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Triggering Effect of the Polar Front on the Eddies in the East Sea

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To find out generating mechanism of eddies in the polar frontal zone of the East Sea, we carried out a series of numerical experiments using the nonlinear 1½-layer model allowing the effect of the polar front. We assumed the polar front at about 39°N in zonal dirction with the cold water region in the northern part and the warm water region in the southern part of the model ocean. To examine the effect of the frontal motion without the influence of the Tsushima Current from the beginning of the geostrophic adjustment, the initial state of the model ocean was assumed motionless.

Eastward current was caused by the geostrophic adjustment process in the polar frontal zone that induced a steady northward coastal current along the Korean coast to satisfy the mass continuity. The overshooting of this coastal current acted as an initial disturbance of the zonal flow field which caused meanders and eddies. The spatial scales of eddies were in good agreement with the baroclinic instability theory.

Key words : Eddy, polar front, nonlinear 1½-layer model, geostrophic adyustment, meandering, baroclinic instability

Introduction

Lots of observational, theoretical and numerical simulation studies have been carried out for the East Sea. In general, the upper layer of the East Sea is known to be divided into two regions; the warm water region in the southern part and the cold water region in the northern part. A polar front is particularly formed between these two water masses and it exists almost permanently between 38°N and 40°N. As a result, a number of eddies from small to mesoscale exist in the polar frontal zone. According to the surface temperature distribution by NOAA infrared imagery, many eddies appeared in the polar frontal zone. Through 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 horizontal scale and these eddies transferred heat energy to the cold region in the north. The frontal instability is one of the possible mechanisms of eddy generation in the frontal region. J rgen and K se (1987) studied the role of the baroclinic and frontal instabilities on the eastward thin frontal jet as a mechanism of the eddy generation.

Because the polar front exists almost permanently in the vicinity of 39°N of the East Sea, and the Sogcho Eddy is located in the polar frontal zone, the polar front may influence on the generation of the Sogcho Eddy. To investigate the generation mechanisms of the Sogcho Eddy by the polar front, we conducted numerical simulation (polar front study) using the nonlinear 1½ - layer model with the effect of the thermal front. We assumed the polar front at 39°N in zonal direction between the cold water region in the northern part and the warm water region in the southern part of the model ocean.

The Model Oceans

The governing equations of the nonlinear 1½ - layer are basically identical to those used by McCreary et al. (1989) except tht the wind forcing terms are not considered in the momentum equations. Instead, we impose the frontal condition to consider the effect of the polar front. The equations of motion are

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

$$Tt + uT_x + vT_y = \frac{Q}{h} - \frac{W_e (T - T_e)}{h} + K_h \nabla^2 T$$

and pressure gradient is

$$\nabla p = \varepsilon g \nabla (h(T-T_d)) - \frac{1}{2}\varepsilon g \nabla T. \qquad (2)$$

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. K_h and v_h are the coefficients of the horizontal thermal viscosity and the horizontal eddy viscosity, respectively. g is the acceleration of gravity, and ε is the coefficient of thermal expansion. T and T_d are constant temperatures of the surface and the deep layer, respectively. Three thermodynamic processes affecting T are the heat flux Q through the ocean surface, horizontal diffusion of heat with coefficient K_h, and entrainment described by the velocity W_e.

The surface heat flux is given by

$$Q = \frac{H}{t_h}(T_o - T) \qquad (3)$$

where H and T_o are the initial values of the thickness of the upper layer and the surface temperature, respectively. According to (3), t_h is a measure of the *e-folding time* for the upper layer temperature to relax back to T_o.

Entrainment is a crucial process in this model. It acts to cool the upper layer, to provide stress at its bottom, and to prevent the interface between the two layers from surfacing. Entrainment is defined by the choice of entrainment velocity W_e (McCreary and Kund, 1988).

$$W_e = \begin{cases} \dfrac{(H_e - h)^2}{(t_e H_e)} & ,h < H_e \\ 0 & ,otherwise. \end{cases} \qquad (4)$$

According to (4), entrainment occurs only when h is less than a specified value H_e, and W_e increases parabolically toward a maximum value of $H_e t_e$ as h goes to zero, where H_e is starting depth of entrainment and t_e is thermodynamic time constant. The entrainment time scale t_e must be chosen small enough to ensure that the interface does not surface in regions of intense upwelling.

Model domain, boundary conditions, model parameters and numerical methods are basically the same as those of the Tsushima Current study (Kim et al., 1997a). Fig. 1 is the model domain of this polar front study. The entrance 200 km wide at the southwestern corner and the exit with the same width at the eastern boundary are given.

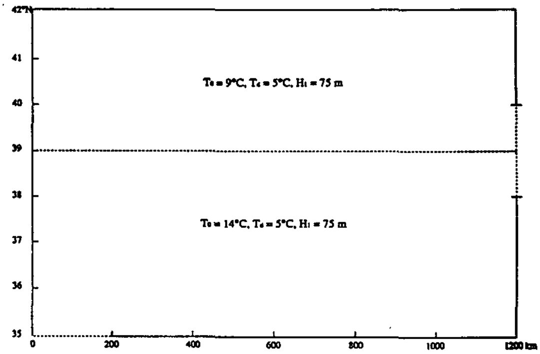

Fig. 1. The model ocean illustrating the model domain and initial conditions.

The polar front study examined the generation of eddies by the polar front, thus the polar front assumed to be in zonal direction along 39°N. Because the stability of front depends on the temperature difference, we carried out a number of additional simulations with various conditions to determine what a critical difference was for the marginal instability for eddy generation. Initial temperature of the upper layer is set at 14℃ in the warm water region of the southern part and 9℃ in the cold water region of the northern part.

When temperature difference between two water masses of the upper layer was bigger than 6℃, the speed of eastward frontal jet with meandering motion and the northward coastal current somewhat increased with temperature difference. In addition, an enclosed circular eddy, larger than that in temperature difference of 5℃, was generated much faster. When temperature difference was 4℃, (i.e, temperatures 10℃ in the northern part and 14℃ in the southern part), general pattern was similar but meanders did not grow from the eddy. Consequently, not only for meandering motion but also for eddies to be developed, temperature difference needs to be at least about 5℃ in this polar front study.

In order to examine the effect of the frontal motion without the influence of the Tsushima Current from the beginning of the geostrophic adjustment, initial state of the model ocean was assumed motionless (u=v=0).

Parameters for the present polar front study are listed in Table 1. Their values were are the same as Kim et al., 1997a except initial temperature of the upper layer (T_o). Additional values of ε, t_e, and t_h may have affected the numerical solutions, but the numerical solutions in the present polar front study were not sensitive to these values throughout various additional calculations.

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

H_I	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	2×106 cm^2/s
g	gravity acceleration	980 cm/s^2

Numerical Results

One of the well-known features of the Sogcho Eddy is that its location is almost always in the polar frontal region. Many eddies are also generated along the polar front. So, possible influence of the polar front on eddy generation was examined in this polar front study. We assumed that the polar front occurred at 39°N, and cold and warm water masses existed in the northern and southern part of 39°N, respectively. In practial, cold and warm water masses in the polar frontal zone of the East Sea have been interacted for a long time. So, the polar front may play an important role in eddy generation.

Since the Available Potential Energy is converted into the Kinematic Energy due to difference in potential energy between warm and cold water masses, current is produced by a geostrophic adjustment process. If the geostrophic current becomes very strong, it gets unstable dynamically, and eddies may be produced as a result of the amplification of meandering motion. As explained in section 2, initial state of the model ocean in the polar front study was assumed to be motionless with temperature difference of 5℃ between two water masses separated by the polar front in order to examine the effect of the frontal motion from the beginning of the geostrophic adjustment process without influence of the Tsushima Current.

At day 1, the velocity field (Fig. 2) shows that an

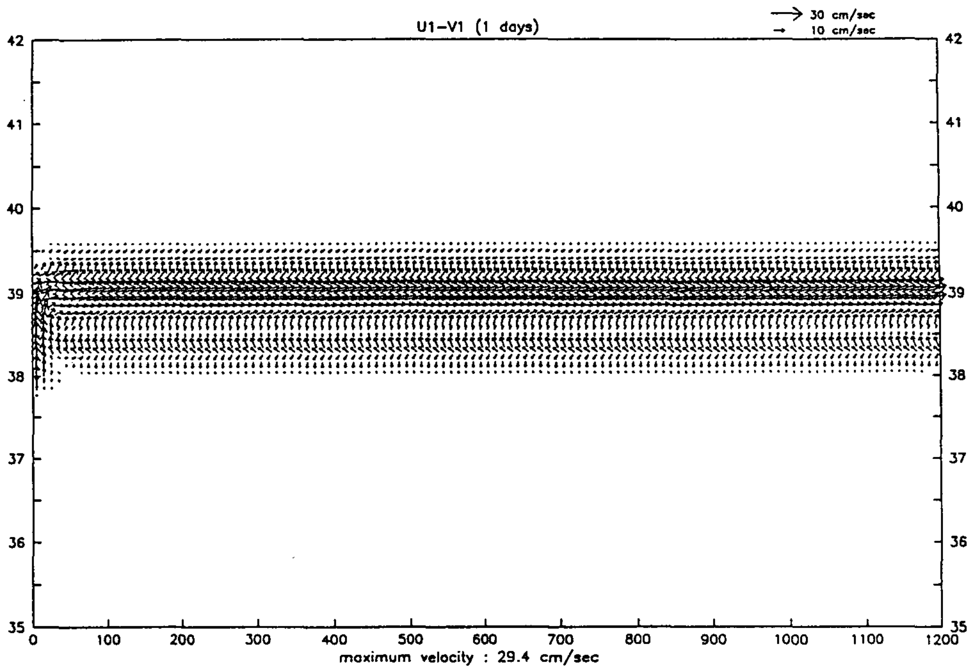

Fig. 2. A current field of the upper layer at day 1.

eastward frontal jet with maximum speed of 29.4 cm/sec is developing along the thermal front and a northward coastal current is induced from 38°N along the western boundary to compensate the geostrophic current flowing out to the east.

Fig. 3 shows the velocity field (Fig. 3a), *h*-field (3b) and temperature field (3c) at day 15. The northward coastal current, which is induced to compensate the mass transport near the coast due to the frontal jet flowing eastward, also requires an inflow through the entrance of which width and speed are about 70 km and 15 cm/sec, respectively. It is important to note that the inertia of the northward coastal current results in overshooting to about 39.5°N. This overshooting is expected to act as an initial disturbance, enhancing the instability of the frontal jet. According to the results of many additional calculations, as temperature differences between warm and clod waters get larger, the northward coastal current becomes stronger, thus the overshooting of coastal current extends northward.

The shallowing of the *h*-field on the left side of current axis and its deepening on the other side in Fig. 3b are manifest from the thermal wind relation. Minimum thickness near the western boundary reaches about 69 m. An eddy of about 80 km in horizontal scale is generated near 39°N because of the overshooting of the northward coastal current, and also thickness at the center of this eddy is increased by the anticyclonic motion. Hereafter this anticyclonic eddy is called as the Sogcho Eddy. A small scale eddy is developed on the east side of the Sogcho Eddy and its thickness at the center is shallowing with a cyclonic motion. Temperature is shown in Fig. 3c. The frontal zone begins to have meandering motion, and colder water appears along the western boundary because of entrainment effect.

At 30 days (Fig. 4), the overshooting of coastal current moves northward to about 40°N, but the center of Sogcho Eddy is still near 39°N. Meandering motion and eddy generation patterns of the frontal jet propagate eastward, and the size of the Sogcho Eddy in zonal direction also increases to about 100 km. In addition, the second anticyclonic eddy was developed of about 70 km in horizontal scale. The cyclonic motion in the frontal zone disappears because of entrainment, while the anticyclonic motions become more dominant. The current speeds less than 1.0 cm/sec were not plotted, but the meander-like eddy in Fig. 4a is actually an enclosed eddy.

To test the triggering effect of the overshooting due to the western boundary, we compared the results of additional numerical experiment with same initial temperature structure except that a channel of an infinite length was assumed. Here the eastern and western boundaries were removed. In this case, the meandering motion began to appear near the eastern boundary only after 150 days and it spread slightly westward with time due to a westward propagation of a Rossby wave packet. The flow field in a channel without western boundary seems to be stable. Therefore, it is evident that the existence of the western boundary promotes eddy generation in the polar frontal region. Ikeda and Apel (1981) forced the initial perturbation to the model ocean first, that is, they applied eddy size corresponding to one wavelength scale of meandering motion on the western side of the eastward frontal jet. In our polar front study, instead of the intentional perturbation, the overshooting of northward flow along the western boundary plays the role of initial disturbance for the marginally unstable current in the frontal zone.

At 60 days (Fig. 5), the horizontal scale of Sogcho Eddy in zonal direction increases to about 130 km and that of second anticyclonic eddy also increases to about 100 km. Meandering motion propagates much faster to the east, and continues to develop due to the frontal instability, then many circular eddies are produced in the frontal zone. Cyclonic eddies with thinner upper layer nearly disappear, instead there is only anticyclonic eddies along the polar front (Fig. 5b). Both anticyclonic and cyclonic motions along the thermal front are developed by frontal instability, but cyclonic motions are eliminated by entrainment in order to conserve the potential vorticity. This problem will be discussed in detail in the offshore winds study (Kim et al., 1997c). Therefore, only anticyclonic eddies survive with time in this type of model.

At 120 days (Fig. 6), amplitudes of meanders are increasing with time due to decay processes caused by horizontal diffusion. Meandering motionis widespread in

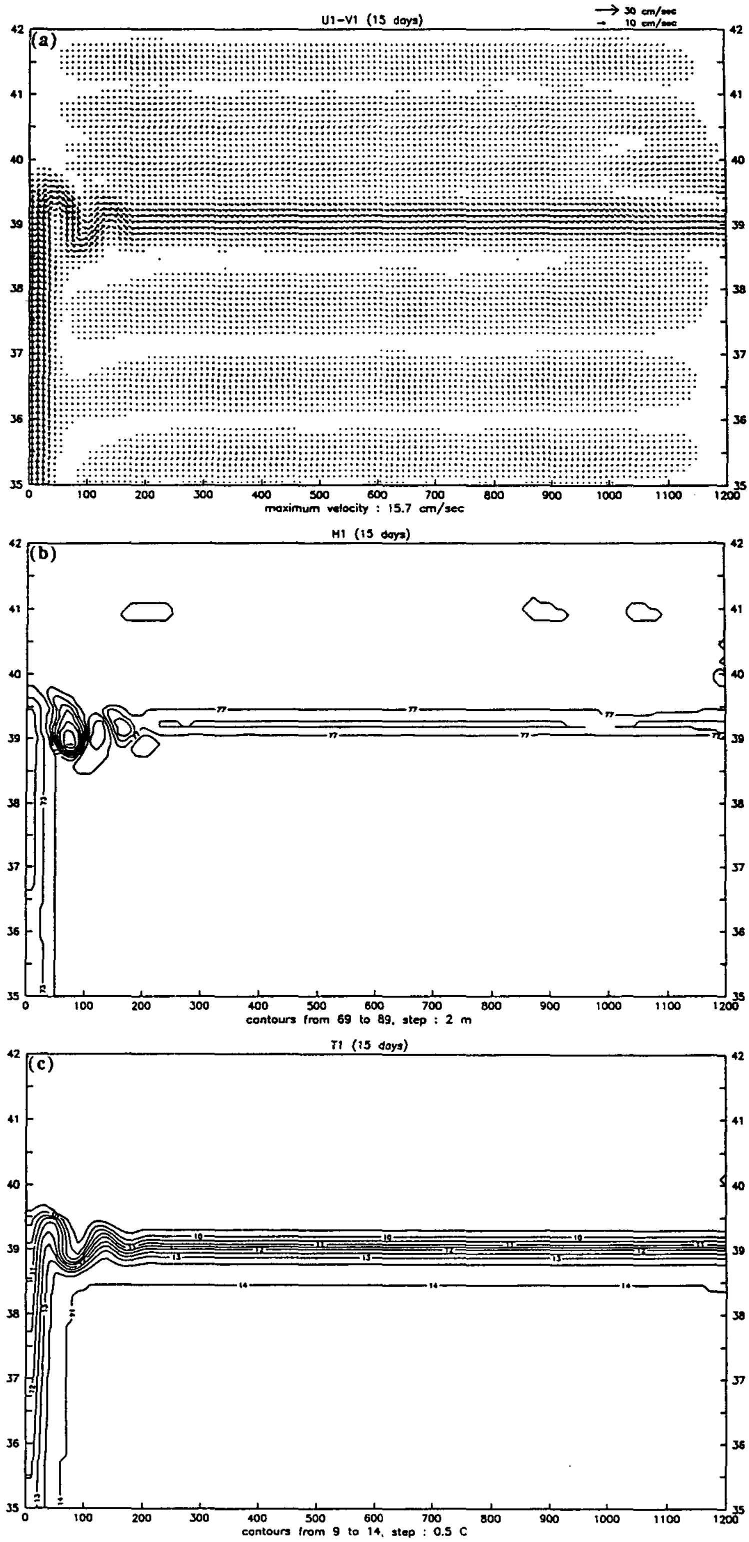

Fig. 3. A current field (a), h-field (b) and temperature field (c) of the upper layer at day 15.

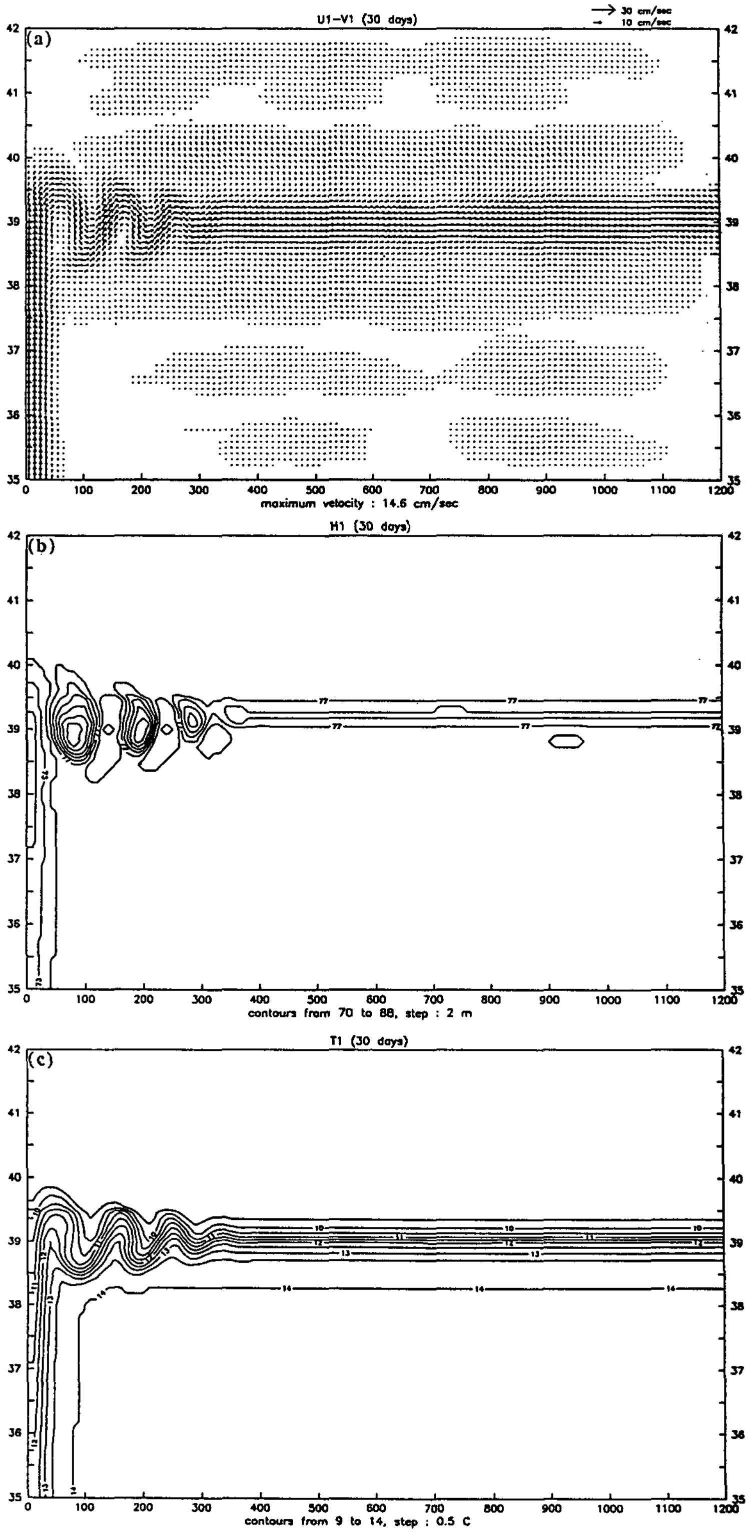

Fig. 4. A current field (a), h-field (b) and temperature field (c) of the upper layer at day 30.

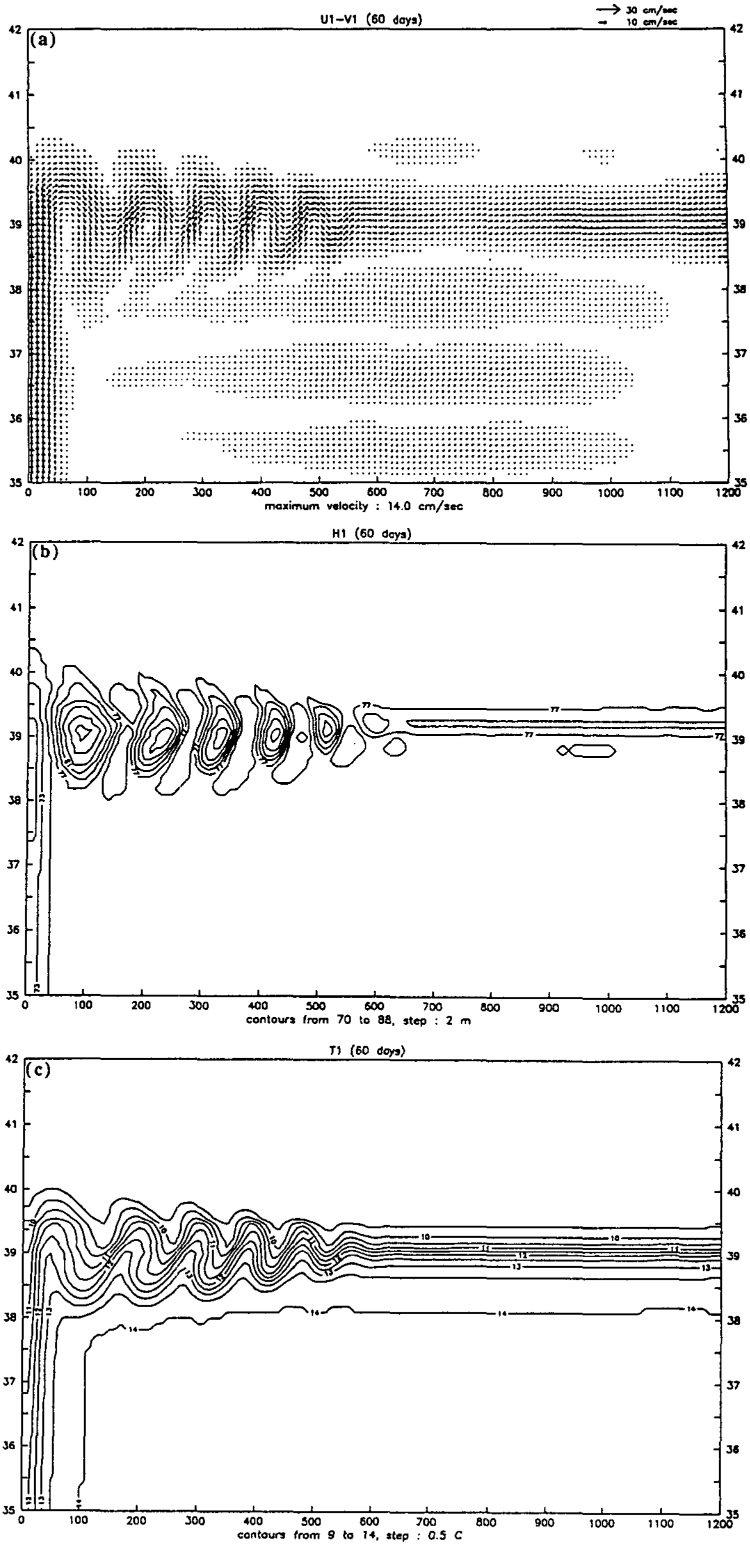

Fig. 5. A current field (a), h-field (b) and temperature field (c) of the upper layer at day 60.

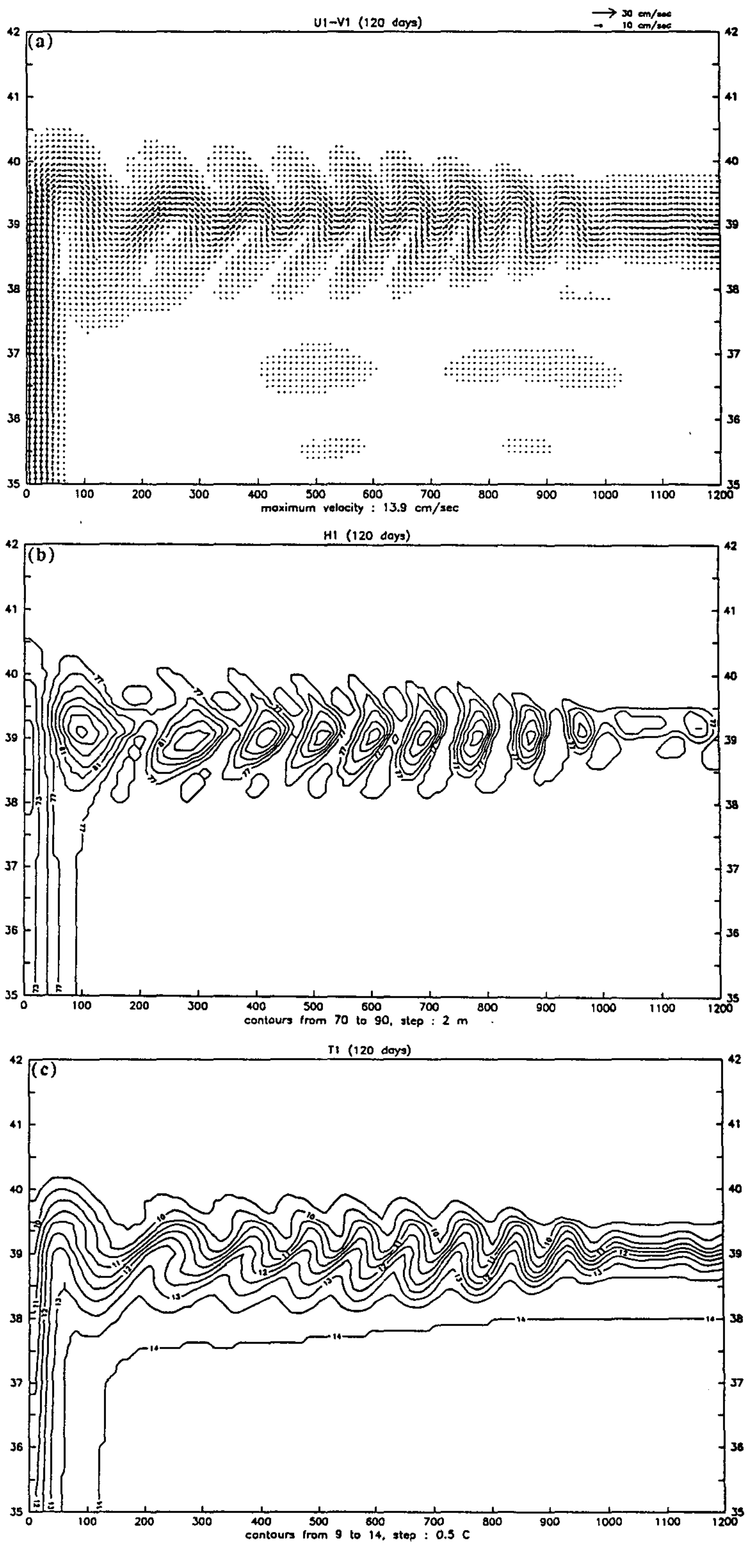

Fig. 6. A current field (a), h-field (b) and temperature field (c) of the upper layer at day 120.

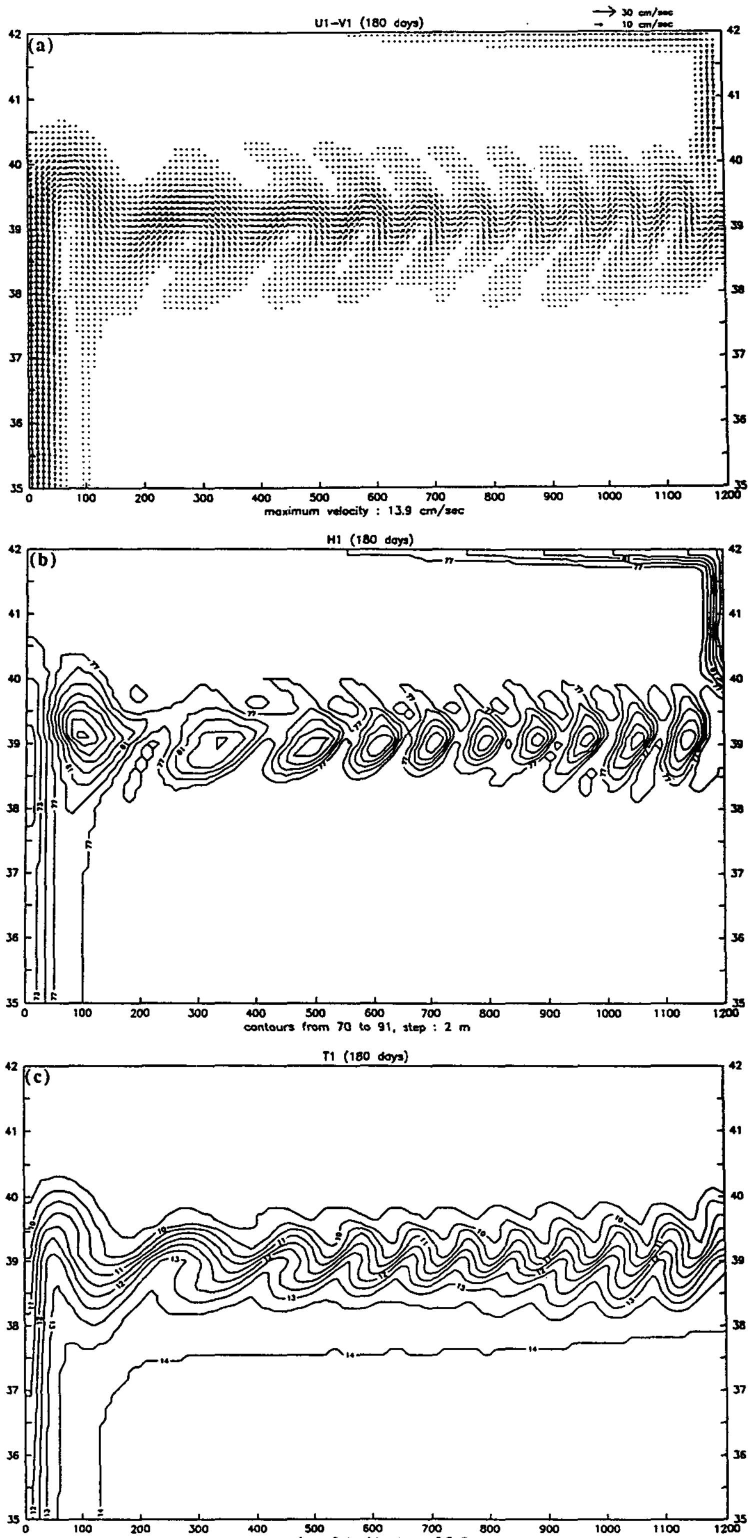

Fig. 7. A current field (a), h-field (b) and temperature field (c) of the upper layer at day 180.

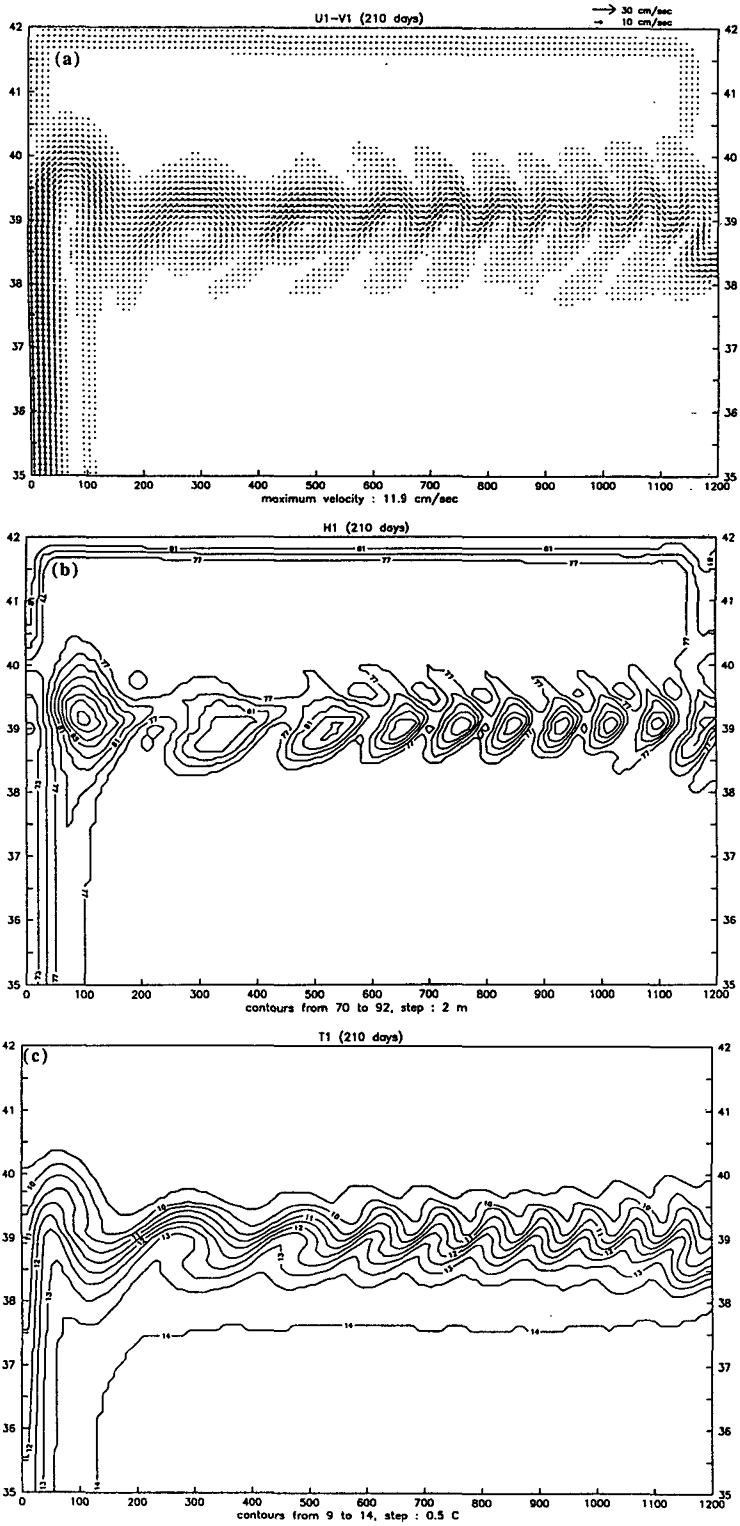

Fig. 8. A current field (a), h-field (b) and temperature field (c) of the upper layer at day 210.

the whole model ocean. In particular, the h-field (Fig. 6b) shows that anticyclonic eddies in the frontal zone are transformed into an elliptical shape in meridional direction, and their asymmetric shapes are due to the advection of warm water.

Fig. 7 shows the velocity field, h-field, temperature field at day 180. Some of eastward current did not flow out through the exit, instead cyclonic circulation is developed in the northern part of the polar front. At 210 days (Fig. 8), the cyclonic circulation becomes more evident. Figures from day 240 to 360 are not presented, but the general features are very similar to that at day 210. The position of Sogcho Eddy does not change, and the coastal current with speed of about 12 cm/sec continues to flow to the north. Eddies and coastal current gradually decay with time due to horizontal diffusion, but they survive until 360 days.

In general, the wavelength of a disturbance calculated according to baroclinic instability is in good agreement with eddies generated in open ocean or western boundary current regions. The Rossby radius of deformation (L_d) in this polar front study is about 12 km. Baroclinic instability theory predicts that the wavelength of disturbance will be about 70 km. This estimation agrees very well with diameters of eddies in this numerical study. In the polar front study, baroclinic instability is the only mechanism for eddy generation. The density field observed in 1992 showed that the diameter of eddy would be about 100 km. But the actual diameter was 200 km (Lee et al., 1995).

Summary and Conclusions

To investigate the generation mechanism of eddies in the polar frontal zone, we carried out a series of numerical experiments using the nonlinear 1½ - layer model allowing the effect of the polar front. To consider the effect of polar front in the East Sea, we imposed the thermal front at 39°N between the cold water in the northern part and warm water in the southern part of the model ocean. Initial state of the model ocean was assumed to be motionless to examine the frontal motion from the beginning of the geostrophic adjustment process without any other forcing.

Eastward flow was developed by geostrophic adjustment process along the thermal front which required a northward coastal current through the entrance in the southern boundary to satisfy the mass continuity in the polar frontal zone. Even if the Tsushima Current driven by the Kuroshio is not forced to enter the East Sea, this northward coastal current is to be induced by the eastward geostrophic current along the polar front.

The Sogcho Eddy was easily generated by the overshooting of induced northward coastal current that acted as an initial disturbance for the velocity field to trigger instability and generate meanders in the frontal zone. Beginning from the western boundary region, occurrence of meanders and growth of eddies proceed eastward. Overshooting of northward coastal current promoted the eddy generation in the polar frontal zone. The horizontal scale of anticyclonic eddies of about 70 km in zonal direction was in good agreement with the wavelength of disturbance based on the baroclinic instability theory. A small portion of the frontal jet did not flow out through the exit, but made a cyclonic circulation gyre in the northern region of the polar front.

Results of the polar front study showed that the persistent EKWC was possible without the injection of the Tsushima Current because it was required to satisfy the continuity in the polar front. If this is true, the concept of the EKWC that it is a kind of western boundary current driven by the inertia of the Tsushima Current should be modified.

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