A numerical study of effects of submesoscale anticyclonic eddies induced by Kuroshio around Ryukyu Islands

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Abstract

In order to maintain biological diversity in the coral coasts around Ryukyu Islands, Japan, a role played by the adjacent Kuroshio warm current is anticipated to be essential for larval and nutrient transport. For better understanding dynamics and mixing between the Kuroshio and the islands, we develop a detailed oceanic downscaling model in a doubly nested configuration using ROMS at horizontal resolutions down to 1km, forced by the assimilative JCOPE2 and JMA-GSM/MSM. A model-data comparison is conducted with the field observation and satellite altimetry data to demonstrate a quite close agreement. According to a diagnostic eddy heat flux analysis, the dominance of negative vorticity is substantial in emergence of submesoscale anticyclonic eddies and the associated asymmetric heat transport from the Kuroshio.

Keywords - Kuroshio, Ryukyu Islands, ROMS

1 Introduction

For preserving biodiversity and marine ecosystem in the coral coasts around Ryukyu Islands, Japan, a role played by the adjacent Kuroshio warm current is considered to be substantial for larval and nutrient transport. Based on a triply nested ocean modeling using POM, Guo *et al*., (2003) reported that the path and vertical structure of Kuroshio in the East China Sea, encompassing Ryukyu Islands, become more realistic as the model horizontal resolution increases. A numerical study using a high-resolution ocean model in this area indicates that the southwestward counter-Kuroshio Current and mesoscale eddies have non-trivial influence on volume and heat transport between Kuroshio and the Islands (Nadaoka *et al*., 2006).

Recently, effects of submesoscale dynamics, *O* (10) km or less, on the mean structure, eddies, frontal processes, stratification, etc. have widely been recognized crucial in the upper ocean dynamics (Uchiyama *et al*., 2012). However, the submesoscale influences on the oceanic structure in the study area have not been fully investigated yet. Furthermore Kuroshio flowing up on the continental shelf off the Okinawa Trough is considered to be largely skewed by the shallow island topography on its east side that may result in unique turbulence. Therefore, in order to better understand dynamics and mixing between Kuroshio and the islands, we develop a detailed ocean downscaling model in a doubly nested configuration using ROMS at horizontal resolution down to 1km around Ryukyu Islands, forced by realistic assimilative meteorological and oceanic products.

2 Numerical model

We rely on a one-way offline nesting approach to successively reduce the horizontal grid size from about 10 km (JCOPE2) → 3 km (ROMS-L1) → 1 km (ROMS-L2) (**Fig. 1**). The outer-most boundary and initial conditions are provided with the interpolated fields of the assimilative JCOPE2 daily-averaged data. The model topography is taken from SRTM 30, which covers the global ocean at 30 geographic arc seconds (about 1 km). QuikSCAT-ECMWF blended wind and JMA GPV-MSM/ GSM data are utilized for the surface momentum forcing. Surface heat and freshwater fluxes are given by the COADS monthly climatology. A 20 day-averaged JCOPE2 data is applied to the sea surface temperature and salinity. The monthly climatology of major river discharges in Dai *et al*. (2009) is considered for Yangtze River in L1. We perform a four-dimensional TS-nudging (nudging strength = 1/20 day^{-1}) towards the 10 day-averaged JCOPE2 temperature and salinity for consistency of the Kuroshio path reproduced by the ROM-L1 with that of JCOPE2.

3 Result

3.1 Surface normalized relative vorticity

An extensive model-data comparison is performed against the field observation and satellite altimetry data to demonstrate a quite close agreement, particularly in stratification in the East China Sea over the Okinawa Trough, and in mean and eddy kinetic energy at surface. Horizontal shear of Kuroshio generates axisymmetric pairs of positive and negative relative vorticity on the west and east sides of the Kuroshio path around Ryukyu Islands. However, the inner-most model at the highest resolution captures the negative vorticity retained significantly on the eastern side of Kuroshio, while the centrifugally-stable positive vorticity is attenuated rather quickly. In order to quantitatively evaluate this negative bias of relative vorticity with increased model resolutions, we define two sub-regions (sub 1 and sub2 as shown in **Fig. 2** Left) to examine the effects

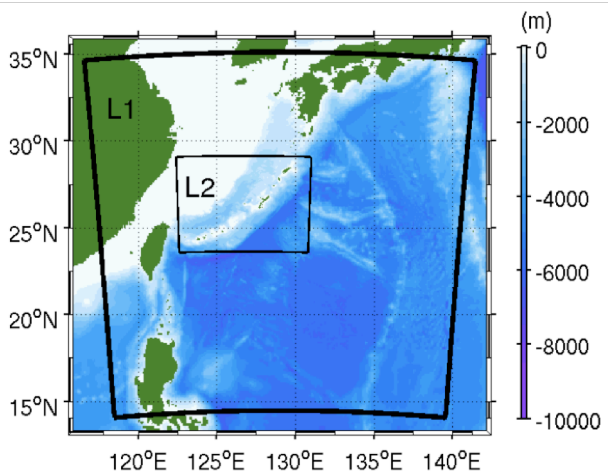

Fig. 1. Bathymetry and domains of doubly nested models: ROMS-L1 (outer box) and ROMS-L2 (inner box).

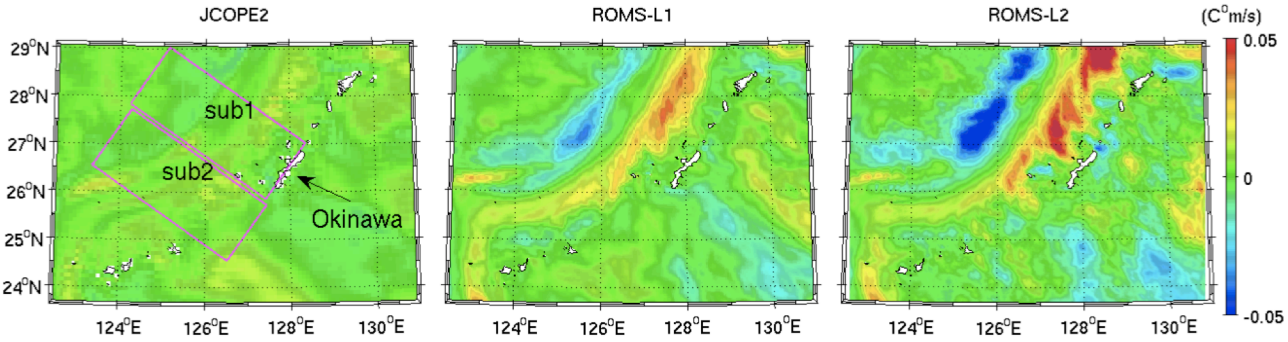

Fig. 2. F_x (eddy heat flux in °Cm/s across the Kuroshio axis) from the 3 models. The boxes in the left panel indicate sub 1and sub 2.

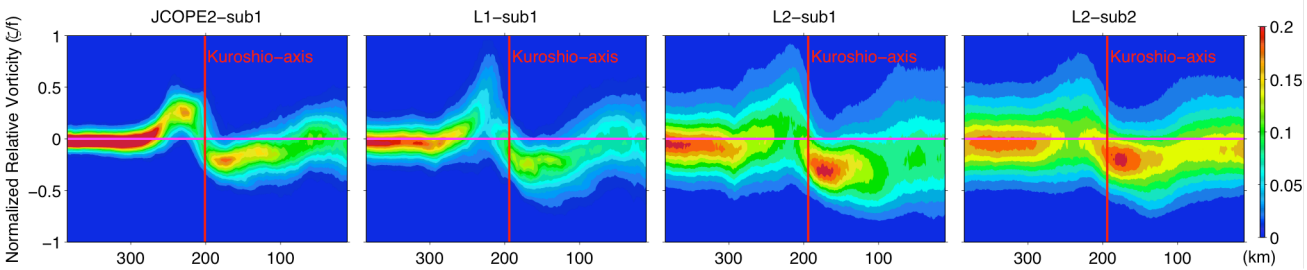

Fig. 3. PDFs of normalized relative vorticity in sub 1 from the 3 models and that in sub 2 of ROMS-L2 (right panel) as function of the distance from the Okinawa Island (in km). Red vertical lines are the approximate location of the Kuroshio axis.

of islands and resolutions. PDFs (probability density functions) of nomalized relative vorticity (ζ / f) at surface for the two-year period is diagnosed as a function of the distance from the Okinawa Island normal to the Kuroshio axis (**Fig. 3**). The PDF is nearly symmetric to the Kuroshio axis although peaks at $\zeta / f < 0$ on the eastern side of the Kuroshio axis while converges to zero as away from the axis to the west. This negative bias on the east is most evident at the highest resolution (L2-sub1, the second right panel). Nevertheless, the asymptote of the PDF peak on the east in L2-sub2 (without islands) is $\zeta / f \rightarrow \pm 0$, and thus the negative bias is less visible. These findings suggest that submesoscale eddies tend to be more anti-cyclones ($\zeta / f <0$) that are prominently enhanced by the island topography.

3.2 Heat flux analysis

The submesoscale anti-cyclonic eddies induced by Kuroshio are anticipated to promote eastward material transport to the west coast of the Okinawa Island through lateral eddy mixing. To quantify this effect, we assess the lateral turbulent mixing of a tracer (heat) in the upper ocean. The time-averaged, vertically integrated heat (potential temperature) transport equation is represented as (*e.g.*, Marchesiello *et al.*, 2003)

$$\int_{-h}^{\eta}\left(\frac{\partial \overline{u}\,\overline{T}}{\partial x}+\frac{\partial \overline{v}\,\overline{T}}{\partial x}\right)dz+\int_{-h}^{\eta}\left(\frac{\partial \overline{u'T'}}{\partial x}+\frac{\partial \overline{v'T'}}{\partial y}\right)dz$$
$$+\int_{-h}^{\eta}\left[Q\left(\overline{T}\right)+D\left(\overline{T}\right)\right]dz=0$$

where T: potential temperature, (u, v): horizontal velocity, Q: sea surface heat flux, D: parameterized, vertical and horizontal subgrid-scale mixing of heat. The variables assigned with the prime are eddy components obtained by removing the seasonal variations. We focus on the transport by eddy flow, that is a divergence of lateral eddy fluxes $\boldsymbol{F} = (F_x, F_y) = (\overline{u'T'}, \overline{v'T'})$ where F_x and F_y are the across and along Kuroshio axis eddy heat flux. Figure 2 demonstrates that F_x becomes larger as the lateral model resolution gets finer, particularly near the islands.

4 Conclusion

A detailed downscaling model is developed to investigate submesoscale dynamics and mixing around Ryukyu Islands. The submesoscale eddy-resolving model (*i.e.*, L2) successfully reproduces negative vorticity significantly retained on the western side of the islands presumably because of topographic eddy shedding. A diagnostic eddy heat flux analysis suggests that the dominance of the negative vorticity is substantial in emergence of more energetic submesoscale anti-cyclonic eddies that lead to promoting lateral material exchange between Kuroshio and the islands.

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