A Numerical Experiment for Bottom Effect of the Izu Ridge on Path of the Kuroshio ?. On the Formation of Stationary Current Path with an Increase in Volume Transport

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A Numerical Experiment for Bottom Effect of the Izu Ridge on Path of the Kuroshio

II. On the formation of stationary current path with an increase in volume transport

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Abstract: As a part of the preliminary studies on the variability of the oceanic current, the influence of the increase in volume transport is investigated numerically by a barotropic model. The results of the stationary inflow and outflow model obtained in Sekine (1979) are used as the present initial condition. To investigate the unstationary conditions of the oceanic current dynamics, the inflow is allowed to increase at a constant rate, with the other properties of the model ocean remaining the same as in Sekine (1979).

The generation of two dominant paths: the topographic mode path along the shelf slope, and the Rossby mode path (or the planetary wave mode path) which has a route zonally to the south end of the ridge, is noticeable in the region west to the ridge. The energy introduced by an increase in volume transport is initially concentrated for a while to the Rossby mode path in the western side of the ridge, and then the energy along the Rossby mode path is transferred gradually to the topographic mode path. It is suggested that this change in the partition of energy between the two mode paths is related to the blocking of planetary waves, which propagate westward, by the ridge. It is thus concluded that the influence of the ridge on unstationary currents is of equal importance to that on stationary current dynamics.

1. Introduction

Many investigations have been made to find a theoretical background behind the generation of the large meander of the Kuroshio to the south of Honshu (e.g. Robinson and Taft, 1972, White and McCreary, 1976, Ishii and Toba, 1977, and Matsukawa, 1979), and it is expected that the variation in the volume transport of the Kuroshio is playing the essential role.

Many long term observations have revealed the existence of the seasonal as well as year-to-year variations in volume transport of the Kuroshio to a considerable extent (e.g. Nitani, 1975, and White, et al., 1978). Consequently, to get a clear idea of the path dynamics of the Kuroshio, it is essential to elucidate the effect of the variation in volume transport in addition to the topographic effect, in the numerical models.

So far, almost all of the numerical models considered fixed boundary conditions and used stationary states. Sekine (1979, hereafter referred to as Part I) studied the bottom effect of the Izu ridge on path of the Kuroshio with a homogeneous model, and showed the formation of a strong current along the easternside of the ridge with its weaking along the western side as a result of the planetary β effect. It seems essential for the present to know whether the path of the current is modified by a change in volume transport, and if so, how it attains the stationary state with the elapse of time. As an initial step to this part of our study, we will investigate the influence of the linear increase in volume transport on the stationary path.

2. Dynamical model including a variation in volume transport

The schematic view of the model ocean is illustrated in Fig. 1, which is the same as used in Part I, and includes the main topographic features of the southern regions adjacent to Japan (details in Part I). We are assuming a homogeneous model and the following vorticity equation as controlling the model ocean:

$$\frac{\partial z}{\partial t} = \frac{\partial}{\partial x}(uz) + \frac{\partial}{\partial y}(vz) + \beta v + f\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + A_h\left(\frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2}\right) \qquad (1)$$

where

$$z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \qquad (2)$$

is the relative vorticity $u = -1/h(\partial\phi/\partial y)$ and $v = 1/h(\partial\phi/\partial x)$ are the eastward (x-axis) and northward (y-axis) velocity component expressed by the volume transprot function ϕ under the rigid lid approximation, h is the depth of the ocean, $f = f_0 + \beta y$ the Coriolis parameter for a β plane, A_h the constant coefficient of horizontal eddy viscosity. All the parameters and constants are common with those in Part I.

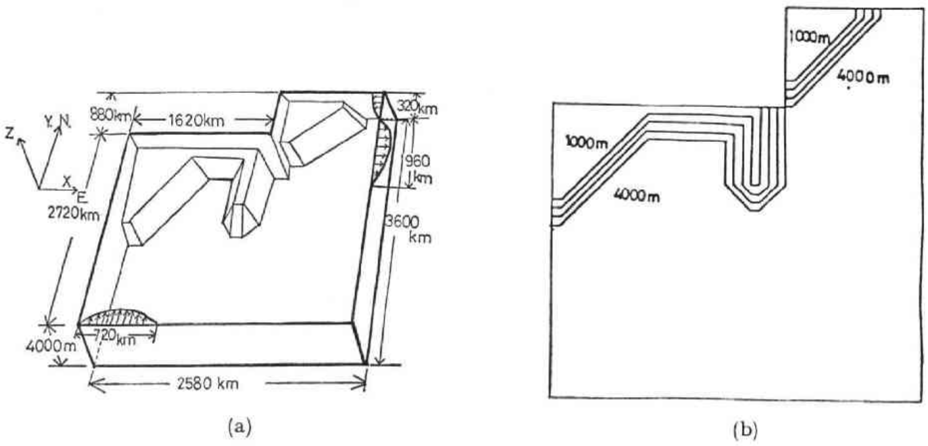

Fig. 1. Schematic view of the model ocean (a) and isopleths of the depth (b).

The time changes of the inflow and outflow at the boundaries are shown in Fig. 2. As the initial condition, a constant inflow of 30 Sv (1 Sv$=10^6$m^{3}s^{-1}) is assumed and the integration is performed for 105 days. Since the numerical solution indicated a stationary oceanic condition by the 105th day as shown in Part I, the total transport at the boundaries is allowed to increase at a constant time rate from the 30 Sv of the

105th day to the 80 Sv of the 109th day. After this, we carried out further time integration with a constant inflow of 80 Sv for the next 50 days, keeping all other conditions the same.

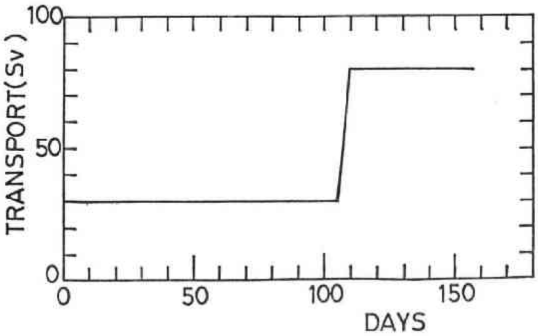

Fig. 2. Time change in the inflowing transport across the boundary.

3. Results

Fig. 3 displays the time series of the numerical solution represented by the velocity vectors calculated from stream function ϕ. The grids with low velocity less than 0.5 cms^{-1} are not indicated.

During the initial stage immediately after the onset of increasing volume transport, the additionally inflowing water has a tendency to flow directly from the inflow region to the outflow region. Afterwards, this water gradually shifts westward as a Rossby wave.

Fig. 4 shows the temporal change of the total kinetic energy. The total energy becomes almost stationary at around the 20th day after the onset of the volume transport increase. Since a disturbance propagates as a Rossby wave, 20 days are considered to be the period for a barotropic Rossby wave to run across from the eastern boundary to the western boundary.

Fig. 5 shows the time-dependent zonal velocity distributions along the line of $x=$ 550 km (distance from the western boundary), which reveals a considerable variation with two peaks in the region south of Japan. In the early stage, the growth rate of the southern branch (Peak II in Fig. 5) is larger than that of the northern one (Peak I). We call the former southern branch the Rossby wave mode path or planetary wave mode path, since this is strongly influenced by the planetary β effect. On the other hand, we call the latter one the topographic mode path, since it is formed by the topographic effect of the continental slope. At a considerably later time, the topographic mode path is fully developed, and the total flow pattern shows a close resemblance to that of the initial state. This reveals that the topographic mode path requires considerably more time for its formation than the planetary mode path does.

The difference in the rate of development between the two paths is the main result of the present study. The basic dynamical properties of the numerical model are consistent with the Munk-type solution (Munk, 1950), with the addition of the topographic mode

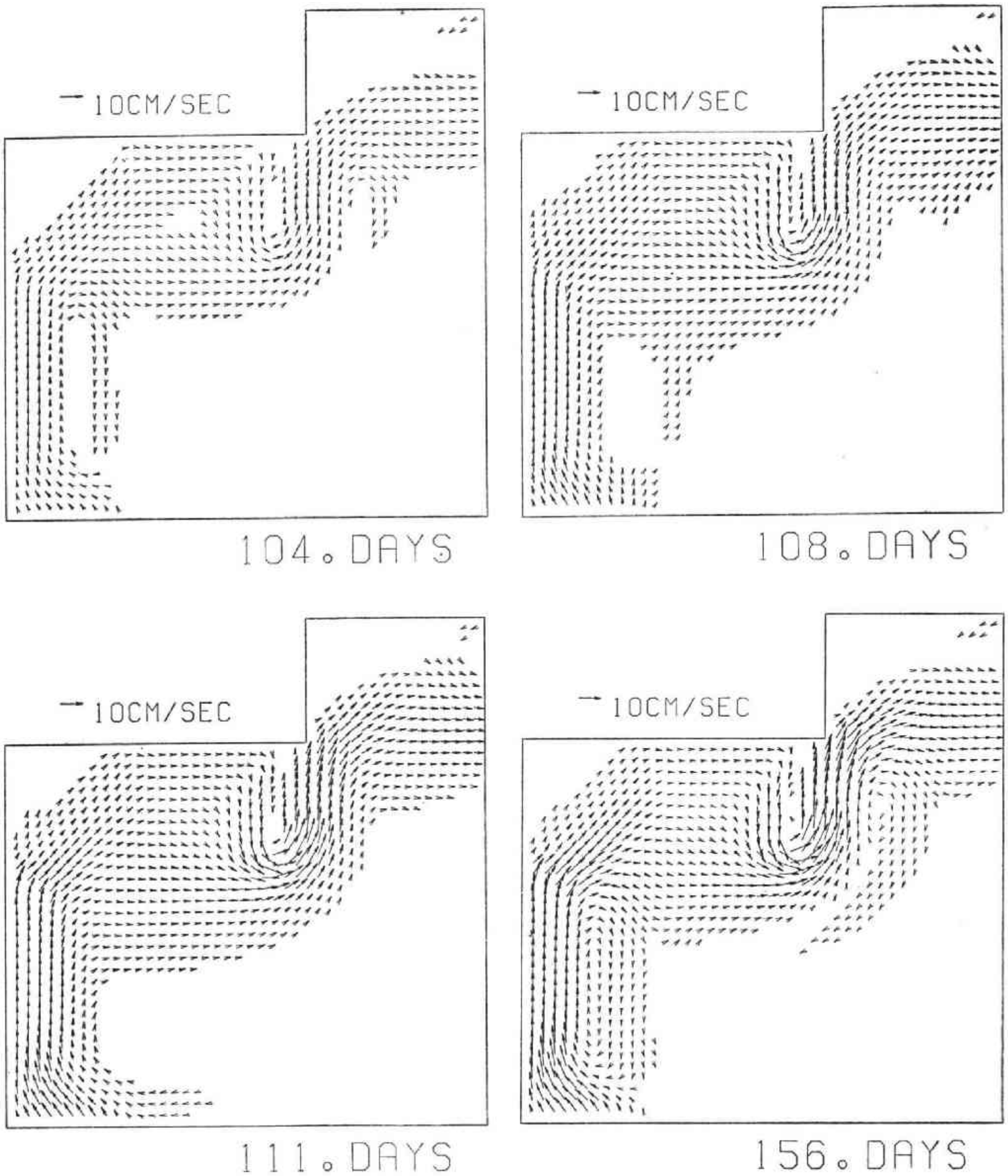

Fig. 3. Time evolution of the numerical solution.

solution which is found along the continental slope. The former, which means a vorticity balance between the β term (βv) and the viscous term ($A_h \nabla^2 Z$), occupies the western boundary region with a flat bottom. Conversely, the latter extends along the continental slope, in which the vorticity balance between the topographic term $f(\partial u/\partial x + \partial v/\partial y)$ and the viscous term is dominant. The time changes of the vorticity balance are shown in Fig. 6, and a schematic representation of the main results of the numerical solution is displayed in Fig. 7.

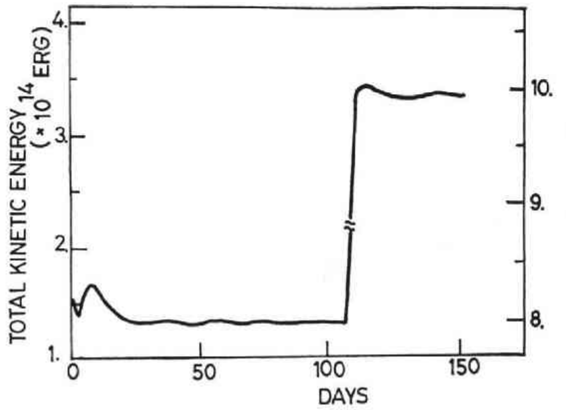

Fig. 4. Time change of the total kinetic energy E. E is defined as $E=1/2\iint_S (u^2+v^2)\,dxdy$.

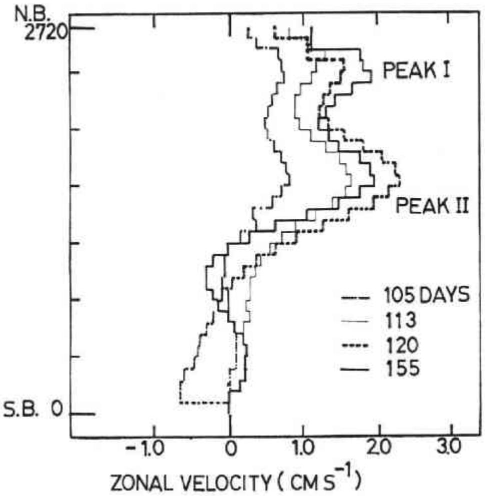

Fig. 5. Time change in the zonal velocity distributions along $x=840$ km (distance from the western boundary).

4. Discussions

In this study, we have investigated the modification of the current path of the Kuroshio due to the increase in volume transport.

A disturbance produced by an increase in volume transport propagates as a planetary wave. If the bottom is flat, the transient planetary wave accumulates along the western boundary and forms the western boundary current (Gates, 1968). If there is some bottom topography such as the ridge, it has a great influence upon the propagation of the planetary wave. The wave generated in the eastern ocean of the ridge can not move westward over it and is accumulated in its eastern side. On the other hand, the western side of the ridge may be regarded as a

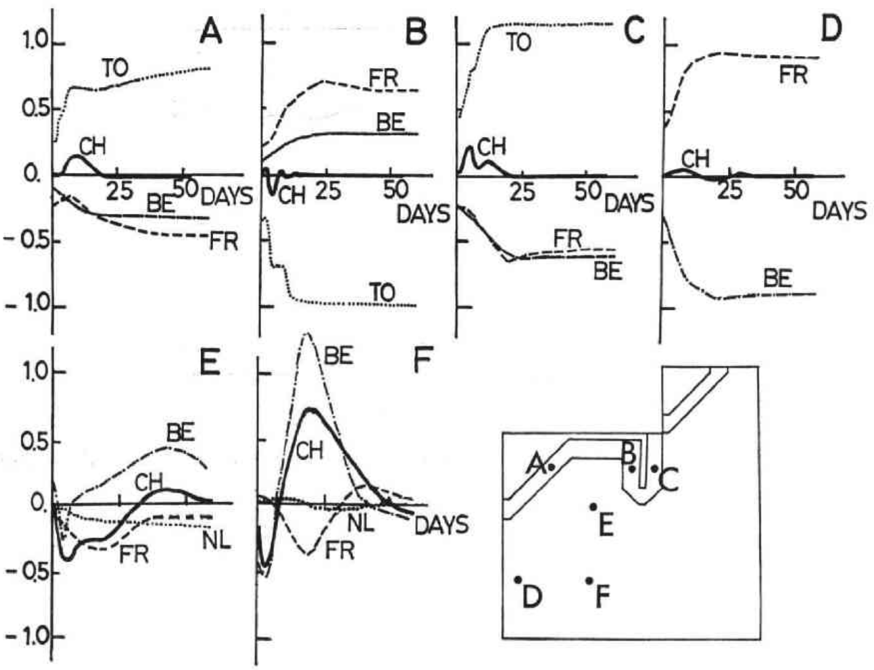

Fig. 6. Time change in the vorticity balance in relative magnitude after the onset of increase in volome transport at five representative points (A-F). The location of these points are also shown in the lower right panel in this figure. TO, FR, BE, NL and CH mean topographic term $f(\partial u/\partial x+\partial v/\partial y)$, friction term $A_h\nabla^2 z$, βterm βv, nonlinear term $\partial/\partial x(uz)+\partial/\partial y(vz)$ and local time change term $(\partial z/\partial t)$, respectively.

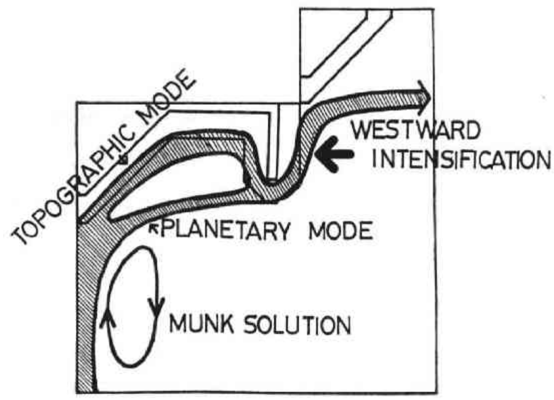

Fig. 7. Schematic representation of the main features of the numerical solution of this study.

shadow region to the westward propagation of planetary wave due to the blocking of it by the ridge. There is a possibility that the slow formation of the topographic mode path in the upstream region to the ridge shown in Fig. 5 is related to this effect. The ridge must have an unavoidable influence in the stationary current dynamics.

However, we can not directly apply these results to the consideration of the real oceanic variability, since we had neglected the density stratification. Nevertheless, it is expected that, if the boundary condition is appropriate, the barotropic response of the current has some similarity with the results of our model.

Longuett-Higgins (1965) and Gates (1970) studied the properties of the incident and reflected planetary waves in the western boundary region. Since we assumed a considerably larger value for the eddy viscosity coefficient, we were not able to include them in our numerical solution. Other problems of the large value of eddy viscosity are a supression of the nonlinear effect and the exclusion of the barotropic instability. These problems need to be included in the next step of the study.

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