Journal of Marine Systems 150 (2015) 41–55

Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

Simulation of eddy-driven deep circulation in the East/Japan Sea by using a three-layer model with wind, throughflow and deep water formation forcings

Yumi Park [a], Hong-Ryeol Shin [a,*], Jong-Hwan Yoon [b], Cheol-Ho Kim [c], Yutaka Yoshikawa [d]

[a] Department of Atmospheric Science, Kongju National University, Shinkwan-dong, Kongju, Chungnam 314-701, South Korea
[b] Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka 816-0811, Japan
[c] Physical Oceanography Division, Korea Institute of Ocean Science & Technology, Ansan 426-744, South Korea
[d] Graduate School of Science, Kyoto University, Kyoto, Japan

A R T I C L E I N F O

Article history:
Received 27 September 2014
Received in revised form 6 May 2015
Accepted 20 May 2015
Available online 27 May 2015

Keywords:
The East/Japan Sea
Three-layer model
Deep circulation of the East/Japan Sea
Deep water formation
Eddy kinetic energy
Eddy-driven circulation

A B S T R A C T

A three-layer model was used to investigate the impact of grid resolution, bottom topography, wind, throughflow (the Tsushima Warm Current) and deep water formation (DWF) forcing on deep circulation in the East/Japan Sea. High grid resolution (1/36°) and real bottom topography are essential to capture the observed features of surface and deep circulation. An increase of grid resolution from 1/12° to 1/36°, wind and DWF forcing dramatically increase the current velocity and eddy kinetic energy (EKE) of the lower-layer. Of the three forcings, the influence of wind forcing is the most powerful on the abyssal circulation, followed by the order of the throughflow and DWF forcing, respectively. DWF forcing does not largely change the horizontal circulation pattern of the lower-layer in the 1/36° resolution model, but it increases the current velocity by 33.9%. Model results indicate that surface EKE is larger in the southern region than in the northern region of the East/Japan Sea, while deep EKE is larger in the northern area. These results are in good agreement with EKE distributions obtained from the surface drifter and the ARGO float trajectories. The EKE maxima of the lower-layer is geographically concentrated on the bottom slope, indicating that the strong circulation in the lower-layer is due to the strong eddy activity on the slope. The flux calculation shows that the primary eddy fluxes of potential vorticity driving deep circulation are layer thickness flux (LAY) and relative vorticity flux (REL).

1. Introduction

The East/Japan Sea is a semi-enclosed marginal sea in the northwestern Pacific, bounded by Korea, Japan, and Russia (Fig. 1). It is connected with other seas by four narrow and shallow straits; the greatest strait depth is less than 200 m. Inflow through the Korea/Tsushima Strait and outflow through the Tsugaru and Soya Straits link the East/Japan Sea to the East China Sea, the northwestern Pacific Ocean and the Okhotsk Sea, respectively. The East/Japan Sea is divided into the Japan Basin in the north, the Ulleung Basin in the southwest, and the Yamato Basin in the southeast. The Japan Basin is the deepest and the largest basin.

The Tsushima Warm Current, after passing through the Korea/Tsushima Strait, branches into two or three flows (Fig. 2A). The Tsushima Warm Current which flows through the eastern channel of the Korea/Tsushima Strait is connected to the Nearshore-branch, most of which flows northward at 200–300 m depth along the Japanese coast (Hase et al., 1999). On the other hand, Tsushima Warm Current which flows through the western channel constitutes the East Korea Warm Current and Offshore-branch. The westernmost flow, the East Korea Warm Current, flows northward along the east coast of Korea, and separates from the coast of Korea near 38°N. The Liman Current and North Korea Cold Current, which moves southward along the coast of Russia and North Korea, meet with the East Korea Warm Current around 38–40°N and then flow eastward along the subpolar front at approximately 40°N.

Recent current meter measurements and ARGO float trajectories in the abyssal layers reveal general deep mean circulation patterns in the entire East/Japan Sea with relatively small basin-scale circulations in the three basins (Fig. 2B). Relatively strong currents flow cyclonically along the basin periphery and weaker currents flow in the interior region (Senjyu et al., 2005; Teague et al., 2005). Deep current in the Japan and Yamato basins flows cyclonically, essentially following the f/H contours (f is the local Coriolis parameter and H is the depth). However, in the Ulleung Basin there is a lower correlation (than in the other two basins) between the direction of deep currents and the f/H contours (Choi and Yoon, 2010). Deep water is thought to be formed in the East/Japan Sea through open-ocean convection south of Vladivostok, by air–sea interactions in the severe winter (Kawamura and Wu, 1998; Senjyu and Sudo, 1996; Seung and Yoon, 1995). In addition, the deep water

* Corresponding author. Tel.: +82 41 850 8529; fax: +82 41 856 8527.
E-mail address: hrshin@kongju.ac.kr (H.-R. Shin).

http://dx.doi.org/10.1016/j.jmarsys.2015.05.006
0924-7963/

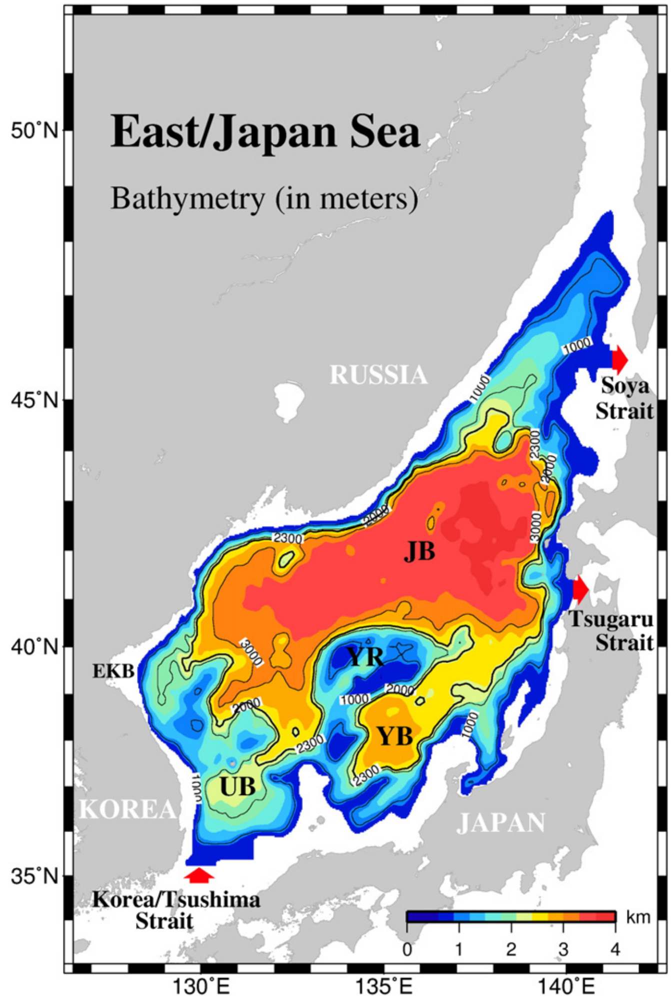

Fig. 1. Bottom topography of the East/Japan Sea. Locations of the inflow and outflow ports in the model are marked as red arrows in three straits. The contour interval is 1000 m, and the bold line of 2300 m depth is also shown. JB: Japan Basin; YB: Yamato Basin; UB: Ulleung Basin; YR: Yamato Rise; EKB: East Korean Bay.

formation (DWF) event is thought to contribute occasionally to the spin-up of the thermohaline circulation in the East/Japan Sea (Senjyu et al., 2002).

A series of numerical experiments have been conducted to simulate and understand the deep circulation of the East/Japan Sea. Using a four layer model, Hogan and Hurlburt (2000) investigated the impact of grid resolution, baroclinic instability, bottom topography, and isopycnal outcropping on the dynamics of wind- and throughflow-forced surface circulation in the East/Japan Sea. They showed that a horizontal grid resolution of at least 1/32° (3.5 km) is necessary to generate sufficient baroclinic instability to produce eddy-driven cyclonic deep flows. However, the abyssal currents suggested by Hogan and Hurlburt (2000) have no verification from the observation such as current meter or ARGO data. Besides, eddy kinetic energy (EKE) of the deep layer is larger in the southern East/Japan Sea than in the northern East/Japan Sea in Hogan and Hulburt (2000), while EKE of the abyssal layer in the observation data is larger in the Japan Basin (Choi and Yoon, 2010; Park and Kim, 2013).

The wind-driven ocean circulation of the East/Japan Sea, using a two-layer model with horizontal resolution of 1/12°, showed a large basin-wide cyclonic surface circulation driven by the positive wind-stress curl (Yoon et al., 2005), but the modeled lower-layer circulation could not explain the observed features of deep currents: an increased horizontal resolution is necessary to produce the observed mean flows, as is the inclusion of the inflow of the Tsushima Warm Current and the DWF forcing. In a primitive ocean general circulation model (OGCM) with extra-fine resolution (a horizontal grid interval of 1/36° and 46 vertical levels), cyclonic deep mean circulation was simulated successfully despite the lack of the DWF forcing (Kim, 2007). However, in the OGCM model (RIAM Ocean Model), maximum volume transport in the Japan Basin was only about 3.5 Sv (1 Sv = 10^6 m^3 s^{-1}); much less than the observed results of about 10 Sv (Choi and Yoon, 2010).

Several previous studies (e.g., Greatbatch, 1998; Greatbatch and Li, 2000; Holloway et al., 1995) simulated the eddy-driven deep circulation with the parameterized eddy forcing (topostress). In the East/Japan Sea, Holloway et al. (1995) showed an abyssal cyclonic circulation through the parameterization of eddy–topography interaction in a coarse (1/6°) resolution numerical model. Yoshikawa (2012) studied an eddy-driven deep circulation caused by deep water formation (DWF) in two- and three-layer model without using the parameterized topostress. He addressed the fact that an eddy-driven circulation is

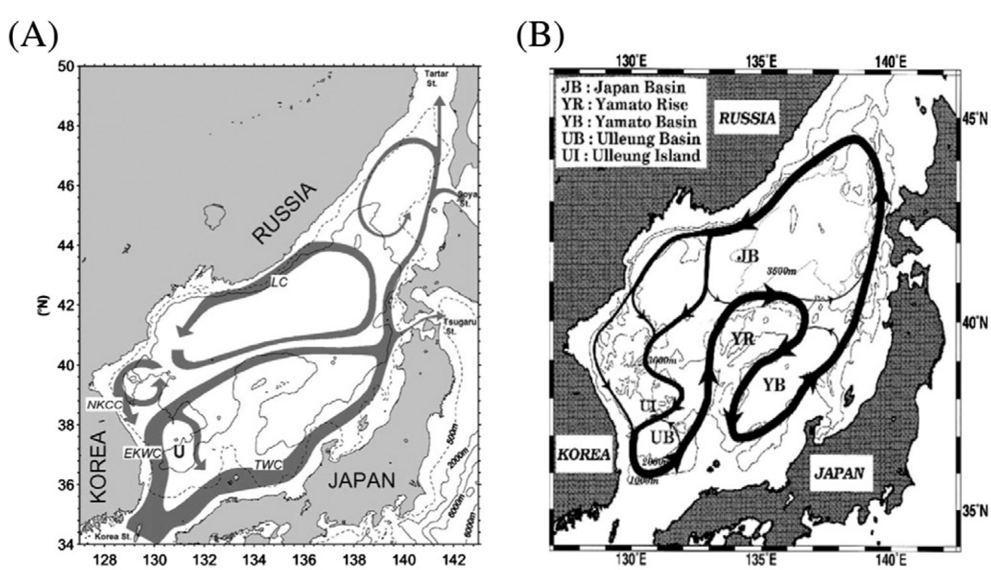

Fig. 2. Conceptual views of the (A) surface and (B) deep circulation (Senjyu et al., 2005) in the East/Japan Sea. EKWC: the East Korea Warm Current, TWC: the Tsushima Warm Current, NKCC: the North Korea Cold Current, U: Ulleungdo, LC: the Liman Current.