Numerical Study of the Kuroshio Current in the Tokara Strait

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Keywords: Kuroshio current, Tokara Strait, high-resolution ocean modeling, Baroclinic tidal effect

Abstract: A high-resolution regional circulation model was configured over the southern coast of Japan including the Amami Oshima to simulate the Kuroshio Current through the Tokara Strait (TS). The results are in good comparison with the currentmeter data from the Acoustic Doppler Current Profiler (ADCP). Comparison experiment with a higher horizontal resolution suggests the Kuroshio current through the four-islands chain presents fine sub-mesoscale structures especially in the downstream. Also the sensitivity experiments suggest the main axis of the Kuroshio in the model with tides moves to the south slightly (offshore) at the eastern part of the TS. Furthermore, there is concentration of the stronger current (magnitude of current speed > 60 cm/s) to the upper layer. The vertical shear of the current becomes larger and the Kuroshio becomes more baroclinic due to the tidal effects.

1 INTRODUCTION

The Kuroshio Current (KC), the famous western boundary current of subtropical gyre in the North Pacific Ocean (NPO), transports large amounts of heat, salt and nutrient from the tropical ocean(Qiu, 2001; Guo et al., 2012; Guo et al., 2013) [1-3] and plays very important roles in water mass formation, transformation and subduction (Nurser and Zhang, 2000). It flows northeastward along the continental slope of the East China Sea (ECS), turns east through Tokara Strait (TS), and proceeds eastward along the southern coast of Japan until it separates from the coast and enters the Pacific basin. Thus, the TS is a key channel/passage connecting the ECS and the NPO, which is regarded as a choke point in considering climate change and cycles of water and materials over the NPO (Nitani, 1972).

The investigations on the velocity, the volume transport and the variations of the KC have been addressed in numerous previous studies. Most of the early studies have used the hydrographic observations to estimate the temporal and spatial variations of the KC, according to the geostrophic calculation that assuming no motion in the deep layers and neglecting the barotropic component of the KC (Guo et al., 2012; Guo et al., 2013; Wei et al., 2013). Later, on account of the availability of the direct current measurements, the fine spatial structures and the temporal variations of the KC have been described in detail (Feng, 1999; Yamashiro, 2008; Zhu et al., 2017).

The tide, as one of the most important physical processes in the ESC, has been investigated for several decades (Ogura, 1934), and it propagates to the northwest in the TS against the KC. In accordance with the direct current measurements and the satellite altimetry analysis, besides the barotropic (external) tide motions, the baroclinic (internal) tides are also active in the ECS and its adjacent water (Yamashiro, 2008; Zhu et al., 2017; Niwa and T, 2004). It is widely accepted the baroclinic tides can be an important sink of the barotropic tide energy and play a significant role in mixing in the deep layer (Munk and Wunsch, 1998; Qiu et al., 2012).

Numerical models have suggested that the TS is one of the most energetic straits in terms of generation of internal tides around the Ryukyu-Taiwan-Luzon island chain (Niwa and T, 2004; Varlamov et al., 2015). The energy of the M_2 baroclinic tide converted from the barotropic tide is

Wang, B., Liu, T., Hirose, N. and Yamashiro, T.
Numerical Study of the Kuroshio Current in the Tokara Strait.
In *Proceedings of the International Workshop on Environment and Geoscience (IWEG 2018)*, pages 395-399
ISBN: 978-989-758-342-1

subject to the local dissipation in TS (Niwa and T, 2004; Varlamov et al., 2015). The propagation speed of the M_2 baroclinic tide is 3.5-4.5m/s around the Ryukyu island chain, which is the same order of the KC (0.75-1.5m/s). The advection effect of KC, which is not represented in the early studies, is considered to be important particularly around the TK where the propagation direction of the baroclinic tide is nearly parallel to the KC path (Niwa and T, 2004). The moored acoustic Doppler current profile (ADCP) data set evidence that the internal tide in the TS is greatly attributed to the third vertical mode (Yamashiro, 2008; Zhu et al., 2017). It seems that the internal tides interfere with each other and the low frequency ocean circulation to create a complicated wave pattern when it propagates seaward. Recent development of the ocean modeling allows the concurrent simulation of tides and lower-frequency ocean circulation. Previous studies suggested that there are active interactions between the baroclinic tides and lower-frequency phenomena, which result in the incoherent nature of the baroclinic tide (Varlamov et al., 2015). The lower-frequency ocean circulation affects the internal tides has been investigated briefly. However, the effect of tidal manipulation on the KC in this region, including the horizontal advection and large amplitude vertical displacement of isopycnal, still has not been examined so far. Furthermore, the previous simulated results indicated that the baroclinic dissipation rate is more dependent on the resolution of the bottom topography (Niwa and T, 2004), though only the rough estimate of the dependence based on the empirical relationship between the baroclinic energy conversion rate and the horizontal resolution has been done. Thus, the main purpose of this study is to clarify the effects of tides on the KC in the TS at a high resolution.

This paper is organized as follows. Section 2 provides a description on the tide-resolving ocean general circulation model for the Kuroshio region with an extremely high resolution in TS, and reports the ship-mounted ADCP data which are used to validate the simulated results. Section 3 describes and validates the simulation results. The final section is devoted to summary of the present study.

2 MODEL CONFIGURATION AND DATA

Niwa and Hibiya (Niwa and T, 2004) suggested the resolution of the bottom topography might be a key factor to predicate the baroclinic dissipation rate of M_2 internal tide. Thus, the Z-coordinate ocean model might have advantage to attain the goal of present study. A high resolution regional circulation model based on the Research Institute for Applied Mechanics (Kyushu University) Ocean Model (RIAMOM) is adapted to the southern coast of Japan, named DREAMS_Energy (shorten as DR_E, (Liu et al., 2018)), which is a 3D primitive equation ocean model adopting the Arakawa B-grid and Z-coordinate.

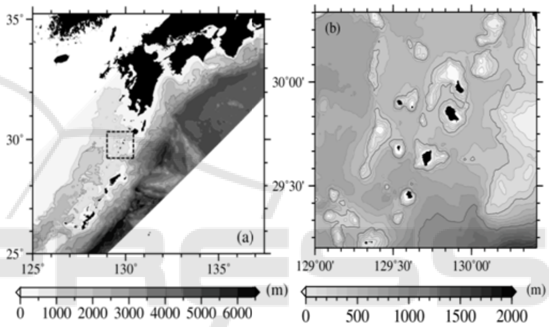


Figure 1: (a) Bottom topography of the large (DR_E) and (b) small (DR_T) models.

The model covers southwest of Japan with the horizontal resolution of 1/60◦ longitude by 1/75◦ latitude and 33 layers in vertical (Figure 1a). The detail configuration of model can be found in Liu et al (Liu et al., 2018). To exam the horizontal resolution effect on the Kuroshio Current, another higher resolution model (1/180◦×1/225◦) DR_T also has been set up (Figure 1b). This model topography is averaged from the JTOPO30 (~1km) and J-EGG500 (500m). The initial and boundary conditions are determined by the simulated results of the DR_E. The other conditions of this model follow DR_E. As compared experiment, another experiment excluding tides, named as DR_T', has been designed (Table 1). The analyzed period is from 1 April 2012 to 30 September 2015. The moving vessel ADCP data along the ferry line between Kagoshima and Naha provided by the Kagoshima University Faculty of Fisheries are used to validate the simulated results. The observed sections in the TS have been shown in Figure 2.

Table 1: A list of experiments.

Experiments	Horizontal resolution	Forcing
DR_E	1/60∘×1/75∘ (~1.5km)	With tides
DE_T	1/180∘×1/225∘ (~500m)	With tides
DR_T'	1/180∘×1/225∘ (~500m)	Without tides

3 RESULTS

3.1 Current Validations

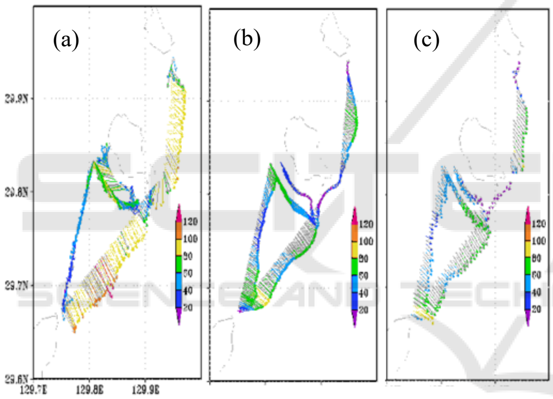


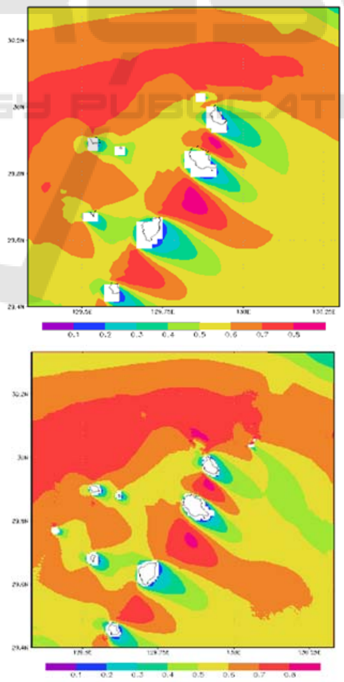
Figure 2. (a) ADCP data on Oct. 21, 2014, (b) simulated results of DR_E model and (c) DR_T model.

The simulated temperatures of DR_E are compared with the observation data. And the basic features of the temperature distributions are represented well by the present model, which has not been shown because of paper length.

Figure 2a and Figure 2b show the ADCP observation and simulated Kuroshio Current pattern of DR_E model on Oct. 21, 2014 at 50m in the TS, respectively. On account of the hourly output of the simulation results, which has the certain time deviation with the ADCP observation, the magnitude and directions of simulated current seem to be a little different compared with the observation. While, the spatial pattern of current has been reproduced well. It suggests that the DR_E model simulated the Kuroshio Current structure realistically.

3.2 Horizontal Resolution Effect on the Kuroshio Current

To investigate the horizontal resolution effect on the Kuroshio Current, another higher resolution model DR_T, which using approximate 500m mesh grids size in horizontal direction. The simulated results of DR_T will be addressed below. There are no essential distinctions between DR_E and DR_T. The strong current approaches the islands closer in DR_T with stronger velocity (Figure 2c) compared with that of DR_E (Figure 2b). Furthermore, the sub-mesoscale eddies could easily be observed in the higher resolution model results. Especially, after the passage of the strong current through the narrow channels between these islands, eddies could interact to each other (Figure 3). In other words, the higher resolution model could simulate more accurate structure of the Kuroshio in the downstream of the TS. It implies that the DR_E (1/60° × 1/75° mesh) model already simulate the Kuroshio pattern realistically.



(a)

(b)

Figure 3: Simulated magnitude of Kuroshio Current during three years (a)DR_E model, (b) DR_T model.

3.3 Tidal Effects on The Kuroshio Current

In order to investigate the tidal effects on the Kuroshio Current, another experiment DR_T' is designed, which excludes the tides from the open boundaries and the other conditions are following the DR_T. Compared to the model without tides (DR_T'), the occurrence of the internal tides and corresponding changes in the density fields are found in the downstream of the TS in the results of DR_T. As shown in Figure 4, the main axis of the Kuroshio in the model with tides moves to the south slightly (offshore) at the downstream of TS. Furthermore, the stronger current (magnitude of current speed > 60 cm/s) concentrates to the upper layer. The vertical shear of the current becomes larger and the Kuroshio becomes more baroclinic after the consideration of the tide motions. Nevertheless, the detailed mechanism for this nonlinear interactions between the Kuroshio Current and the internal waves must await further investigation.

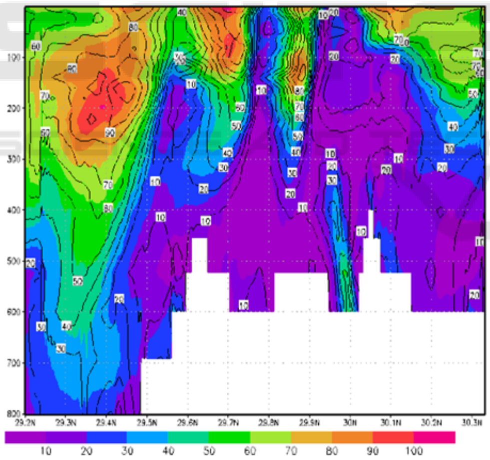


Figure 4: Magnitudes of the simulated Kuroshio Current in summer along 130◦E for the DR_T model (color map) and DR_T' model (contours).

4 SUMMARY

A high-resolution regional circulation model is configured over the southern coast of Japan to simulate the Kuroshio Current through the Tokara Strait. The simulated results are in good agreement with hydrographic and currentmeter observations. The compared experiment suggested that the simulated Kuroshio Current patterns are sensitive to the horizontal resolution especially in the downstream of the four-islands chain. Furthermore, compared to the model without tides, the occurrence of the internal tides and corresponding changes in the density fields are found in the downstream of the TS. The main axis of the Kuroshio in the model with tides moves to the south slightly at the eastern part of the Tokara Strait. Furthermore, there is concentration of the stronger current (magnitude of current speed > 60 cm/s) to the upper layer. The vertical shear of the current becomes larger and the Kuroshio becomes more baroclinic due to the tidal effects. Nevertheless, the detailed mechanism for this nonlinear interactions between the Kuroshio Current and the internal waves must await further investigation.

ACKNOWLEDGMENTS

This work was supported by National Natural Science Foundation of China (Project 41706023), the Natural Science Foundation of Jiangsu Province (Grants No 20170871), the Fundamental Research Funds for the Central Universities (2016B11514) and the Open Fund of the Key Laboratory of Ocean Circulation and Waves, Chinese Academy of Sciences. The authors also would like to thank the editor and the anonymous reviewers for their work on this paper.

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