La mer 47 : 19-27, 2009
Société franco-japonaise d'océanographie, Tokyo

Transition to the Large Meander Path of the Kuroshio as Observed by Satellite Altimetry

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Abstract: By combining satellite altimeter data and sea-surface drifter data, we examine the transient processes leading to the Large Meander (LM) path of the Kuroshio south of Japan in 2004, which occurred for the first time after the TOPEX/POSEIDON altimetry started in 1992. The transition to the LM path was preceded by the generation of the "trigger meander" southeast of Kyushu, which then propagated eastward south of Shikoku. After the trigger meander passed Cape Shiono-misaki, it slowed down with its trough rapidly amplified over Koshu Seamount located about 200 km to the south of Cape Shiono-misaki. Consequently, the Kuroshio meander looped back west of the Izu-Ogasawara Ridge, leading to the formation of the LM path. The time series of the Kuroshio axis from 1993 through 2005 shows that the meander trough extended over Koshu Seamount only in 2004. All of these observed features are well reproduced in the model results by ENDOH AND HIBIYA (2001) , who demonstrated the important role of baroclinic instability over Koshu Seamount in the formation of the LM path of the Kuroshio.

Keywords: *Kuroshio large meander, trigger meander, Koshu Seamount, satellite altimetry*

1. Introduction

The Kuroshio is the western boundary current constituting part of the subtropical gyre in the North Pacific. It flows northward east of Taiwan and then approximately eastward south of Japan with a horizontal width of about 100 km. It is well known that the Kuroshio path south of Japan can be categorized into two typical patterns, namely, the Non Large Meander (hereafter referred to as NLM) path where the Kuroshio flows along the southern coast of Japan and the Large Meander (hereafter referred to as LM) path where the Kuroshio flows far away from the coast off the Enshu–nada. Each path persists for several years once it is formed (KAWABE, 1987). This bimodal feature cannot be found in the other western boundary currents.

Based on the hydrographic surveys along the PN line in the East China Sea from 1955 to 1992, KAWABE (1995) found that the Kuroshio took the LM path while the Kuroshio volume transport exceeded 23.5 Sv (1 Sv$\equiv 10^6$ m^3s^{-1}), although no clear relationship could be found for the NLM path. This is consistent with the results from previous numerical models showing the existence of the multiple equilibrium state where both the LM and NLM paths can exist for large volume transport of the Kuroshio (e.g. CHAO, 1984; YOON and YASUDA, 1987; AKITOMO *et al.*, 1997; MASUDA and AKITOMO, 2000). In the multiple equilibrium state, the Kuroshio path selected by the numerical models strongly depends on the transient response.

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Therefore, in order to identify the physical parameters related to the bimodal feature of the Kuroshio, we need numerical models capable of reproducing the observed features during the transition between the LM and NLM paths.

Prior to the transition from the NLM path to the LM path off the Enshu–nada, a small meander is generated southeast of Kyushu and then propagates eastward; after passing Cape Shiono–misaki in about 4 months, this small meander rapidly amplifies evolving into the LM so that it is called a "trigger meander" (SOLOMON, 1978). Several numerical studies have been carried out to reproduce the transition from the NLM path to the LM path using inflow–outflow regional models (e.g. ENDOH and HIBIYA, 2001; WASEDA *et al.*, 2003) and basin–scale models (e.g. TSUJINO *et al.*, 2006). However, *in situ* observations of sea–surface current velocity are too sparse both in time and space to check the validity of each model result quantitatively. For example, the location of the Kuroshio axis, along which the largest velocity of the Kuroshio can be found, has been indirectly estimated by interpolating the temperature index defined as isothermals at 200 or 400 m depth (KAWAI, 1969; KAWABE, 1980).

In contrast, combining satellite altimeter data and sea–surface drifter data has enabled us to estimate the time series of the instantaneous sea–surface velocity field over a wide area with much higher temporal resolutions (UCHIDA and IMAWAKI, 2003; IMAWAKI *et al.*, 2003). Based on the sea–surface velocity data obtained in this way, AMBE *et al.* (2004) determined the detailed spatial and temporal distributions of the Kuroshio axis from 1993 through 2000 during which period the Kuroshio had been taking the NLM path.

In 2004, the Kuroshio shifted from the NLM path to the LM path for the first time after the TOPEX/POSEIDON altimetry started in October 1992. In the present study, based on the absolute geostrophic velocity distribution estimated by the method of UCHIDA and IMAWAKI (2003), we first examine the details of the generation and evolution of the trigger meander leading to the formation of the LM path of the Kuroshio in 2004. Next, we compare the observed Kuroshio axis tracked using the method of AMBE *et al.* (2004) with that determined from the model result obtained by ENDOH and HIBIYA (2001).

2. Data and Methods

In the present study, the sea–surface velocity field and the Kuroshio axis position were estimated at intervals of 1/3°every 7 days from October 1992 through December 2005 using the method of UCHIDA and IMAWAKI (2003). In each gridded location, time averaged sea–surface velocity $\overline{\mathbf{V}}\ (\boldsymbol{x})$ was first calculated by subtracting the altimeter–derived velocity anomaly $\mathbf{V'a}\ (\boldsymbol{x}, t)$ from the drifter–measured absolute velocity $\mathbf{Vd}\ (\boldsymbol{x}, t)$, and then ensemble averaged in time, i.e. $\langle\overline{\mathbf{V}}\ (\boldsymbol{x})\rangle = \langle\mathbf{Vd}\ (\boldsymbol{x}, t) - \mathbf{V'a}\ (\boldsymbol{x}, t)\rangle$. Next, by adding $\mathbf{V'a}\ (\boldsymbol{x}, t)$ to $\langle\overline{\mathbf{V}}\ (\boldsymbol{x})\rangle$, the time series of absolute sea–surface velocity field $\mathbf{V}\ (\boldsymbol{x}, t)$ was obtained (IMAWAKI *et al.*, 2003). Based on the obtained $\mathbf{V}\ (\boldsymbol{x}, t)$, we determined the Kuroshio axis by tracking the locations of the largest velocity every 15 km downstream from the south of Kyushu (AMBE *et al.*, 2004).

We created the gridded sea–surface height anomaly data based on the satellite altimeter data from TOPEX/POSEIDON, Jason-1, ERS-1/2 and Envisat, which were produced by Ssalto/Duacs and distributed by Aviso, France (DT–MSLA "Ref") (AVISO, 2006). The positions of sea–surface drifting buoys were interpolated every 6 hours by AOML, U.S.A. These drifting buoy data were low–pass–filtered through 30–hours running mean. The Ekman currents were also calculated by incorporating the surface wind data from Quikscat and ERS-1/2 (IFREMER, 2002a, 2002b) into the formula of NIILER *et al.*, (2003) and were subtracted from $\mathbf{Vd}\ (\boldsymbol{x}, t)$.

3. Formation of Large Meander Path in 2004

Figure 1 shows the sea–surface velocity field and the Kuroshio axis south of Japan every 4 weeks during February 25 to November 3 in 2004. We can see that the trigger meander was generated southeast of Kyushu in February with an anticyclonic mesoscale eddy (marked by symbol A) on the offshore side (Fig. 1a). The trigger meander then propagated eastward up to Cape Shiono–misaki in about 4 months with its trough reaching over the western edge

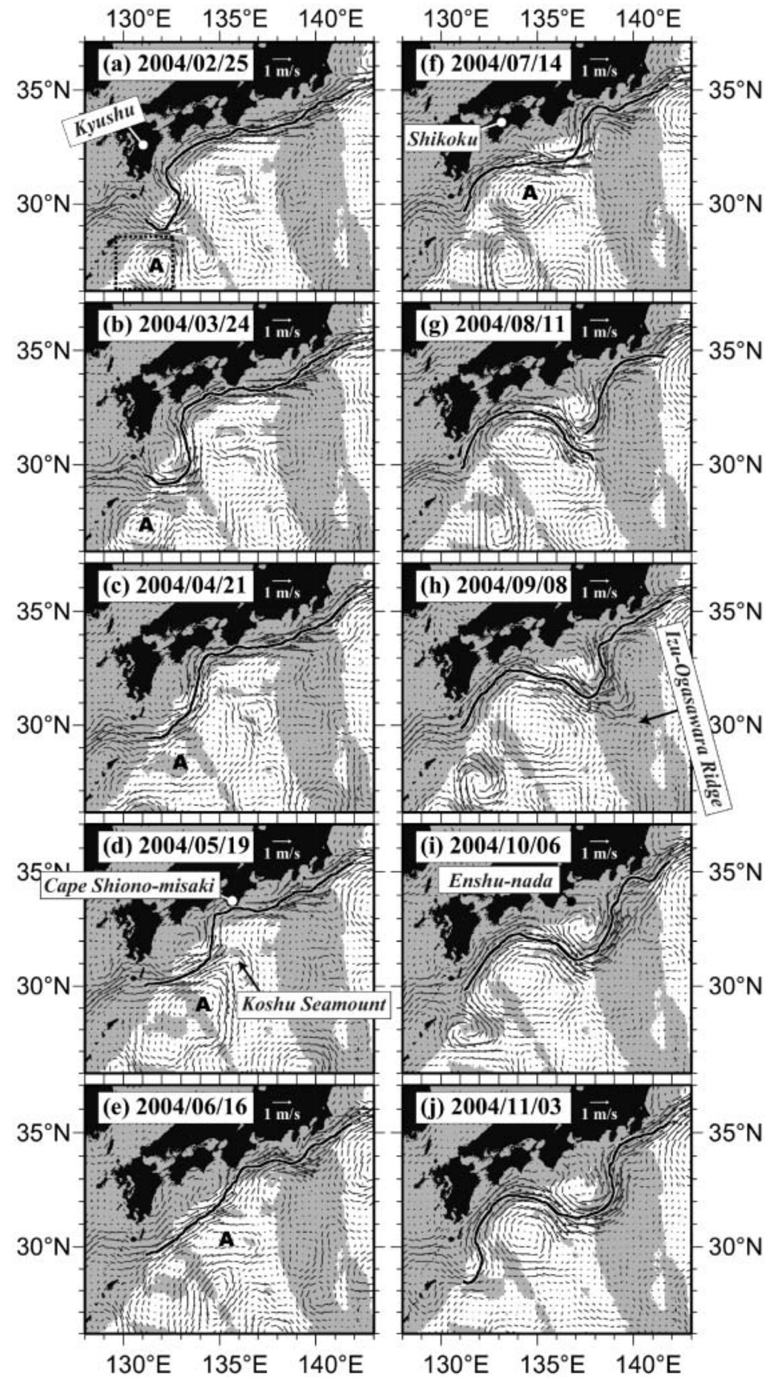

Fig. 1. Time series of the sea-surface velocity field (vectors) and the Kuroshio axis (solid line) in 2004, both estimated using satellite altimeter data combined with drifting buoy data. Since the trigger meander amplifies rapidly at 138 °E, it is impossible to track the Kuroshio axis throughout in panel (g). For this reason, the Kuroshio axis east of 138 °E is tracked upstream. Areas with the depth shallower than 4000 m are shaded. Symbol A indicates an anticyclonic mesoscale eddy. Enclosed by the dashed line in panel (a) is the area where the relative vorticity anomaly is averaged (see Fig. 3).

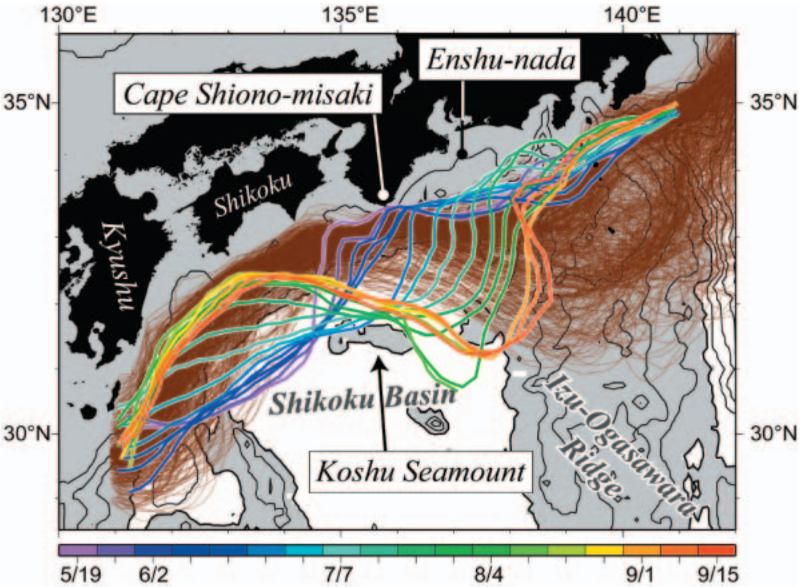

Fig. 2. The Kuroshio axis every 7 days from May 19 to September 15 in 2004 (thick colored lines) and from 1993 to 2003 (thin brown lines), superposed on the bottom topography (contour interval is 1000 m). For the date of each observed Kuroshio axis in 2004, see the color bar under the panel. Areas with the depth shallower than 4000 m are shaded.

of Koshu Seamount (Figs. 1d and 1e). Thick colored lines in Fig. 2 depict the time series of the observed Kuroshio axis after the trigger meander trough reached over Koshu Seamount. We can see that the trigger meander trough rapidly amplified over the eastern side of Koshu Seamount so that the Kuroshio axis extended southward to 30.5 °N, whereas the Kuroshio axis west of Koshu Seamount shifted northward approaching the southern coast of Shikoku (see also Figs. 1f and 1g). Consequently, the Kuroshio looped back west of the Izu–Ogasawara Ridge by the middle of September (see also Fig. 1h). Thereafter, with the relaxation of the sharpness of this meander trough, the stationary LM path was formed off the Enshu–nada (Figs. 1i and 1j).

Superposed by thin brown lines in Fig. 2 are the time series of the Kuroshio axis from 1993 to 2003 during which period the Kuroshio was taking the NLM path. We can see that, during 1993 to 2004, the transition to the LM path oc-

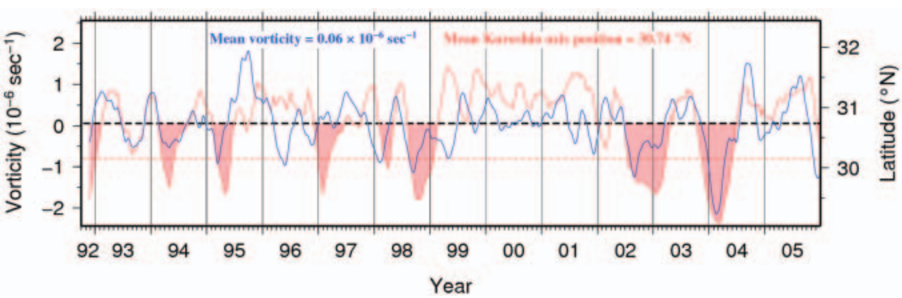

Fig. 3. Time series of the latitude of the Kuroshio axis at 132 °E (red solid line) and the relative vorticity anomaly averaged within the rectangular area shown in Fig. 1a (blue line). Both time series are low-pass-filtered through 90-days running mean, the averages of which are denoted by black dashed line. Red shades denote the periods during which the amplitude of the southward displacement of the Kuroshio axis exceeded the standard deviation (red dashed line).

curred only in 2004 when the amplitude of the small meander off Cape Shiono–misaki was large enough for the meander trough to reach over Koshu Seamount. The importance of the amplitude of the small meander was already pointed out by NITANI (1977) and SEKINE (1992), who examined the stream patterns reported by the Japan Maritime Safety Agency (Quick Bulletin of Ocean Condition) to show that the evolution of the small meander into the LM took place only when the offshore distance of the Kuroshio axis from Cape Shiono–misaki was large. The present study adds a new focus on the relative position of the meander trough with respect to Koshu Seamount during the transition to the LM path.

The relative vorticity anomaly calculated from **V′ a** (***x***, *t*) suggests that the amplitude of the small meander generated southeast of Kyushu is strongly linked with the intensity of the anticyclonic mesoscale eddy on the offshore side of the Kuroshio. Figure 3 shows the time series of the latitude of the Kuroshio axis at 132°E together with the relative vorticity anomaly averaged within the rectangular area shown in Fig. 1a. During 1993 to 2005, a total of 8 small meanders (denoted by red shades) were identified by the southward displacement of the Kuroshio axis, the amplitude of which exceeded the standard deviation (denoted by red dashed line). We can see that the occurrence of the small meander is linked with the negative vorticity anomaly south of Kyushu except for 1997. It should be noted that the southward displacement of the Kuroshio axis together with its offshore negative vorticity anomaly was largest in 2004.

4. Comparison Between the Observation and Model Results

Satellite altimeter can provide only the sea–surface velocity field. Nevertheless, detailed comparison of the surface velocity field with numerical model results is a necessary preliminary step toward a complete understanding of the dynamical process for the Kuroshio path transition. We therefore compare the Kuroshio axis estimated here with that determined from the sea–surface velocity field calculated by ENDOH and HIBIYA (2001). Using an inflow–outflow numerical model in which realistic ocean bottom topography was taken into account, they reproduced the observed stream patterns during the transition from the NLM path to the LM path in 1989 reported by the Japan Maritime Safety Agency (Quick Bulletin of Ocean Condition).

As the measure of the agreement between the model–derived and the observed Kuroshio axis, we introduce here

$$D\,(t_{obs},\, t_{model}) = S\,(t_{obs},\, t_{model})\,/L\,(t_{model}),$$
$$t_{obs} = t_0 + t_{model},$$

where L is the length of the model–derived axis from 131 °E to 142 °E at time t_{model} and S is the area sandwiched between the two current axes within the same longitudinal range at time t_{obs} with t_0 the reference date determined so that the small meanders obtained in the numerical simulation would be in phase with the observed small meanders over a period of one year.

Figure 4 shows the time series of the sea–surface velocity field (vectors) as well as the Kuroshio axis derived from Experiment I of ENDOH and HIBIYA (2001) (dashed line) which best simulates the time series of the observed Kuroshio axis (solid lines) during one year from (t_0=) November 19, 2003. The value of D averaged over one year is 34 km, comparable to the spatial resolution of the observed sea–surface velocity field (1/3°, namely, about 37 km). Their Experiment I shows that the trigger meander is generated through the interaction between the Kuroshio and the strong anticyclonic mesoscale eddy (marked by symbol A) south of Kyushu, and then propagates eastward with the anticyclonic mesoscale eddy behind it. Compared with the observed sea–surface velocity field, the amplitude of the trigger meander southeast of Kyushu is smaller (Figs. 4a and 4b) and the Kuroshio axis shifts northward to the southern coast of Shikoku earlier (Figs. 4d–f). Nevertheless, during and after the rapid amplification of the trigger meander trough over the eastern side of Koshu Seamount, the model–derived Kuroshio axis is almost identical to the observed one (Figs. 4g–j).

ENDOH and HIBIYA (2001) also found in their Experiment IV that the interaction with a weak anticyclonic mesoscale eddy with the Kuroshio resulted in the small meander

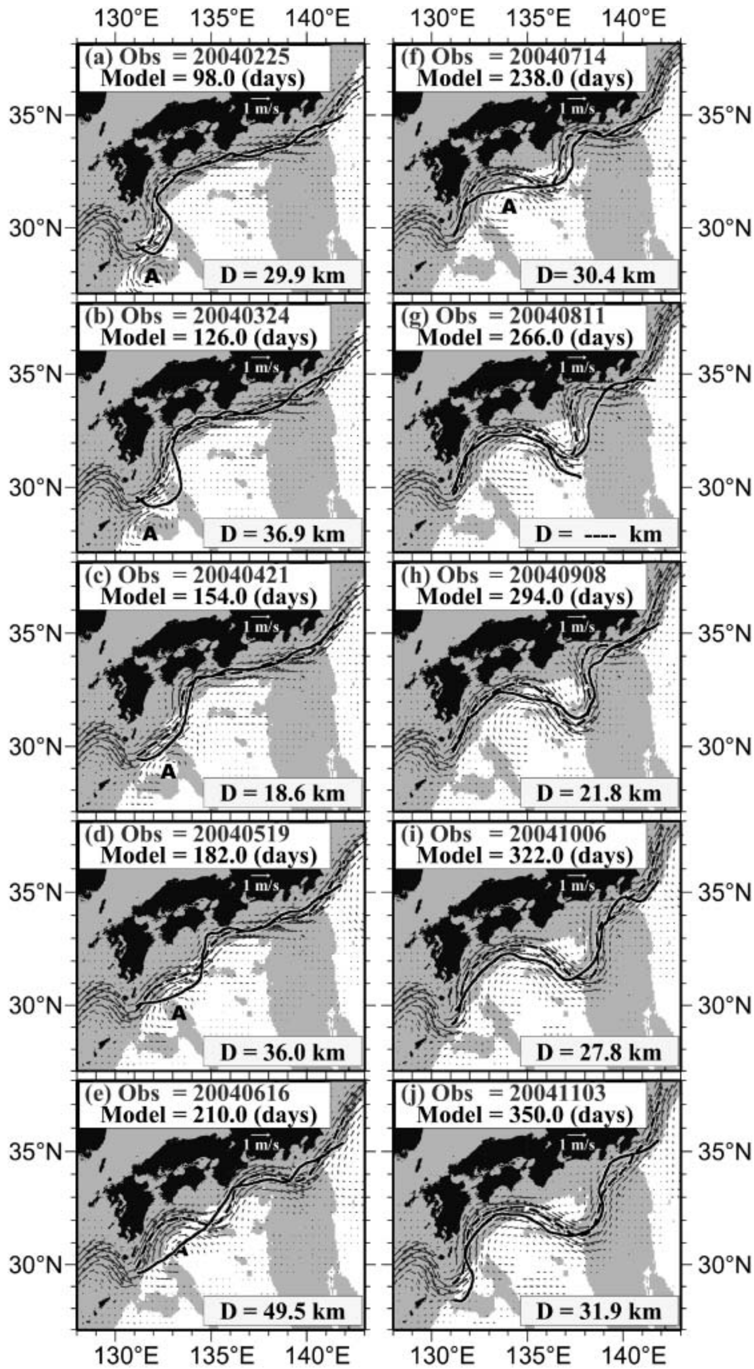

Fig. 4. Time series of the sea-surface velocity field (vectors) and the Kuroshio axis (dashed line), both derived from Experiment I of ENDOH and HIBIYA (2001). Time series of the observed Kuroshio axis is superposed by solid line. The spatially averaged difference between the model-derived and the observed Kuroshio axis (D) is indicated at bottom right of each panel. Note that D is not calculated for panel (g), because the rapidly amplifying trigger meander cannot be tracked throughout. Symbol A indicates an anticyclonic mesoscale eddy.

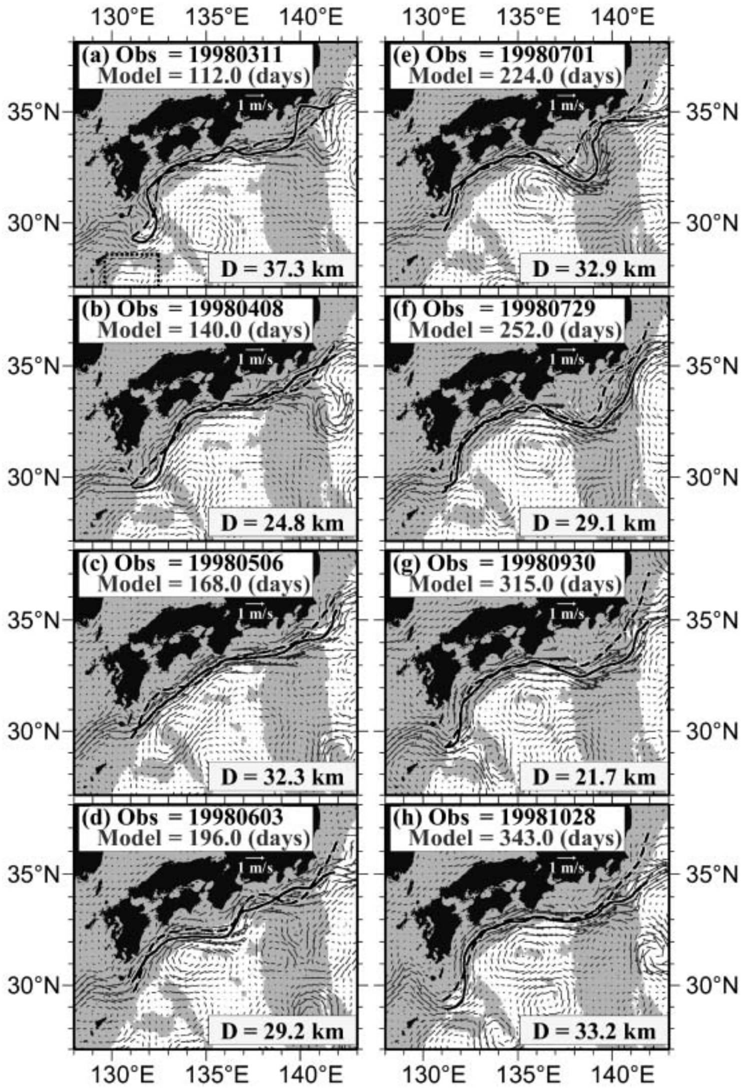

Fig. 5. Time series of the sea-surface velocity field (vectors) and the Kuroshio axis (solid lines) in 1998, both estimated using satellite altimeter data combined with drifting buoy data. Time series of the Kuroshio axis derived from Experiment IV of ENDOH and HIBIYA (2001) is superposed by dashed line. The spatially averaged difference between the model-derived and the observed Kuroshio axis (D) is indicated at bottom right of each panel.

propagating eastward away over the Izu–Ogasawara Ridge without being amplified off Enshu–nada, consistent with the results from satellite observations shown in Fig. 3. In fact, the time series of the Kuroshio axis derived from their Experiment IV agrees well with the observed one during one year from (t_0=) November 19, 1997 (Fig. 5) where the value of D averaged over one year is 30 km, again comparable to the spatial resolution of the observed sea–surface velocity field.

The observed time series of the Kuroshio axis is thus shown to be in rough agreement with the calculated one by ENDOH and HIBIYA (2001), implying that the essential physics of the phenomenon is successfully simulated in their model.

5. Concluding Remarks

Combining satellite altimeter data and sea–surface drifter data has enabled us to estimate the time series of the instantaneous sea–surface velocity field over a wide area and with high temporal resolutions. Based on the absolute geostrophic velocity distribution obtained in this way, we have examined the transient processes leading to the formation of the LM path of the Kuroshio south of Japan in 2004, which occurred for the first time after TOPEX/POSEIDON altimetry started in October 1992.

The transition to the LM path of the Kuroshio was preceded by the generation of the "trigger meander" southeast of Kyushu which then propagated eastward south of Japan. After the trigger meander passed Cape Shiono–misaki in about 4 months, it slowed down with the trough rapidly amplified over the local topographic feature, Koshu Seamount, located about 200 km to the south of Cape Shiono–misaki. As a result, the Kuroshio meander looped back west of the Izu–Ogasawara Ridge, leading to the formation of the LM path off the Enshu–nada. The time series of the Kuroshio axis from 1993 through 2005 shows that the transition from the NLM path to the LM path occurred only in 2004 when the amplitude of the small meander off Cape Shiono–misaki was large enough for the meander trough to reach over Koshu Seamount (Fig. 2).

We have found that all of these observed features are well reproduced in the numerical experiment by ENDOH and HIBIYA (2001) who demonstrated that baroclinic instability over Koshu Seamount plays a key role in the rapid amplification of the trigger meander and hence the transition from the NLM path to the LM path of the Kuroshio. As mentioned already, satellite altimeter can provide only the sea–surface velocity field so that this does not automatically affirm their claim that the existence of Koshu Seamount is essential to the transition from the NLM path to the LM path. *In situ* observations combined with high–resolution model studies are indispensable for more detailed discussions on the dynamical processes for the transition to the LM path. On this point, spatially and temporally high–resolution sea–surface velocity data derived from satellite altimetry is expected to serve as an important reference to check the validity of each model result.

Acknowledgments

We would like to thank Drs. K. ICHIKAWA and S. UMATANI of the Research Institute for Applied Mechanics of Kyushu University and Dr. A. OKUNO of the National Research Institute of Fisheries Science of Fisheries Research Agency for their useful comments. We also greatly appreciate the comments by two anonymous reviewers, which were helpful in revising the manuscript. Most of the present study was carried out when the first author was working at the Research Institute for Applied Mechanics of Kyushu University. The present study was financially supported from the Japan Society for the Promotion of Science.

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Received: January 23, 2009
Accepted: March 5, 2009