1. Title

Coupling of the shelf process and the Kuroshio in the development of hypoxia off the Changjiang Estuary

2. Members' names and affiliations

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3. Aim

(1) Understand how many Kuroshio-related nutrients are transported to the mid-shelf and the estuary, and their contributions to the phytoplankton blooms

(2) Make clear how much low dissolved oxygen (DO) water is transported to the mid-shelf and the estuary and thus reduces the concentration of DO before and during the period when hypoxia usually occurs

(3) Promote the exchanges and cooperation between the Second Institute of Oceanography, Ministry of Natural Resources, China and the Center for Marine Environmental Studies (CEMS) in Ehime University.

4. Procedure

Both observational data and numerical modelling are used in this study. First, in situ DO and remotely-sensed Chl a dataset (Fig. 1) are used to give a seasonal variation (Fig. 2). Then a coupled numerical model ROMS-CoSiNE is used to simulate the physical process and ecosystem in the East China Sea (ECS), and a series of sensitivity experiments are set to examine the different effects of nutrient loadings from rivers and Kuroshio, advection, diffusion, and biological on the variation of hypoxia off the Changjiang Estuary.

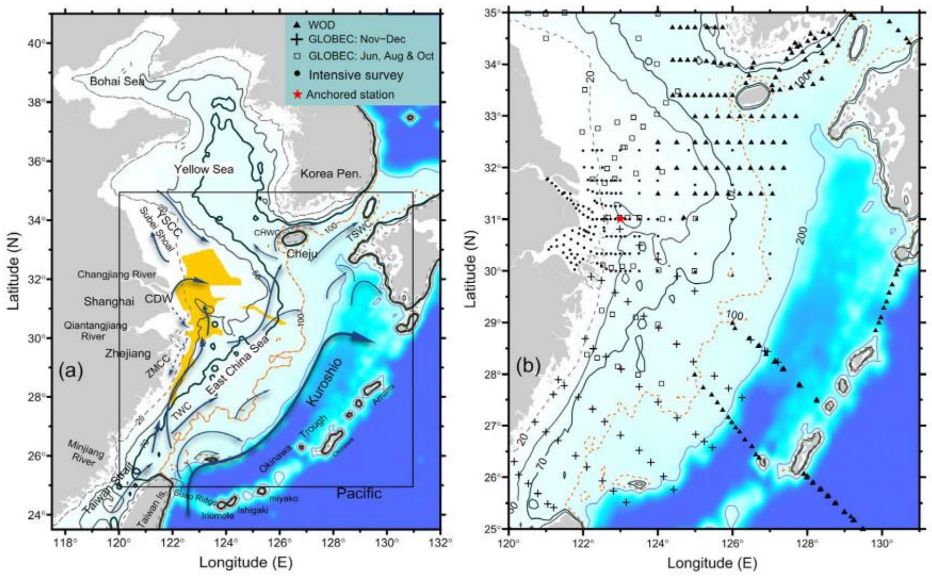

Fig. 1. (a) Historical location of hypoxia in the East China Sea and (b) field measurements in 2006 from different data sources. Yellow shading indicates areas with the dissolved oxygen (DO) concentration less than 3 mg L^{-1} occurred during stratified seasons of 1998–2011 based on published studies (Li et al., 2002, 2011; Chen et al., 2007; Wei et al., 2007; Wang, 2009; Zhou et al., 2010). Solid arrows represent schematic circulations during stratified seasons: the Yellow Sea Coastal Current (YSCC), the Cheju Warm Current (CHWC), the Tsushima Warm Current (TSWC), the Taiwan Warm Current (TWC), the Changjiang Diluted Water (CDW) and the Kuroshio (after Zhou et al., 2015). Dashed arrows represent episodic flows during stratified seasons: the southward extension of the CDW and the Zhe-Min Coastal Current (ZMCC). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

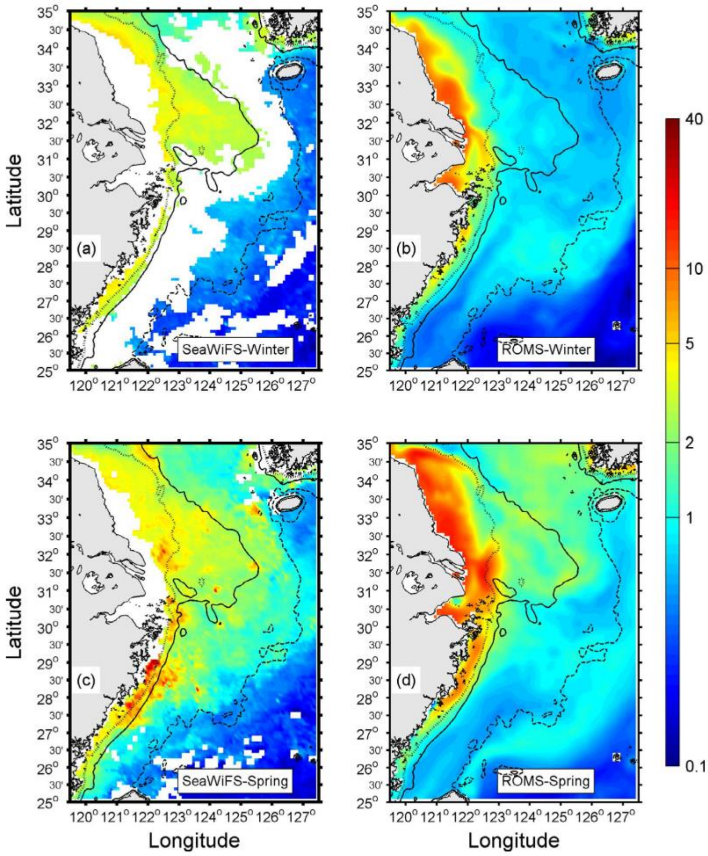

Fig. 2. Seasonal-mean surface chlorophyll a concentration (mg m^{-3}) in 2006. a, c, e and g are from the SeaWiFS, and b, d, f, h are from the reference run. The contours are isobaths of 20 (dotted), 50 (solid) and 100 (dashed) m.

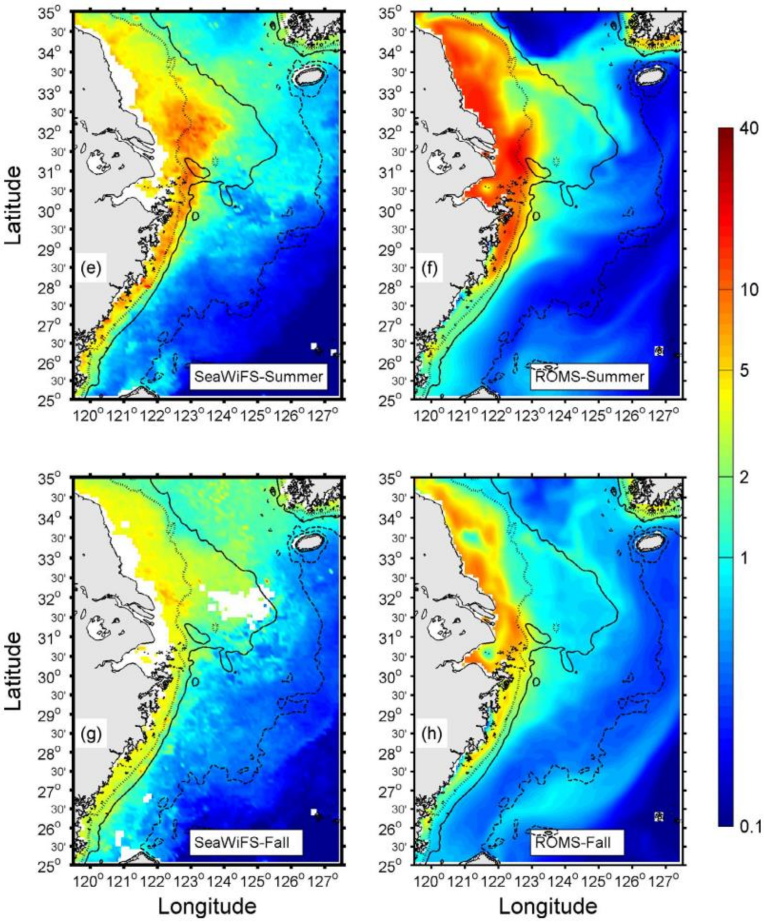

Fig. 2. (*continued*)

5. Results

The simulated seasonal-mean Chl a concentrations show similar spatial patterns and seasonal variations as the observed (Fig. 2). They were high in the inner shelf where water depth is less than 50 m, decreasing towards the outer shelf and slope with local maximum concentrations off the Changjiang Estuary. Although the satellite data coverage in winter (December–February) was poor, the available data still show low Chl a because phytoplankton growth was limited by low temperature and insufficient light. In winter and spring, Fig. 2 shows large Chl a compared to the observations southeast of the 100-m isobath. There was a trend of offshore extension of mid-shelf water with high concentration of Chl a at the surface at 28°N–30°N (Fig. 2b). Close to the suspected location, we analyzed the observations along Transect PN. Fig. S4 shows a strong nitrate-cline below 200 m with low concentration of nitrate near the surface in January 2006. There was a dome of high nitrate at the shelf edge, resulting in an upward tilt of nitrate-cline. A similar low-oxygen dome also occurred at the shelf edge, above which an oxygen minimum appeared near surface. The offshore extension was probably caused by the offshore branch of the TWC, which also induced upwelling at the shelf edge. A significant increase of Chl a appeared in spring (March–May), when the satellite Chl a concentration reached the highest value of 17.3 mg m^{-3} off the Zhejiang coast, while the simulated value was 18.4 mg m^{-3} off the Subei Shoal.

The profiles in Fig. 7 show large variability of DO structure in the vertical. The observed oxygen-cline becomes shallower and intensifies from June to August. The DO below the oxygen-cline is as low as 4.0 mg L^{-1} in June and decreases to less than 2.0 mg L^{-1} in August. In addition to the mid-depth minimum, the observed DO profile on August 13 also shows a local maximum at 15 m (Fig. 7b), likely due to episodic entrainment of phytoplankton from the upper layer into pycnocline.

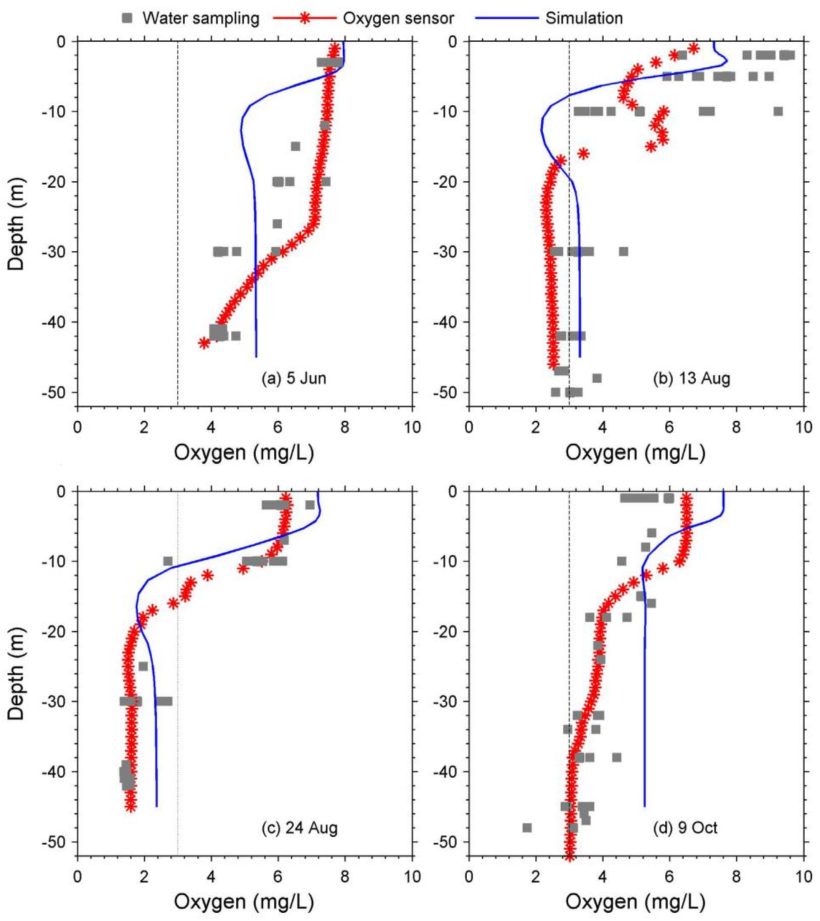

Fig. 7. Comparison of DO profiles at (123°E, 31°N): Observed DO concentration from water sampling (grey square) and DO sensor (red star) bounded with CTD during four cruises, and modeled DO profile (blue curve). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Large variability of hypoxia in the ECS can also be seen from the horizontal distribution of DO, particularly in terms of hypoxic water extent. Hypoxia is observed in June–October and in two different regions (Fig. 8). In June hypoxia appears only off the Zhejiang coast (Fig. 8a), while in July it appears mainly off the changjiang estuary with a small area at the eastern edge of the study region (Fig. 8b). In August, hypoxia is widely observed but most significantly north of the changjiang estuary (Fig. 8c). In September-October, the hypoxia center occurs south of the changjiang estuary. The observed hypoxia area increased from 0.46×10^4 km^2 in June to 0.74×10^4 km^2 in July, and then to 7.70×10^4 km^2 in August. The extent in September is approximately 1/7 of that in August (note that we had less observational data in September) and increases slightly in October. The simulated hypoxic water appears southeast of the changjiang estuary in late June. From July to August, both observations and simulations show that hypoxic water expands significantly. Though large misfit of hypoxic zones occurred in August, the model reproduced the significant northward spread of hypoxia north of the changjiang estuary, resembling the observations from July to August. The model captured the essential intraseasonal and seasonal variability of hypoxia, except for that in October, when hypoxia disappeared unrealistically. Note that from July to September the simulated hypoxic water was separated into two parts with the main body off the changjiang estuary and the northern part southeast of the Subei Shoal (Fig. 8g–i). The northern part of the hypoxia is likely associated with the detached low-salinity water from the Changjiang diluted water plume, which carries nutrient-rich water northward (Xuan et al., 2012). It could also be related to the seaward transport of nutrients and phytoplankton from the Subei Shoal. The northern hypoxic zone appears in waters deeper than 30 m rather than in the Subei Shoal where water is shallower than 20 m and usually well mixed vertically.

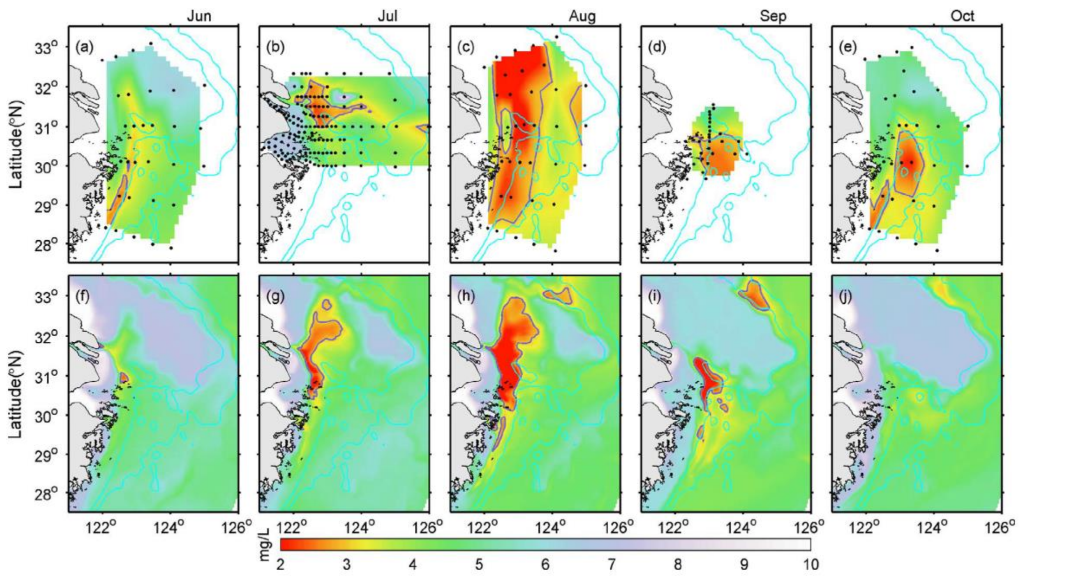

Fig. 8. Hypoxia extent based on observations (a–e) at the sea bed in 2006, and simulations of corresponding periods (f–j). Contour represents the area with DO less than 3.0 mg L^{-1}. (a), (c) and (e) were redrawn from Zhu et al. (2011); (b) was redrawn from Li et al. (2011); and (d) was redrawn from Wang et al. (2012).

6. Publication/Conference presentation

Publication

[1] Jiang, Z., J. Chen, H. Zhai, **F. Zhou**, X. Yan, Y. Zhu, J. Xuan, S. Lu, and Q. Chen, 2019, Kuroshio shape composition and distribution of filamentous diazotrophs in the East China Sea

and Southern Yellow Sea, *Journal of Geophysical Research: Oceans*, doi: 10.1029/2019JC015413.

[2] Ye, W., G. Zhang, P. Li, **F. Zhou**, and C. Liu, 2019, Variations in dissolves methane in the Yellow Sea during the spring algal blooms of 2009, *Journal of Ocean University of China*, 18, 896-912. Doi:10.1007/s11802-019-3993-4.

[3] Jiang, Z., J. Chen, Y. Gao, H. Zhai, H. Jin, **F. Zhou**, S. Lu, X. Yan, and Q. Chen, 2019, Regulation of spatial changes in phytoplankton community by water column stability and nutrients in the Southern Yellow Sea, *Journal of Geophysical Research: Biogeosciences*, doi: 10.1029/2018JG004785.

[4] Xuan, J., Y. He, **F. Zhou**, C. Tang, X. Zheng, H. Liu, L. Yu, and J. Chen, 2019, Aquaculture-induced boundary circulation and its impact on coastal frontal circulation, *Environmental Research Communications*, 1, 051001.

[5] Hao, Q., F. Chai, P. Xiu, Y. Bai, J. Chen, C. Liu, F. Le, and **F. Zhou**, 2019, Spatial and temporal variation in chlorophyll a concentration in the Eastern China Seas based on a locally modified satellite dataset, *Estuarine, Coastal and Shelf Science*, 220, 220-231.

Conference presentation

Zhou F., 2019, Coupling of the shelf process and the Kuroshio in the development of hypoxia off the Changjiang Estuary, International symposium on coastal ecosystem change in Asia: hypoxia, eutrophication, and nutrient conditions, Ehime University, Matsuyama, Japan, Oral, November, 2019.

7. Perspectives in Future

(1) More integrated observations are expected to improve the prediction of hypoxia variability by monitoring hypoxia and related important parameters, sch as the PAR at the estuary and nutrient loading at the river mouth.

(2) An improved algorithm of under-water light availability incorporating into the coupled model is also necessary to capture reasonable distribution of phytoplankton, particularly in turbid coastal waters.

(3) Enhance the cooperation between Ocean University of China and CEMS of Ehime University.