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Effects of the Submesoscale Anticyclonic Eddies Induced by Kuroshio in East China Sea

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ABSTRACT

For maintaining biological diversity in the coral coasts around Ryukyu Islands, Japan, a role played by the adjacent Kuroshio warm current is anticipated to be necessary for larval and nutrient transport. In order to understand dynamics and mixing between Kuroshio and the islands, we develop a detailed ocean downscaling model around Ryukyu Islands in a doubly nested configuration using ROMS at horizontal resolutions down to 1km, forced by the assimilative JCOPE2 and JMA-GSM/MSM. The model successfully reproduces anticyclonic eddies that are significantly retained on the western side of the islands to promote lateral mixing in the area.

KEY WORDS: ROMS; downscaling; submesoscale; eddy mixing; Kuroshio; Ryukyu Island; East China Sea

INTRODUCTION

Okinawa is home to ecologically significant coral reefs situated at the northernmost end of the border between the Pacific and the Indian Oceans. These corals lie within a biodiversity hotspot that supports the highest diversity of endemic species, plants and animals in the world. For preserving biodiversity and marine ecosystem in the coral coasts around Ryukyu Islands, a role played by the adjacent Kuroshio warm current is considered to be substantial for larval and nutrient transport. Guo *et al*. (2003) showed that the path and vertical structure of the Kuroshio in the East China Sea, including the Ryukyu Islands, become more realistic as the model's horizontal resolution increases on the basis of a triply nested ocean modeling using POM. Another numerical study using a high-resolution ocean model in this area indicates that the southwestward counter-Kuroshio Current and mesoscale eddies, at *O* (100) km, have non-trivial influence on volume and heat transport between Kuroshio and the Islands (Nadaoka *et al*., 2006).

Recently, to enhance the clarity of the dynamical processes in the upper oceans, studies on effects of submesoscale dynamics, at *O* (10) km or less, on the mean structure, eddies, frontal processes, stratification, etc. have been conducted quite actively (*e.g.*, Uchiyama *et al*., 2012). However, effects of the submesoscale phenomenon on the oceanic structure have not been fully investigated yet around the Ryukyu Island. Another important point here is that the Kuroshio in the area is considered to be largely affected by the shallow island topography on its east side that may result in unique turbulence. Therefore, we focus in the present study on two effects of 1) submesoscale eddies and their stirring, and 2) shallow island topography, in order to better understand dynamics and mixing between the Kuroshio and the islands. We thus conduct numerical experiments based on a detailed doubly nested ocean downscaling model using ROMS (Regional Ocean Modeling System; Shchepetkin and McWilliams, 2005) at horizontal resolution down to 1km around the Ryukyu Islands, forced by realistic assimilative meteorological and oceanic products to approach these scientific questions.

NUMERICAL MODEL

Figure 1 shows the oceanic downscaling model in doubly nested configuration embedded in the JCOPE2 (Japan Coastal Ocean Predictability Experiments; Miyazawa *et al*., 2009) domain. We rely on an 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). The outer domain is ROMS-L1 with a horizontal resolution of 3km and 32 vertical -layers, designed to encompass a fairly wide area to consider possible impacts of the Kuroshio flowing in from the Taiwan Strait and the Luzon Strait, and climatological freshwater discharge of the Yangtze River. The inner ROMS-L2

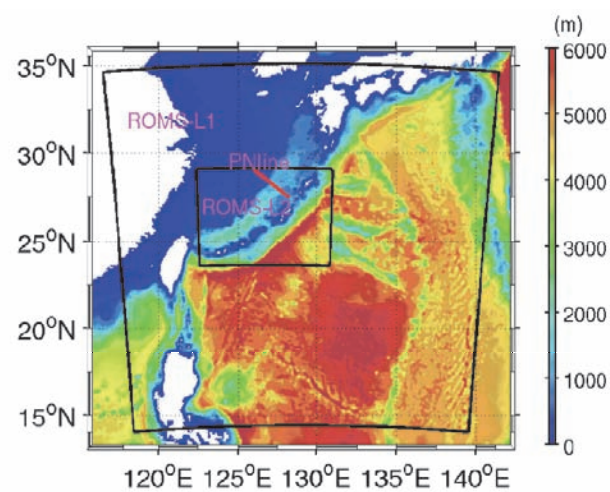

Fig. 1. Bathymetry and domains of doubly nested models: ROMS-L1 (outer box) and ROMS-L2 (inner box). The red line shows the JMA 's transect called PN-line.

Table 1. The configlations for ROMS-L1 and ROMS-L2.

	L1	L2
MPI Tile	128(32core×4node)	128(32core×4node)
Time step	240 sec	60 sec
Computational period	1/1/2005 ~10/21/2012	12/27/2010 ~10/21/2012
Horizontal grids	768× 768 (×32 level)	832×608 (×32 level)
Horizontal resolution	3.0 km	1.0 km
Surface wind stress (1/1/2005~12/31/2007)	QuikSCAT-ECMWF(daily)	JMA GPV-MSM(hourly, 12/27/2010~
Surface wind stress (1/1/2008~)	JMA GPV-GSM(daily)	
Surface flux	COADS（monthly）	COADS (monthly)
SST SSS	JCOPE2(20-day averaged)	JCOPE2(20-day averaged)
Major riverdischarges (Yangtze River)	Dai and Trenberth 2009(monthly)	n/a
Boundary・Initial condition	JCOPE2(daily)	L1（daily）
T-Snudging(1/20day−1)	JCOPE2(10-day averaged)	n/a
Topography	SRTM30	SRTM30

Table 2. The specifications of “camphor”.

Specifications	Machine	Cray XE6
	Number of Nodes	940
	Theoretical Peak Performance	300.8 teraflops
	Total Memory Capacity	59 TB
	Network Topology	3-D torus interconnect
	Bisection Bandwidth	1.7TB/s
Node Specifications	Processor (Core)	2 (2x16 = 32)
	Theoretical Peak Performance	320 gigaflops
	Memory	DDR3-1600 64GB 102.4GB/s
	Interconnect	Gemini 9.3GB/s or 4.6GB/s
Processor Specifications	Processor	AMD Opteron 6000 series processors
	Architecture	x86-64
	Clock	2.5 GHz
	Number of Cores	16
	Theoretical Peak Performance	160 gigaflops

domain with a horizontal resolution of 1km and 32 vertical -layers covers the entire chain of the Ryukyu Islands, from the Amami Islands of Kagoshima Prefecture to the north, all the way down to the Yaeyama Islands of Okinawa Prefecture.

Table 1 shows the configlation for the numerical model. The outer-most boundary and initial conditions are provided from the interpolated fields of the assimilative JCOPE2 daily-averaged data. The model topography is taken from SRTM 30 (Shuttle Radar Topography Mission), which covers the global ocean at 30 geographic arc seconds (about 1 km). We utilize the QuikSCAT-ECMWF blended wind and JMA GPV-MSM/GSM (Japan Meteorological Agency Meso-Scale Model/Global Spectral Model) data for the surface momentum forcing. Surface heat and freshwater fluxes are given by the COADS (The Comprehensive Ocean-Atmosphere Data Set) monthly climatology. A 20 day-averaged JCOPE2 data is applied to the sea surface temperature and salinity for the surface flux restoration. The monthly climatology of major river discharges in Dai *et al*. (2009) is considered for Yangtze River in ROMS-L1. A four-dimensional TS-nudging (nudging strength = 1/20 day^{-1}) towards the 10 day-averaged JCOPE2 temperature and salinity fields is performed for consistency of the Kuroshio path reproduced by the ROM-L1 with that of JCOPE2. The model computational period is about 22 months, from December 27, 2010 to October 21, 2012.

COMPUTATINAL RESOURCES

We make use of a linux-based supercomputer Cray XE6 named “camphor” at Kyoto University to run our model. **Table 2** shows the specifications of “camphor”. We typically use 128 AMD Opteron cores with parallelization based on MPI. For instance, the 16 months consecutive model run on the finest resolution took us about 2 days with 128 MPI processes.

RESULT

An extensive model-data comparison is performed against the field observation and satellite altimetry data to demonstrate the capability of reproducing the Kuroshio and 3D oceanic structure quite well. For example, seasonally averaged temperature and salinity in the vertical section along the transect are compared with the JMA’s observational hydrography (**Fig.1**; red line). Both of two model results exhibit an overall agreement with the observed temperature and salinity data not only in spring and summer (**Fig. 2**), but in all the four seasons (not shown here). Furthermore, the modeled mean and eddy kinetic energy at surface agree well with the altimeter-derived kinetic energy (not shown).

Figure 3 shows daily-averaged, surface relative vorticity normalized by the background rotation *f*, representing the significance of

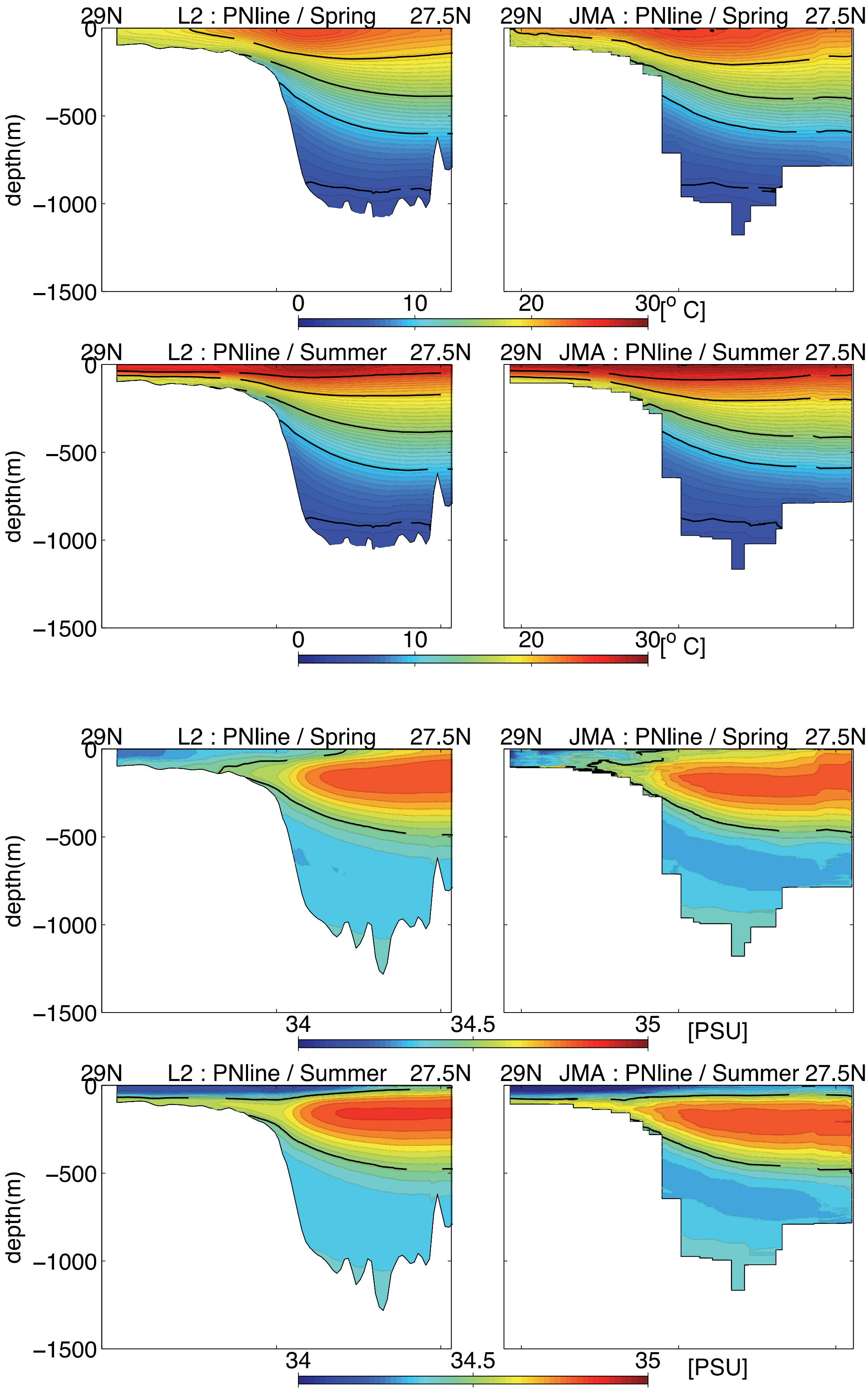

Fig.2. Vertical sections of seasonally averaged temperature (upper) and salinity (lower) from ROMS-L2 and *in-situ* data along the PN-line (Spring and Summer).

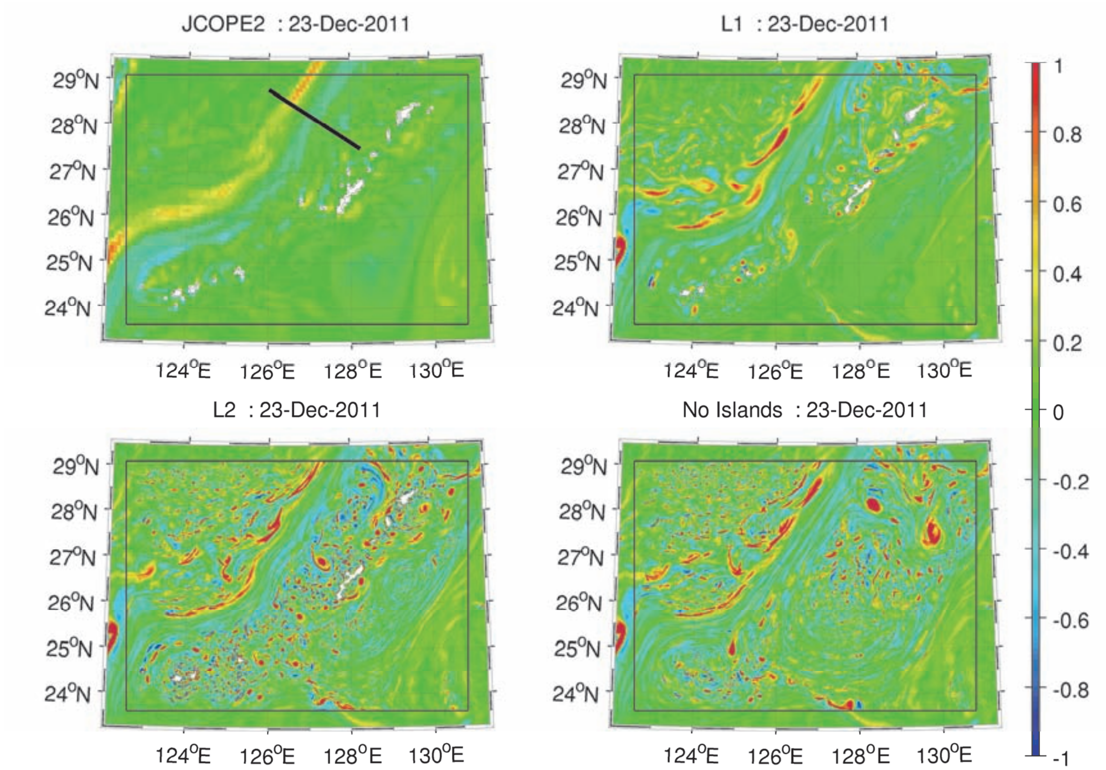

Fig.3. Surface relative vorticity normalized by the planetary vorticity, ζ / f (no dimension) on December 23, 2011, from the 4 models. The black line indicetes the transect for the vertical cross-sectional plots in Fig. 3 (b).

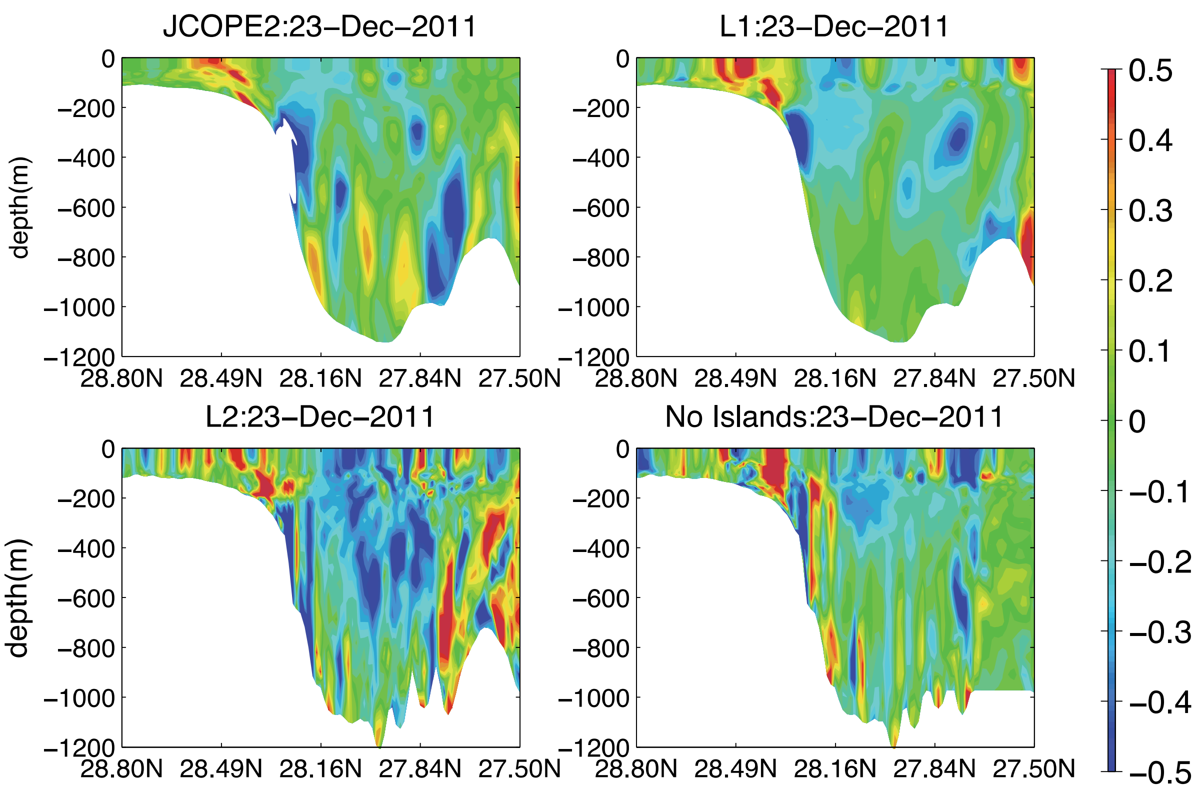

Fig.4. Cross sections (indicated by the black line in Figure 3) for normalized relative vorticity on December 23, 2011, from the 4 models.

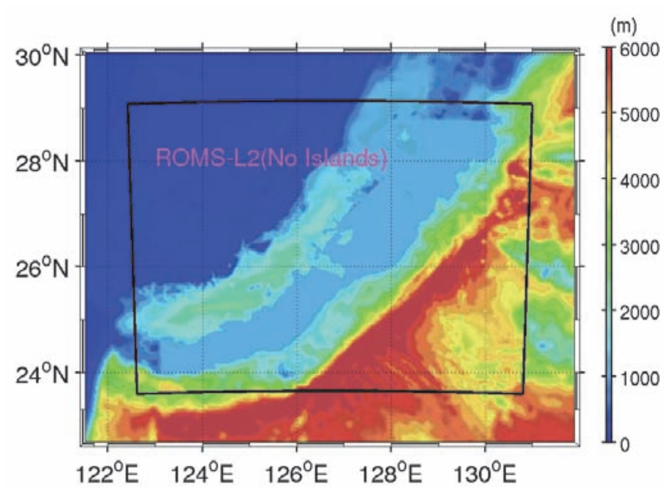

Fig. 5. Bathymetry and domains of "No Islands" experiment.

submesoscale eddies with its negative values. As resolution gets finer, size and magnitude of the resolved vortices are pronouncedly enhanced. We notice that negative vorticity in blue develops more strongly and widely on the east side of the Kuroshio than those on the other side, where positive vorticity in red dominates. ROMS-L2 has smallest eddies and largest negative vorticity near the island while the centrifugally-stable positive vorticity on the west side of the Kuroshio is attenuated rather quickly. This negative bias in the zonal direction near the islands is likely to be related to the model's grid resolutions. These findings suggest that submesoscale eddies on the east tend to be more anti-cyclones enhanced by the island topography. In order to evaluate this negative bias of relative vorticity with the island topography, we conduct an alternative numerical experiment directly examining the island topography effects around the Ryukyu islands. For the case with "no islands" (see its topography in **Fig. 5**), the islands and shallow topography h(m) < 1000 are sunk to h(m) = 1000 m while the other configurations are held unchanged as in the original ROMS-L2 model.

The submesoscale negative vorticity on the east side of the Kuroshio in the no island case is much weaker than that in ROMS-L2 and negative bias is almost disappeared (see the lower right of **Fig.3**). **Figure 4** shows vertical slices of the daily-averaged vertical normalized relative vorticity near the Okinawa main island. ROMS-L2 has largest negative vorticity not only at surface but also at depth than the other cases. These largest subdepth negative vorticity, however, is easily attenuated in the "no island" case. Therefore, emergence of the unique negative bias of surface relative vorticity between Kuroshio and the Ryukyu Islands is presumably caused by the lateral shear and resultant eddy shedding associated with the ridge topographic affected by the meridional mean momentum transport due to Kuroshio.

SUMMARY AND CONCLUSION

An elaborated high-resolution numerical oceanic downscaling model is developed to investigate submesoscale dynamics and mixing around Ryukyu Islands. An extensive model-data comparison is performed against the field observation and satellite altimetry data to demonstrate a quite close agreement. ROMS-L2 successfully reproduces negative vorticity significantly retained on the western side of the islands. No islands experiment suggests that the negative bias on the eastern side of Kuroshio is caused by topographic eddy shedding. It is expected that nutrients, larvae and other marine substances are transported from Kuroshio to the islands through these anticyclonic submesoscale eddies and associated lateral mixing in the upper ocean.

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