied the surface layer of the YE, reached above 0.5 mmol m^{-2} s^{-1}, and were caused by the southward current triggered by northerly winds in winter. The inflow of DIN into the western part of YE was caused by the invasion of the YSWC. In spring (Fig. 4b), the inflow of DIN reached approximately 1 mmol m^{-2} s^{-1} in the water layers of the upper 10 m from 122°E to 123°E, which was due not only to the high DIN concentrations but also to the strong discharge of the CDW. Owing to the stratification in the eastern part of the YE, the DIN fluxes were low in the surface layer and high in the bottom layer. In summer (Fig. 4c), the western area of YE exhibited high DIN fluxes, which was a result of the further expansion of the CDW. In the eastern waters, owing to the intensification of stratification, high DIN fluxes were concentrated in the bottom layer. The inflows of DIN were approximately 0.5 mmol m^{-2} s^{-1}. Autumn is a transitional period (Fig. 4d). The outflows of DIN in the surface layers of the YE were similar to those in winter. The location of the isoline of 0.5 mmol m^{-2} s^{-1} isoline was similar to that in summer, but the area with high values expanded in autumn.

4 Future Challenges

In future studies, the interannual variations of DIN flux across YE can be analyzed. In addition, the influencing factors of DIN flux seasonal and interannual variations across the YE will be discussion. Moreover, contribution of nutrient exchanging across the YE to the DIN budget of the YS also can be investigated.

Reference

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