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# Variability of nutrient transport and associated upper ocean primary production induced by Kuroshio meanders in the Enshu-nada Sea, Japan

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**Abstract.** Towards the desirable preservation of the marine environment under a changing global climate, this study aims to investigate the coastal biological response to varying oceanic conditions, namely the Kuroshio meander, and associated nitrate transport on the Pacific coast of Japan around the Enshu-nada Sea, using a coupled three-dimensional regional ocean circulation model with a nitrogen-based ecosystem model. A prominent difference was found in nitrate transport processes between for a period when the Kuroshio took a meandering path and for a non-meandering period, leading to about 1.5 times higher surface primary production measured by chlorophyl-a concentration during the non-meandering period than during the meandering period. The upper ocean nitrate flux budget analysis showed that the subsurface nitrate was transported upward as a vertical diffusive flux around the north (shoreward) of the Kuroshio path and as a mean vertical advective flux in the Kuroshio downstream region around the Izu-Ogasawara Ridge. In contrast, high-frequency eddy vertical advective fluxes caused downward transport, but to a degree about 20% smaller than the other fluxes. After nitrate was supplied to the upper layer, it was transported horizontally by the counterclockwise rotating cyclonic eddy formed between the coast and the Kuroshio and supplied to phytoplankton in the Enshu-nada Sea. These results suggest that carbon sequestration due to biological pump may also vary in response to the Kuroshio that is influenced by basin-scale oceanic conditions.

## 1 Introduction

Carbon sequestration in the ocean is attracting attention from the perspective of global warming countermeasures. This carbon sequestration is achieved when carbon absorbed by the ocean through primary production is ingested by marine organisms and then deposited on the seafloor by their detritus. Phytoplankton plays a major role in primary production in

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the ocean, with its biomass generally sustained by nitrogen, primarily in the form of nitrate found at depth. Therefore, the transport of nitrate to phytoplankton-rich but nitrate-depleted surface water is crucial for primary production, serving as the major source of nutrients for these organisms. A previous study on vertical nitrate transport has been conducted around the Enshu-nada Sea (Figure 1) under influences of the Kuroshio and accompanying mesoscale and submesoscale eddies using a climatological numerical ocean model [1]. The Kuroshio is known to fluctuate its flow path seasonally and interannually [2]. Zhang [3] showed that when the Kuroshio meanders in the Enshu-nada Sea, the nitrate transport in the surface layer tends to be active in the coastal areas while it is suppressed offshore. In general, the Kuroshio is considered to be nitrate-rich in the subsurface layer [7]. However, the vertical transport of nitrate from the subsurface to the surface, as well as the fate of the surfaced nitrate by horizontal transport, have not yet been fully investigated, particularly with regard to its fluctuating path. Therefore, this study is aimed to assess the three-dimensional transport process and its underlying mechanism of the subsurface nitrate and resultant phytoplanktonic responses in the Enshu-nada Sea, by using a synoptic downscaling numerical ocean circulation-biogeochemical model.

## 2 Methods

To accomplish the above objective, a synoptic 3D numerical modeling was conducted in the seas around Japan using a 3D hydrodynamics model ROMS (Regional Oceanic Modeling System) [4] coupled with the nitrogen-based pelagic biogeochemical model NPZD (Nutrient, Phytoplankton, Zooplankton and Detritus) model [5,6], *viz.*, the ROMS-NPZD model (Figure 1). The model was initialized and forced by the JAMSTEC JCOPE2 regional oceanic reanalysis and JMA GPV-GSM global atmospheric analysis with the horizontal grid resolution of 3 km. The computational period spans from 2011 to 2015, excluding the spin-up precomputation period. Further details on the numerical configurations can be found in Zhang et al. [1] and Zhang [3].

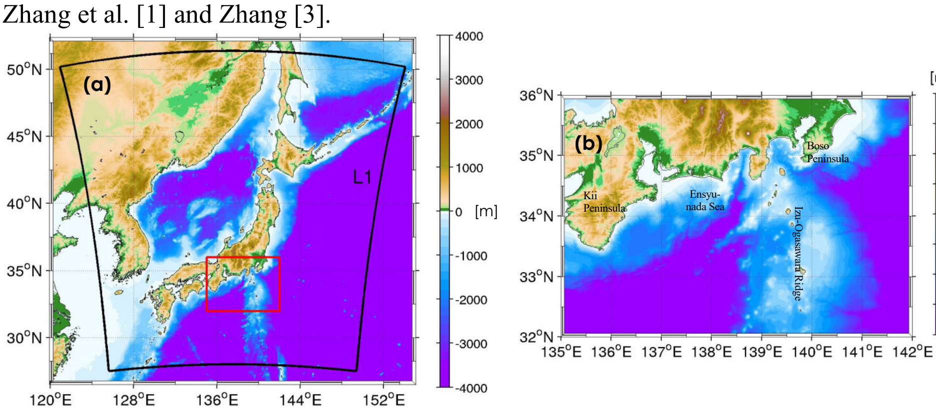


**Fig. 1.** (a) ROMS-NPZD L1 computational domain (outer black box) and bathymetry in m (color). The inner red box is the study area encompassing the Enshu-nada Sea taken from the east side of the Kii Peninsula to the Boso Peninsula. (b) Enlarged view of the red box in (a).

## 3 Results

Figure 2 shows the seasonally averaged sea surface heights (SSH) and surface horizontal current velocity vectors around the Enshu-nada Sea. The SSH and velocities are time averaged for the three months from December 2013 to February 2014 (meandering period:

MP) and from December 2014 to February 2015 (non-meandering period: NMP). Our intension was to compare these two periods in the following analyses as they represent the meandering and non-meandering period and thus to extract differences in the dynamical and biogeochemical processes due to the paths, while other oceanic and meteorological conditions would be almost identical. It is found that a cyclonic mesoscale eddy is persistently formed on the north side of the Kurishio and centered at 138–139oE. The SSH around the eddy is lower for MP than for NMP with higher velocity as required by geostrophic balance, where the steeper the SSH gradient, the more energetic the cyclonic eddy was formed for MP.

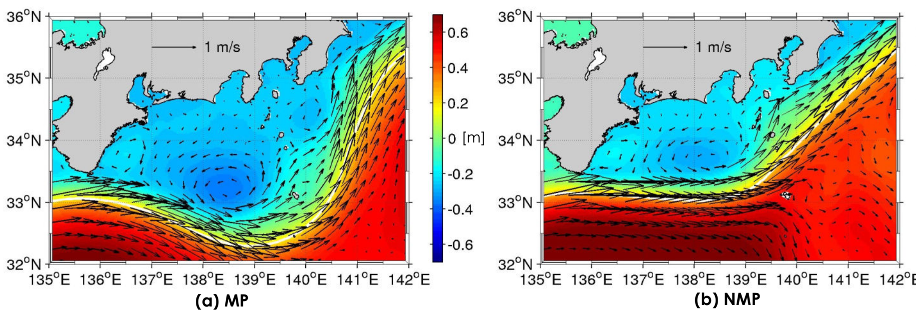


**Fig. 2.** Time averaged sea surface heights (SSH, color) and subsampled, time averaged surface horizontal current velocity vectors for (a) a meandering period (MP, winter 2014) and (b) a non-meandering period (NMP, winter 2015) around the Enshu-nada Sea for the analysis area depicted in Figure 1b. The white line indicates the mean axis of the Kuroshio path.

Figure 3 displays the time-averaged chlorophyll-a (chl-a) concentrations at the surface for MP and NMP, indicating primary production in the upper ocean. The surface chl-a distributions demonstrate that the surface primary production in the Enshu-nada Sea is largely influenced by the Kuroshio. The north side of the path is much more productive than the south side of the path. Nearshore chl-a enhancement occurs presumably due to coastal upwelling and other enhanced vertical mixing that promote upward nitrate transport to enrich the surface nitrate-depleted water. The overall chl-a is higher for NMP than for MP, with the pelagic chl-a maximum appearing near the persistent cyclonic eddy center (Figure 2). Surprisingly, this chl-a maximum is about 1.5 times higher for NMP than for MP. This result suggests that the dynamical differences associated with the different paths may be attributable to pelagic primary production.

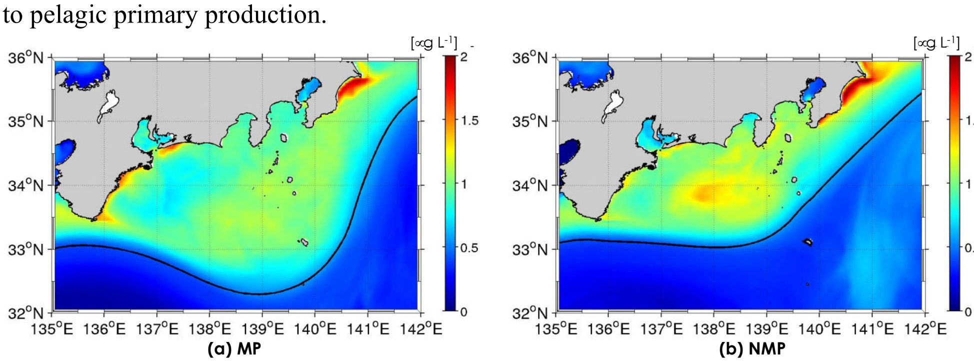


**Fig. 3.** Same as Figure 2, but for the time averaged surface chlorophyll-a (chl-a) concentrations (color) for (a) MP and (b) NMP. Black line shows the corresponding Kuroshio axis (identical to the white line in Figure 2).

# 4 Discussion

## 4.1 Nitrate flux budget analysis

To examine mechanisms behind the differences in productivity (i.e., chl-a concentration) in the upper ocean off the Enshu-nada Sea due to the different Kuroshio path (MP or NMP), the nitrate flux budget analysis was conducted. The conservative advection-diffusion equation of nitrate is represented as follows.

$$\frac{\partial N}{\partial t} + \nabla(N\mathbf{u}) = \frac{\partial}{\partial z} K_z \frac{\partial N}{\partial z} \tag{1}$$

where $N$ is nitrate ($NO_3^-$) concentration, $\boldsymbol{u}$ = ($u$, $v$, $w$) is eastward, northward, and upward velocity, and $K_z$: vertical eddy diffusivity derived from the KPP turbulence model in ROMS. Note that in our ROMS-NPZD model, lateral diffusion is not explicitly accounted for, and thus is omitted in Equation (1). In addition, the source and sink terms representing interactions among the NPZD components are also neglected in Equation (1) to extract dynamical effects on the nitrate supply. Next, Reynolds decomposition was performed to separate mean and eddy advective components using a cut-off period of 90 days because Zhang et al. [1] reported the significance of vertical eddy nitrate flux on the near-surface nitrate transport. Assuming cross terms are insignificant, the advective nitrate flux can be represented by the following Equation (2).

$$N\mathbf{u} \approx \bar{N}\bar{\mathbf{u}} + \overline{N'\mathbf{u}'} = (\bar{N}\bar{u} + \overline{N'u'}, \bar{N}\bar{v} + \overline{N'v'}, \bar{N}\bar{w} + \overline{N'w'}) \tag{2}$$

where overbars indicate an ensemble averaging operator, and prime denotes eddy component for periods of less than 90 days. Consequently, the nitrate transport for the vertical component $F_z$ may be expressed as a sum of mean advection, eddy advection, and diffusion as in Equation (3):

$$F_z = \underbrace{\bar{N}\bar{w}}_{\text{mean adv.}} + \underbrace{\overline{N'w'}}_{\text{eddy adv.}} \underbrace{- K_z \frac{\partial \bar{N}}{\partial z}}_{\text{diffusion}}. \tag{3}$$

Similarly, the horizontal nitrate flux $\mathbf{F}_H$ is defined as (notice lateral diffusion vanishes) as in Equation (4):

$$\mathbf{F}_H = (F_u, F_v) = (\bar{N}\bar{u} + \overline{N'u'}, \bar{N}\bar{v} + \overline{N'v'}) \tag{4}$$

In the subsequent analyses, the contribution to the accumulation of nitrate supplied from underneath the base of the surface mixed layer is investigated. Hence, each flux term in Equations (3) and (4) is averaged over the three-month periods ($T$) corresponding to MP and NMP. Then the vertical averaging is done over the surface mixed layer, where phytoplankton grows, from the lower bound of the surface mixed layer ($h_{bls}$) to the sea surface ($\zeta$). The temporal and vertical averaging operator, e.g. for $F_z$, is thus represented as in Equation (5):

$$\langle F_z \rangle = \frac{1}{\zeta + h_{bls}} \int_{-h_{bls}}^{\zeta} \left( \frac{1}{T} \int_T F_z dt \right) dz \tag{5}$$

## 4.2 Vertical nitrate transport in the surface mixed layer

Figure 4 illustrates the vertical nitrate flux balance in the analysis area (Figure 1b) around the Enshu-nada Sea for MP and NMP. The eddy nitrate flux is mostly negative in the entire area north of the Kuroshio axis, while the diffusion flux is predominantly positive, particularly on the north side of the Kuroshio path. The downward transport of nitrate depletes near-surface nitrate below the mixed layer, as represented by the negative eddy flux, although its magnitude is only about 25% of the other fluxes. It is important to note that this negative eddy flux is reduced around the eddy centers for both MP and NMP, indicating that eddy-induced upwelling near the eddy center suppressed downward eddy transport. In contrast, the mean nitrate advective flux exhibits mixed positive and negative values with an overall positive bias, maintaining primary productivity in the upper ocean. Near the Kuroshio path, the mean flux is positively biased, whereas it is negative on the north side. In NMP, the mean fluxes are positive, indicating upward transport is predominant around the Izu-Ogasawara Ridge stretching meridionally between 139–140ºE. However, this upward predominance is reduced for MP. Therefore, the interaction between the Kuroshio and the ridge topography in NMP leads to the enhancement of upwelling of subsurface nitrate in the downstream region of the Kuroshio.

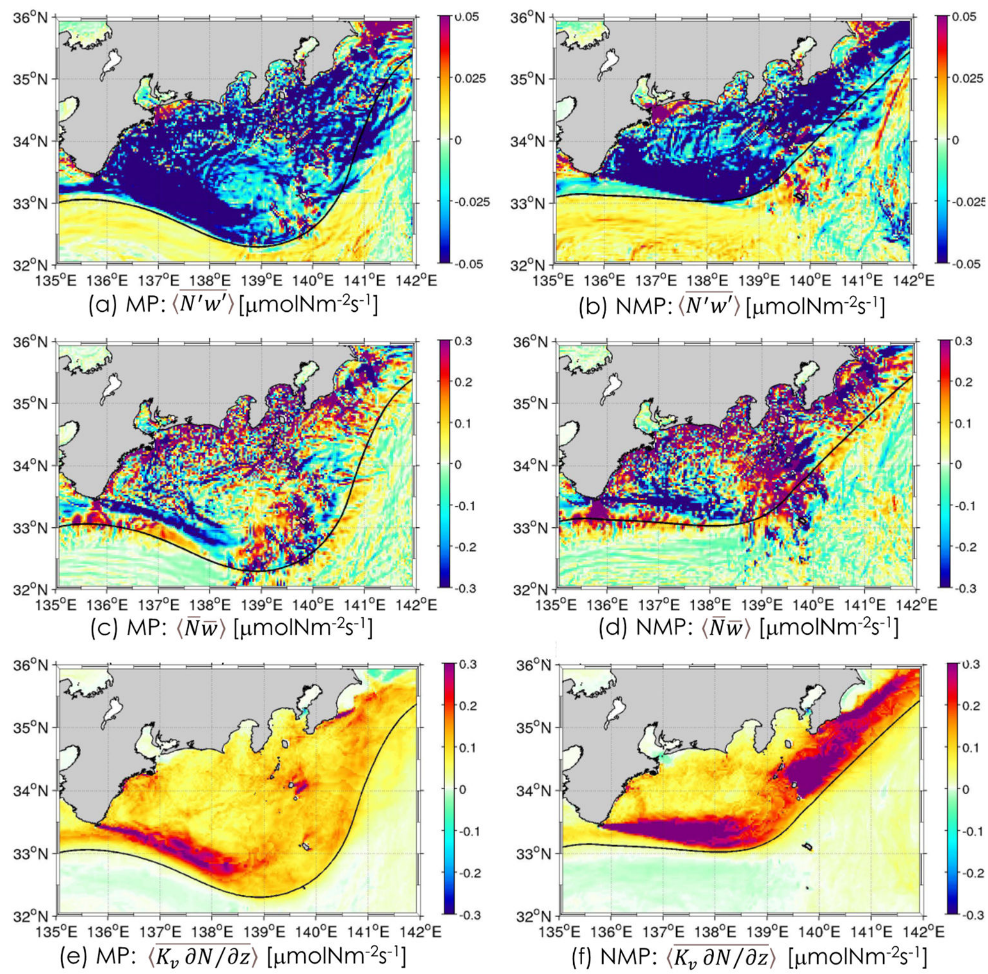


**Fig. 4.** Time and mixed-layer averaged vertical nitrate flux terms represented by Eqs. (3) and (5). The left panels (a, c, and e) are for the meandering period (MP, winter 2014) and the right panels (b, d, f) are for the non-meandering period (NMP, winter 2015). Upper panels (a–b): eddy vertical nitrate flux $\overline{N'w'}$, middle panels (c–d): mean vertical nitrate flux $\bar{N}\bar{w}$, and lower panels (e–f): vertical diffusion flux $\overline{K_H\, \partial N/\partial z}$. Black line shows the Kuroshio axis.

### 4.3 Horizontal nitrate transport in the surface mixed layer

To further examine the fate of the surfaced nitrate fluxes shown in Figure 4, the horizontal nitrate flux represented by Equation (4) averaged temporally over the three-month periods and vertically within the surface mixed layer as Equation (5) are depicted for MP and NMP (Figure 5). The horizontal nitrate flux follows the counterclockwise-rotating surface mean currents (Figure 2). The Kuroshio transports high $F_H$ from the western upstream region to the eastern downstream region. The counterclockwise transport extracts the high $F_H$ from the Kuroshio and brings it towards the coast and westward. The center of the counterclockwise transport approximately collocated at the mesoscale cyclonic eddy center with reduced $|F_H|$. Hence it is evident that the persistent cyclonic eddy and associated surface circulation transport the nitrate supplied in the Kuroshio downstream region around the Izu-Ogasawara Ridge, where upwelling of the nitrate-rich subsurface water occurred, towards the eddy center. This results in high productivity, as evidenced by the high chl-a concentration (Figure 3).

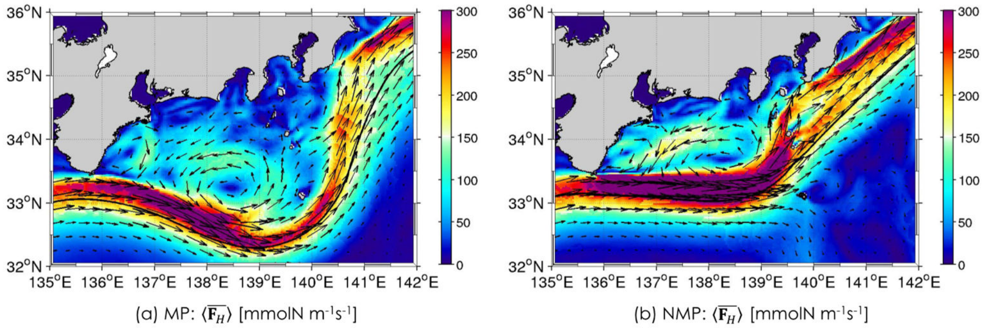


**Fig. 5.** Same as Figure 4, but for the horizontal nitrate flux $\mathbf{F}_H$ for (a) MP and (b) NMP. Colors are the magnitude $|\mathbf{F}_H|$ with overlaid arrows indicating subsampled horizontal nitrate flux vector $\mathbf{F}_H$.

## 5 Conclusions

The present study demonstrated that the fluctuating path of the Kuroshio has an impact on primary production in the Enshu-nada Sea, Japan, using a synoptic coupled ocean circulation-biogeochemical ROMS-NPZD model. The results showed that the maximum surface chl-a concentration was significantly higher during a non-meandering period (NMP) than during a meandering period (MP), with an increase of about 1.5 times. The nitrate flux budget analysis revealed that the non-meandering Kuroshio path induced an increase in the upper-ocean nitrate due to the upwelling of subsurface nitrate-rich water, particularly in the downstream region around the Izu-Ogasawara Ridge. This upward vertical nitrate transport occurred because of both mean advective and diffusive flux and was considerably enhanced for NMP. Subsequently, the surfaced nitrate was effectively transported back to the Enshu-nada Sea by a persistent cyclonic mesoscale eddy and associated counterclockwise horizontal circulation formed between the Kuroshio and the shore as the mean horizontal nitrate fluxes. The nitrate then accumulated near the eddy center to promote high chl-a concentrations in that area. This result suggests that the synoptic-scale fluctuation of the Kuroshio plays a crucial role in altering the primary production in the coastal region off Japan. A possible engineering implication of this finding is the need to predict the indirect changes in the coastal ecosystem due to climate change that could affect the Kuroshio path.

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## References

1. X. Zhang, Y. Uchiyama, E. Masunaga, Y. Suzue, Seasonal variability of upper ocean primary production along the Kuroshio off Japan: Roles of eddy-driven nutrient transport. Front. Mar. Sci. **9**, 990559 (2022). https://www.frontiersin.org/articles/10.3389/fmars.2022.990559/full
2. M. Kawabe, Variations of current path, velocity, and volume transport of the kuroshio in relation with the large meander. J.Phys. Oceanorg. **25**, 3103-3117 (1995). https://doi.org/10.1175/1520-0485(1995)025%3C3103:VOCPVA%3E2.0.CO;2
3. X. Zhang, Dynamical impacts on marine ecosystem of coastal and marginal seas around Japan. Doctoral thesis, **8066**, Kobe University, Japan (2023). https://da.lib.kobe-u.ac.jp/da/kernel/D1008066/
4. A. F. Shchepetkin and J. C. McWilliam, The regional ocean modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model, Ocean Modelling., **9**, 347–404 (2005). https://doi.org/10.1016/j.ocemod.2004.08.002
5. M. J. R. Fasham, H. W. Ducklow, and S. M. McKelvie, A nitrogen-based model of plankton dynamics in the oceanic mixed layer. J. Mar. Res. **48**, 591–639 (1990)
6. N. Gruber , H. Frenzel, S. C. Doney, P. Marchesiello , J. C. McWilliams, J. R. Moisan, J. Oram, G.-K. Plattner and K. D. Stolzenbach. Eddy-resolving simulation of plankton ecosystem dynamics in the California current system. Deep-Sea Res. **539**, 1483–1516 (2006). https://doi.org/10.1016/j.dsr.2006.06.005
7. T. Nagai, S. Clayton and Y. Uchiyama, Y.: Multiscale routes to supply nutrients through the Kuroshio nutrient stream, In: Kuroshio Current: Physical, Biogeochemical and Ecosystem Dynamics, Geophysical Monograph Series, Eds: Nagai, T., Saito, H., Suzuki, K. and Takahashi, M., John Wiley & Sons, NY, USA, ISBN:1119428343 (2019)