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Response of Nutrients and Primary Production over the Shelf in the East China Sea to the Reduction of Oceanic Nutrient Supply

Xinyu GUO[1] and Liang ZHAO[2]

[1]Center for Marine Environmental Studies (CMES), Ehime University,
2-5 Bunkyo-cho, Matsuyama 790-8577, Japan
[2]Physical Oceanography Laboratory, Ocean University of China,
238 Songling Road, Qingdao 266100, P.R. China

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Abstract—A three-dimensional coupled biophysical model was used to examine the response of oceanic nutrients and primary production over the continental shelf to reduction of the oceanic nutrient supply in the East China Sea (ECS). The model consisted of two parts: the hydrodynamic module was based on a nested model with a horizontal resolution of 1/18 degree, whereas the biological module was a low trophic level ecosystem model including two types of phytoplankton, three elements of nutrients, and biogenic organic material. After completing a control calculation designed to reproduce the climatological conditions of this low trophic level ecosystem, the concentrations of nutrients in the Kuroshio water were artificially reduced by 30%. A reduction in nutrients over the shelf was then observed in the bottom layer from spring to summer, and in the surface layer from autumn to winter. A reduction in primary production over the shelf was found not only in the surface layer in winter but also in the subsurface layer over the shelf from spring to autumn.

Keywords: ecosystem modelling, oceanic nutrients, Kuroshio, East China Sea, primary production

INTRODUCTION

The East China Sea (ECS) is one of the major marginal seas of the northwestern Pacific (Fig. 1). Many rivers, including the Changjiang River (Yangtze River), provide a substantial input of freshwater and nutrients into adjacent seas (Zhang, 1996). On the other hand, the ECS also receives water and associated nutrients from the Taiwan Strait, whose volume transport is greater than river discharge into the ECS by as much as two orders of magnitude (Isobe, 2008). The Kuroshio in the ECS flows along the shelf break (see 200 m isobath in Fig. 1), and the onshore volume transport of the Kuroshio across the break has been reported to be within the same order as the transport through the Taiwan Strait (Guo *et al.*, 2006; Isobe, 2008).

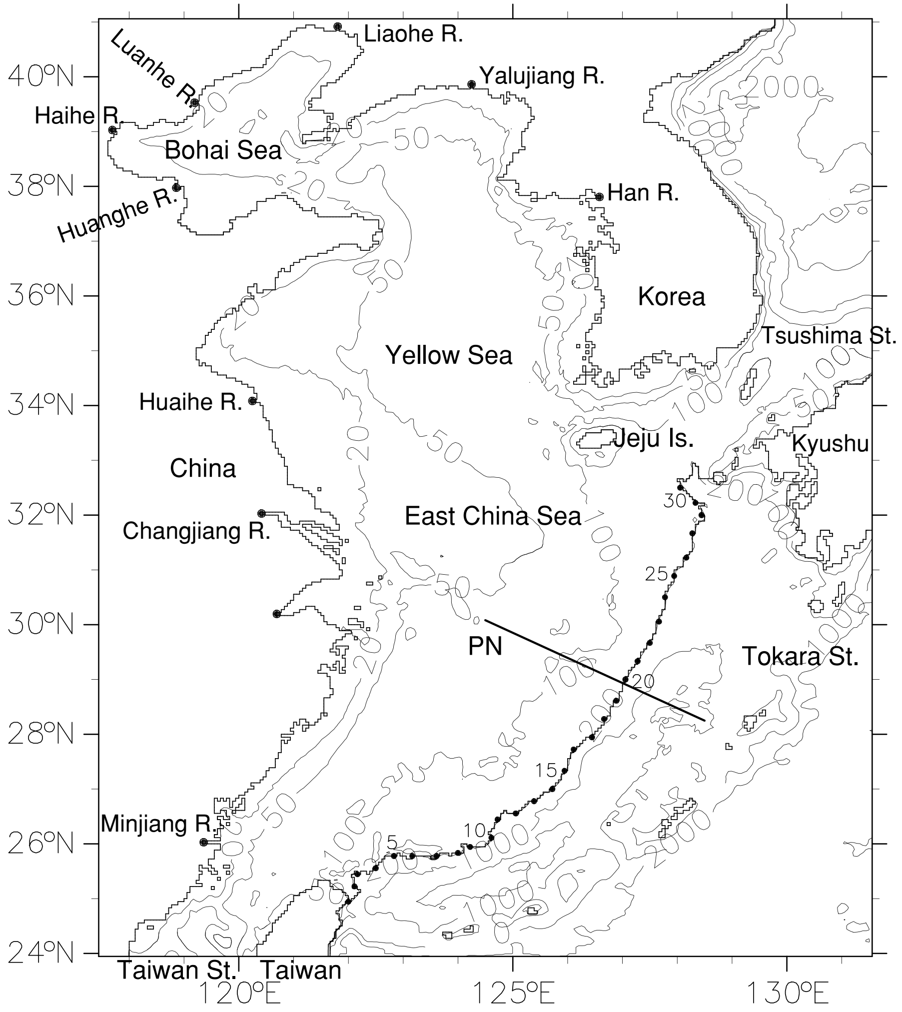

Fig. 1. Model domain and bathymetry. Rivers are denoted by dots along the coastline; contours with numbers are isobaths in meters. The 200 m isobath along the shelf break is overlapped by a line with dots and numbers, across which the fluxes of volume and nutrients are calculated and presented in Table 1.

Using a box model to calculate the annual nutrient budget over the shelf of the ECS, Chen and Wang (1999) suggested the Kuroshio subsurface water has a more important role in supplying nutrients onto the ECS shelf than rivers do. Zhang, J. *et al.* (2007) revisited this calculation for budget in summer and winter and confirmed the important role of the nutrients supplied by Kuroshio subsurface water intrusion onto the shelf. These findings are supported by a passive tracer experiment following Kuroshio water with a three-dimensional numerical model

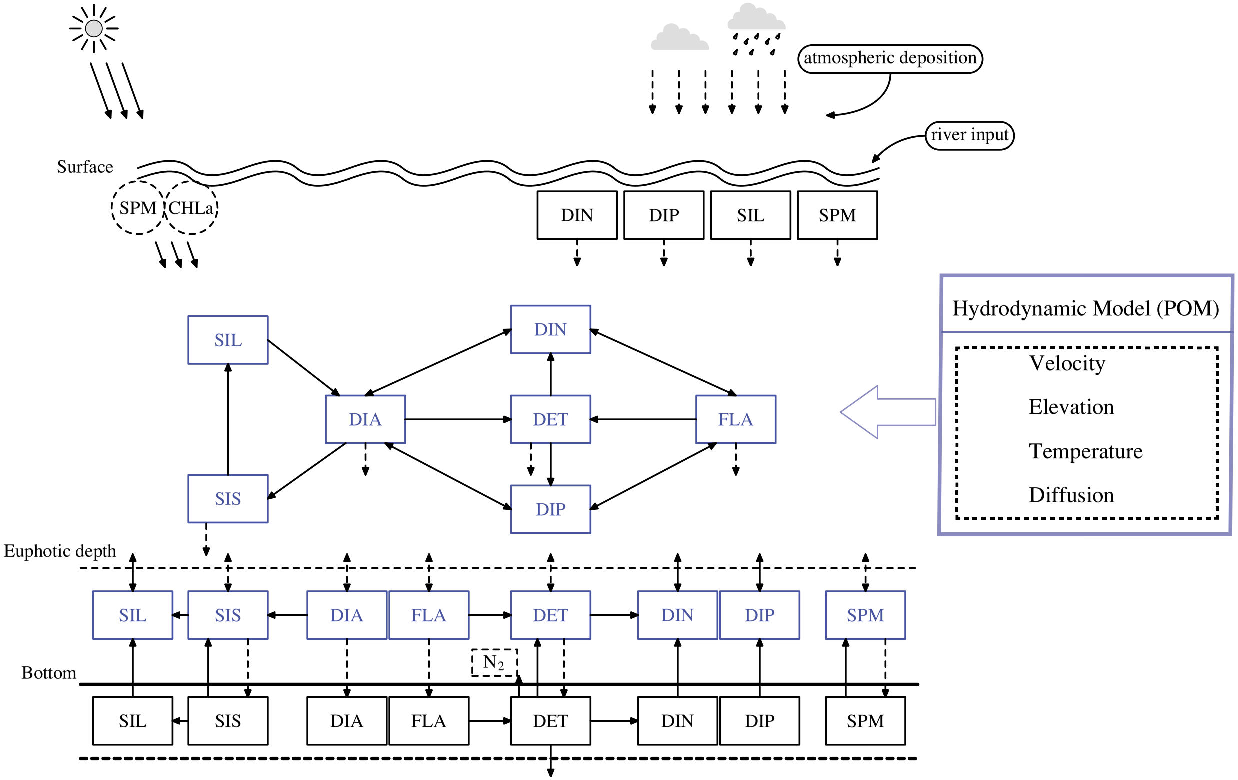

Fig. 2. Schematic illustration of the biophysical model that has a hydrodynamic module and a biological module. The hydrodynamic module is based on the Princeton Ocean Model (POM) (Mellor, 2003). The biological module includes three elements of nutrients (dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), and silicate (SIL)), two types of phytoplankton (diatoms (DIA) and flagellates (FLA)), and two types of biogenic organic materials (dead organic matter containing nitrogen and phosphorus (DET) and biogenic silica (SIS)). See Zhao and Guo (2011) for the processes included in this module.

Table. 1. Change in onshore flux of volume, DIN, DIP and silicate across the shelf break defined by the 200 m isobath shown in Fig. 1.

	Volume (Sv)	DIN (kmol s^{-1})	DIP (kmol s^{-1})	SIL (kmol s^{-1})
Case (ctrl)	1.531	9.361	0.718	18.219
Case (-30%)	1.531	6.270	0.476	11.837
Ratio	1	0.670	0.663	0.650

(Guo *et al.*, 2006).

Recently, we re-evaluated the nutrient flux across the shelf break using a three-dimensional numerical biophysical model and demonstrated that oceanic nutrients were readily utilized by phytoplankton over the shelf in the ECS (Zhao and Guo, 2011). In this study, we applied the same model to examine the responses of nutrients and primary production over the shelf to a reduction in the onshore flux of oceanic nutrients across the shelf break.

MODEL CONFIGURATION AND CALCULATION PLAN

Our model consisted of two parts: a hydrodynamic module and a biological module. The hydrodynamic module provided physical parameters, such as water temperature, velocities, and diffusivity coefficients, to the biological module. The two modules were run simultaneously in coupled runs.

The hydrodynamic module is based on the Princeton Ocean Model (Blumberg and Mellor, 1987; Mellor, 2003) and configured with a nesting method to obtain a high horizontal resolution (1/18 degree) for the ECS, as described in detail by Guo *et al.* (2003). In the vertical direction, 21 sigma levels were used. Differences from the previous version were the explicit inclusion of freshwater input from sea surface and rivers and the addition of tidal forcing (M_2, S_2, K_1 and O_1 tides) along the lateral boundary (Wang *et al.*, 2008).

The biological module (Fig. 2) is based on the biological part of NORWECOM (Aksnes *et al.*, 1995; Skogen *et al.*, 1995; Skogen and Søiland, 1998) and reconstructed for the ECS. The model components include three elements of nutrients (dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), and silicate (SIL)), two types of phytoplankton (diatoms (DIA) and flagellates (FLA)), and two types of biogenic organic material (dead organic matter (DET) and biogenic silica (SIS)). For the details including parameters and some equations used in this model, please refer to Zhao and Guo (2011).

The model domain covers the Bohai Sea, Yellow Sea, and ECS with an open boundary along the southern and eastern boundaries (Fig. 1). With the objective of reproducing seasonal variation, the hydrodynamic module was driven by monthly river runoff, monthly heat flux, monthly evaporation and precipitation rates, and monthly ocean currents at the open boundary. During model integration, the monthly data were linearly interpolated to every time step. The tidal currents were specified at the open boundary as described by Wang *et al.* (2008). A

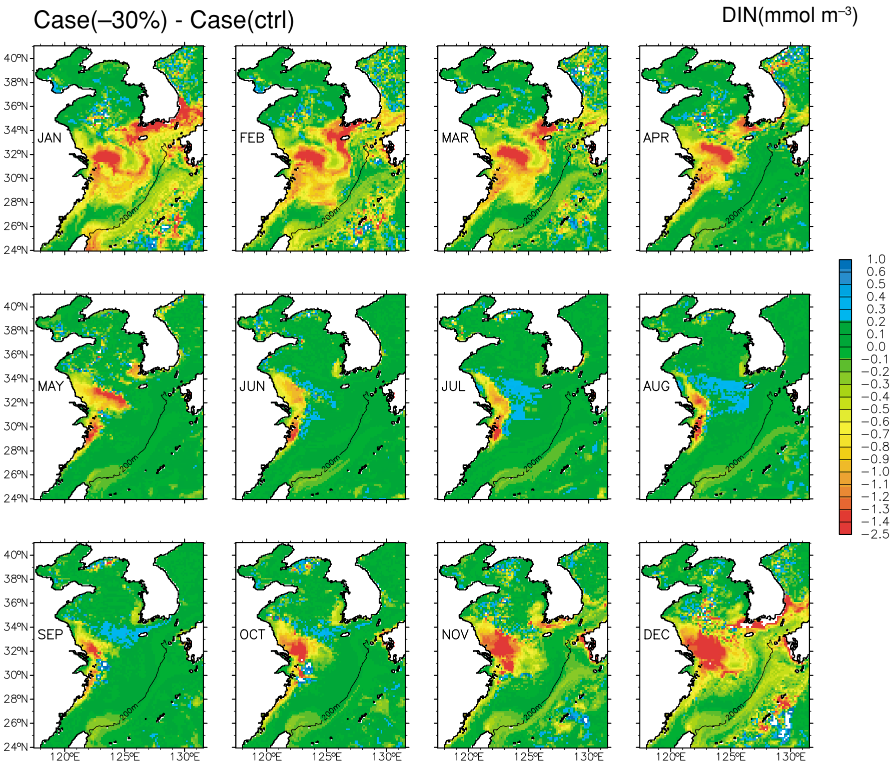

Fig. 3. Anomaly of monthly DIN (mmol m^{-3}) in the surface layer (2 m depth) between Case (-30%) and Case (ctrl).

regression relation with nine coefficients (annual mean, two harmonic constants each for the annual period, for the semi-annual period, for the 4-month period, and for the 3-month period) in the Scatterometer Climatology of Ocean Winds (Risien and Chelton, 2008) was used to describe the wind fields at every time step. In order to reproduce the seasonal variations of nutrients and chlorophyll *a*, the same monthly conditions were prescribed at river mouths, at the open boundary, and at the air-sea interface for the biological module.

The calculation was started with winter initial conditions and was spun up for two years; model results in the third year were analyzed. The initial conditions for three elements of nutrients followed Chen (2009), while those along open boundaries were from the World Ocean Atlas 2005 (WOA2005) (Garcia *et al.*, 2006a, b). Runoff from ten major rivers (Fig. 1) was from the Marine Atlas of Bohai Sea, Yellow Sea, East China Sea, Hydrology (Chen, 1992). The concentrations of nutrients in rivers and those for atmospheric dry and wet deposition of nutrients were obtained from published data (Zhang, 1996; Wan *et al.*, 2002; Zhang, G. S. *et al.*, 2007; Liu *et al.*, 2009). Solar radiation was

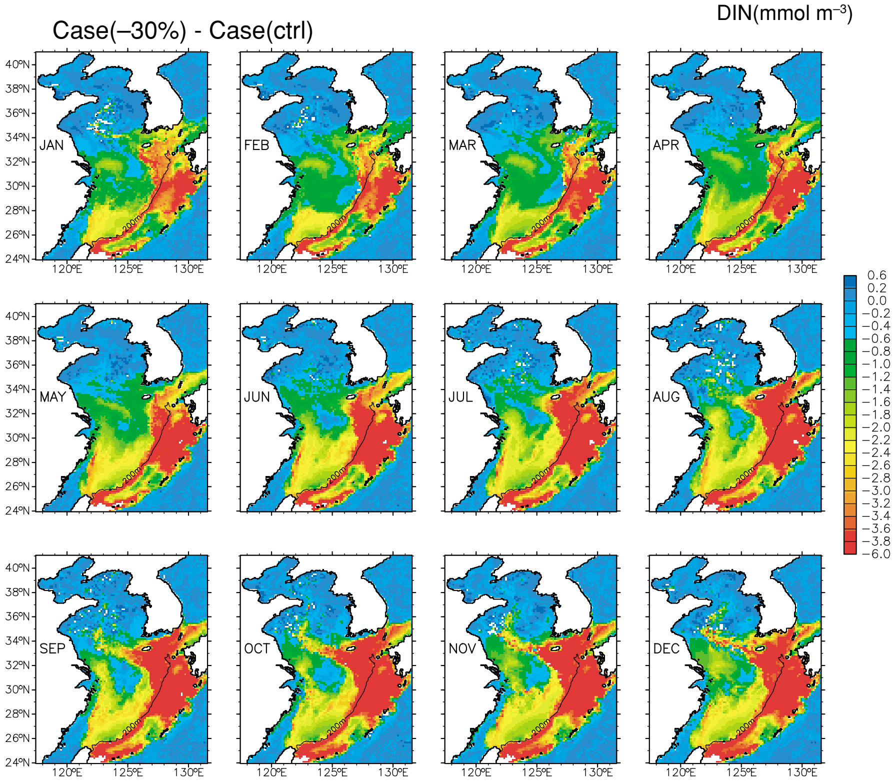

Fig. 4. Same as Fig. 3 but for DIN (mmol m^{-3}) in the bottom layer, defined as the deepest sigma layer. The color range is different from that used in Fig. 3.

calculated using the model given by Dobson and Smith (1988), and cloud cover data was from the NCEP/NCAR reanalysis (Kalnay *et al.*, 1996). With the above configuration, the model has been demonstrated to be able to reproduce seasonal variations in nutrients and chlorophyll *a* found in observational data from the ECS (Zhao and Guo, 2011). Hereafter, we call this simulation the control experiment and denote it as Case (ctrl).

To see the response of nutrients and chlorophyll *a* to a reduction in the oceanic nutrient supply across the shelf break of the ECS, we applied sensitivity experiments in which we multiplied the concentration of nutrients (DIN, DIP, and silicate) in Kuroshio water from the sea surface to bottom along the southern boundary (from Taiwan to 124°E) by a constant of 0.7, but kept the other boundary conditions, initial conditions, and model integration schedule the same as in the control experiment. As shown in Table 1, this method reduced the supply of oceanic nutrients across the shelf break from the Kuroshio but did not affect the flow fields. Hereafter, we call this case a sensitivity experiment and denote

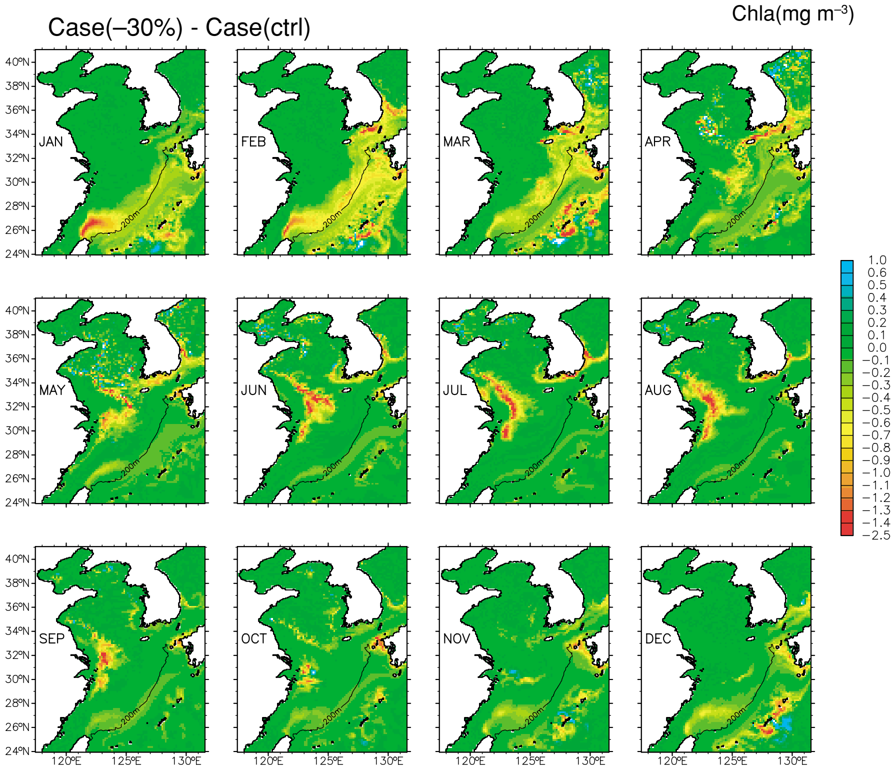

Fig. 5. Same as Fig. 3 but for chlorophyll *a* (mg m^{-3}) in the surface layer.

it as Case (-30%). The difference in results between Case (-30%) and Case (ctrl) is only caused by the change in the supply of oceanic nutrients across the shelf break, and therefore it can give us some insight as to the potential role of changing oceanic nutrient concentrations in the low trophic level dynamics of the ECS ecosystem.

CHANGES IN SURFACE AND BOTTOM NUTRIENTS AND SURFACE CHLOROPHYLL *A* OVER THE SHELF OF THE ECS

The decrease in nutrients (e.g., DIN) in the surface layer appeared mostly offshore of the Changjiang estuary (Fig. 3). In summer (June–August), a negative anomaly in DIN concentration (Case (-30%) – Case (ctrl)) was found along the coast from 29°N to 34°N, but offshore the DIN anomaly was positive. After September, the area with a negative DIN anomaly grew and extended to the Jeju Strait (the channel between Jeju Island and the southern coast of Korea) and farther to the Tsushima Strait in winter (December–February).

The decrease in nutrients (e.g., DIN) in the bottom layer over the shelf

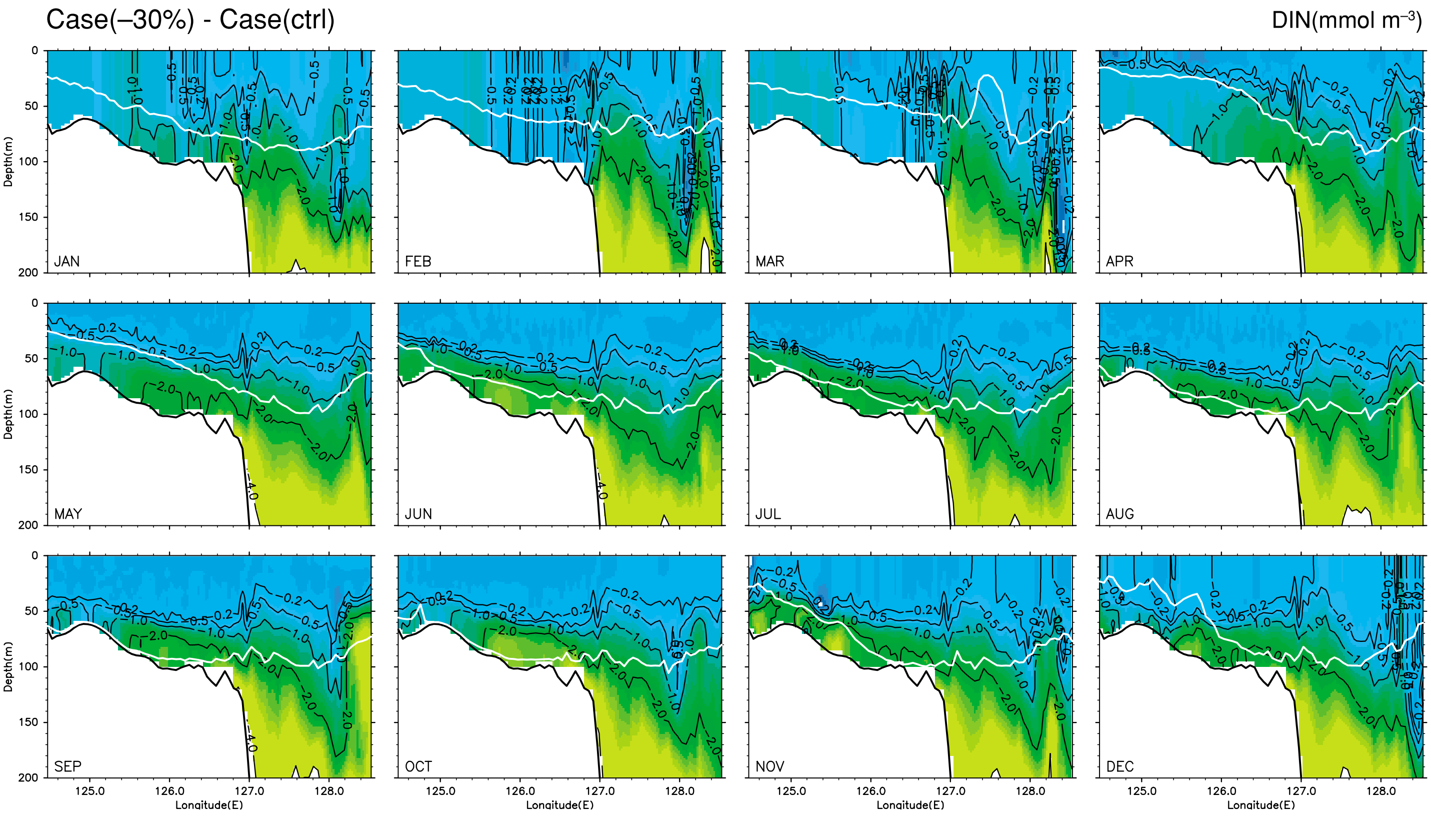

Fig. 6. Anomaly of monthly DIN (mmol m^{-3}) along the PN line between Case (-30%) and Case (ctrl). The white line denotes euphotic depth.

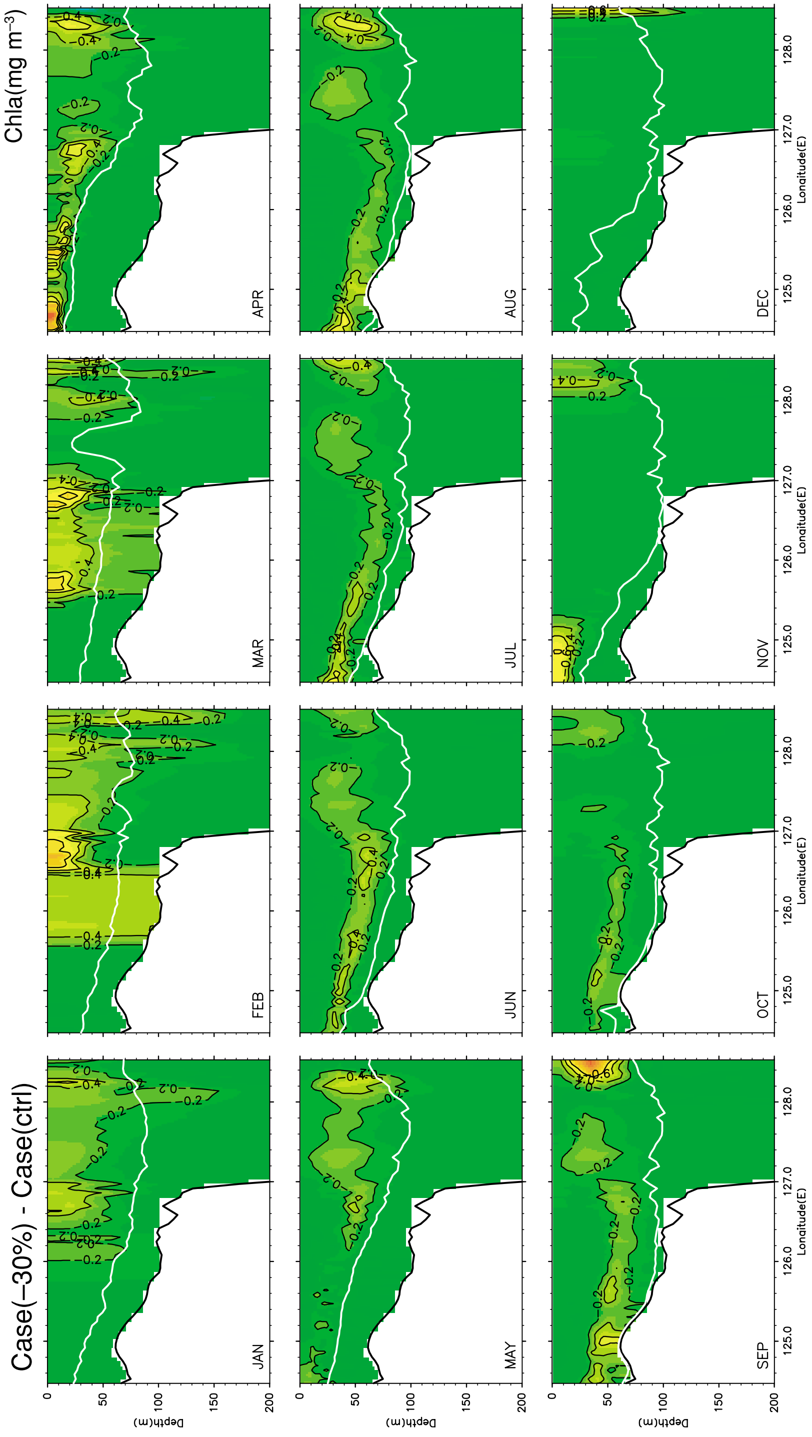

Fig. 7. Same as Fig. 6 but for chlorophyll *a* (mg m^{-3}).

appeared mostly northeast of Taiwan and southwest of Kyushu (Fig. 4). In the area northeast of Taiwan, a negative anomaly in bottom layer's nutrients can be identified throughout the year. However, its distribution over the shelf grew from April to September. In the area southwest of Kyushu, the area with negative anomaly in bottom layer's nutrients grew from June to September, after which a northwestward branch of negative nutrient anomaly appeared and reached the Yellow Sea.

The response of chlorophyll *a* in the surface layer to reduction of oceanic nutrients in winter appeared in Kuroshio pathway, in particular, northeast of Taiwan where a local maximum in the chlorophyll *a* anomaly can be identified (Fig. 5). The reduction of chlorophyll *a* over the shelf in winter was difficult to identify, although that in nutrients was apparent (Fig. 3), indicating that primary production over the shelf in winter was not limited by nutrients.

CHANGES IN SUBSURFACE NUTRIENTS AND CHLOROPHYLL *a* ACROSS THE SHELF OF THE ECS

The reduction of oceanic nutrients in the sensitivity experiment depended on the original concentration in the control experiment, and therefore it was small in the surface layer and large in the subsurface and bottom layers. From January to March, contours of reduced oceanic DIN concentration were distributed horizontally along the PN section; from April to June, the 2 mmol m^{-3} contour of reduced DIN concentration moved from the shelf break to the middle and inner shelf and stayed over the shelf (Fig. 6). An important point shown in Fig. 6 is that some of the nutrient reduction can enter the euphotic zone.

The reduction in nutrients caused a decrease in chlorophyll *a* in the surface layer in cold months (November–March) and in the subsurface in warm months (June–October) (Fig. 7). April through May appears to be a transition period when the decrease in chlorophyll *a* moves from the surface to the subsurface layer.

CONCLUDING REMARKS

By artificially reducing the concentration of oceanic nutrients in the Kuroshio water, we confirmed that it influences nutrients and primary production over the shelf of the ECS. The area with a nutrient decrease is in the bottom layer from the shelf break to the offshore region of the Changjiang estuary from spring to summer, and it is in the surface layer mainly from autumn to winter. The decrease in primary production over the shelf can be found not only in the surface layer (mainly at the outer shelf and shelf break in winter and in the region outside the turbidity zone of the Changjiang estuary in summer), but also in the subsurface layer over the shelf from spring to autumn. All these results are consistent with the new understanding of the role of oceanic nutrients in primary production over the shelf of the ECS (Zhao and Guo, 2011).

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X. Guo (e-mail: guoxinyu@sci.ehime-u.ac.jp)