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DEEP CURRENT OF THE KUROSHIO AROUND THE IZU RIDGE
— LARGE MEANDER OF THE KUROSHIO IN 1975–1980 (IV) —

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Abstract

Deep current data taken at five mooring stations around the Izu Ridge are analyzed to investigate the effect of the ridge on the deep Kuroshio flow during the period of the Kuroshio stationary meander. Comparison of the current data and the surface Kuroshio path shows that the Kuroshio extends deeper than the sill depth of the ridge. Based on close comparison, schematic charts which show deep current patterns around the ridge are presented in three cases of the Kuroshio meander pattern. It was observed that the deep current pattern did not follow the movement of the surface meander pattern in the disappearing stage of the meander. This result seems to indicate that the ending of the Kuroshio meander occurs due to a modification of the Taylor column through a weakening of the deep flow.

1. Introduction

The Izu-Ogasawara Ridge (from now on referred to as the Izu Ridge for simplicity) extends southward from the Izu Peninsula along about 140°E. North of 33°N, this ridge is rather shallow except one narrow deep channel located at about 34°N. Surface current of the Kuroshio very frequently crosses over this northern portion of the ridge (Taft 1972, Ohtsuka 1976). Japanese oceanographers have long conceived the idea that the Izu Ridge may act as a barrier to the deep Kuroshio current and have an effect on the fluctuation of the Kuroshio south and east of Japan (for example, Hayami 1955, Fukuoka 1958, Nan'niti 1958, Yoshida 1961, Ishii and Toba 1977, Matsukawa 1979). Ohtsuka (1976), based on the analysis of 1000 m temperature distribution, indicated that the deep Kuroshio is deflected southward by the effect of the Izu Ridge.

It is well known that the Kuroshio has a stationary meandering mode west of the Izu Ridge. Since Uda (1937)'s first report, many descriptions and discussions about this Kuroshio meander have been made (for example, Shoji 1972, Nitani 1972). In spite of many attempts to try to explain how this meander is generated and maintained, the dynamical process has not been clarified yet. Because such stationary meander has not been reported in the Gulf Stream which does not have a shallow ridge on its way, it is natural to assume that the Izu Ridge play an important role in the generation and maintainance of the Kuroshio meander. Several authors indicated the direct influence of the Izu Ridge (Nan'niti 1958, Ishii and Toba 1977, Ikeda 1979). Nan'niti suggested that the northward movement of the North Pacific Intermediate Water under the Kuroshio results in a upwelling of that water at the corner formed by the continental slope and the Izu Ridge, producing a cold eddy west of the ridge. Ishii and Toba presented the idea that the deep water of the

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Kuroshio upwells because of the barrier effect of the Izu Ridge when the Kuroshio deepens until it goes below the sill depth of the ridge. Matsukawa (1979) suggested that this deepening of the Kuroshio might be caused by the baroclinic response of the ocean to the change of the wind field over the North Pacific Ocean. Ikeda (1979) showed in his two-layer model that when the Kuroshio current is confined to the upper layer the stationary meander can be produced to the west of the Izu Ridge. Indirect influence of the Izu Ridge on the Kuroshio meander was suggested by White and McCreary (1976). They indicated the "gate effect" of the deep channel on the ridge which plays a role of node in the Rossby Lee wave caused by the coastline of Kyusyu Island. Several attempts have been made to include the effect of the ridge in numerical experiments (Endoh 1972, 1978, Yoon 1976, Sekine 1979, Miura 1980). Barotropic and baroclinic models showed that in steady states the deep Kuroshio flowed along the isobath of the ridge, but they did not succeed to reproduce the Kuroshio meander west of the ridge.

The direct measurement of the deep Kuroshio current around the Izu Ridge is expected to provide a necessary information about the possible role of the ridge on the Kuroshio stationary meander. This paper concerns with the deep current data taken during the period of the Kuroshio meander at five mooring stations which are located on the deep channel and on the slope of the Izu Ridge. Analysis is centered on the correlation between low-passed current and surface Kuroshio path which were identified with GEK data and near surface temperature distribution.

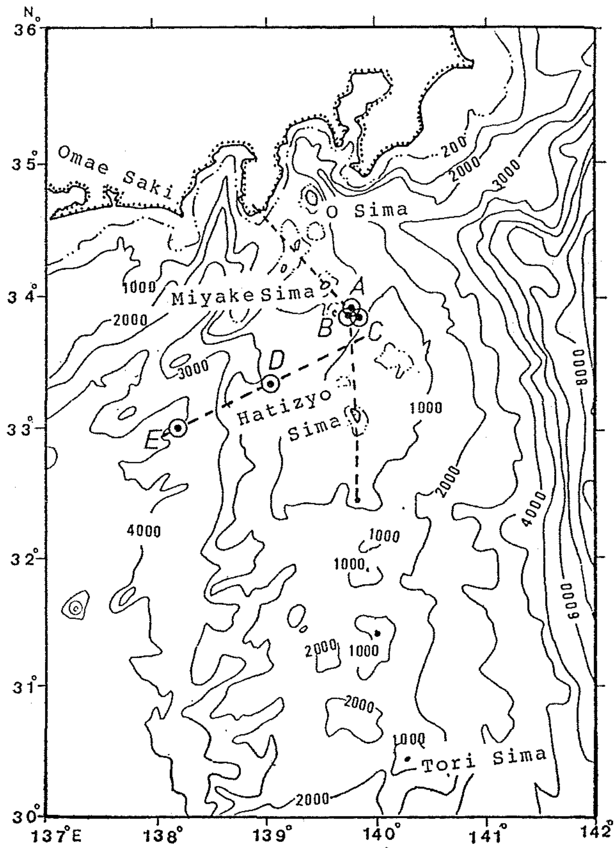

Figure 1 Locations of mooring stations and the bathymetry around the Izu Ridge

2. Observation

The locations of the mooring stations and the bathymetry of the Izu Ridge are shown in Figure 1. Geographical names used in this paper are included in Figure 1. The vertical sections (Figures 2 and 3) are drawn along two dashed lines in Figure 1. One of them is a north-south section along the summit of the ridge on which the mooring stations A, B and C are located. The other is a east-west section across the ridge on which stations D and E are located. Stations A, B and C are on the channel oriented in northeast and southwest between Mikura Sima and Hatizyo Sima (Figure 2). This channel, having a maximum depth of 1200 m and a width of 9 miles, is the only

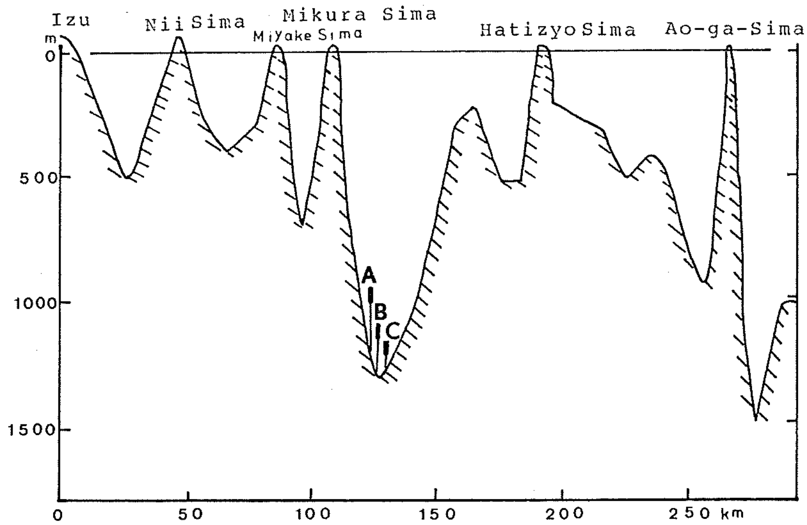

Figure 2 Vertical profile of the Izu Ridge in north-south direction and the locations of the stations A, B and C

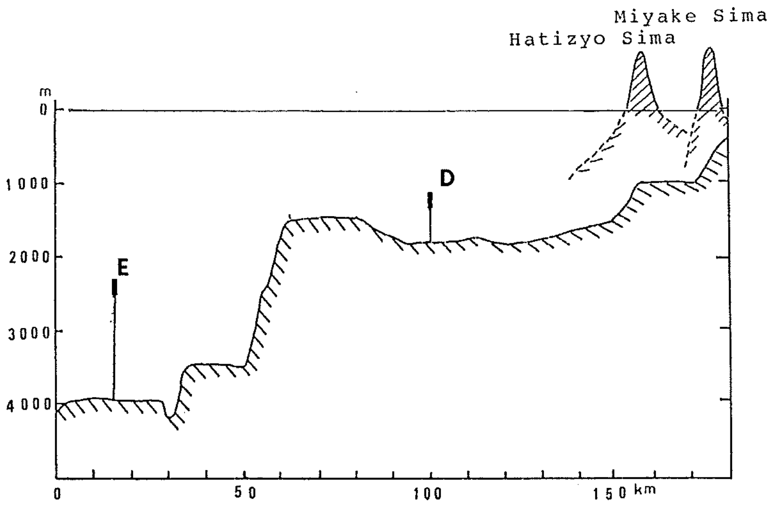

Figure 3 Vertical profile of the Izu Ridge in east-west direction and the locations of the stations D and E

Table 1 Environmental data on mooring stations

Station	Date deployed	Date recovered	Observation days	Location	Bottom depth (m)	Current meter depth (m)	Interval (min.)
A	Nov. 9, 1977	Feb. 25, 1978	107	33°-53.7′N 139°-47.7′E	1190	940	20
B	May 21, 1978	Aug. 30, 1978	102	33°-54.0′N 139°-44.7′E	1205	1155	15
C	Nov. 6, 1978	Feb. 24, 1979	111	33°-50.3′N 139°-48.8′E	1175	1075	15
D	May 20, 1979	Aug. 7, 1979	80	33°-18.1′N 139°-00.5′E	1780	1280	30
E	Nov. 11, 1979	May 12, 1980	186	33°-00.0′N 138°-10.0′E	3980	2450	30

deep passage of the Izu Ridge north of 33°N. In order to avoid the disturbance caused by small-scale bottom undulations, the current meters for stations A, B and C were placed at 50–250 m above the bottom. Stations D and E are located on the western slope of the Izu Ridge where a step-like structure is found (Figure 3). Station D is on the terrace of 80 km width at the depth of 1800 m. While station E is on the terrace of 30 km width at he depth of 4000 m. Current meters for stations D and E were placed at the depths of 1280 m and 2450 m respectively. Those depths were chosen so as to detect the effect of 1000 m and 2000 m isobath upon the deep current. Environmental information are tabulated in Table 1. Because of the rotor trouble, no data was obtained after July 17 1977 at station A.

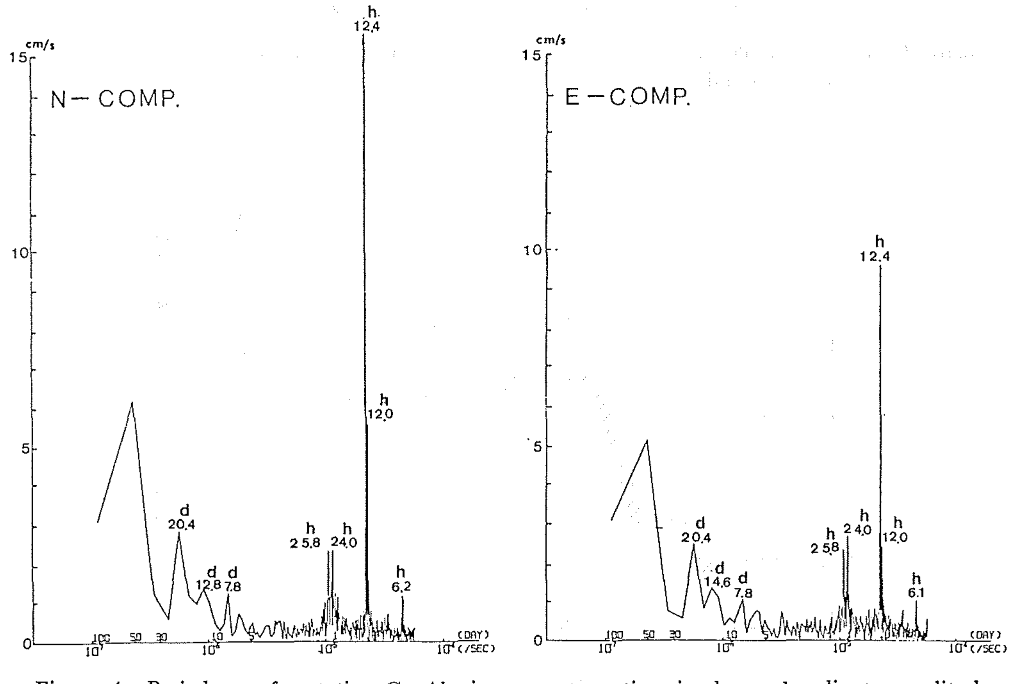

Figure 4 Periodgram for station C. Abscissa represents time in day and ordinate amplitude in centimeter

3. Spectral Analysis

Periodgrams for the stations C, D and E are shown in Figures 4, 5 and 6. Periodgram for stations A and B, which are not shown in this paper, have similar curves as that of station C. The station on the channel (station C) have diurnal and semidiurnal tidal components of large amplitudes. The inertial period for this latitude is 22.7 hours and may contribute to the diurnal peak.

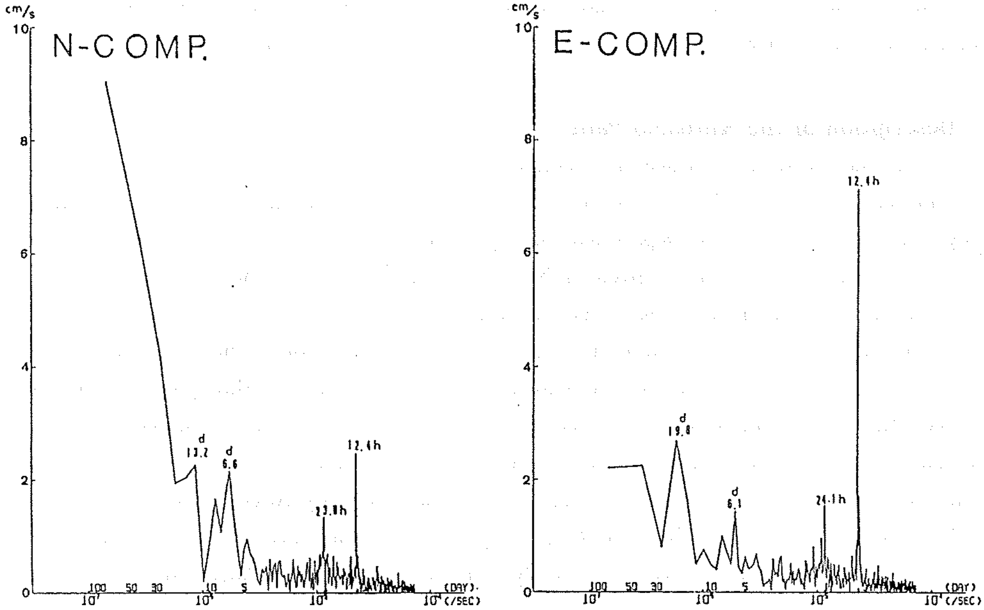

Figure 5 Periodgram for station D

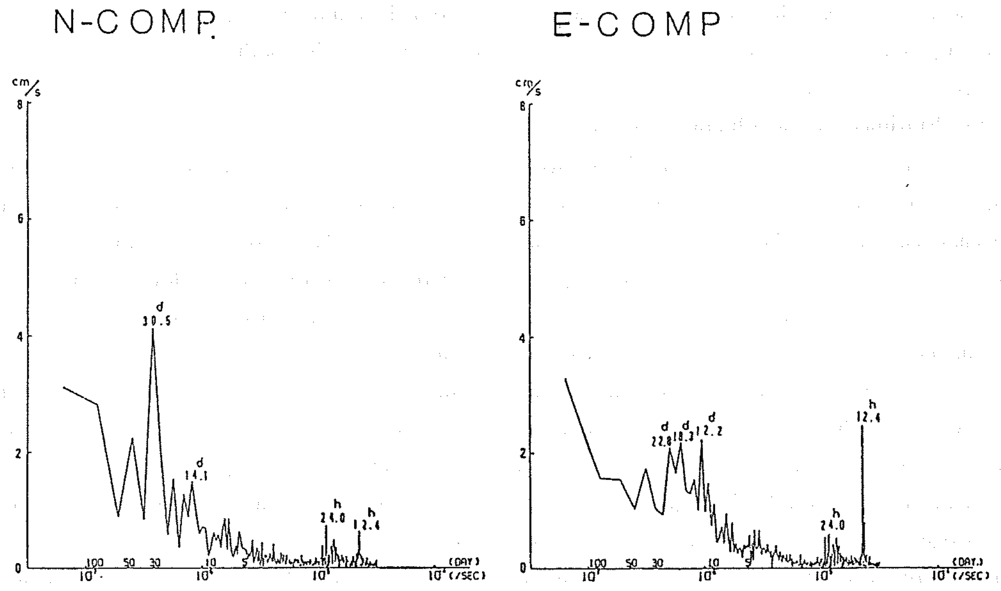

Figure 6 Periodgram for station E

This large amplitude of tidal components seems to be caused by the geographical configuration that the channel is a deep passage across the ridge. Tidal periods are also found in sations D and E, though the amplitudes are smaller than those of stations C. Other periods which outstand in the station D are 6 and 20 days in east-west component, 6 and 13 days in north-south component. In the periodgram for station E, 30 days is conspicuous in north-south component. Among them, 30 days in the station E may be attributed to the fluctuation of the Kuroshio path as discussed later. Taira (1981) found the period of 33.3 days in the spectrum of the current data west of Hatizyo Sima. Phenomena to which other periods can be attributed are not yet known.

4. Description of the Kuroshio Path

Kuroshio paths near surface are identified with the surface current by GEK and with 100 m and 200 m temperature distribution by BT. Kuroshio paths as identified have been published bimonthly from the Hydrographic Department of Japan since April 1960. Detailed description of the Kuroshio meander in 1975–1980 is given in Nishida (1982). To make the discussion easier, a brief summary of the description of the Kuroshio meander in 1975–1980 is given in this section.

The Kuroshio meander established in September 1975. Prior to the establishment, an eastward movement of the small meander off Sikoku was observed. In 1975 through 1976, the meander was stable. In 1977 it shifted westward and at the same time it became unstable experiencing a production of a current ring and coalescence of the ring with a newly generated meander. In 1979 it again became unstable experiencing a separation of the cold eddy twice in April and August. By the end of 1979, it approached the Izu Ridge very closely and in May 1980 it rode over the ridge. After some oscillations near Izu Ridge, it finally left away eastward in Aug. 1980.

5. Comparison of the Surface Kuroshio Path and Deep Current

In this section detailed comparison of the observed deep current with surface Kuroshio path will be made. The current meter data were smoothed by time-averaging for 25 hours to eliminate the tidal effect. Vector plots of current data and the Kuroshio path for each period are shown in Figures 7 to 9 and Figures 11 to 12.

(1) Stations on the Channel (A, B, C)

During the periods of the deep current observation at stations A, B and C, the surface Kuroshio had been flowing over the Izu Ridge near Miyakesima which is located to the north of the channel. Because the maximum geostrophic current at deep layers is found to the south of the surface Kuroshio path, it is natural to suppose that there is a northeastward flow on the channel. In fact, for most of the period a northeastward current is observed. This northeastward current on the channel is reported by Hasunuma (1978). But, in the record of the station A (Figure 7), a southwestward current is observed for one thirds of the period. Looking at the surface Kuroshio path in 1–4 Dec. 1977 when a southwestward current is observed, the north-going eastern portion of the Kuroshio meander is found to be located apart from the Izu Ridge. Temperature distribution at a depth of 400 m in early Dec. 1977 (Figure 10) reveals a warm eddy between the Kuroshio meander and the Izu Ridge. This may be indicative of a southward deep current just west of the ridge. No deeper temperature distribution is available. Furthermore, on inspection of Figures 8 and 9, hte magnitude of the northeastward current seems to be correlated with the distance between the meander and the

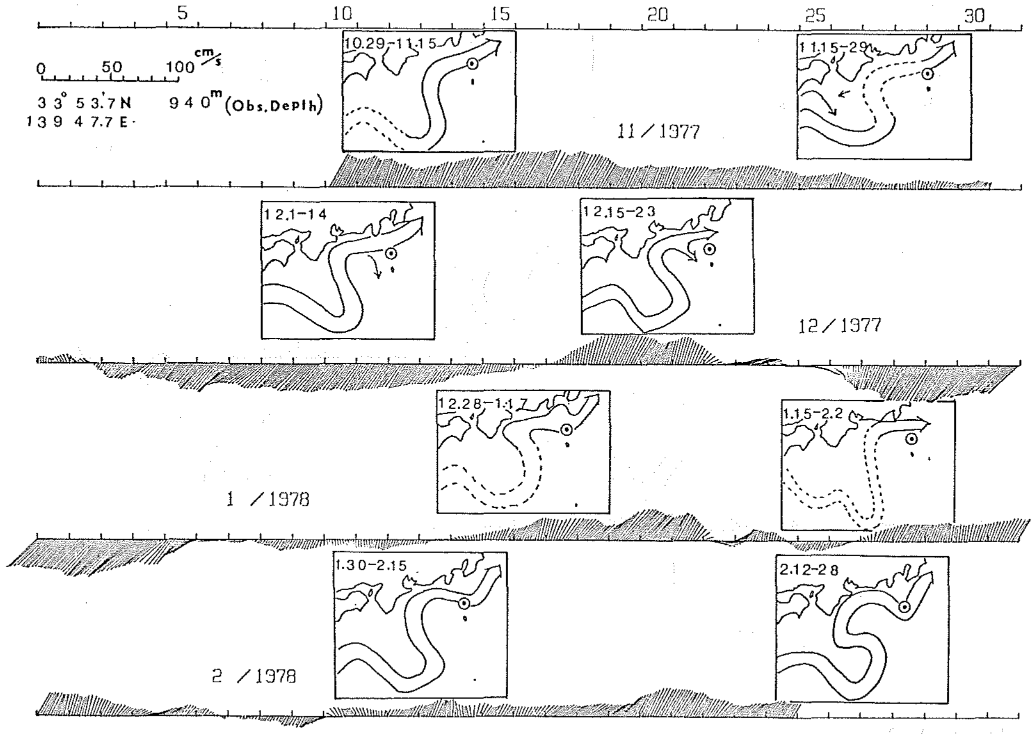

Figure 7 Vector plot of current data at station A and the surface Kuroshio path for the same period

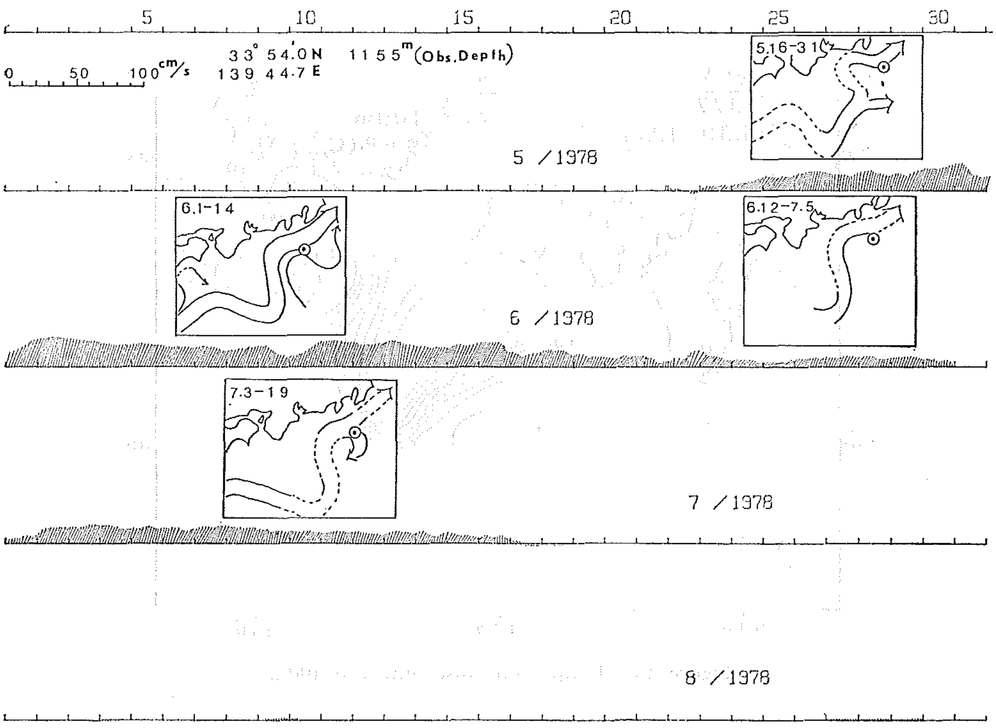

Figure 8 Vector plot of current data at station B and the Kuroshio path for the same period

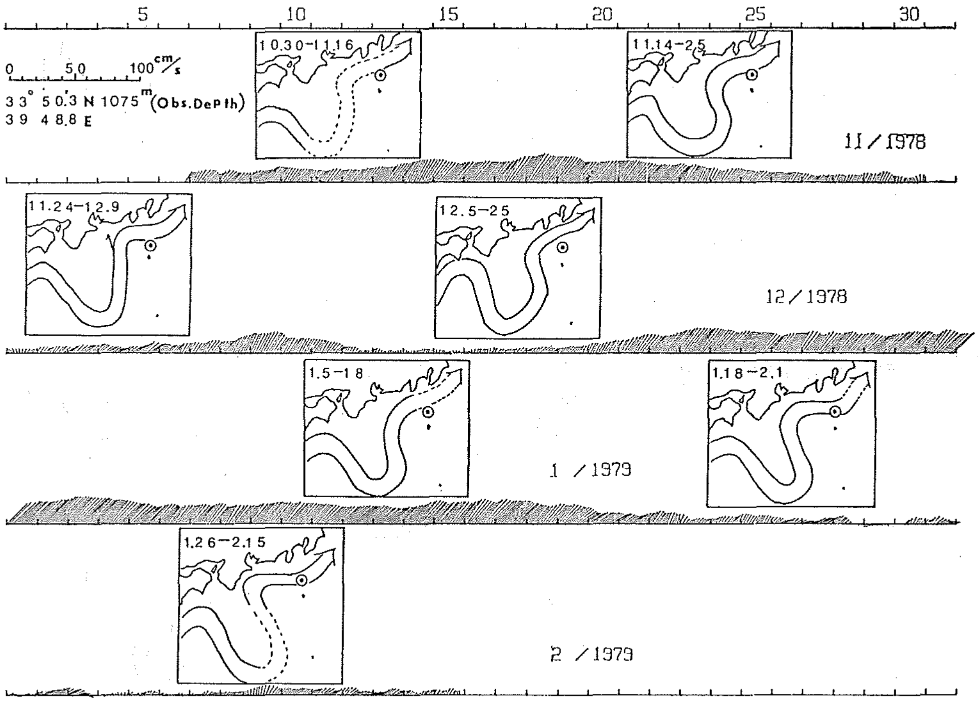

Figure 9 Vector plot of current data at station C and the surface Kuroshio path for the same period

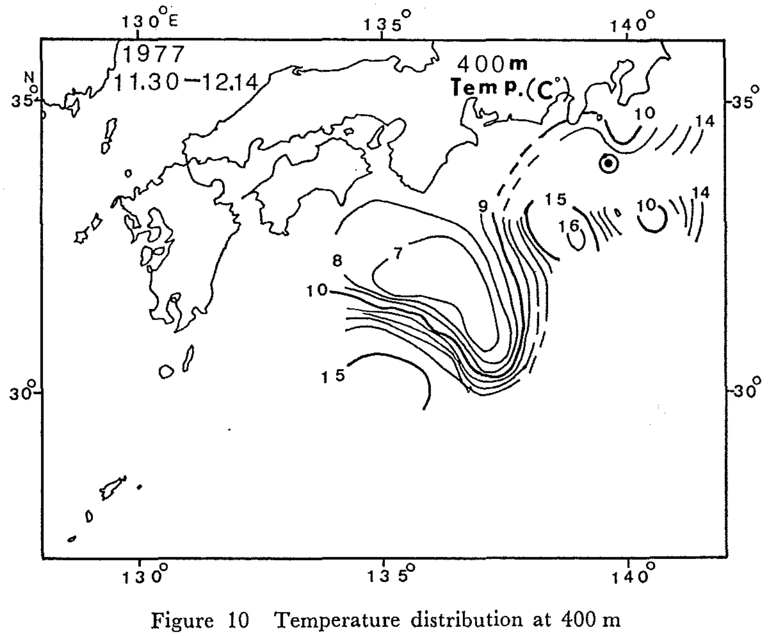

Figure 10 Temperature distribution at 400 m

Izu Ridge. That is, as the meander moves westward, the current on the channel decreases. On the basis of the above facts, it may be deduced that when the Kuroshio meander is located close to the ridge the deep flow crosses over the channel, but when the meander is located apart from the ridge, the deep current goes southward along the western slope of the ridge.

(2) Station D

A southward flow is found in May to mid-June 1979. Surface Kuroshio path for that period shows that the north-going eastern portion of the Kuroshio meander is very apart from the ridge. For the same reason as discussed in 5.1, the deep current of the Kuroshio seems to have flowed southwards along the western slope of the ridge for the period. From mid-June through July, the mooring station (station D) was just under or to the west of the surface Kuroshio path. During this period a northward flow is observed. Taking into account that there is no passage on the Izu Ridge to the north of this station at this depth (1280 m), it may be deduced that the current at this layer recirculates in the cold eddy north of the meander. Strong northward flow is found in late July to August. Between late July and early August a southern portion of the cold eddy was separated and became a current ring (Nishiyama 1980, Nishida 1982). The Kuroshio meander has a very unusual shape after the separation of the current ring as shown in Figure 11 (the current path for 30 July–14 August). During that period, the deep current had a strong northward component constantly. This inconsistence between surface and deep current may indicate that the variation of the Kuroshio path for that period is confined to upper layers.

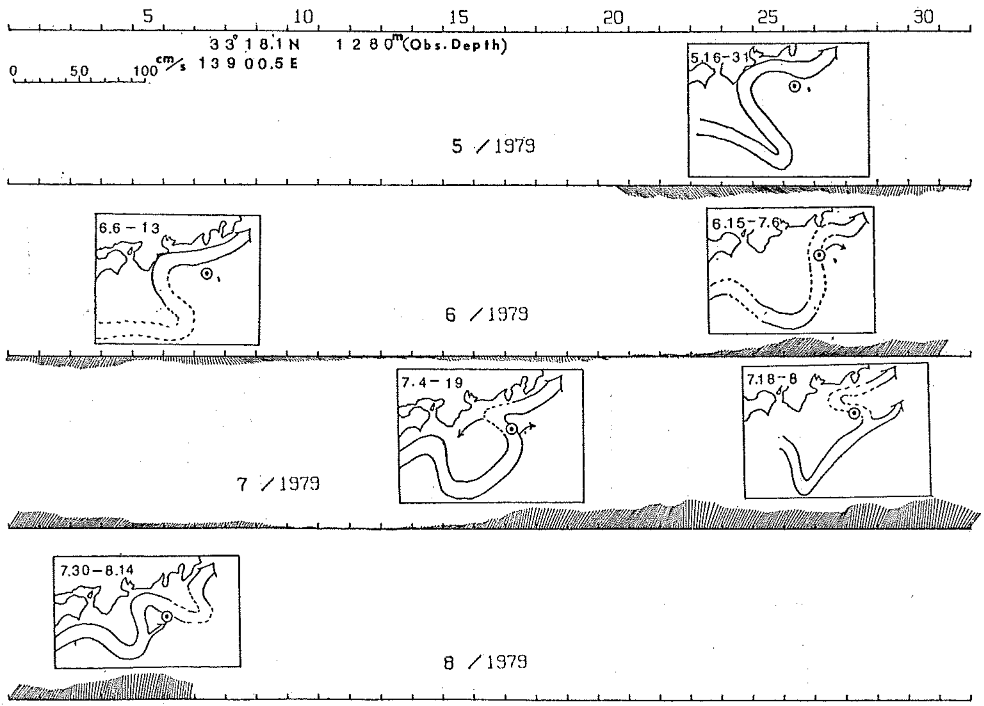

Figure 11 Vector plot of current data at station D and the surface Kuroshio path for the same period

(3) Station E

The station E had been located to the north of the Kuroshio path through the observation period. This means that station E was inside the cold eddy. Comparison between the surface Kuroshio paths and the deep current shows that when the north-going portion of the meander comes close to the station, the northward deep current increases, and when the center of the cold eddy comes

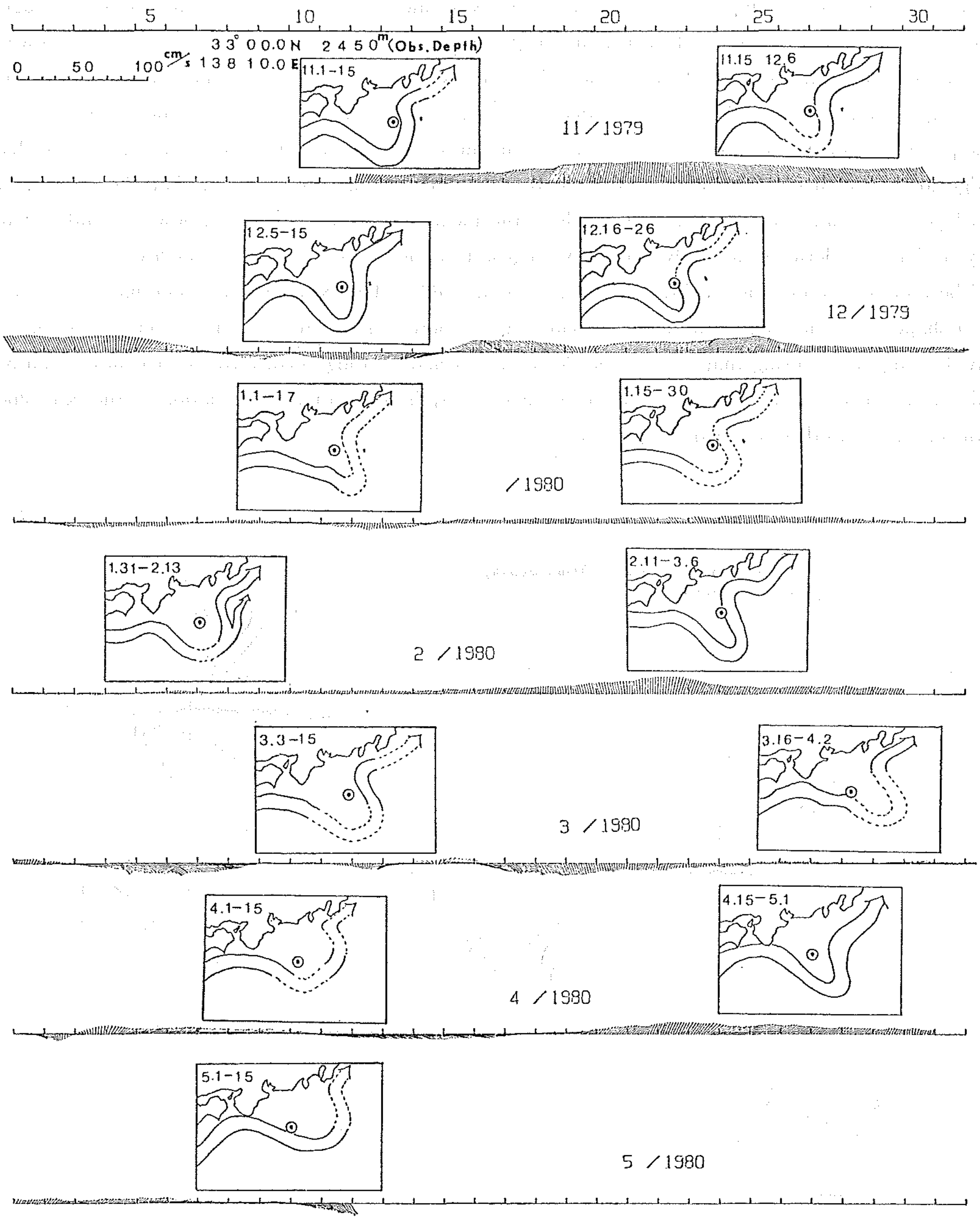

Figure 12 Vector plot of current data at station E and the surface Kuroshio path for the same period

close to the station very weak current is observed at deep layers. Entering into its disappearing stage, the meander gradually moved eastward in Mar. to May, and the eastern portion of the meander rode over the ridge in April. The deep current during this period does not seem to be consistent with the surface pattern of the meander. It may indicate that the crossing of the meander over the ridge occurred in only upper layers and the deep cold eddy remained as it was.

6. Statistical Character of the Current Data

Fundamental statistics computed from the data smoothed for 25 hours are shown in Table 2.

The data at the station A has a exceptionally high value of eddy variability (ratio of K_E to K_M). This is because there is a southwestward flow in the record of the station A for one thirds of the observation period (see 5.1). The currents at stations B and C show rather small eddy variability. Because the channel has rather special bathymetric setting, it seems difficult to compare these data with the ones taken at other locations.

The eddy variability at the stations on the western slope of the ridge (D and E) can be compared with the ones in Taft (1978). He found the mean value of 8.0 in the ratio of eddy to mean energy on the continental slope under the Kuroshio when the meander is absent. Observed values of 2.6 and 4.0 on the western slope of the ridge are rather small compared with those of Taft. Geographical locations are different. But this small value may indicate that the deep condition is more stable when the meander is present than when it is absent. The statistics show larger value of eddy variability at station E than at station D, though the depth of the former station is deeper than that of the latter. This may indicate that the deep condition becomes unstable in the disappearing stage of the meander.

The values of eddy momentum flux ($<u'v'>$) at stations A, B, C, and D are all positive, while it is negative at the station E. It should be noted that the former four stations stayed to the south of Kuroshio path, while the latter stayed to the north of the path. The combined effect results in a momentum convergence in the Kuroshio path. Similar results were obtained in the deep layer of the North Atlantic (Schmitz 1977) and in the surface layer of the Kuroshio Extension (Nishida and White 1981).

Table 2 Fundamental statistics computed from the current data smoothed for 25 hours. $< \ >$ represents the time average and prime represents the deviation from the mean. $<u>$ and $<v>$ are the mean east and north component. K_E, K_M and K_T are the eddy, mean and total kinetic energy. K_E/K_M is the ratio of eddy to mean kinetic energy. $<u'v'>$ is the eddy momentum flux.

Station	Record length (day)	$<u>$ (cm/sec)	$<v>$ (cm/sec)	σ_u (cm/sec)	σ_v (cm/sec)	K_E	K_M	K_T	K_E/K_M	$<u'v'>$ (cm²/sec²)	Correlation
A	106.7	0.9	2.9	10.7	14.0	155.3	4.7	160.0	32.9	132.0	0.88
B	55.6	4.5	11.1	2.0	4.9	14.4	72.1	86.4	0.2	6.8	0.67
C	101.0	8.3	9.6	5.2	5.9	31.2	80.6	111.7	0.4	28.0	0.90
D	78.3	4.4	4.3	3.8	9.2	49.6	18.8	68.5	2.9	14.5	0.41
E	181.8	2.5	2.9	5.3	5.5	29.5	7.4	36.9	4.0	−5.3	−0.18

7. Summary and Discussions

Five mooring stations were occupied on the channel and the western slope of the Izu Ridge to investigate the Ridge's effect on the deep flow of the Kuroshio. During the observation period the large stationary meander of the Kuroshio was present. Rather strong deep current which is fairly consistent with the surface Kuroshio current was observed. It proves that the Kuroshio extends at least to 2000 m level. This is in agreement with the fact that there is a temperature gradient at 3000 m in the cold eddy region (Nishida 1982). From the close comparison of the deep current and the surface Kuroshio path, the followings were indicated.

1) When the meander is apart from the Izu Ridge, the deep Kuroshio flows southward along the isobath on the western slope of the ridge.
2) When the meander is close to the ridge, the deep current at 1000 m layers passes in the channel, but the deeper current circulates in the cold eddy.
3) In the disappearing stage of the Kuroshio meander, only the surface pattern crosses over the ridge.

On the basis of the above indications, schematic charts showing surface and deep current conditions are presented. Figure 13 represents three typical meander patterns and the deep current conditions at 1000 m and 2000 m. When the meander has a typical shape (Figure 13-1), the current at 1000 m layers crosses over the channel between Miyake Sima and Hatizyo Sima. A part of the current might go around to the south of Hatizyo Sima. The current at 2000 m layer recircu-

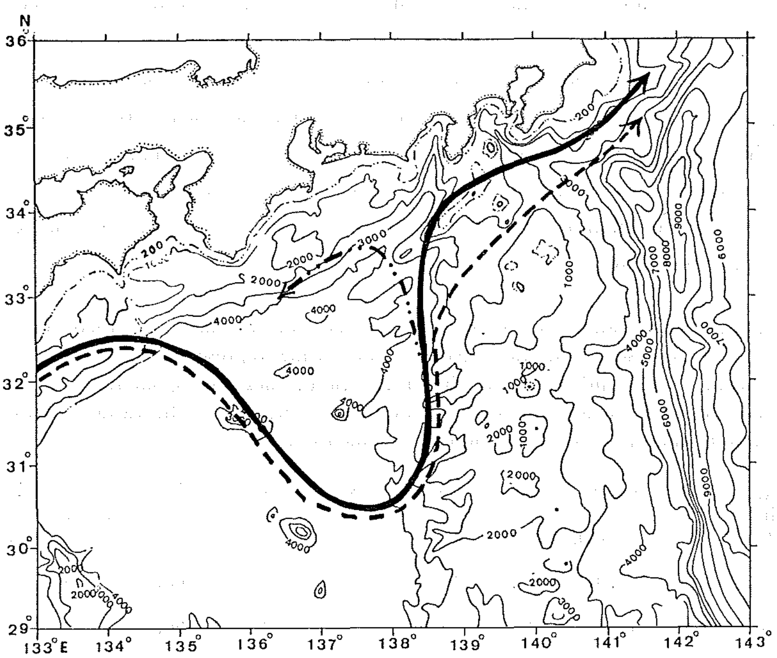

Figure 13-1 Schematic charts of the deep current around the Izu Ridge in three cases of typical Kuroshio meander pattern. Explanation of the symbols is as follows
——: surface Kuroshio path
– – – –: current at 1000 m
–··–··: current at 2000 m

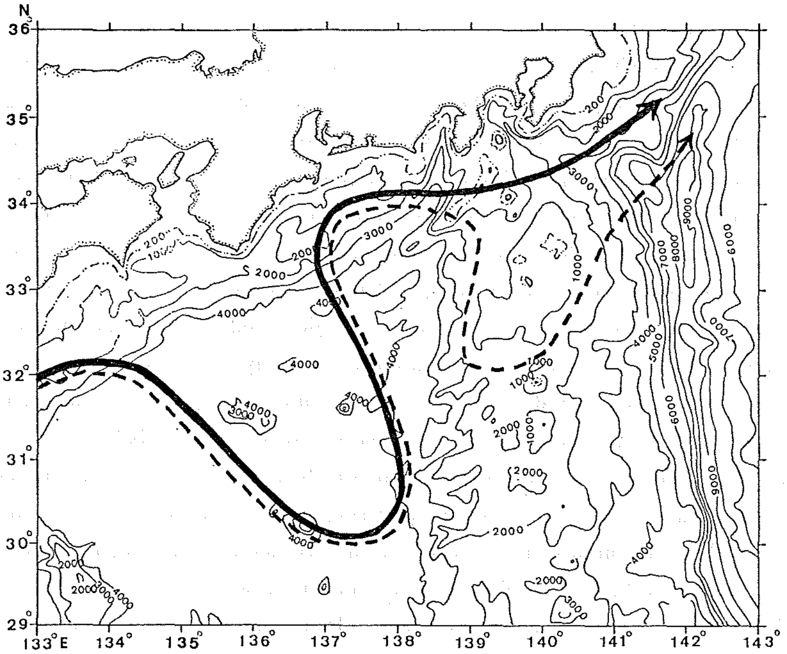

Figure 13-2 Schematic charts of the deep current around the Izu Ridge in three cases of typical Kuroshio meander pattern. Explanation of the symbols is as follows
——: surface Kuroshio path - - - -: current at 1000 m
-··-··: current at 2000 m

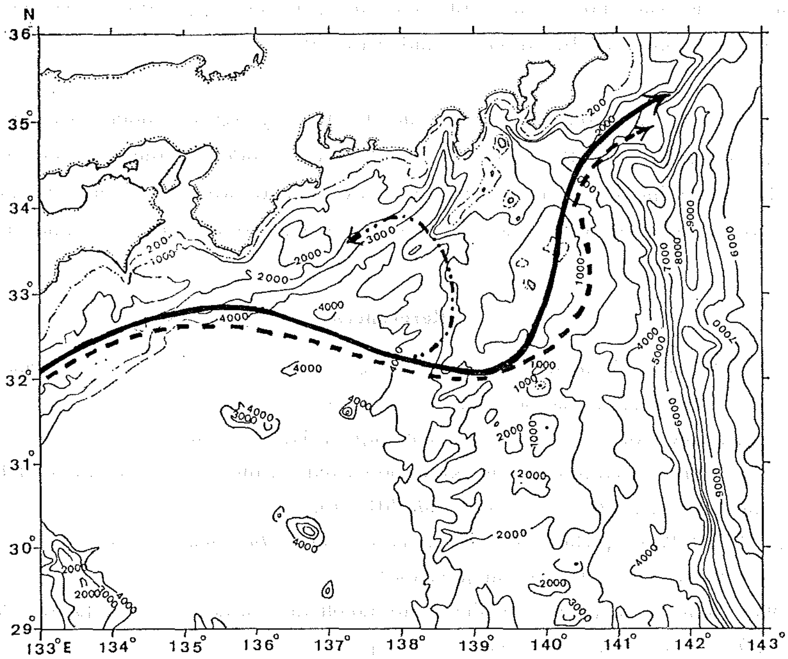

Figure 13-3 Schematic charts of the deep current around the Izu Ridge in three cases of typical Kuroshio meander pattern. Explanation of the symbols is as follows
——: surface Kuroshio path - - - -: current at 1000 m
-··-··: current at 2000 m

late in the cold eddy. When the meander moves westward (Figure 13-2), the current at 1000 m layer does not go into the channel but go around to the south of Hatizyo Sima. Numerical experiments showed this type of deep current. When the meander itself crosses over the ridge in its decaying stage, the deep circulation in the cold eddy remains to the west of the ridge (Figure 13-3).

The separation of the upper layers and deep layers observed in the decaying stage of the Kuroshio meander seems to be important for the ending mechanism of the meander. Nishida (1982) found the deep waters of the cold eddy have different water-types to the west and east of the Izu Ridge, when the meander rides over the ridge. The observed deep current condition in the decaying stage of the meander is consistent with this fact. Ishii (1982) found that the average temperature of the deep layers at the center of the cold eddy gradually increased in the decaying and disappearing stages. Nitani (1975, 1982) showed that the inferred depth of no-motion layer is deeper when the meander is present than when the meander is absent. The probable explanation for these facts would be the following. The deep current of the Kuroshio is stronger in the meander period than in the no-meander period, and the disappearing stage of the meander is a changing process from one state to the other in which the deep current weakens. The larger value of the mean energy and the smaller values of stability observed on the western slope of the Izu Ridge compared with Taft (1978) also support the above hypothesis. If the deep current weakens, it may be possible that the constraint on the upper layer flow exerted by the Izu Ridge through Taylor column (Yamagata 1978) is released and the surface meander leaves eastward according to the Rossby wave character in a eastward general flow (Nitani 1976, 1982). This mechanism of meander ending is essentially the same as the one proposed by Ishii and Toba (1977). Although this discussion concerns only with the ending of the Kuroshio meander, the weakening of the deep flow in its decaying stage is contrary to the theory proposed by Robinson and Taft (1972).

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