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Numerical Experiment on the Ulleung Eddy due to the Variation of the Tsushima Current in the East Sea

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In order to understand the generation mechanism of the Ulleung Eddy, we carried out a series of numerical experiments using the nonlinear 1½ - layer model allowing the inflow of the Tsushima Current.

According to our numerical results, the Ulleung Eddy was generated due to the inflow variations of the Tsushima Current. Its inflow through the Korea Strait was deflected to the east due to the Coriolis force and the nonlinear self advection. Thus, an anticyclonic motion was formed at the north of the Korea Strait. The inflow became a coastal boundary current, and finally flowed out model ocean through the eastern exit. When the speed of inflow decreased slowly, the eddy- like motion at the north of the Korea Strait changed into an enclosed anticyclonic eddy of about 200 km in diameter.

The Ulleung Eddy became circular shape due to the nonlinear self advection, then changed into elliptical shape in meridional direction because of the blocking effect of the western boundary.

Key words : Ulleung Eddy, nonlinear 1½-layer model, variation of Tsushima Current, nonlinear self-advection, blocking effect

Introduction

Eddies in the East Sea have been actively studied in recent years. According to the previous studies, (Fukuoka, 1961; Moriyasu, 1972) eddies appeared to be circular or elliptic and they were sometimes recognized by isotherms at 100 m or 200 m in depth With the satellite infrared imagery, Legeckis (1978) showed many eddies might be generated in the East Sea like in open ocean. From the study of the horizontal turbulence in the East Sea using the satellite infrared imagery, Toba et al. (1984) suggested that the horizontal turbulence was eddies of about 100 km in diameter and these eddies transferred heat energy to the cold region in the northern part. Tameishi (1987) investigated the eddy in the region of East Korea Warm Current (EKWC) using the satellite infrared imagery, and proposed a sequence of formation, evolution and decay processes. Ichiye and Takano (1988), after studying the distribution of mesoscale eddies in the East Sea using the hydrographic data, showed that many eddies of 30~160 km in diameter existed in the East Sea. Isoda and Saitho (1993), based on the hydrographic and satellite data, studied the northward intrusion of eddies developed off the east coast of Korea. From the study of the distributions of eddies off the east coast of Korea with AVHRR from 1987 to 1991, Min et al. (1995) suggested that a mesoscale eddy greater than 100 km in diameter existed almost all the time between Mukho and Wonsan Bay. Lee et al. (1995) called this eddy the Sogcho Eddy and observed its structure in May 1992. Shin et al. (1995) also observed this Sogcho Eddy from March to June in 1992, and they claimed that the Sogcho Eddy persisted for one year.

Existence of a warm eddy in the southwest of Ulleungdo has been one of the most interesting features in relation to the Tsushima Current. That warm eddy has been studied using the hydrographic data (Fukuoka, 1961; Tanioka, 1968; Na, 1988; Kang and Kang, 1990; Seung et al., 1990; Cho et al., 1990; Kim, 1991; Na and Paeng, 1992; Seung and Kim, 1993; An et al., 1994). According to the results of the previous studies using the hydrographic data, a warm eddy appeared often near the Ulleungdo and its spatial scale was about 100~130 km in diameter. It had a isothermal mid-layer like warm eddies found in open ocean or western boundary current regions. This semi-permanent eddy is called the Ulleung Eddy in this paper. Kim (1991) surveyed the Ulleung Eddy for the first time using the CTD in 1989. Its structure was observed by Kim et al. (1993) in April, September and November 1993. Lie et al. (1995) also analyzed the Ulleung Eddy with trajectories of surface drifters, CTD and ADCP from November 1992 to September 1993.

From the distributions of surface current observed in 1933, Kim (1995) showed that the presence of two eddies existed off the east coast of Korea were already recognized in 1933. Kim (1993) also showed existence of two anticyclonic eddies using the surface temperature distribution by NOAA infrared imagery in April 1993. Those two anticyclonic eddies off the east coast of Korea seem to be nearly permanent features.

For the Sogcho Eddy, the internal Rossby radius is about 15 km yielding the wavelength of the unstable Rossby wave of about 100 km (Lee et al., 1995). However, the size of the Sogcho Eddy of about 200 km is twice as large as that generated by the baroclinic instability theory. Consequently, other generating factors may have played an important role in the generation of the Sogcho Eddy in addition to the baroclinic instability. Since the Sogcho Eddy is always found between Mukho and Wonsan Bay, Min et al. (1995) speculated that specific eddy-generating mechanism may be responsible for the consistent location of the eddy. Lee et al. (1995) also suggested that the strong offshore winds off the east coast of Korea might exert significant influence because the Sogcho Eddy is generated mostly in winter.

In general, the Tsushima Current flows into the East Sea through the Korea Strait and flows out to the Pacific Ocean through the Tsugaru and the Soya Straits. Its volume transport shows a large seasonal and inter-annual variation which are very interesting phenomena. Kawasaki and Sugimoto (1984) showed that the Tsugaru warm gyre was developed near the Tsugaru Strait because the Tsushima Current had a remarkable seasonal change in its outflow pattern when it flowed into the East Sea Ocean through the Korea Strait. So, the Ulleung Eddy may be also generated by the seasonal change of the Tsushima Current.

There have been many numerical models for the East sea, but most of them were confined mainly to understand the branching of the Tsushima current and East sea circuiatiion (Yoon, 1982a, b; Kawabe, 1982b; Sekine, 1986, 1988; Seung and Kim, 1933). but, we focussed to understand the generation mechanism of Sogcho and Ulleung eddies in this numerical simulation.

The Model Oceans

1. The nonlinear 1½ - layer model

The nonlinear 1½ - layer model has a single active layer of density ρ_1 overlying a deep inert layer of density ρ_2 where the pressure gradient is set to zero. Then the lower layer in this model is assumed to be motionless. In this study, we modified the nonlinear 1½ - layer model used by McCreary et al. (1989), and also we imposed the inflow condition through an entrance instead of the wind forcing. The equations of motion are

$$\begin{aligned} &(hu)_t+(uhu)_x+(vhu)_y-fhv+hp_x=\nu_h\nabla^2(hu) \\ &(hu)_t+(vhv)_y+(vhu)_x+fhu+hp_y=\nu_h\nabla^2(hv) \\ &h_t+(hu)_x+(hv)_y=0 \end{aligned} \quad (1)$$

and pressure gradient is

$$\nabla p=\varepsilon g\nabla(h(T-T_d)) \quad (2)$$

In these equations, u and v are zonal and meridional components of current velocity respectively, the instantaneous thickness of the surface layer is h, p is the pressure in the layer, f is the Coriolis parameter, ν_h is the coefficients of horizontal eddy viscosity, g is the acceleration of gravity, and ε is the coefficient of thermal expansion. T and T_d are temperatures of the surface and the deep layer respectively, and they remain constant.

2. Model domain and the inflow variation

Most previous numerical models were in-and-out flow schemed models in which equal amounts of inflow were forced to balance with outflow from the beginning. This suggests that the entire basin immediately responds to the inflow without any phase lag. As a result, the interior of model ocean has to espond to the injection of inflow as well as the intentional suction through the exit. In this numerical study the inflow was assumed to have discharged from the model ocean without intentional sucking out, because it is more likely that water flows out by dynamical adjustment in the interior.

The scale of model ocean is chosen as realistic as possible to the actual scale, so the model ocean basin for the numerical simulations is 1200 km zonally and 770 km (about 7°) meridionally (Fig. 1). In this numerical study, only the injection of the Tsushima Current with variable intensity is considered. The Tsushima Current enters the model ocean through the entrance with a width of 140 km at the southern boundary, and it flows out through the exit of 200 km in width at the eastern boundary. From the results of many additional calculations, when the exit was narrower than that in this present model, the inflow did not entirely flow out model ocean through the exit. Instead, some of the inflow flowed northward to make a recirculation. The width of exit is, therefore, larger than that of the entrance to reduce an effect of the southward return current in this study. The initial temperature of the surface layer is chosen to be 14℃ because the purpose of this numerical study is to investigate eddy generation due to the variation of the Tsushima Current without any other influence.

In order to simulate the Tsushima Current in the Korea Strait, the inflow of the Tsushima Current is divided into two branches as shown at the southwestern corner in Fig. 1. Although there have been many studies on the seasonal fluctuations of the Tsushima Current (Hidaka and Susuki, 1950; Yi, 1966; Yi, 1970; Kawabe, 1982a; Toba et al., 1982; Hahn, 1991). According to Miita and Ogawa (1984), the maximum and average speeds in the western channel were about 80.0 cm/sec and 34.8 cm/sec, respectively. In the eastern channel, they were about 40 cm/sec and 17.8 cm/sec. With reference to their result, we determined the simplified spatial and temporal structures of the Tsushima Current through the Korea Strait.

Fig. 2 illustrates the spatial and temporal structures of inflow through the entrance in the southern boundary. The spatial structure is presented in detailin Fig. 2a. The actual velocity value to be imposed will be velocity scale times velocity in Fig. 2b. The temporal structure (Fig. 2b)

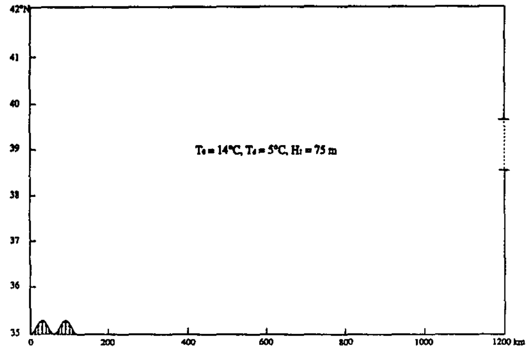

Fig. 1. The model ocean illustrating the model domain and initial conditions.

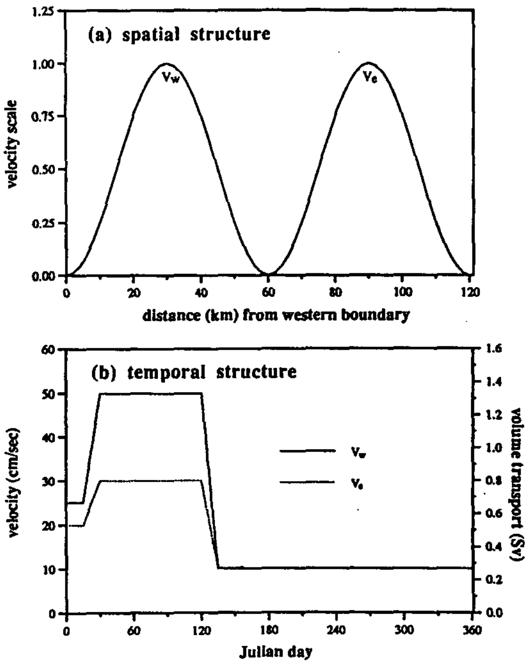

Fig. 2. A schematic diagram illustrating the spatial (a) and temporal (b) structures of the inflow of the Tsushima Current.

consists of a greater inflow through the western channel (Vw) and smaller one in the eastern channel (Ve). Vw is constant with 25 cm/sec for the first 15 days. After 15 days, it increases linearly from 25 cm/sec to 50 cm/sec by day 30, and flows with a constant speed of 50 cm/sec by day 120, and then decreases from 50 cm/sec at day 120 to 10 cm/sec ad day 135, thereafter it is constant. The temporal variation of Ve is also the same as Vw except that its maximum speed is smaller than that of Vw. Those temporal structures are applied to examine if the variation of the Tsushima Current can generate the eddy.

3. Boundary conditions and model parameters

The boundary conditions at the southern entrance and eastern exit are the open boundary conditions as defined by equation (3a), whereas the close boundary conditions (3b) are applied to the rest part.

$$u_n = v_n = 0,\ h_n = 0 \qquad (3a)$$

$$u = v = 0,\ h_n = 0 \qquad (3b)$$

where the subscript n indicates a partial derivative in the normal direction to the boundary, and the conditions of h in equations (3) is mass conservation.

Parameters for the present numerical study are listed in Table 1. Their values were chosen to be consistent with the observational data in 1992 and mean oceanographic charts of the adjacent seas of Korea published by Fisheries Research and Development Agency of Korea (FRDA, 1986). In Table 1, H_l is the thickness of the upper layer in the East Sea, which represents the depth of thermocline. T_o is also set to as a realistic value as possible in the East Sea and 14℃ is the typical value in the vicinity of 38°N of the East Sea in winter season (FRDA, 1986). The Coriolis parameter (f) is calculated for each grid box.

In general, horizontal mixing coefficient ν_h is taken to be constant with values of $2\times10^6 \sim 2\times10^7$ cm²/s. Sekine (1988) chose horizontal eddy viscosity of 1×10^7 cm²/s when he simulated the seasonal variation of the East Sea circulation. Recently Seung and Kim (1993) took horizontal eddy coefficients as 5×10^6 cm²/s for viscosity and 1×10^6 cm²/s for diffusivity when they studied East

Table 1. Parameters for all the ocean models used in this paper

H_l	initial upper layer thickness	75 m
H_e	starting depth of entrainment	75 m
T_o	initial temperature of upper layer	14℃
T_d	temperature of deep layer	5℃
ε	coefficient of thermal expansion	3×10^{-4}/℃
ν_h	horizontal mixing coefficient	2×10^6 cm²/s
g	gravity acceleration	980 cm/s²

Sea circulation through a numerical model. Horizontal mixing is very influential on eddy generation. In fact, with larger values of ν_h (2×10^7 cm²/s), eddy velocity decreases. With small values (2×10^5 cm²/s), eddy velocity is very strong and grid scale noise appears. Throughout a number of additional calculations using values of $\nu_h = 2\times10^5 \sim 2\times10^7$ cm²/s, proper value of ν_h was 2×10^6 cm²/s. Value of ε may have affected the numerical solutions, but in the present study the numerical solutions were not sensitive to this value from the results of various additional calculations.

4. Numerical methods

The numerical solutions are evaluated on a staggered grid with variables defined in a rectangular grid box of Δx by Δy. The point for h value is located in the middle of a grid box, and the points for u and v are centered on their meridional and zonal edges, respectively. The equations of motion are forward differenced in time using the leap-frog scheme, and all fields are averaged between two time levels every 40 time steps in order to control time-splitting instability. Diffusive terms are evaluated at the backward time level, and all other terms are at the central time level.

For all the solutions shown in the figures, the grid dimensions $\Delta x = \Delta y = 10$ km and the time step $\Delta t = 24$ min. The time step is chosen to be small enough to satisfy the CFL conditions : $\Delta t \le \Delta x / 2\sqrt{2}_c$, where c is the internal gravity wave speed.

Numerical Results

In this Tsushima Current study, we imposed the inflow variation for 360 days to investigate eddy generation by

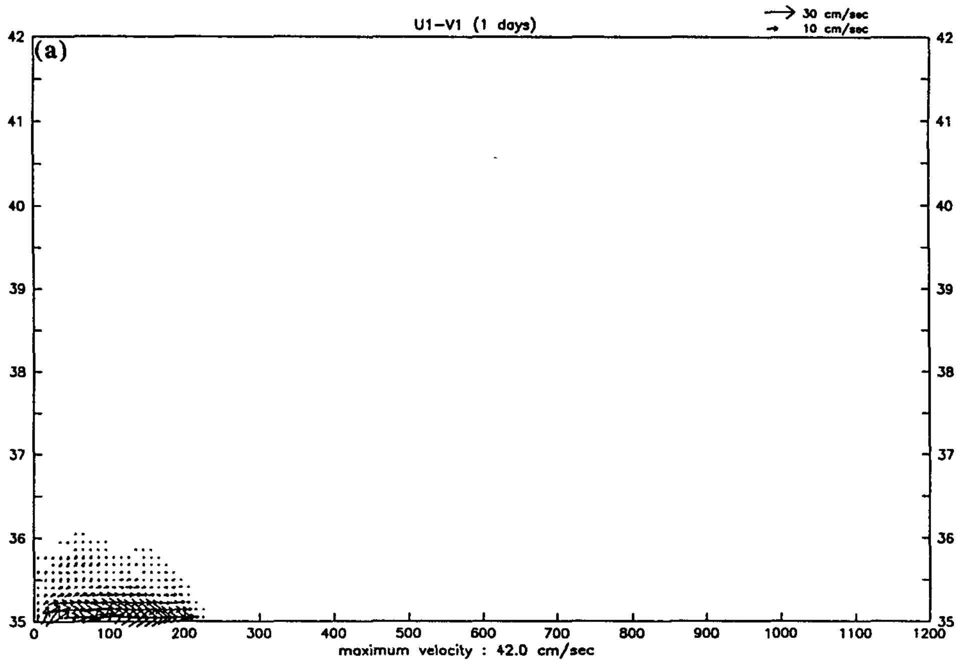

Fig. 3. A current field of the upper layer at day 1.

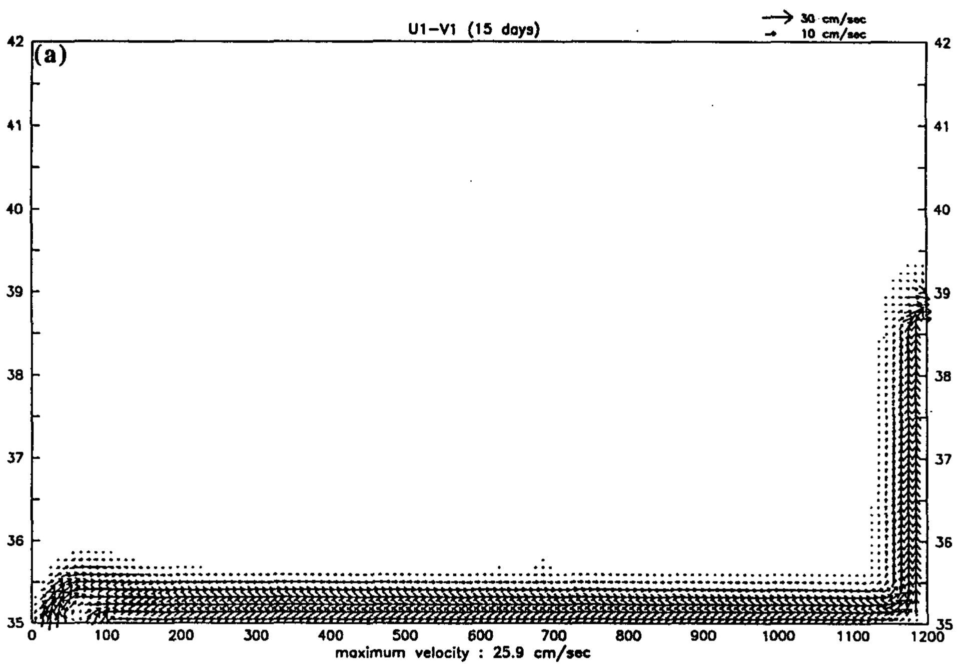

Fig. 4. A current field of the upper layer at day 15.

the variations of the Tsushima Current without any other influence.

After oneday 1, the velocity fields shows that the inflow deflects eastward right after entering the basin and then keeps flowing to the east along the southern boundary (Fig. 3). Fig. 4 is the velocity fields after 15 days. The inflow penetrates somewhat to the north and deflects eastward. It is noted that this current flows out through the exit at the eastern boundary from this stage. After 30 days (Fig. 5), the speed of the inflow increases from 25 cm/sec to 50 cm/sec and from 20 cm/sec to 30 cm/sec in the western and eastern channels respectively, so clockwise deflection of the inflow increased and the eastward coastal current along the southern boundary becomes stronger. After 60 days (Fig. 6), the horizontal dimension of clockwise

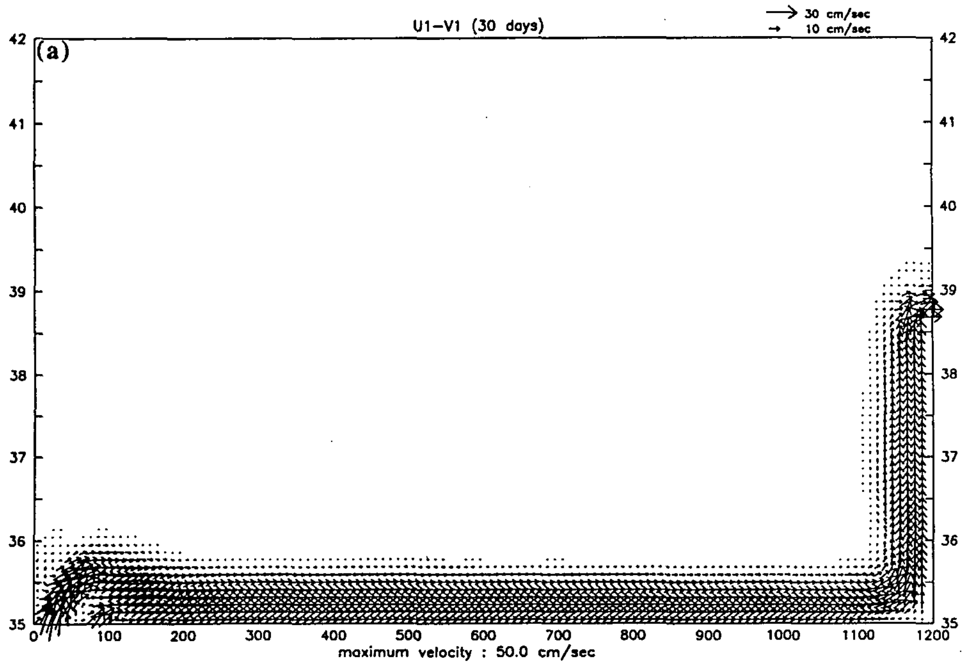

Fig. 5. A current field of the upper layer at day 30.

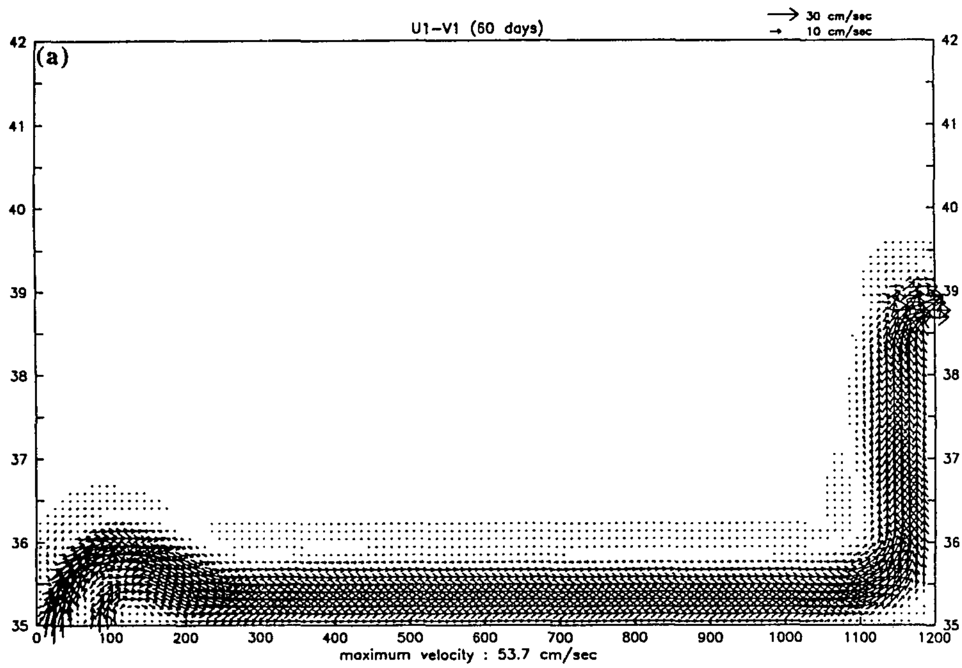

Fig. 6. A current field of the upper layer at day 60.

deflection increases because the speed of the inflow increases from day 30, and maximum velocity reaches 53.7 cm/sec. After 90 days (Fig. 7), the inflow moves to the north, to about 37.5 N, and the horizontal dimension of clockwise deflection increases to about 200 km. After 135 days (Fig. 8), the inflow through the western and eastern channels join together, then the clockwise deflection becomes an anticyclonic eddy of

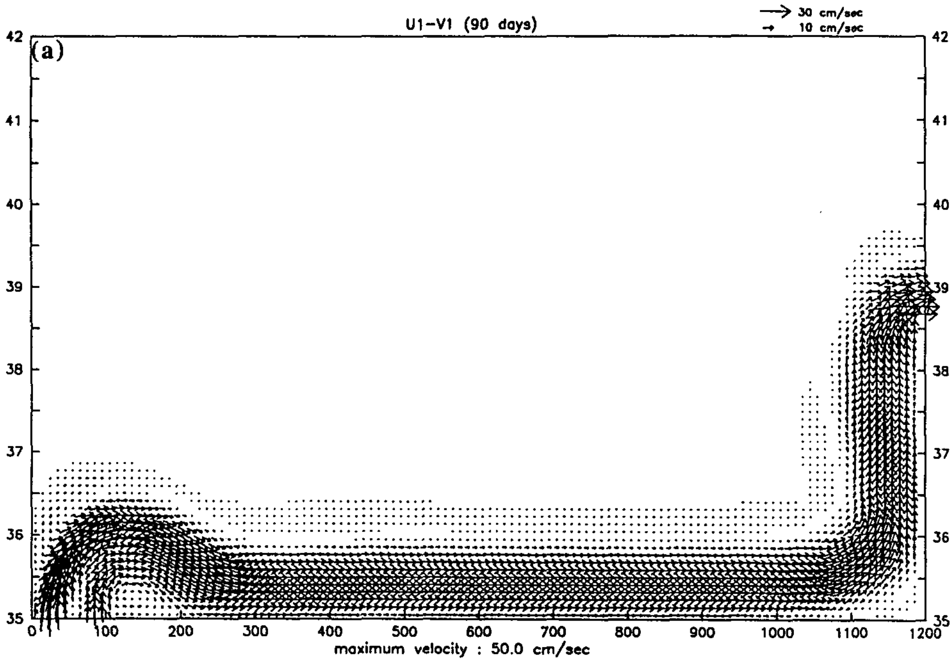

Fig. 7. A current field of the upper layer at day 90.

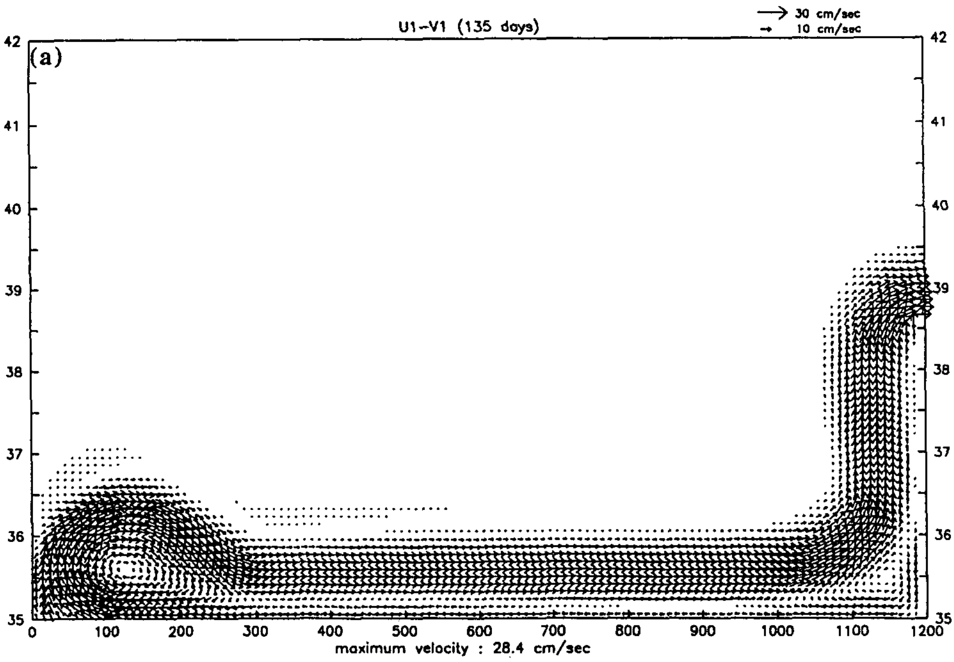

Fig. 8. A current field of the upper layer at day 135.

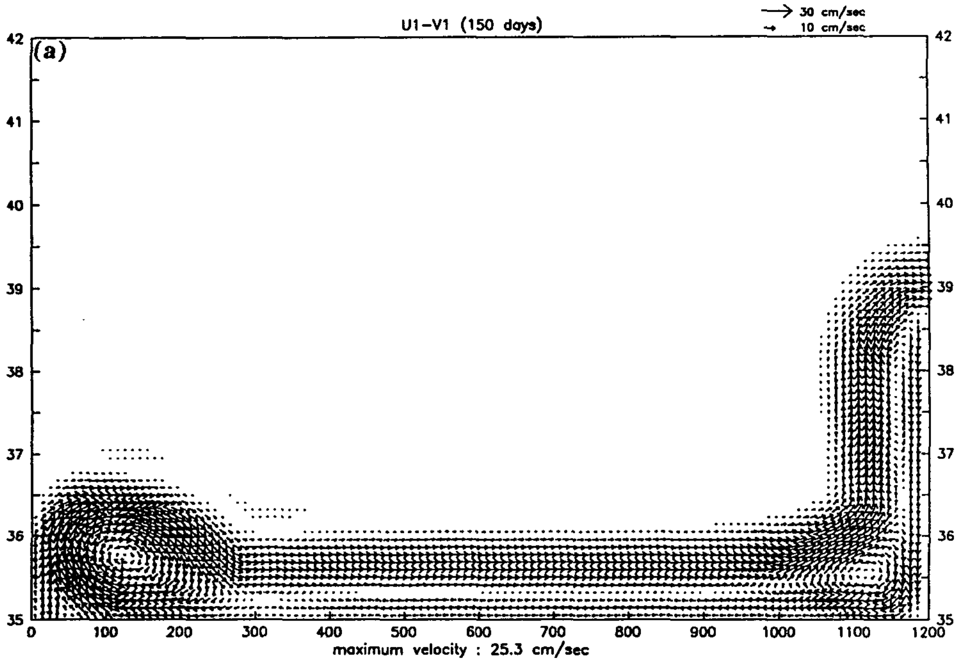

Fig. 9. A current field of the upper layer at day 150.

about 200 km in diameter. Hearafter this anticyclonic eddy is called as the Ulleung Eddy in this paper.

After 150 days (Fig. 9), the Ulleung Eddy begins to change into a circular shape due to nonlinear self advection effect, and its center (Xm, Ym) is located at Xm=130 km, Ym=35. 7 N. There is also a corresponding weakening of the current in speed from 28.4 cm/sec at day 135 to 25.3 cm/sec at day 160. As the speed of the inflow decreases abruptly, a return current along the eastern and southern boundaries develops. As a results, two anticyclonic eddies are produced in the southeast corner of the model ocean. In the real East Sea, the anticyclonic eddies, which seem to be generated by irregular topography and coastal geometry, are formed in the vicinity of the Noto peninsula and Oki island (Isoda and Nishihara, 1992), but they are different from two artificial eddies produced in this numerical experiment.

After 270 days (Fig. 10), the Ulleung Eddy has a circular shape due to nonlinear advection, its center (Xm, Ym) shifts slightly move to the north than at day 150, and its maximum speed decreases to 15.4 cm/sec due to horizontal diffusion. Fig. 11 shows the solutions at day 360. Overall features are very similar to that at day 270 (Fig. 10). The Ulleung Eddy slowly drifts to the north and changes into an elliptical shape in meridional direction because its westward movement is blocked by the western boundary. The blocking effect by the western boundary will be discussed in the following offshore wind study (Kim et al., 1997c).

The center of Ulleung Eddy (Xm, Ym) shifts from Xm = 130 km, Ym=35.7 N at day 150 to Xm=100 km, Ym =36.1 N at day 360, so that the northward mean drift for 210 days is about 0.26 km/day. According to some additional experiments, where both of the polar front and injection were combined, a steady northward coastal current made the Ulleung Eddy stronger and move faster (about 0.69km/day between 140 days and 360 days). Therefore, the northward movement of the Ulleung Eddy seems to be increased by advection of the northward coastal current. The northward movement of eddies will be also discussed in detail in the offshore wind study (Kim et al., 1997c).

Kawasaki and Sugimoto (1984) suggested that the Tsugaru warm gyre of about 150 km in diameter was developed near the Tsugaru Strait from summer to fall due to a seasonal change of the Tsugaru warm current. In addition, Wang (1987) investigated numerically the inflow variation through the narrow strait using a two -

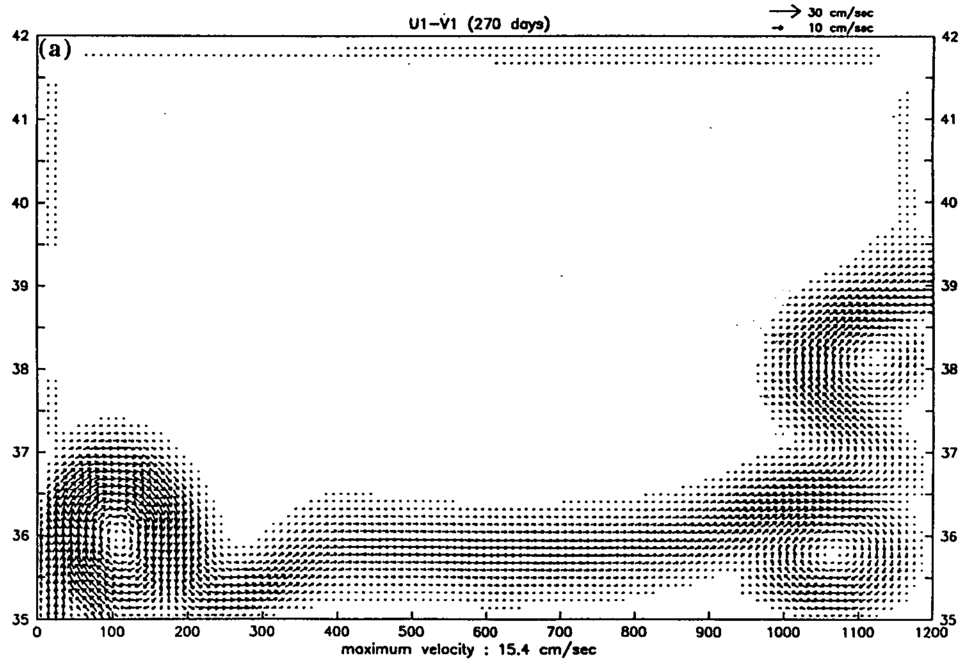

Fig. 10. A current field of the upper layer at day 270.

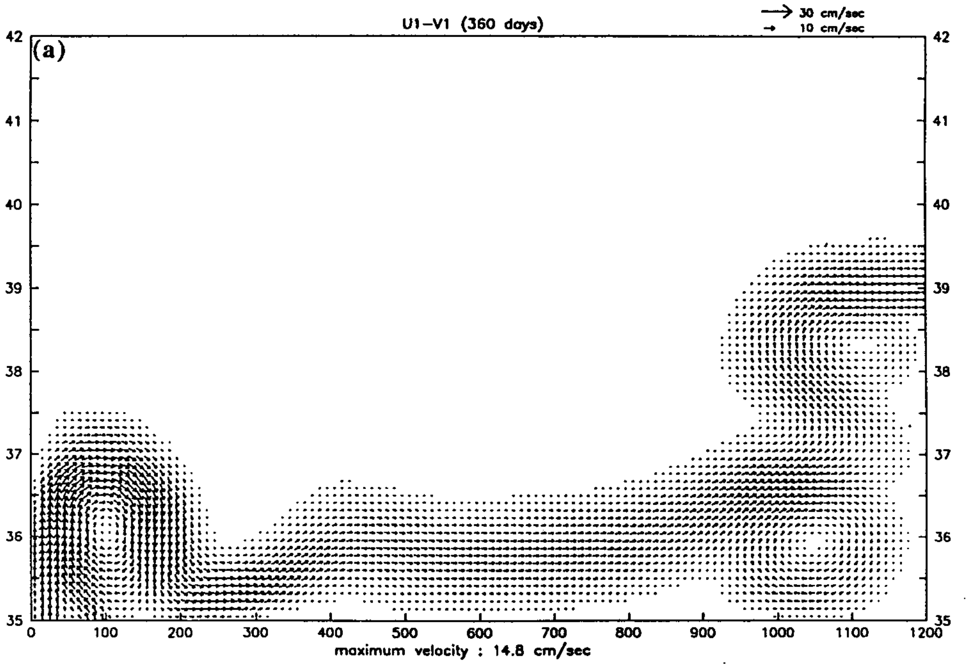

Fig. 11. A current field of the upper layer at day 360.

layer model and showed that the strait surfaceoutflow generated anticyclonic eddy after passing through the strait due to the nonlinear self advection. In earlier studies, bottom topography was regarded as a major factor of the Ulleung Eddy generation (Seung et al., 1990; Na and Kim, 1990; Kim et al., 1991). But the Ulleung Eddy could also be produced due to the variation of the inflow in this numerical experiment.

Summary and Conclusions

The generation of the Ulleung Eddy was numerically investigated using the nonlinear 1½-layer model allowing the variation of the Tsushima Current having two channels.

Right after the northward penetrating through the Korea Strait, the inflow turns to the east due to the Coriolis force and the nonlinear self advection as in Wang (1987), and followed the southern and eastern boundaries, then finally flowed out through the eastern exit. As the speed of inflow decreased, the eastward deflection became an enclosed anticyclonic eddy of about 200 km in diameter that moved northwestward with a mean drift of 0.26 km/day. The anticyclonic eddy became circular shape due to the nonlinear self advection effect, then changed into elliptical shape in meridional direction because of the blocking effect of the western boundary. In conclusion, the Ulleung Eddy might be generated due to the variation of the Tsushima Current.

Because the major purpose of this Tsushima Current was to understand the generation mechanisms of the Ulleung Eddy, we imposed abrupt change of the inflow condition through the Korea Strait. As a result, an anticyclonic return current and two eddies were develope in the southeast corner of the model ocean. However, these phenomena seem to be artificial in this numerical experiment due to the unrealistic coastal boundary. In the future experiment, these unrealistic features need to be improved. In additional experiments, as maximum speed of the inflow decreased to 25 cm/sec or 20 cm/sec through both western and eastern channels instead of 10 cm/sec, the return current along the eastern and southern boundaries was hardly developed and two eddies were very weak and small. Instead, the Ulleung Eddy was restored to the meandering motion right after transforming into an enclosed circular eddy. Therefore, if the speed of the inflow gradually decreases, the return current and two eddies could not be developed, unlike this Tsushima Current experiment.

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