

BAROTROPIC NUMERICAL STUDIES ON THE DRIVING MECHANISMS OF THE EAST KOREAN WARM CURRENT*

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INTRODUCTION

The circulation of the Japan/East Sea (hereafter JES) is a central problem of physical oceanography. Uda (1934) gave the first schematic surface current chart for this area. Moriyasu (1972) summarized the general hydrographic features of the JES. Yoon (1982 a-c) and Kawabe (1982 a, b) pioneered research on the JES circulation was focused on the path of the Tsushima Current. After then, many numerical simulations of the JES circulation were reported.

The formation of the East Korean Warm Current (EKWC) is one of the most important problem in the JES circulation. Some early investigators (Yoon, 1982a; Kawabe, 1982b; Kang, 1988; etc.) suggested that the EKWC is a western boundary current induced the planetary β -effect. Their results showed the EKWC is a permanent current. It is very strange that the EKWC did not appear at all in 1981 (Kim and Legeckis, 1986). So it is necessary to study further the driving force of the EKWC.

In this study, a Princeton Ocean Model (known as POM97) was employed to simulate the circulation in the JES. The open boundary inflow and outflow conditions with realistic water depth in the numerical model are first set. Then, several experiments with artificial topography were made to test how the topography affects the circulation pattern in the JES.

NUMERICAL MODEL

The hydrodynamic model used in this study was the Princeton Ocean Model (POM, the new version is POM97). POM was developed in Princeton University by Blumberg and Mellor (1980) and had been applied to various areas such as estuarine (Oey *et al.*, 1985a, b; Blumberg and Goodrich, 1990; Galperin and Mellor, 1990), coastal (Blumberg *et al.*, 1993; Chen and Beardsley, 1995; Allent *et al.*, 1995) and oceanic (Mellor and Ezer, 1991) bodies of water. POM97 is a free surface primitive three-dimensional (sigma coordinates), time-dependent hydrodynamic model with complete thermodynamics and a second moment turbulence close sub-model. For more details of

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POM97, please see POM Users Guide (Mellor, 1998) whose variables are used in this paper.

The computational domain is from 128 °E to 140 °E, 34 °N to 46 °N (Fig. 1). The open boundaries are set at the Tsushima Strait (southern open boundary) and the Tsugaru Strait (eastern open boundary). The other parts of the boundaries are closed according to the real coastline. The horizontal resolution is $\frac{1^\circ}{10} \times \frac{1^\circ}{10}$ where DX is from 8.34 km to 9.57 km and DY is about 11.12 km in a spherical coordination system. In the vertical, 10 layers are set. In sigma coordinate, they are:

$$\begin{aligned} \text{ZZ}(k) = & -0.0025, -0.00875, -0.01875, -0.0375, -0.0625, -0.1, \\ & -0.1875, -0.375, -0.625, -0.875 \end{aligned}$$

where k is the layer number from top ($\sigma=0$) to bottom ($\sigma=-1$).

Some parameters used in the model are as follows:

TBIAS = 10. (temperature shift value in order to reduce round-off error in 32-bit arithmetic)

SBIAS = 35. (salinity shift value in order to reduce round-off error in 32-bit arithmetic)

DAYS = 30. (length of running in days)

ISPADV = 5 (step interval wherein external mode advective terms are not updated)

SMOTH = 0.05 (constant in time smoother to prevent solution splitting)

HORCON = 0.2 (constant in Smagorinsky horizontal viscosity formulation)

TPRNI = 0. (horizontal diffusivity inverse Prandtl number A_H/A_M)

In the barotropic experiments, we set MODE = 4 and used constant $T (= 8^\circ)$ and $S (= 34 \text{ psu})$.

We begin our simulation from “cool condition” ($u = v = w = 0$, $\text{ele} = 0$) with ramping period of about 0.8 day which is a half pendulum day of the center point of the computational domain. Of course, we can “hot restart” our simulation by giving initialization variable files. The inflow and outflow are set at the southern open boundary and the eastern open boundary respectively, and are kept in balance in the computation. At the southern open boundary, the ratio of inflow fluxes into the west channel of Tsushima Strait to that into the east channel is 2:1. The vertical structure of horizontal velocity at the open boundary is more artificial. At the southern open boundary, velocity is simply set at the same value in different layers, and at the eastern open boundary we make more water flow out from upper layers. The inflow (or outflow) is $2 Sv (10^6 \text{ m}^3/\text{s})$.

Fig. 2 shows the topography of the JES. The maximum depth exceeds 3700 meters. Using our fine grid system with real topography in the JES, the CFL condition is $\Delta t \leq 17.127$ seconds.

So we set the external mode time step DTE = 15s and the internal mode time step DTI = 750s.

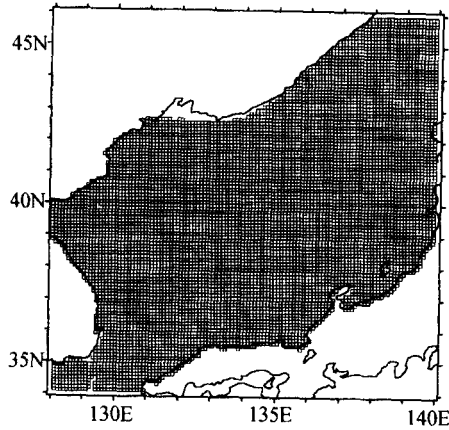


Fig. 1 Mesh of computational domain

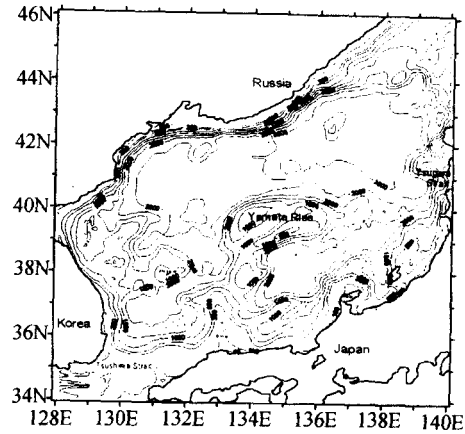


Fig. 2 The topography of the Japan/East Sea

NUMERICAL EXPERIMENTS

Experiment 1 uses the real depth data. Fig. 3(a) is the surface current result; Fig. 3(b) is the elevation result, which also is an index of inflow and outflow water balance. Fig. 3(c) is the water flux result, which is the product of the grid point depth-average velocity multiplied by the grid box vertical section area. Fig. 3(a) shows a strong current along the Japan coastline, but no strong current along the east Korean coastline, i. e. there is no EKWC. The elevation result (Fig. 3b) also shows high elevation gradient near the Japan coastline and fairly flat elevation gradient in the other area of our computational domain. The elevation distribution implies that the main part of the current along the Japan coastline is geostrophic current. Fig. 3(c) shows many meanders along the Japan coastline from the Tsushima Strait to the Tsugaru Strait.

Under the realistic topography, there is no EKWC which expected by some two-layer models (Yoon, 1982a, *et al.*). So a new experiment (Exp. 2) was made. Exp. 2 was a flat bottom experiment with the 500 m depth through out the entire calculation domain. Fig. 4 shows the result of Exp. 2. The surface current result (Fig. 4a) showed a current along the east Korean coastline corresponding to the EKWC. Fig. 4(b) and (c) confirm the current comes along the east Korean coastline from the Tsushima Strait to the Tsugaru Strait. This result implies that the EKWC exists when there is no topography β -effect (such as flat bottom). So there will be some balance between the planetary β -effect and the topography β -effect which control the barotropic circulation pattern in the JES. If the planetary β -effect is more important than the topography β -effect, the current will flow along the east Korean coastline (such as in Exp. 2). But in the realistic topography, the planetary β -effect cannot be stronger than the topography β -effect, so there is no EKWC (Exp. 1). Comparison between Exp. 1 and Exp. 2 indicates that the topography is a more important factor in controlling the circulation pattern in the JES. The slope near the Japan coastline is important in formation of the nearshore branch of the Tsushima Warm Current which flows along the Japan coastline.

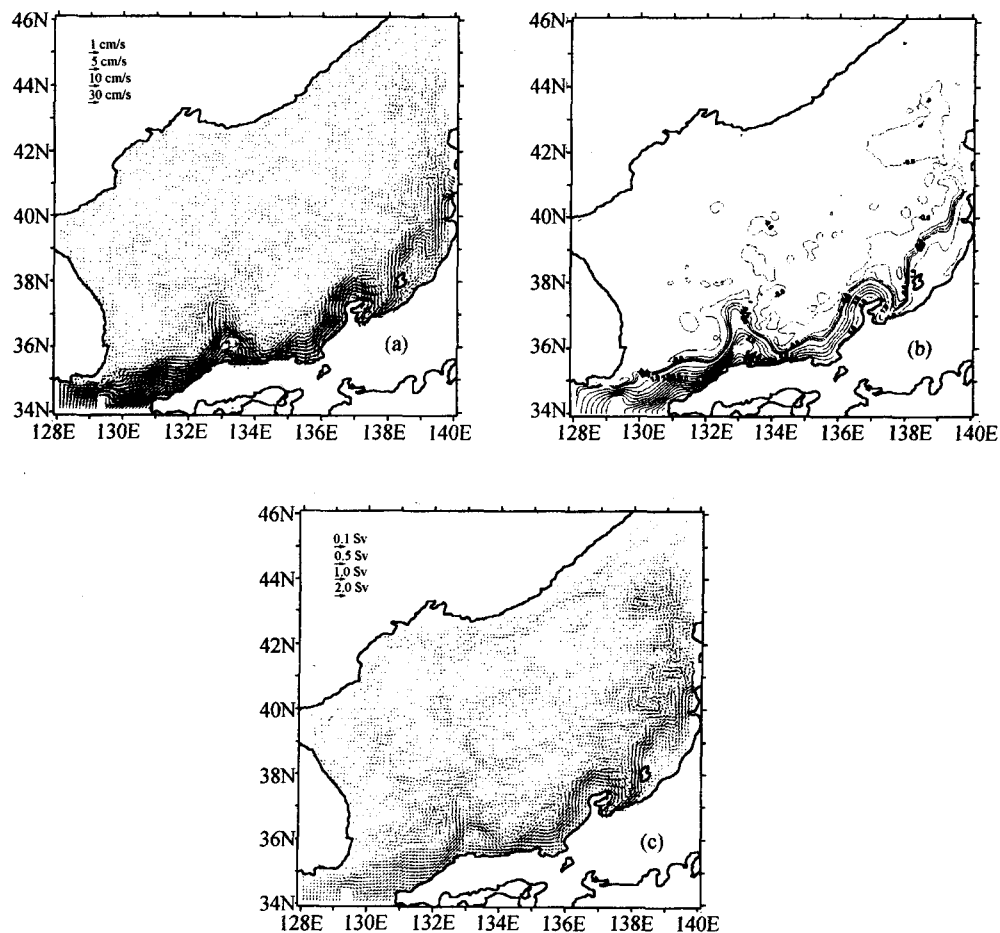


Fig. 3 The realistic topography result with 2 Sv inflow (Exp. 1)

(a)surface current; (b)elevation; (c)water flux

It can be found from following experiment that the planetary β -effect is not stronger than the topography β -effect, in the realistic topography of the JES. When we "cut" the depth shallower, the topography β -effect will become weaker. So the current will appear along the east Korean coastline. We designed the new experiment, Exp. 3, and set the maximum depth of the JES as 200 m. If the depth is shallower than 200 m, the depth is not changed. Otherwise, if the depth is deeper than 200 m, the depth will be replaced by 200 m. Fig. 5 shows the result of Exp. 3. From the surface current result (Fig. 5a), the current flowing into the JES from Tsushima Strait first goes northeastward along the Japan coastline; then at Oki Island (near 36°N 133°E), the main part of the inflow turns northwestward and goes along the east Korean coast. The rest of the inflow continues flow northeastward along the Japan coastline to form the Nearshore Branch of the Tsushima Warm Current in the JES. The elevation result (Fig. 5b) illustrates that the surface current flows almost along the isoline of elevation and Fig. 5(c) shows that the water is mainly transported along the S-shaped route from

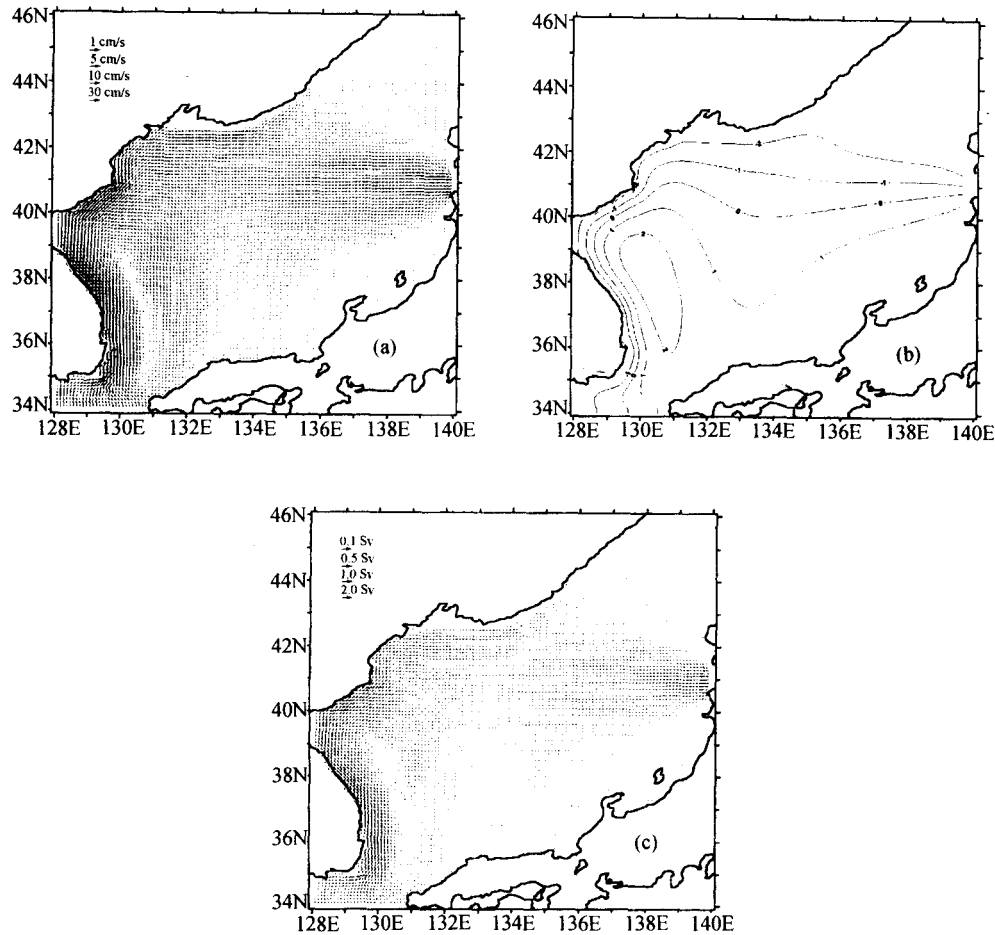


Fig. 4 The result of 500 m flat bottom with 2 Sv inflow (Exp. 2)
(a) surface current; (b) elevation; (c) water flux

the Tsushima Strait to the Tsugaru Strait. Exp. 3 showed there is a balance between the planetary β -effect and the topography β -effect. Only in special topography cases (such as $\text{depth} \leq 200$ m or flat bottom), the planetary β -effect is clearly important in the barotropic case. But in the realistic JES topography, the planetary β -effect cannot support a strong current along the east Korean coastline in the barotropic case.

DISCUSSION

The reason for selecting a 30 days run in the barotropic case is that we found the kinetic energy became stationary after was run for 30 days. Running it longer did not change the result significantly. Fig. 6 shows the kinetic energy of Exp. 1. The other experiments had the same kinetic energy

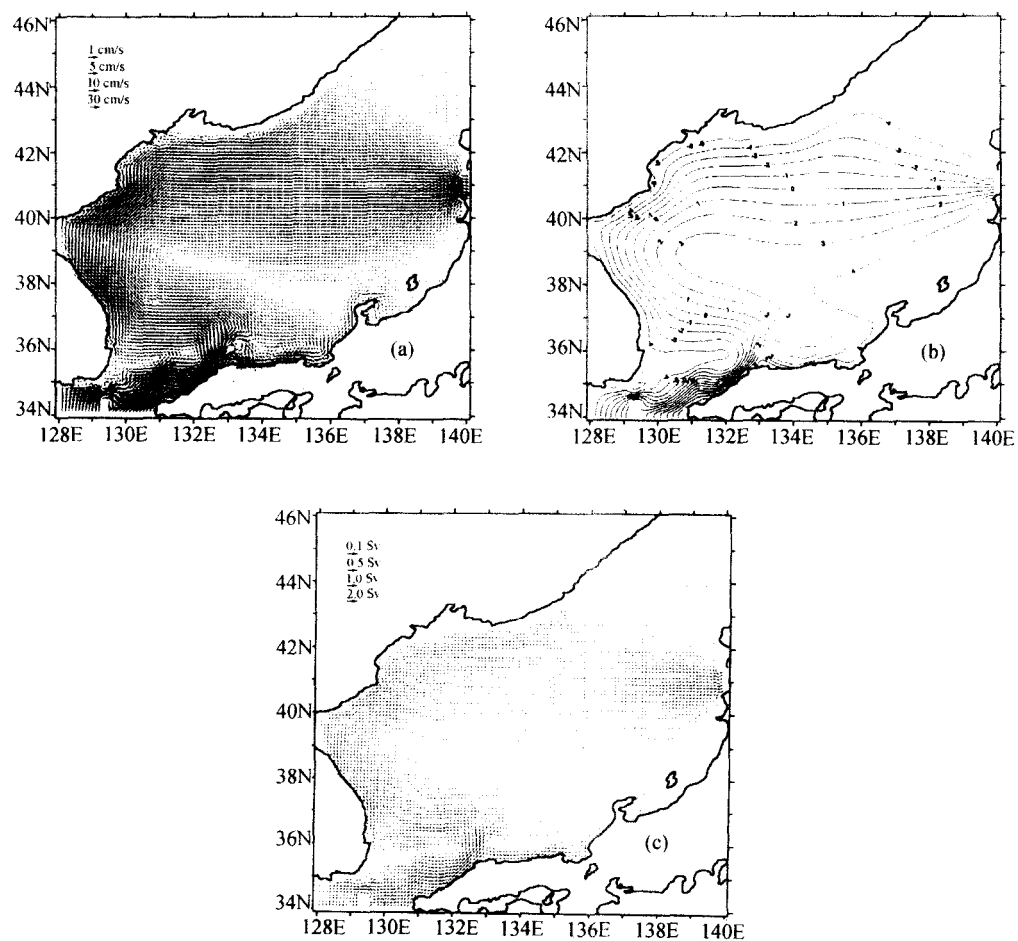


Fig. 5 The result of depth ≤ 200 meter with 2 Sv inflow (Exp. 3)
(a)surface current; (b)elevation; (c)water flux

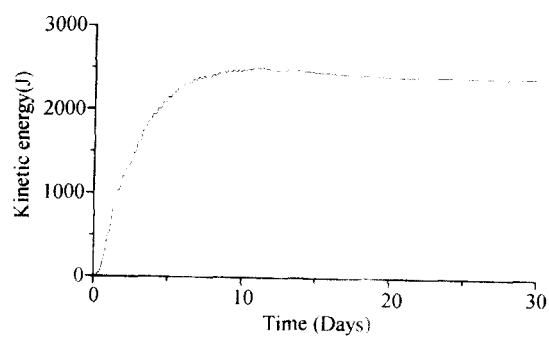


Fig. 6 The kinetic energy of Exp. 1

result.

Besides Exp. 2, we also tested other different flat bottom cases by taking water depths equal to 1000m, 200m, and 100m (results not shown). All experiments showed a current along the east Korean coast. We also found that when the flat bottom was deeper, the width of the current along the east Korean coastline was narrower. This is the effect of friction. If we simply introduce linear depth-averaged equations to represent the flat bottom case, the equations can be written as follows:

$$\nabla \cdot \vec{U} = 0$$

$$\gamma \vec{U} + f \vec{k} \times \vec{U} + hg \nabla \zeta = 0$$

where $\vec{U}$ is the vertically integrated horizontal transport, f is the Coriolis parameter, $\vec{k}$ is the unit vector in vertical direction, h is the depth and ζ is the water elevation from the undisturbed water level, γ is a linear friction coefficient (sometimes called Rayleigh friction parameter). In our flat bottom case, the inflow is kept as 2 Sv. So the deeper the flat bottom, the smaller the γ will be. As pointed out by Kang (1988), the parameter $\frac{\gamma}{\beta}$ is a characteristic width index of the East Korean Warm Current where $\beta = \frac{\partial f}{\partial y}$. Hence a smaller γ means the current along the east Korean coastline is narrower.

In order to confirm the conclusion that the planetary β -effect cannot support the EKWC in the realistic topography of the JES in the barotropic case, we set a current along the east Korean coastline as initialization condition, then ran the model under the realistic topography of the JES. It will directly validate above conclusion if there is no current along the east Korean coastline in the final result. Because the result of Exp. 2 had a current along the east Korean coastline, the new experiment (Exp. 4) was designed to use the results of Exp. 2 as initialization condition and “hot” restart to run the model for 60 days more by using the realistic topography of the JES. In the sigma coordinate, it is easy to set the initialization velocity of Exp. 4 by simply reading the result of Exp. 2 in and don't consider the depth. Fig. 7 shows the kinetic energy result of Exp. 4.

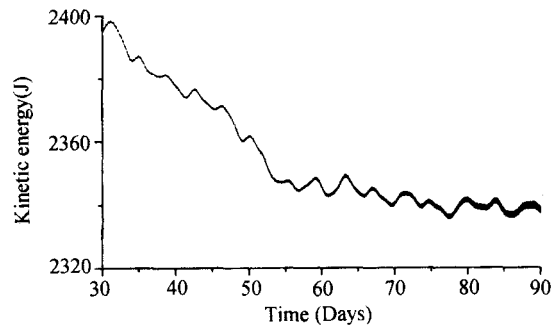


Fig. 7 The kinetic energy result of Exp. 4

After running for more than 60 days, although the kinetic energy had undulations, it tended to approach the final kinetic energy value of Exp. 1. A check at this time showed that the surface circulation pattern, elevation result and current flux result were almost the same as the results of Exp. 1

(figures not shown). This means that even if a current along the east Korean coastline is initialized, we can finally only get a current along the Japan coastline from the barotropic model using the real topography. This experiment directly confirmed that the planetary β -effect cannot support the EKWC in the barotropic and realistic topography case.

CONCLUSIONS

In this study, POM97 was used to develop a simply inflow and outflow model to test the effect of topography on the JES circulation. We find that the planetary β -effect cannot support the EKWC in the realistic topography of the JES in the barotropic case. Our preliminary conclusions are as follows:

(i) The topography is a more important factor in controlling the barotropic circulation in the JES. The branch of Tsushima Warm Current along the Japan coastline is partly controlled by topography.

(ii) The EKWC cannot reproduce in a barotropic model with realistic JES topography. However, it reproduced in a barotropic model with flat bottom. This indicates that the stratification is essential in the formation of the EKWC, because stratification can reduce the topography β -effect.

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东韩暖流驱动机制的正压数值研究^{*}

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摘 要

本文基于 POM(Princeton Ocean Model)建立起日本海环流的数值模式。通过几个在有人(出)流情况下的正压变水深数值实验,检验了地形对日本海环流的影响。结果表明地形是控制日本海环流的重要因子。对马暖流在日本近岸的分支较多地受到地形的影响,这与前人的结论相一致。本文的研究发现在真实地形下,东韩暖流在正压情况下却很难由行星 β 效应维持。因此,层化效应是形成东韩暖流的必要因素。

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