

Kuroshio and recirculation gyres

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The Kuroshio path dynamics is discussed using a high resolution primitive equation model of the Kuroshio and the Oyashio region. The model includes realistic topography, coastal line, and temperature and salinity stratification. The Kuroshio and the Oyashio are driven by inflow/and outflow boundary conditions. It has been shown that the model represents typical features of the Kuroshio flow well.

Here, we discuss a mechanism for the bimodality of the Kuroshio path. Interaction between the Kuroshio and an anti-cyclonic recirculation off the south coast of Japan has been particularly emphasized, since it provides a positive feedback mechanism to the meander formation as follows. When the model Kuroshio takes the meandering path, the potential vorticity of the recirculation is markedly homogenized, accompanying strong transport fluctuations of 50-100 day period. This intensifies the anti-cyclonic recirculation through the 'eddy Sverdrup' balance, which further leads to the enhancement of the Kuroshio meander.

Key Words: Kuroshio, meander, recirculation gyre, numerical model

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1 Introduction

The Kuroshio is a western boundary current flowing along western perimeter of the North Pacific basin. It is well-known that the Kuroshio takes multiple paths off the coast of Japan. Kawabe (1985) classified it into three types: large meander path, non-large-meander nearshore path, and non-large-meander off-shore path (Fig. 1). Since the Kuroshio path gives a strong impact on fisheries, maritime safety, ship navigation, local climate and so on, a lot of research from various angles have been conducted. Among them, a hypothesis of non-linear multiple equilibria first discussed by Charney and Frierl (1981) and Masuda (1982) has attracted interests as a large meander mechanism. Motivated by these theories, several numerical experiments has been conducted looking into non-linear nature of the Kuroshio paths, paying attention to the topographic effect of Kyushu and Izu Ridge (e.g. Chao, 1984; Yasuda et al, 1985; Yoon and Yasuda, 1987; Akitomo et al., 1991). Another approach is to discuss the effect of local topography on non-linear waves or eddies, such as Kyushu (White and McCreary, 1976), Kii Peninsula (Yamagata and Umatani, 1989) and Izu Ridge (Mitsudera and Grimshaw, 1994). All these models show multiple paths of the Kuroshio relative to Kuroshio inflow transport or velocity.

These works use simple reduced gravity or quasi-geostrophic models, with inflow-outflow boundary conditions for Kuroshio.

Simple models are useful to identify the important physical processes. However, these are in turn so simple that direct comparison with observations was difficult.

Here we will describe results from a high-resolution regional model with realistic topography, coastal line, and stratification. The Kuroshio flow is forced by inflow/outflow boundary conditions, so that we can discuss the sensitivity of the Kuroshio path to various infow conditions. The modeled Kuroshio flow field is found to be remarkably similar to that of observation as shown later. This makes us examine the Kuroshio path problem in a realistic framework, and in fact, we have obtained transition of the paths in realistic range in transport.

In this paper, the role of the anti-cyclonic recirculation gyre off Shikoku in the Kuroshio path dynamics is to be highlighted. For a modeled meandering path, the potential vorticity is homogenized in the recirculation gyre, leading to further enhancement of the meander of the Kuroshio. The recirculation gyre accompanies 50-100 days variations, which is particularly pronounced when the path takes the large meander. These suggest the eddy Sverdrup balance of recirculation gyres discussed by Jayne et al (1997). It is worth pointing out that sea-level observation by TOPEX/POSEIDON (e.g. Imawaki et al, 1997) also shows such strong 50-100 days variations in the recirculation gyre off Shikoku.

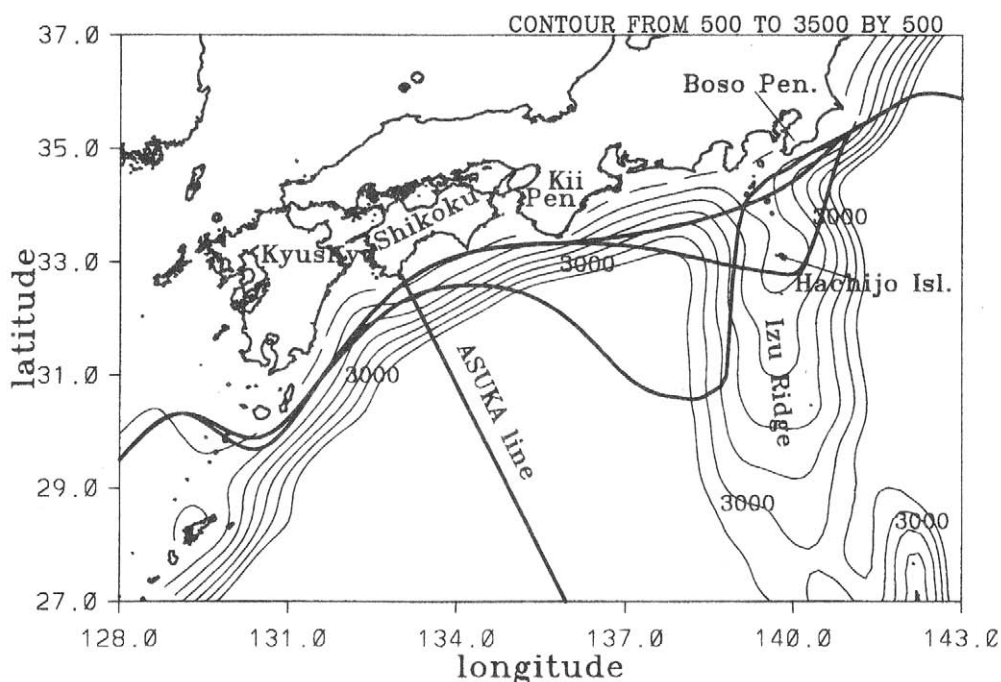


Fig.1 The model geometry near the coast of Japan. Readers refer to Mitsudera et al (1997) for the geometry of the entire domain. The three typical paths by Kawabe (1985) are also indicated.

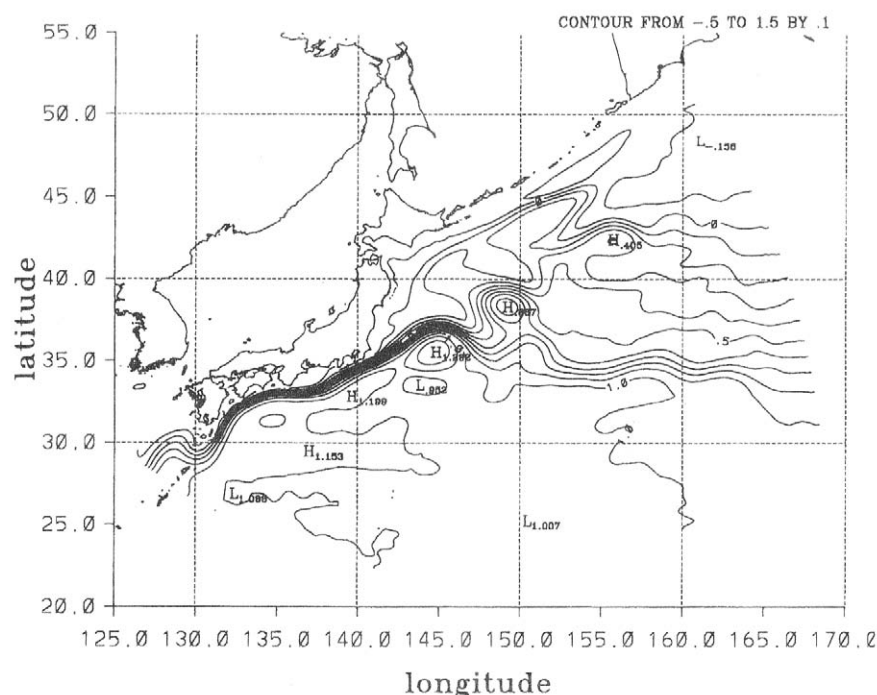


Fig.2 One-year mean Sea Surface height field obtained from the model.

2 Model configuration

We shall briefly describe the configuration of this model in this section; more detailed description may be found somewhere else (e.g. Mitsudera et al 1997). We use a sigma-coordinate, primitive equation ocean model described by Blumberg and Mellor (1987), so-called the Princeton Ocean Model (POM). A curvilinear coordinate grid is used, where the resolution is as high as 1/12 degree near the Japanese coast. Bottom topography is smoothed so that spurious flow should not occur due to the sigma-coordinate of POM. We used Hellerman and Rosenstein (1983) wind stress, and heat flux derived from COADS with weak relaxing to Levitus SST (e.g. Ezer and Mellor, 1992) as the surface boundary conditions. As for the lateral boundary condition, radiation condition is used for the barotropic mode, while a sponge layer is used for the baroclinic modes. A turbulent closure model (level 2.5) of Mellor and Yamada (1982) is used to calculate vertical viscosity and diffusivity coefficients, while Smagorinsky scheme is used to estimate horizontal ones.

Figure 2 shows a sea surface height field from a typical run, including seasonal wind stress and heat flux forcings. Although we shall not discuss this result in detail here (but elsewhere), we would like to point out that the overall features of the Kuroshio system are well represented in this model. For example, we can see: 1) narrow and strong Kuroshio; 2) well-defined recirculation gyres; 3) sharp separation of the Kuroshio

from the Boso Peninsula, and distinct Kuroshio extension.

We also show a cross stream structure of the modeled Kuroshio on the ASUKA line (Fig. 3). Comparing with observed Kuroshio structures by Imawaki et al (1997; their Fig. 3), the model Kuroshio captures observed characteristics very well. For example, eastward current extends to 31°N, and 0.2m/s contour reaches 1000m depth. Further, velocity maximum forms below the surface offshore from the velocity core in the model as well as in the observation. Model maximum velocity is about 1.5m/s, which may appear to be larger than the observed one. However, velocity as fast as 1.8m/s was indeed observed by a moored ADCP at 32.5°N, so that the model velocity structure well represents the observation.

3 Numerical experiments with various inflow transport

In the following experiments we only vary inflow/outflow boundary conditions; wind stress and heat flux forcings are steady here. Figure 4 shows examples of the Kuroshio paths with varying the inflow transport and shear structure. We can see that three types of the Kuroshio path are realized, corresponding to the three different inflow conditions.

In the 25Sv case (Fig. 4a), Kuroshio flows along Kyushu and Shikoku, then slightly separates after the Kuroshio passes Kii Peninsula. This is a typical feature of the non-large-meander path, and is suggestive of the role of the coastline topography in the path dynamics (e.g. Yamagata and Umatani, 1989).

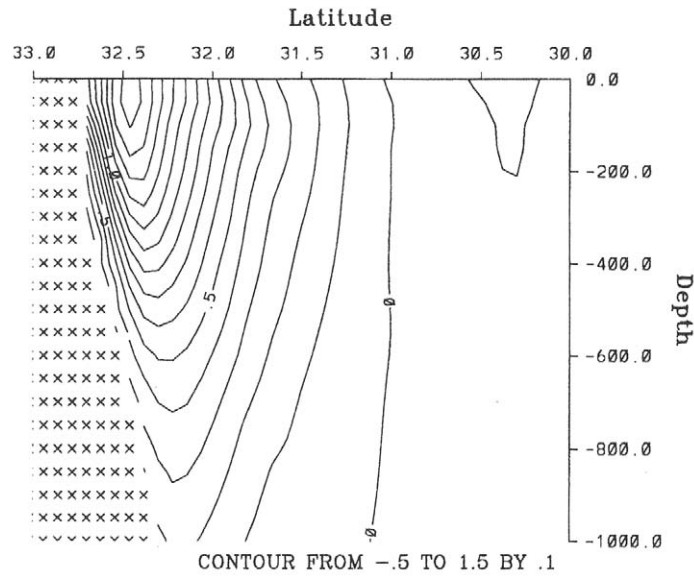


Fig.3 Velocity section of a model Kuroshio along the ASUKA line(one-year mean). Inflow transport is 25Sv

Then, the Kuroshio passes the northern flank of the Hachijo island (see Fig. 1 for the topography) to flow over the Izu Ridge. This corresponds to the typical non-large meander nearshore path according to Kawabe (1985). The 35Sv case (Fig. 4b) represents the non-large-meander offshore path. The Kuroshio separates the Japanese coast from the Kii Peninsula, and passes the southern flank of the Hachijo island in this case. The 45Sv case (Fig. 4c) represents the large meander path. The Kuroshio has a well-defined meander in this case off the south coast of Japan. Note that the Kuroshio returns to the coast westward from the Izu Ridge. It then passes through the ridge on the northern flank of the Hachijo island, flowing out to the Kuroshio extension area.

These figures indicate that the model Kuroshio tends to take the large meander path when the inflow transport is large. This tendency is similar to that in various numerical experiments such as Chao (1983), Yoon and Yasuda (1987), and Akitomo et al (1994).

What causes this difference in this model? From the figures in Fig.4, we notice that the recirculation gyre in the 45Sv case is remarkably intensified compared to that of the 25Sv case. We therefore examined the potential vorticity field in the recirculation gyre. Figure 5 shows scatter plots of the depth-integrated potential vorticity in terms of the transport function in the Shikoku basin for the non-large meander case and the large meander case. Here, the transport function ψ along a section s and the depth-integrated potential vorticity Q are defined as

$$\psi = \int_s H \mathbf{V} \cdot \mathbf{n} ds, \quad Q = (f + \nabla H^{-1} \nabla \psi) / H,$$

where V, f, H , and $\mathbf{n}$ are the depth integrated velocity vector, the Coriolis parameter, total depth, and the unit vector normal to the section s , respectively.

Difference in the potential vorticity distribution between the two cases is striking. The non-large meander case shows that the potential vorticity is almost linearly proportional to the potential vorticity. Since the model bottom topography is flat in the Shikoku basin, where $H=4000\text{m}$, except for the continental slope area, the potential vorticity is dominated by the Coriolis parameter. On the other hand, the large meander case shows that the homogeneous potential vorticity exists in the large range of the transport function.

It is now clear that the intensive recirculation in the meander case is caused by this homogeneous potential vorticity structure. From the 'eddy Sverdrup' balance (Jayne et al, 1997), we can see that

$$\bar{\mathbf{V}} \cdot \nabla \bar{Q} \approx - \nabla \cdot \int_{-H}^0 \overline{q' \mathbf{v}'} dz,$$

where the overbar and the prime denote the time mean and anomaly, respectively. q' and $\mathbf{v}'$ are the anomalous potential vorticity and the anomalous velocity vectors, respectively, so

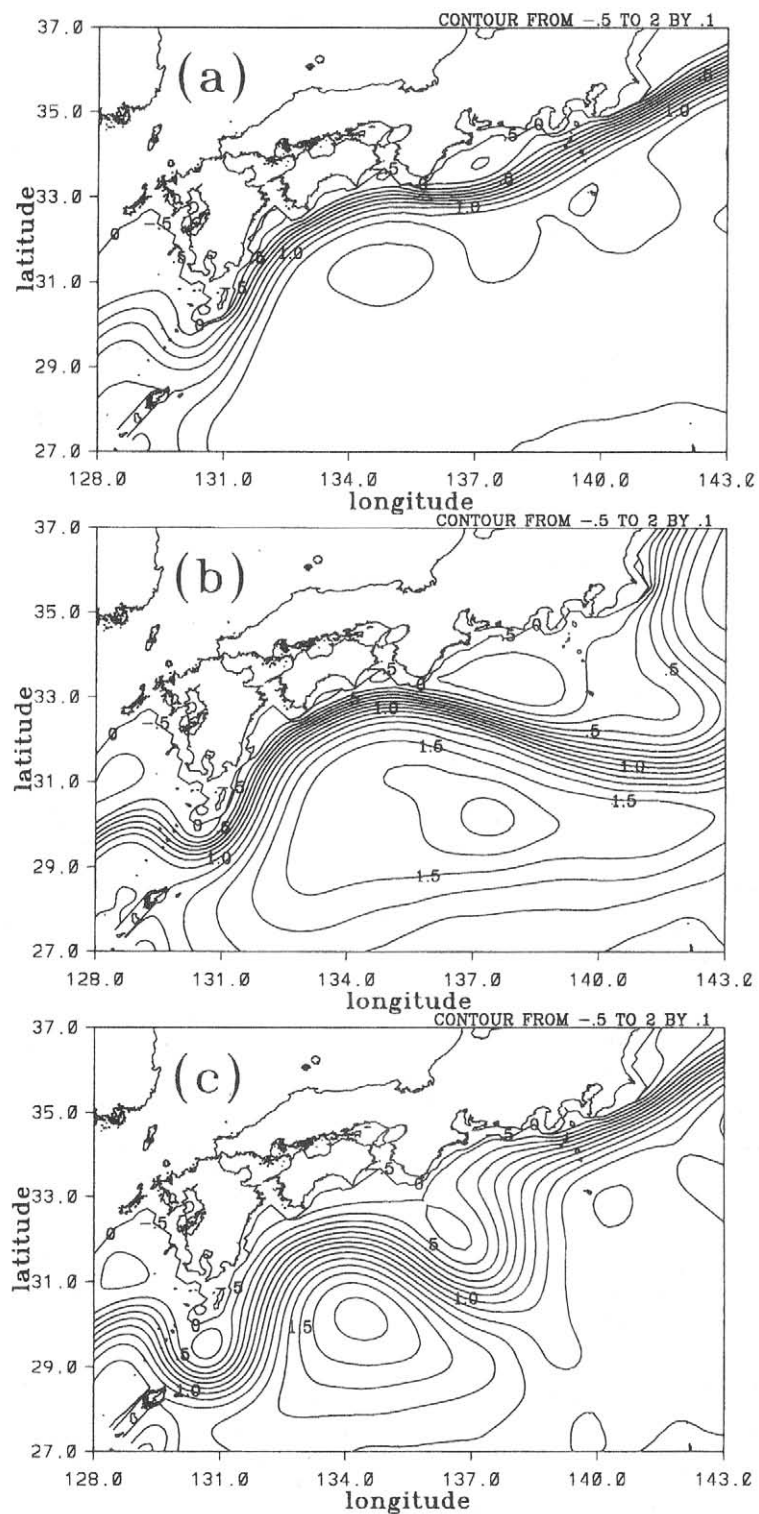


Fig.4 Three typical paths simulated in the model. Inflow transport is 25Sv (top panel), 35Sv (middle panel) and 45Sv (bottom panel).

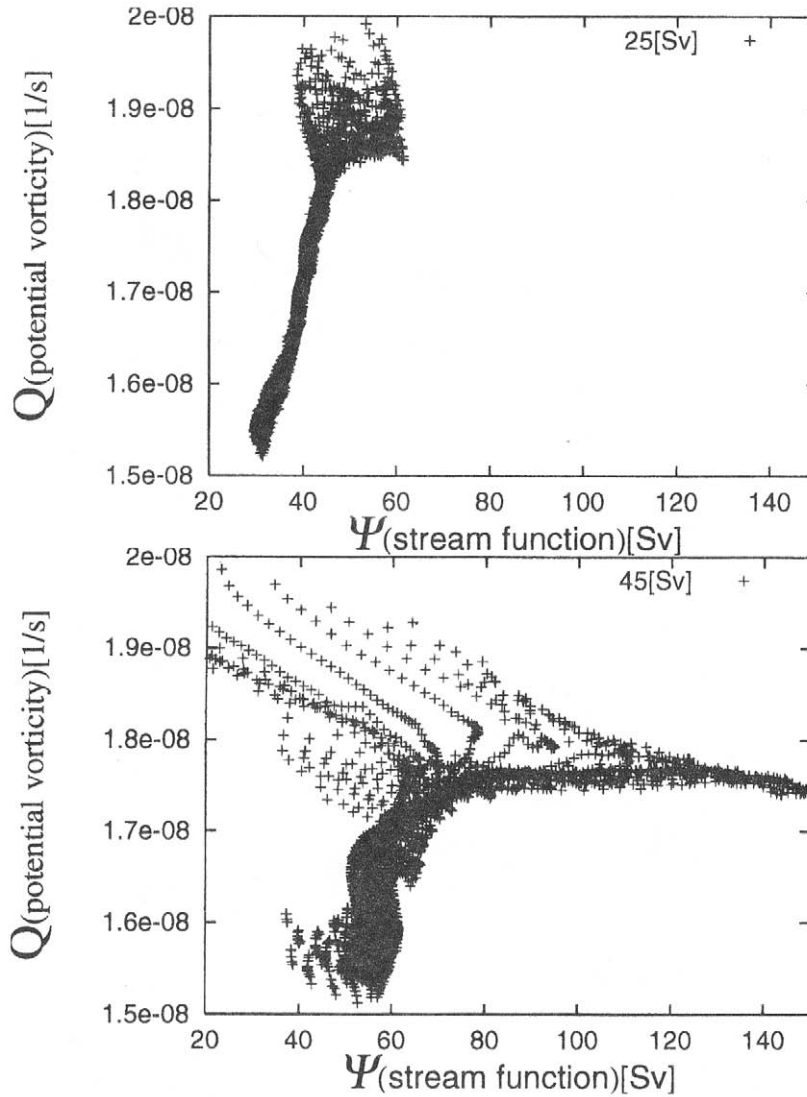


Fig.5 Scatter plots showing relationship between potential vorticity and stream function. Top panel (bottom panel) displays 25Sv (45Sv) case.

that the right-hand side represents the convergence of the eddy (or Eliassen and Palm) flux. Since the potential vorticity gradient in the left-hand side is almost zero where $\bar{Q}$ is nearly constant, $|\mathbf{V}|$ may be large even if the eddy forcing is small. The eddy flux convergence from the barotropic eddy component may be represented as $\overline{J(\psi', \nabla H^{-1} \nabla \psi' / H)}$.

Figure 6 shows the variation of the eastward transport anomaly for both the non-large meander and the large meander cases along the ASUKA line off Shikoku (see Fig. 1 for its location) as an index of the eddy field. There are distinct intra-seasonal variations of 50-100 day fluctuations. Further, amplitude of the fluctuations in the large meander case (45Sv) is much larger than that of the non-large meander case (25Sv). Therefore, the barotropic eddy forcing is much larger in the 45 Sv case than that of the 25 Sv case.

In conjunction with the homogenised potential vorticity structure in the recirculation gyre, it appears that the eddy-mean interaction in the large meander case provide a positive feedback mechanism to the large meander formation. That is, strong eddies mix the potential vorticity effectively, as well as provide strong eddy forcing, leading to the intensification of the recirculation gyre. Then, the intensified recirculation interacts with the Kuroshio current to enhance the meander, which further induce even stronger eddies and fluctuations.

Figure 7 indicates the latitude of the Kuroshio path, defined as the maximum velocity off the south coast of Japan, when the inflow transport is increased very slowly from 25 Sv to 45 Sv with the rate of 5Sv increase per year. The boundary forcing is considered to be quasi-steady because of this slow changes in the inflow condition. In the case of increasing transport, the Kuroshio starts to take the meander path when the transport

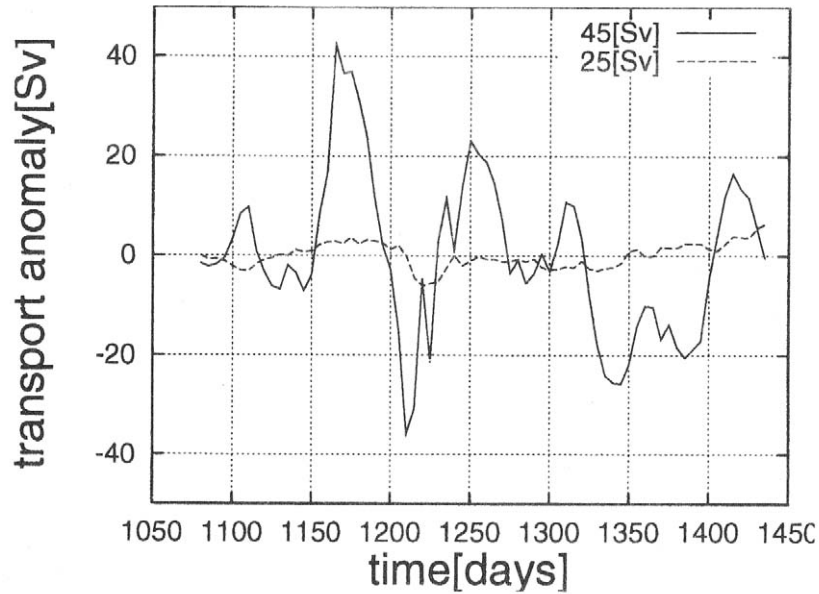


Fig.6 Fluctuation of eastward transport along the ASUKA line. Solid(dashed) line denotes the 45Sv (25Sv) case.

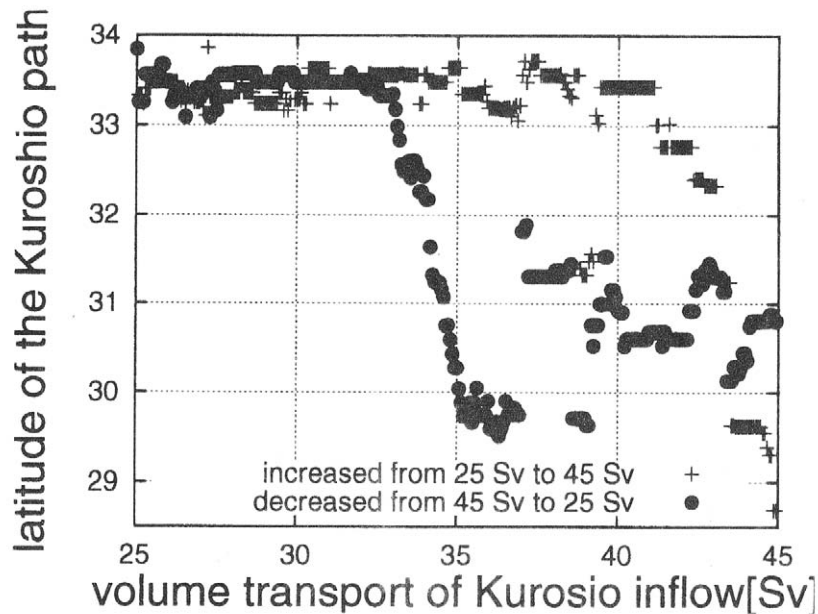


Fig.7 Relation between the inflow transport and the position of the southernmost Kuroshio axis, indicating the amplitude of the meander.

passes about 40Sv. In the case of decreasing transport, the Kuroshio meanders initially, it then suddenly takes the non-meander path from about 30 Sv. Therefore, there are multiple states in the Kuroshio path in the inflow transport range between 30 Sv and 40 Sv in this experiment. We can also see that there is stronger variability in the axis position when the Kuroshio took the large meander path. This implies that this multiple states arise from the non-linear nature of the recirculation whose potential vorticity is markedly homogenized as discussed above.

4 Conclusion

We have shown that the high resolution regional model successfully simulate the multiple paths of the Kuroshio. In this paper, it has been particularly highlighted that the non-linear nature of the Kuroshio path in this model arises from the potential vorticity mixing in the recirculation gyre off Shikoku; potential vorticity there is markedly homogenized when the Kuroshio takes the large meander path.

The potential vorticity mixing is accompanied with strong 50 - 100 day variations in transport. Such variations have been indeed observed along the south coast of Japan. For example,

TOPEX/POSEIDON altimeter has detected this variation as shown by Imawaki et al (1997). There were strong fluctuations in sea-level height (which has a good correlation with transport) in 1993. The Kuroshio tended to meander at that time, although it did not develop to a stationary meander. From a further analysis of the ASUKA line data, Imawaki et al (1997) mentioned that these variations can be attributed to those in the recirculation gyre. Detailed comparison between observation and models awaits further study.

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REFERENCES

- 1) Akitomo, K., T. Awaji, and N. Imasato, 1991: Kuroshio path variation south of Japan 1.: barotropic inflow-outflow model. *J. Geophys. Res.* 96, 2549-2560.
- 2) Blumberg, A. F. and G. L. Mellor, 1983: Diagnostic and prognostic numerical circulation studies of the South Atlantic Bight, *J. Geophys. Res.*, 88, 4579-4592.
- 3) Chao, S.-Y., 1984: Bimodality of the Kuroshio. *J. Phys. Oceanogr.*, 14, 92-103.
- 4) Charney, J.G., and G.R. Frierl, 1981: Ocean analogue of large-scale atmospheric motion. *Evolution of Physical Oceanography*, B. Warren and C. Wunsch eds., MIT Press, 504-548.
- 5) Ezer, T and G. L. Mellor, 1992: A numerical study of the variability and the separation of the Gulf Stream induced by surface atmospheric forcing and lateral boundary flows, *J. Phys. Oceanogr.*, 22, 660-682.
- 6) Imawaki, S., H. Uchida, H. Ichikawa, M. Fukasawa, S. Umatani and ASUKA group, 1997: Time Series of the Kuroshio Transport Derived from Field Observations and Altimetry Data., *International WOCE Newsletter*, 25, 15-18.
- 7) Jayne, S.R., N.G. Hogg, and P. Malanotte-Rizzoli, 1996: Recirculation gyres forced by a beta-plane jet. *J. Phys. Oceanogr.*, 26, 492-504.
- 8) Kawabe, M., 1985: Sea level variations at the Izu Islands and typical stable paths of the Kuroshio. *J. Oceanogr. Soc. Japan*, 41, 307-326.
- 9) Masuda, A., 1982: An interpretation of bimodal character of the stable Kuroshio path. *Deep-sea Res.*, 29, 471-484.
- 10) Mellor, G. L. and T. Yamada, 1982: Development of a turbulent closure model for geophysical fluid problems, *Rev. Geophys. Space Phys.*, 20, 851-875.
- 11) Mitsudera, H. and R. Grimshaw, 1994: Capture and resonant forcing of solitary waves by the interaction of a baroclinic current with topography. *J. Phys. Oceanogr.*, 24, 2217-2244.
- 12) Mitsudera, H., Y. Yoshikawa, B. Taguchi and H. Nakamura, 1997: High-resolution Kuroshio/Oyashio System Model: Preliminary Results, *JAMSTECR*, 36, 147-155.
- 13) White, W.B. and J.P. McCreary, 1976: The Kuroshio meander and its relationship to the large scale ocean circulation. *Deep-Sea Res.*, 23, 33-47.
- 14) Yamagata, T. and S. Umatani, 1989: Geometry-forced coherent structures as a model of the Kuroshio large meander. *J. Phys. Oceanogr.*, 19, 130-138.
- 15) Yasuda, I., J.-H. Yoon, and N. Sugimotohara, 1985: Dynamics of the Kuroshio Large meander-Biotropic model. *J. Oceanogr. Soc. Japan*, 41, 259-273.
- 16) Yoon, J.-H. and I. Yasuda, 1987: Dynamics of the Kuroshio meander: Two-layer model. *J. Phys. Oceanogr.*, 17, 66-81.

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