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DESCRIPTION OF THE KUROSHIO MEANDER IN 1975–1980 — LARGE MEANDER OF THE KUROSHIO IN 1975–1980 (I) —

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Abstract

A large Kuroshio meander was established off the southern coast of Japan in August 1975, and stayed there for the next five years. This Kuroshio meander, and the associated cold eddy from 1975 to 1980, is described mainly on the basis of bimonthly current paths. Those current paths are identified with the maximum temperature gradient being at 100 m and 200 m.

During the period from April to August 1975, prior to the establishment of the Kuroshio large meander, the eastward movement of a small meander along the coast of Japan was observed. This eastward proceed is similar to those in 1953 and 1959. During the five-year meander period, the meander was generally stable in autumn seasons, while it was rather unstable in the spring time. In May 1977, and in April and August 1979, the cold eddy was separated, and a cold current ring was produced to the south of the Kuroshio. In the first two cases of the separation, newly generated small meanders off Kyusyu moved eastward, and coalesced with the ring (1977) or the meander (1979). Through these coalescences, the Kuroshio meander returned to the typical A-type.

However, in the case of August 1979, a small meander was not generated off Kyusyu, and the Kuroshio meander remained small, entering into the disappearing stage. In the disappearing stage, the meander moved eastward and finally crossed the Izu Ridge, with E-W oscillation superimposed.

The deep serial observations revealed the horizontal temperature gradient in the deep layers (100 m–3000 m) throughout the meander period indicating the existence of the influence of the Izu Ridge on the Kuroshio deep flow. The analysis of T-S and T-O_2 relations revealed that the cold eddy water consists of Kuroshio water. It upwelled by 300–400 m in every layer from the surface to the near bottom at the time of the beginning of the cold eddy. The comparison of the water characteristics of the waters on the east and west of the Izu Ridge in the disappearing stage indicated that the deep waters did not move together with the shallow waters when the meander crosses over the ridge.

1. Introduction

The stationary Kuroshio meander south of Japan and the associated cold eddy between the Kuroshio main current and the southern coast of Japan have long been a great concern of Japanese oceanographers. In spite of many efforts to explain the dynamical mechanism of this meander, a full explanation has not been obtained yet. The systematic observational efforts which covers the Kuroshio area were initiated in early 20th century by Japanese agencies. Since then, the large

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Kuroshio meander occurred four times, namely in 1934 to 1945, 1953 to 1955, 1959 to 1963 and 1975 to 1980. Recently Okada and Nishimoto (1978) analyzed the long time series of tide record at several stations along the coast of Japan and pointed out that the Kuroshio meander may have occurred another two times, namely in 1906 to 1912 and in 1917 to 1922. Because of its stationarity and continuity, the Kuroshio meander has come to be recognized as one of the stable modes of the Kuroshio path (Masuzawa, 1965; Taft, 1972). The first report about the Kuroshio meander was made by Uda (1937) as an anomalous condition of the Kuroshio. Later Yoshida (1961) analyzed merchant ship's log and determined the duration of this meander (1934 to 1945). But because of the World War II the time of the ending of this meander is not clear. The meander in 1953 to 1955 are described in several articles (Moriyasu, 1954, 1956) mainly on the basis of the routine observations which were made four times a year by Japanese agencies. The semimonthly observation of the Kuroshio with BT and GEK was started by Hydrographic Department of Japan in 1960. This rather frequent observaiton made possible to describe the Kuroshio meander in 1959 to 1963 in more detail than the previous ones (Shoji, 1972). A covienient summary about the meanders in 1934 to 1970 is found in Nitani (1972).

Yoshida (1961) analyzed the shape of the cold eddy which is associated with the Kuroshio meander and proposed the names of A, B and C types of cold eddy. Type A corresponds to the large cold eddy of long continuity, type B corresponds to the smaller cold eddy of shorter continuity, both of them being located west of the Izu Ridge. On the contrary, type C corresponds to the cold eddy which lies over the Izu Ridge. Nitani (1969) used above names to redifine the Kuroshio patterns which produce the corresponding cold eddies and added two more names, N and D types. N type corresponds to the straight path of the Kuroshio along the coast of Japan and D type corresponds to the meandering path east of the Izu Ridge. The long-lived Kuroshio meander which is the concern of this paper is the A-type Kuroshio meander. But other names are also used to express the shape of the meander in this paper.

Preceding the establishment of the Kuroshio meander, a small disturbance of the Kuroshio path occurred east of Kyusyu and moved downstream slowly until reaching in the offing of Ensyu-nada. It grew large there resulting in the large Kuroshio meander (Yoshida, 1961; Moriyasu, 1961a). An offshore displacement of he Kuroshio path off Sionomisaki in early 1953 was reported by Masuzawa (1954) and Ichie (1954). Nitani (1972) thought this displacement was a forerunner of the establishment of the Kuroshio meander. A similar eastward progress of the small meander was found in 1969 (Shoji, 1972). Although it grew large and obtained the size of the A-type Kuroshio meander, it did not stay to the west of the Izu Ridge and moved away from the south of Japan soon. This meander in 1969 is classified as A′-type meander by Nitani (1972).

In this paper, the description of the Kuroshio meander in 1975 to 1980 is given. For this meander period, the data coverage is more dense in space and time than for the previous ones and also the deep observation down to the bottom was often made in this period. Section two deals with the bathymetry south of Japan. An outline of the development of the Kuroshio meander in 1975 to 1980 is given in section three. Detailed annual description on the paths of the Kuroshio is given in sections four and five. Section six deals with the deep temperature structure, especially the structure below the sill depth of the Izu Ridge. In section seven the water type of the cold eddy is discussed on the basis of the T-S and T-O_2 relaitons.

2. Bathymetry of the Kuroshio Region South of Japan

The bottom topography in this region is one of the main factors which prescribes the Kuroshio behavior south of Japan. A full description of the bathymetry in the western North Pacific is given in Mogi (1972) and the features which concerns with the Kuroshio south of Japan is discussed by Taft (1972). In Figure 1, a schematic bathymetric chart of the Kuroshio region is shown

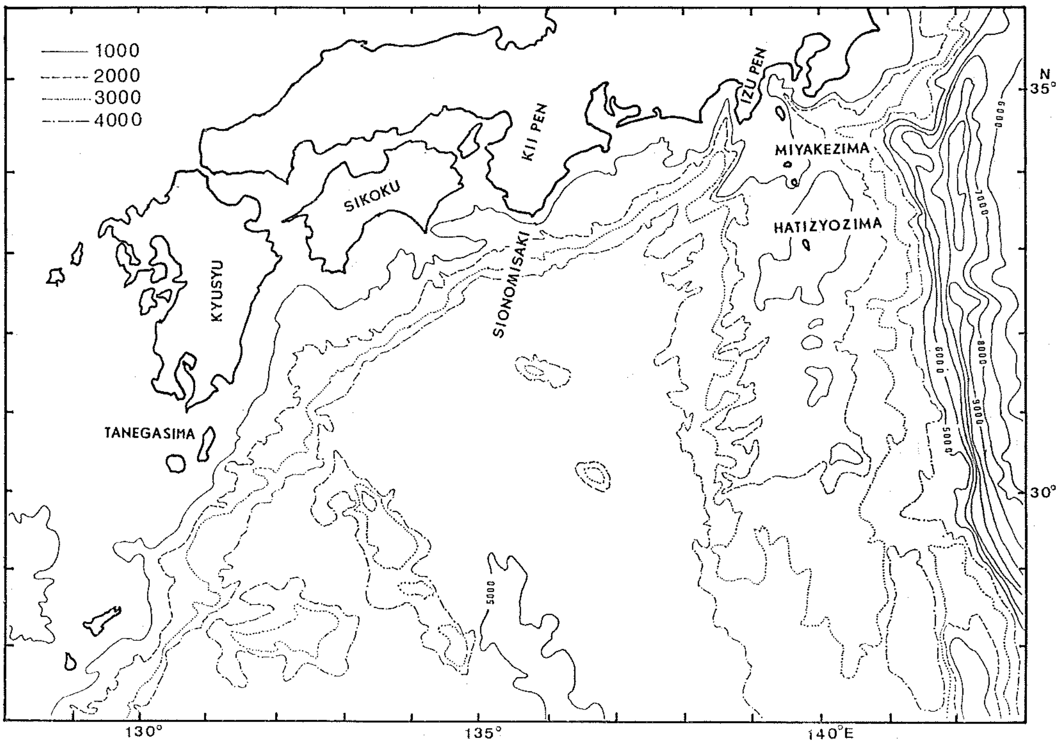

Figure 1 Bathymetry of the Kuroshio area south of Japan

with the contours at every 1000 m. Geographical names which is used in this paper are also included in this chart. Main part of this region is occupied by Sikoku Basin which is flanked by two ridges, namely Izu-Ogasawara Ridge on the east and Kysyu-Palau Ridge on the west. This basin has an average depth of 4000 m which is shallower by about 2000 m than the northwest Pacific Basin east of Izu-Ogasawara Ridge. Two important features which may affect the Kuroshio flow are the continental slope and the Izu-Ogasawara Ridge. With very narrow continental shelf, the continental slope on the north acts as a wall. Izu-Ogasawara Ridge rises rather sharply from the ocean bed, and may acts as a barrier to the deep Kuroshio flow. Kuroshio mostly crosses the shallowest part of the ridge, namely between 32° and 34°N. This part of the ridge has a depth of less than 1000 m, with a exception of a channel between Miyakesima and Hatizyozima Is., which has a depth of slightly deeper than 1000 m.

3. Outline of the development of the meander

In order to have a general idea on the Kuroshio meander in 1975 to 1980, the time sequence of the meander development is outlined in this section.

In April 1975, a small meander of the Kuroshio was generated to the east of Kyusyu. This small meander moved downstream slowly for the next month, and reached in the offing of Sikoku in May. After a upstream return in late May, it began to move downstream again rather swiftly. After passing off Sionomisaki, it grew larger, and finally in August it changed into the "large meander stage" in the offing of Ensyunada which is just west of the Izu Ridge. This large Kuroshio meander is classified as A-type Kuroshio path according to Yoshida (1961) and Nitani (1969). This generation process of the Kuroshio stationary meander is very similar to the previous ones. This large Kuroshio meander and the associated cold eddy stayed for next five years to the south of Japan. From the establishment of the meander in August 1975 through 1976 it was stable. In April 1977, the cold eddy was elongated in northwest-southeast direction, and in May it was separated into two parts. The southern half became a current ring, while the northern half became a reduced meander off Sionomisaki. The reduced small meander off Sionomisaki proceeded eastward and disappeared in a month, while a new meander was generated east of Kyusyu in June. This new meander moved eastward and the current ring moved northwestward. In August they coalesced with each other producing a A-type large Kuroshio meander again. For the rest of 1977 the meander was rather stable. In the spring of 1978, the Kuroshio path displaced southward in the offing of Kyusyu and Sikoku and a very large area between the Kuroshio and the coast of Japan was covered with cold water. This is the time when the area of the cold eddy has its largest value during the whole meander period. In May 1978 the Kuroshio flowed temporarily to the south of Hatizyozima. From the experience in 1963 (the end of the previous meander), this phenomenon was considered as forerunner of the decay of the Kuroshio meander. But it was only temporal and the meander returned to the usual pattern soon. In April 1979, the meander took a elongated shape similar to the 1977

Table 1 Summary of the events of the Kuroshio meander development

1975	Apr.	Generation of a small meander off Kyusyu
	Apr.-Aug.	Downstream progress and Growth of the above meander
	Aug.	Establishment of the large meander off Ensyunada
1976		The meander was very stable throughout the year
1977	Jan.-Mar.	Westward shift of the meander
	May	Separation of the cold eddy and production of a cold current ring
	Jun.	Generation of a new small meander off Kyusyu
	Aug.	Coalescence of the cold ring with the small meander off Kyusyu
1978	Jan.-Jul.	Large offshore displacement of the Kuroshio path off Sikoku
1979	Apr.	Second separation of the cold eddy
	Jun.-Jul.	Generation of a new small meander off Kyusyu and its coalescence with the cold eddy
	Aug.	Third separation of the cold eddy
1980	Jan.-Aug.	Eastward movement of the cold eddy around the Izu Ridge and superimposed east-west oscillation
	Aug.	Disappearance of the meander from the south of Japan

case, resulting in the second separation of the cold eddy. This time the life history of the produced current ring is not known. But, similarly to the 1977 case, a small meander was generated east of Kyusyu. It moved eastward and coalesced with the meander which was left off Sionomisaki when the cold eddy was separated. In August 1979 the third separation occurred. But, this itme, the remaining small meander was not replenished with a small disturbance off Kyusyu. From this time on, the meander remained in smaller size and gradully moved eastward. In February 1980, the meander rode over the Izu Ridge and a C-type meander was observed. In hte first half of 1980, the meander moved back and forth around the Izu Ridge, experiencing B-type and C-type Kuroshio meander alternately. In August 1980 the meander moved away eastward and the stationary meander period ended. For convienience the above time sequences of the meander development are summarized in Table 1.

4. Annual Kuroshio Paths

Kuroshio paths are identified with surface current by GEK and with near-surface temperature distribution by BT twice a month in Hydrographic Department of Japan. The paths thus identified are published semimonthly from the department as the Prompt Report on the Oceanographic Conditions. The Kuroshio paths taken from above reports are shown in Figures 2 to 8 for each year of the meander period. For 1979 the paths are grouped into two; from Jan to Aug, and from Sept to Dec, because the dominant flow patterns are different for those two periods.

In order to compare Kuroshio patterns in the meander period with the patterns in no-meander period, Kuroshio paths in 1970 to 1975 are shown in Figure 9. Those figures clearly show two characterisitc Kuroshio pattern, no-meander pattern and meander pattern. In no-meander period, Kuroshio is very stable in the offing of Sionomisaki, behaving like a knot in a vibrating system. On the contrary, there seems a fluctuation in two regions, off Sikoku and Kyusyu, and around the Izu-Ogasawara Ridge. Nitani (1972) and Taft (1972) made similar comparisons using the data taken in 1956 to 1965.

As is shown in Figure 2, the Kuroshio meander was rather small in 1975, the trough of the meander being located at 31°N. In 1976, it grew larger and displaced southwestward. Throughout 1976, the meander was very stable (Figure 3). In 1977 it shifted further southwestward and became very unstable at the same time. The separation and recombination of a cold current ring occurred this year. In the spring of 1978, large offshore displacement of the Kuroshio axis occurred and also the meander was rather unstable this year and was elongated in east-west direction sometimes. These conditions are shown in Figure 5. In the first half of 1979, the meander was unstable as in the cases of 1977 and 1978 (Figure 6). But after the separation of a cold current ring in August, it became small and took the position just west of the Izu Ridge (Figure 7). In 1980, the meander gradually moved eastward and finally disappeared in August (Figure 8).

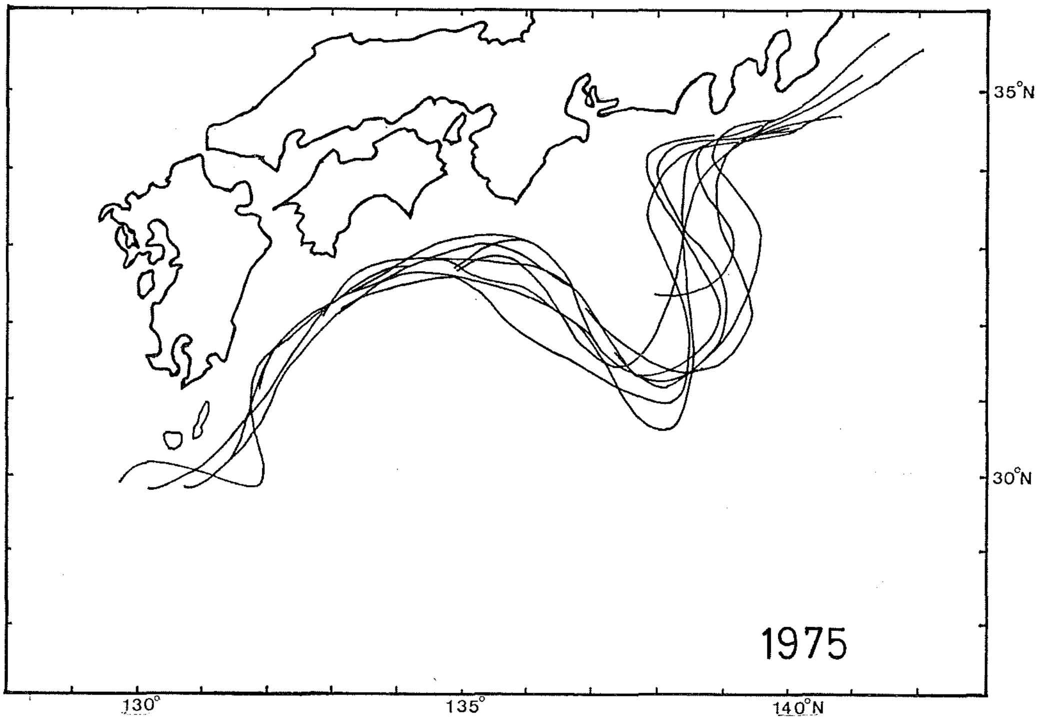

Figure 2 Kuroshio paths in 1975

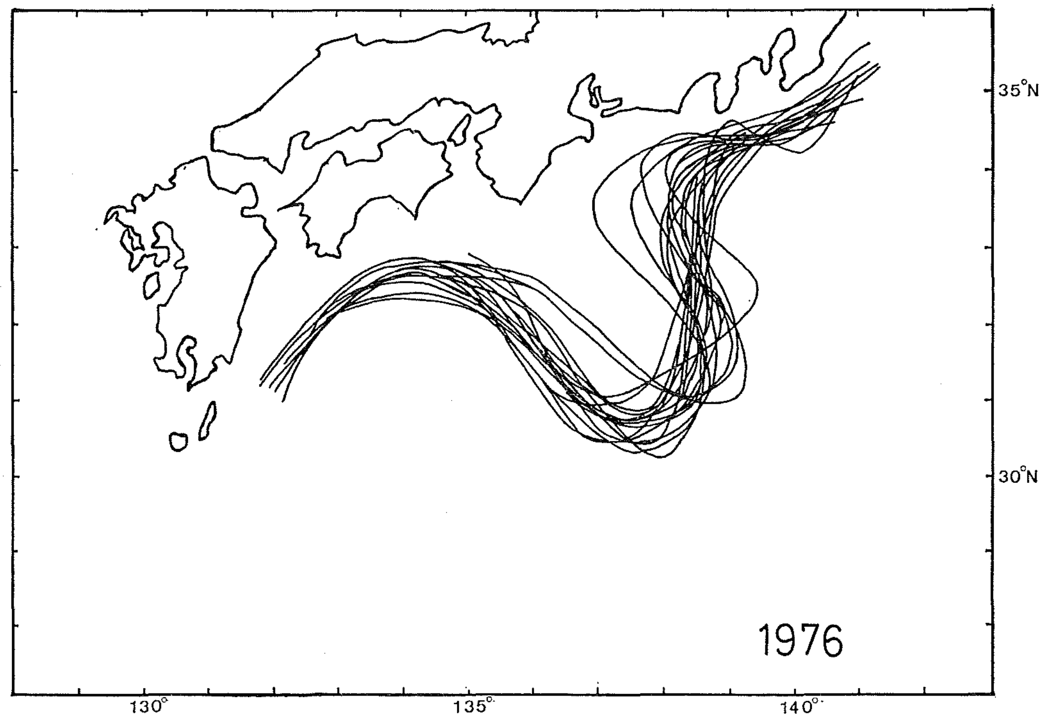

Figure 3 Kuroshio paths in 1976

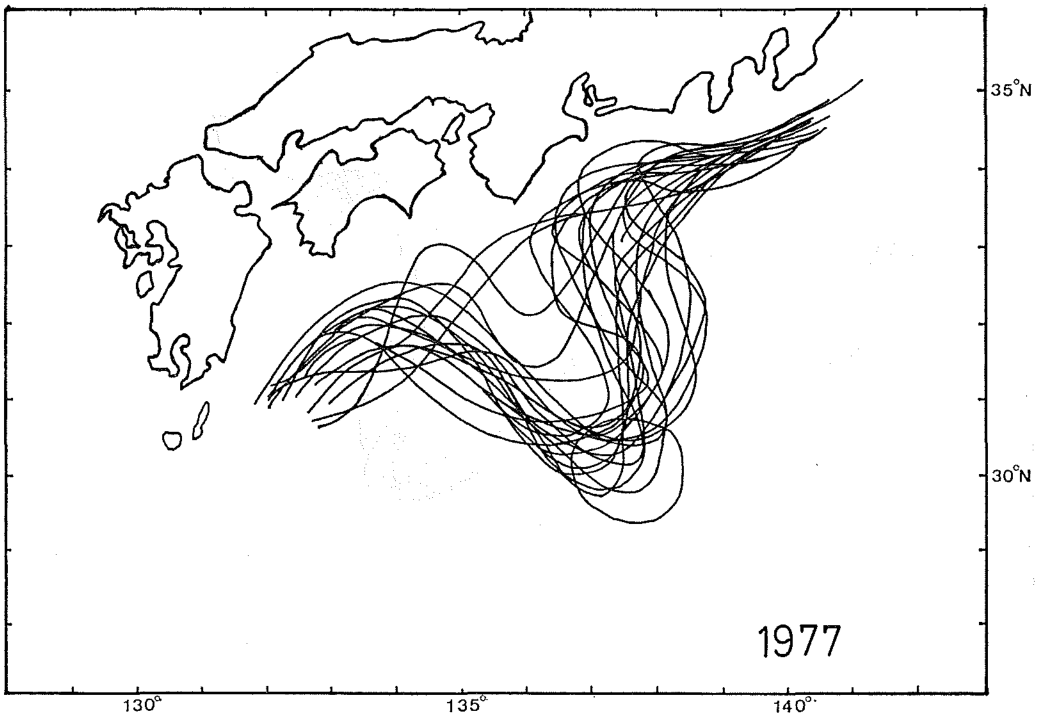

Figure 4 Kuroshio paths in 1977

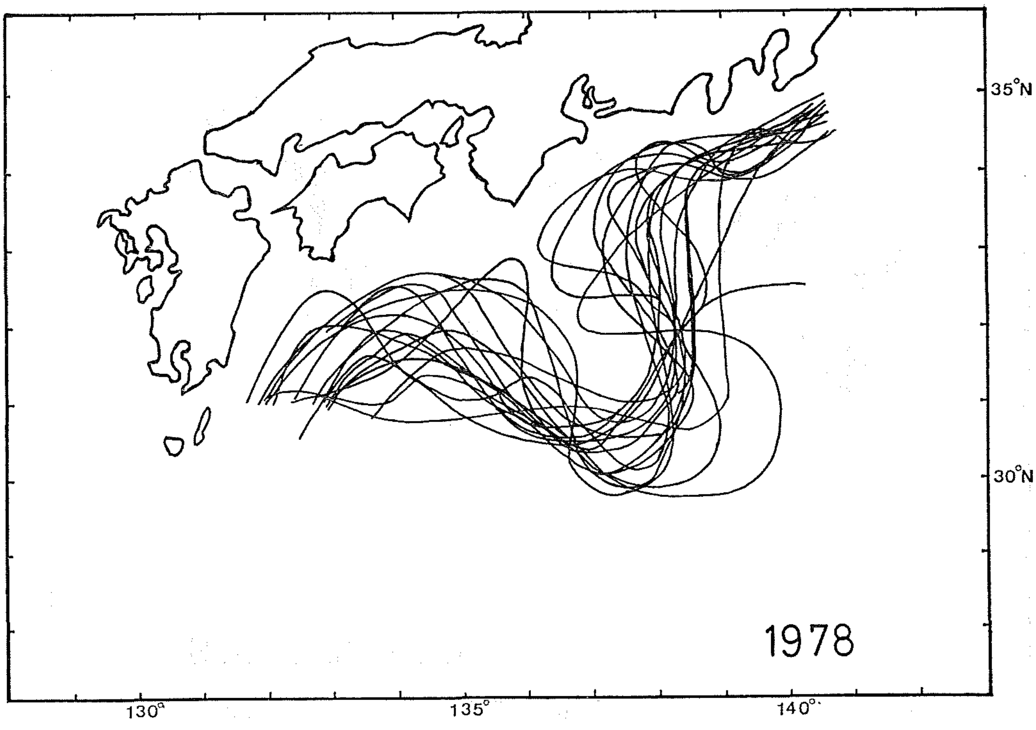

Figure 5 Kuroshio paths in 1978

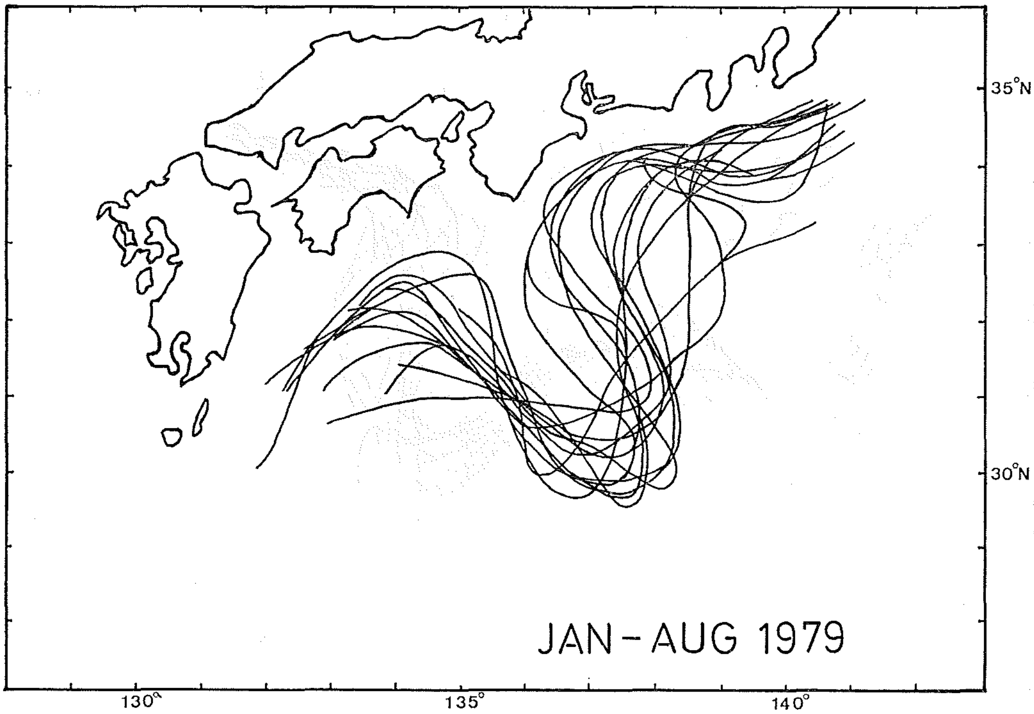

Figure 6 Kuroshio paths in Jan. to Aug. 1979

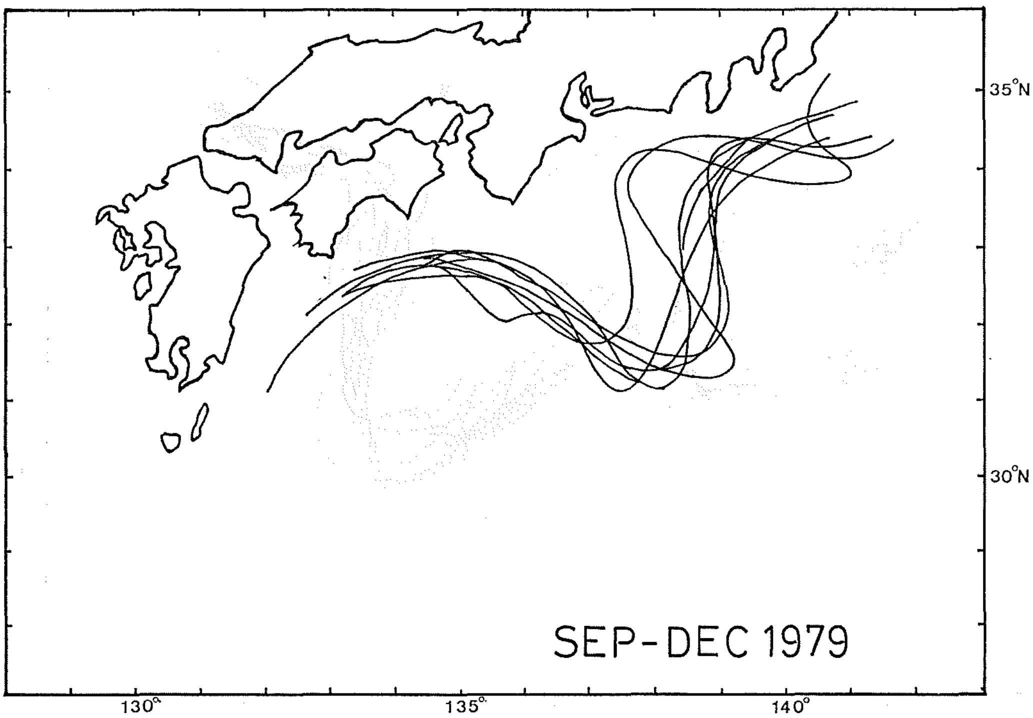

Figure 7 Kuroshio paths in Sep. to Dec. 1979

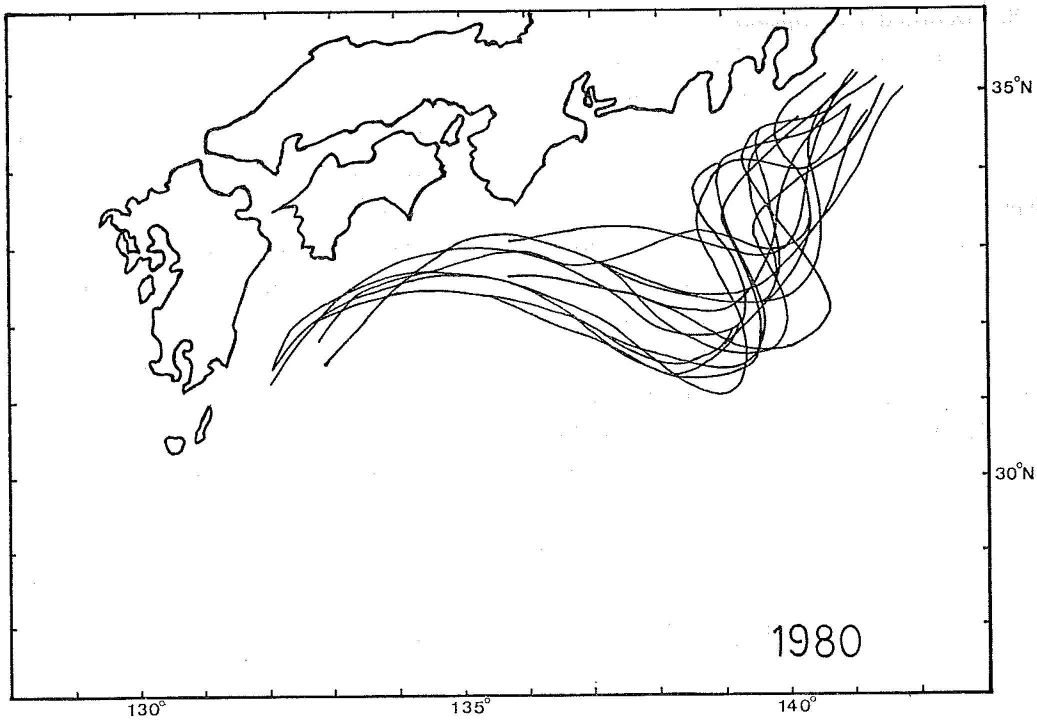

Figure 8 Kuroshio paths in 1980

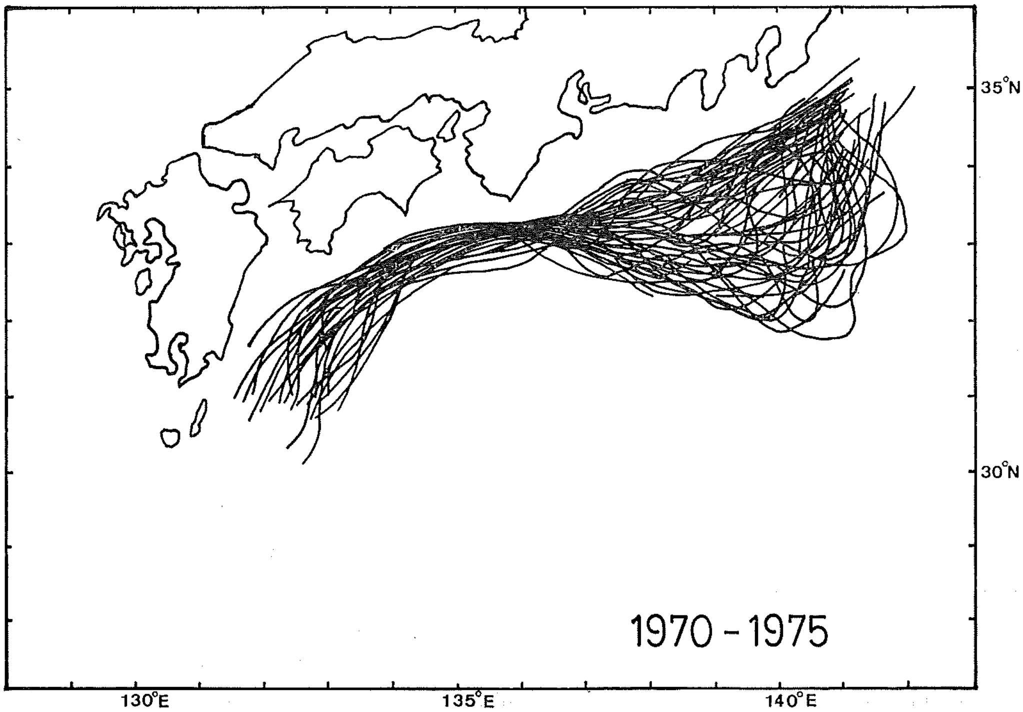

Figure 9 Kuroshio paths in 1970 to 1975

5. Detailed Description

In this section detailed descriptions are made on the several features of the Kuroshio meander which deserves closer examinations. In order to look at the change of the Kuroshio path in more detail, temperature distribution charts at a depth of 100 m are prepared. These charts are drawn for every 10 days in 1975–1978 and for every two weeks in 1979 and 1980. The depth of 100 m was chosen because there are more data available at 100 m than at 200 m, though 200 m has been a traditional choice to identify the Kuroshio. The representative temperature value at 100 m indicative of the Kuroshio axis are reported by Yamauchi (1978) and Nakabayashi (1970). Their results show that the temperature value indicative of the Kuroshio axis changes from place to place and from season to season ranging 15°C in February around the Izu Ridge to 25°C· in October to he south of Kyusyu. In this paper 20°C is used to fix the Kuroshio axis.

(1) Generation stage: April–August 1975

Kuroshio paths from April to August in 1975 are shown in Figure 10. A small meander

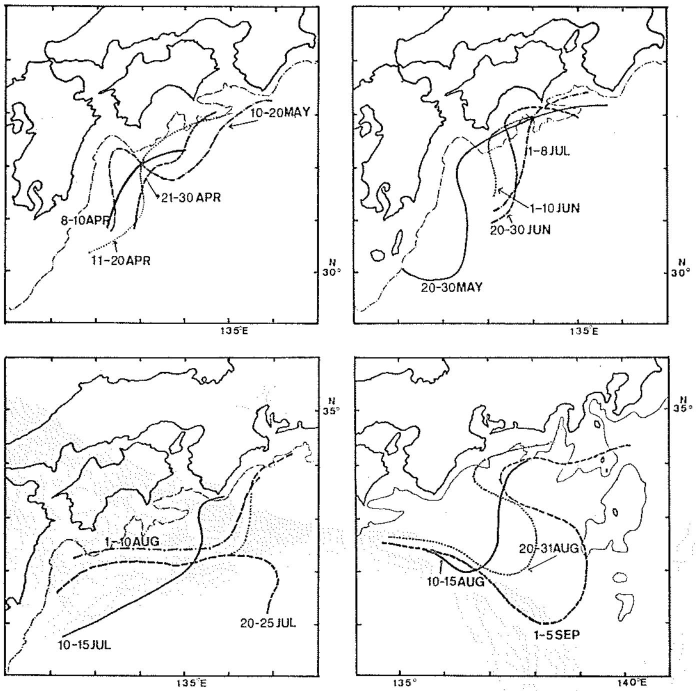

Figure 10 The eastward movement of the small meander in 1975 prior to the establishment of the large meander

was generated in mid-April as is shown in the current path in 11–20 April. This small meander proceeded downstream along the continental slope in next one month reaching in the offing of Sikoku in mid-May. However, in late May, the small meander seems to have disappeared or returned upstream (See the current path in 20–30 May). The small meander found to the east of Tanegasima in late May proceeded downstream again. It continued moving eastward through June and July and passed off Sionomisaki in late July. This passing off Sionomisaki seems to be important for the Kuroshio meander to become large, because a disturbance off Sionomisaki is scarcely found when the large Kuroshio meander is absent (see Figure 9). After passing off Sionomisaki, the meander extended in southeast direction and became a typical A-type meander in early September. Phase speed of the movement of this small meander is shown in Figure 11. Maximum phase speed

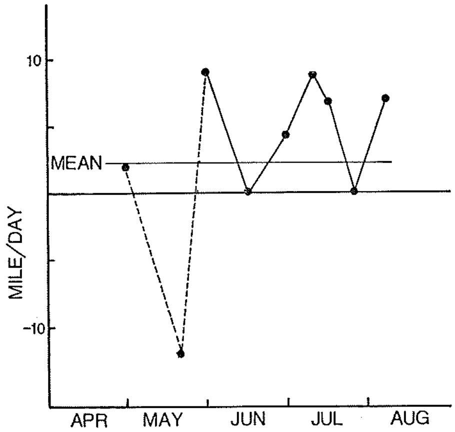

Figure 11 Phase speed of the eastward movement of the meander in 1975

of 10 nautical miles/day is found in late May and mid July. The mean phase speed in the total period is 2.2 nautical miles/day. This value is compared with the phase speed of 3 nautical miles/day in the past two cases in 1959 and 1969 (Nitani, 1977). The small disturbance to the east of Kyusyu is frequently observed especially in winter season (Moriyasu, 1961b). And often it proceeds eastward (Solomon, 1978). But, in very few cases it grows to a large Kuroshio meander. The reason why the small meander becomes large in some cases but it doesn't in other cases should be investigated.

(**2**) The separation and recombination of a cold ring in 1977

The Kuroshio condition in the period from the separation of a cold current ring to the recombination of it in 1977 is described in this sub-section on the basis of the current paths.

After being in very stable condition in 1976, the Kuroshio meander shifted westward, and at the same time it became unstable. Kuroshio paths in April to August in 1977 are shown in

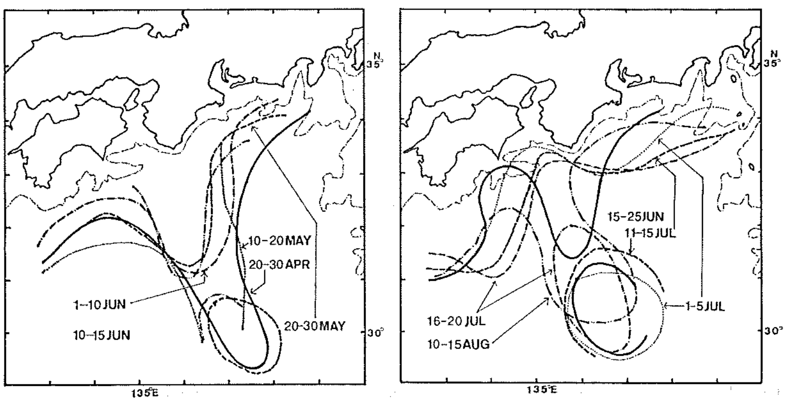

Figure 12 The separation of the cold eddy in May 1977 and the coalescence with the small meander off Sikoku

Figure 12. Kuroshio paths in April are inferred from surface temperature distribution using 20°C contour as a representative isotherm, while the paths in May to August are determined from 100 m temperature distribution. The meander in late April and mid May have a long and narrow shape extending to the south-southeast. In late May, the elongated cold eddy was separated into two parts, the southern half becoming a cold current ring and the northern half a contracted meander off Sionomisaki. Current rings are often found to the east of the Izu-Ogasawara Ridge where the Kuroshio Extension is very fluctuative. However, a ring formation to the south of Japan has never been observed in the past. Kamihira *et al.* (1978) reported a detailed structure of this ring on the basis of the Shumpumaru's observations in May and July*. According to them the separation of the cold eddy extended to a depth of 1000 m. This ring moved northwestward in next two months (Figure 12). On the contrary the contracted meander off Sionomisaki became small gradually and moved eastward. In mid June another meander was generated to the east of Kyusyu and proceeded eastward replacing the contracted meander. In August the newly generated meander coalesced with the cold ring producing a large meander again (the Kuroshio path in 10–15 Aug). The phase speed of the northwestward movement of the ring is about 1.5 nautical miles/day.

(**3**) Kuroshio paths in the spring of 1978

The Kuroshio in the spring of 1978 has two typical patterns. One pattern is observed in

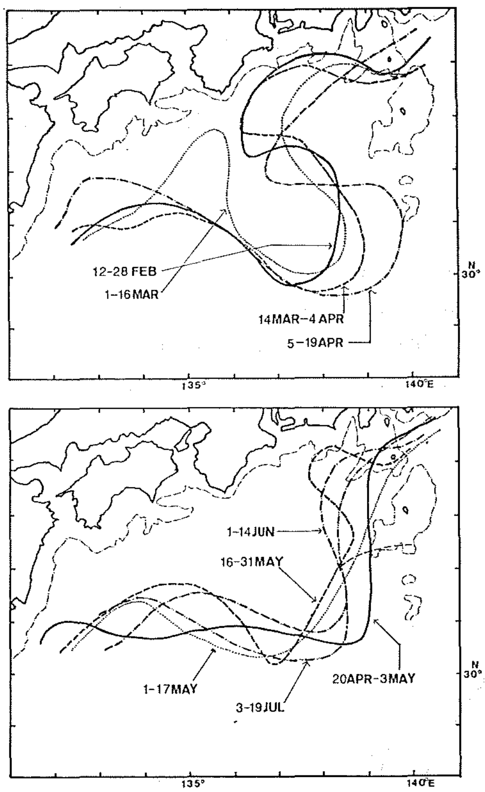

Figure 13 Two typical patterns of the Kuroshio meander in the spring of 1978

* Kobe Marine Observatory of JMA to which Shumpumaru belongs named the ring "Harukaze" after the Japanese style pronounciation of the ship's name Shumpu.

February to April (Figure 13, upper), and the other is observed in late April to June (Figure 13, lower). In February to April the Kuroshio meander has a S-like shape west of the Izu Ridge, and at the same time an eastward extension of the meander tip is observed (Figure 13, upper). This extension resembles to the situation in August 1975 (see Figure 10), though the horizontal scale is larger in 1978 than in 1975. The southward displacement of the current axis off Sikoku observed in February to July is another characteristic of the Kuroshio path in the spring of 1978. As is shown in 200 m temperature distribution in Figure 14, there are two cold eddies. One eddy is

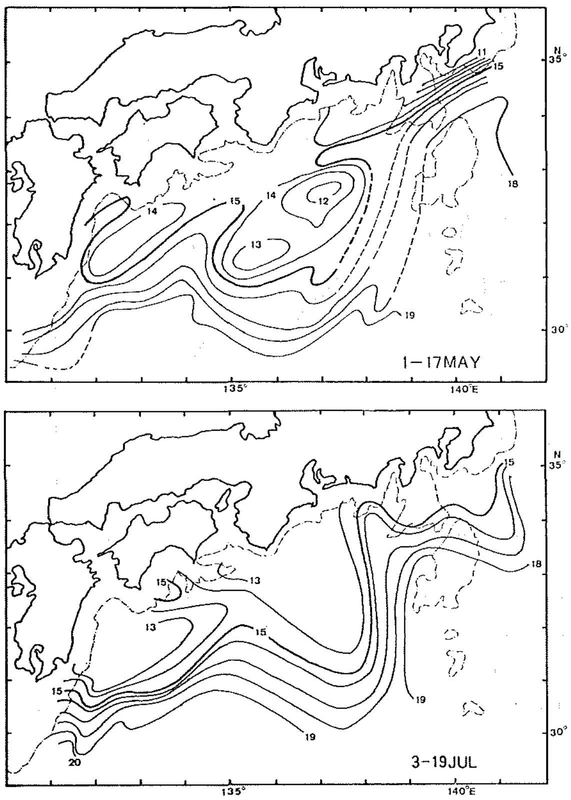

Figure 14 Temperature distribution at 200 m in May and July 1978

off Sikoku and the other off Kii Peninsula. The area of the cold eddy is largest in the spring of 1978. However, the temperature around the eddy center is rather high, having the value of 12°C compared with the usual value of 10°C. In late July, the meander returned to its typical pattern and remained as it was for the rest of the year.

(**4**) The second and third separation in 1979

In April 1979, the second separation of the cold eddy was observed. Kuroshio paths from March to May are shown in Figure 15. There is no BT data available in early April, and the Kuroshio path in 28 Mar–9 Apr was determined from the surface temperature distribution. Similarly to the case in May 1977, the meander became narrow and the trough extended in south southeast direction. In early April the southern tip of the cold eddy was separated and became a ring. But the subsequent progress of it is not clear. The ring may have coalesced with the Kuroshio meander

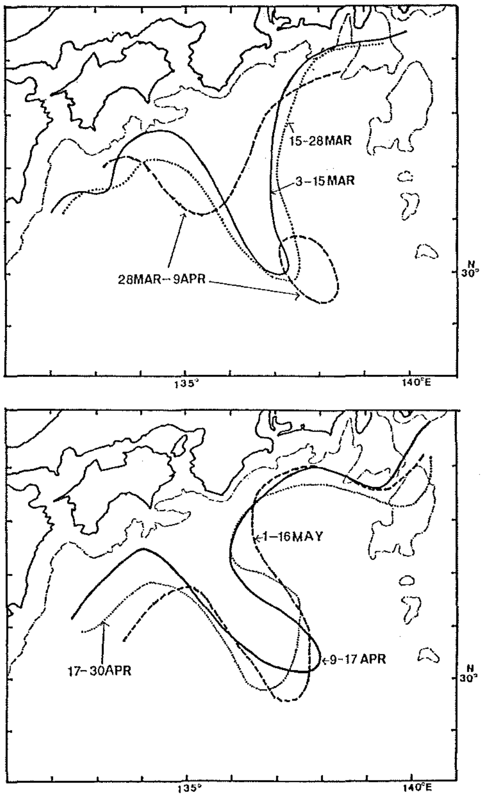

Figure 15 The second separation of the cold eddy in April 1979

soon after the separaiton, because the shape of the meander after the separation (Figure 15, lower) is still elongated in southeast direction. On the other hand, in the offing of Kyusyu, a new cold eddy developed during April and May (Figure 15, lower). In June, it coalesced with the eddy off Siono-misaki, resulting in a single large eddy. This is shown in 200 m temperature distribution in Figure 16.

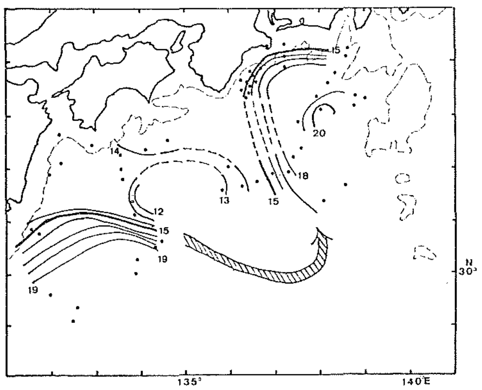

Figure 16 The temperature distribution at 200 m in June 1979

In August, the third separation of the cold eddy occurred (Figure 17). The shape of the meander just before the separation (18 Jul–1 Aug) is very unusual, having two tips; one is on

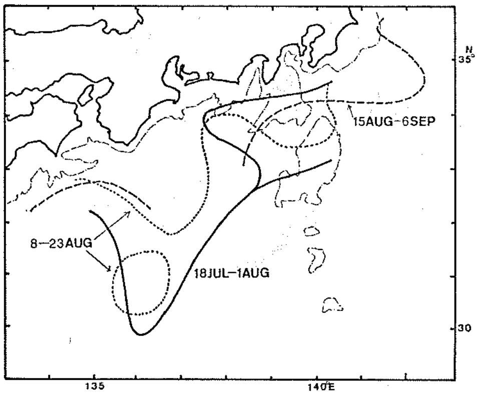

Figure 17 The third separation of the cold eddy in August 1979

the south and the other on the east. It seems that the southern tip became a ring and the other tip became a small meander around Miyakesima, as shown in the Kuroshio path in 8–23 Aug. In next ten days the small meander around Miyakesima moved eastward and the contracted meander off Sionomisaki also shifted to the east (the Kuroshio path in 15 Aug–6 Sep). After the contraction by the third separation in August 1979, the supply by a newly generated meander off Kyusyu was not given to the Kuroshio meander. The meander remained as it was for the rest of 1979, keeping the contracted size, and entered into the disappearing stage.

(**5**) The disappearing stage: January–August 1980

The Kuroshio meander, which was contracted by the third separation in August 1979, moved eastward very slowly, reaching just west of the Izu Ridge by the end of 1979. The meander continued moving eastward during the first half of 1980, and finally disappeared from the south of Japan in August. The condition in this disappearing stage is described in detail in this subsection. The Kuroshio paths in January to August 1980 are shown in three charts in Figure 18. It is clearly seen that the meander gradually shifted eastward and at the same time the length of the meander in north-south direction was shortened. A typical C-type Kuroshio meander is observed in May to July. This disappearing process of the Kuroshio meander is very similar to that of the previous meander (1959–1963), which is described in Nitani (1977), although the decay of the meander by the separation of a cold ring was not observed in the previous meander period. The longitudes at which the Kuroshio path crosses the 33°N line are plotted for the period from January to July 1980 (Figure 19). Figure 19 also shows that the sea level for the total five-year period at Hatizyo-zima, which is located at about 33°N and 140°E. The sea level at Hatizyozima is a good indicator of the location of the Kuroshio path around the Izu Ridge. That is best exemplified by the good correlation between the longitudes of the Kuroshio path and the sea level at Hatizyozima in January to July 1980. The temporal southward displacement of the Kuroshio path in May 1978, which was discussed in 5.3, is represented as a dip in the sea level. Similar dips are found in October and December 1977, and in July and November 1979. But the corresponding fluctuation of the Kuroshio path was not observed because of the lack of data.

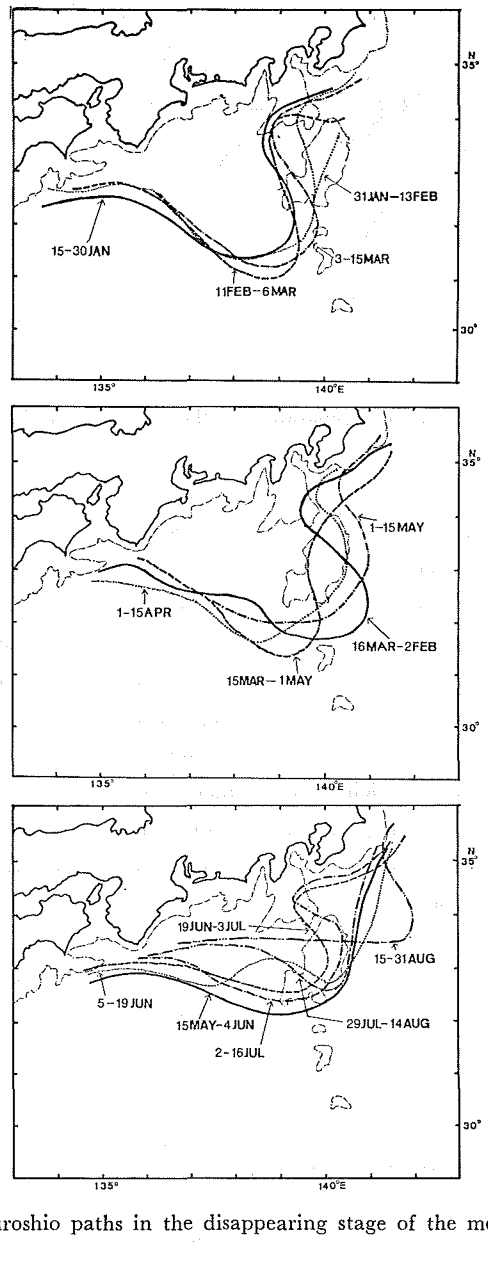

Figure 18 Kuroshio paths in the disappearing stage of the meander in 1980

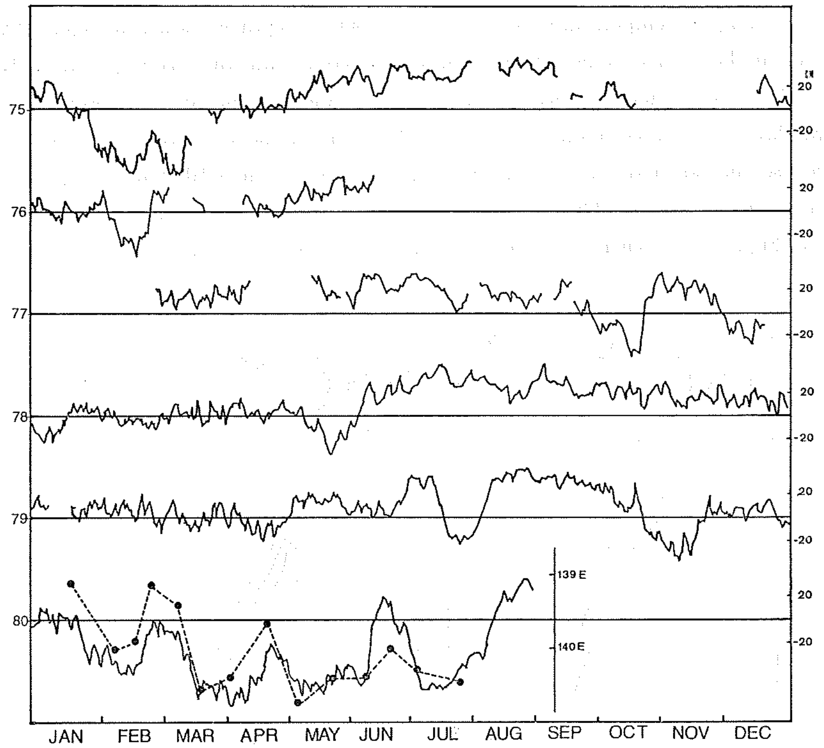

Figure 19 Seal level at Hatizyozima and the positions of the Kuroshio paths in 1980 expressed by the longitude at which the Kuroshio cross 33°N line. Solid lines shows the sea level and the dashed line at the bottom of the figure shows the longitudes

6. The Deep Structure of the Kuroshio Cold Eddy and the Warm Eddies South of the Kuroshio

Deep serial observations down to the bottom, which was rarely made in the previous meander periods, were made rather frequently during the meander period from 1975 to 1980. With the use of those deep observation data, the better understanding of the deep temperature structure of the cold eddy can be obtained.

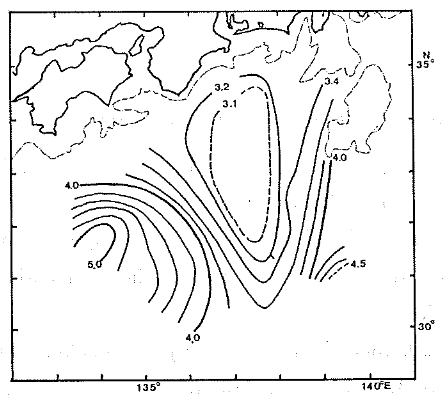

Figure 20 Temperature distribution at 1000 m in May 1976

As an example, temperature distribution at 1000 m depth is shown in Figure 20. The cold eddy is located on the corner made by the continental slope and the Izu-Ogasawara Ridge. The temperature still has a gradient at this depth. If this gradient indicates a substantial geostrophic velocity at this layer, it is very natural to assume the strong influence of the Izu Ridge on the Kuroshio flow, because the northern portion of the ridge is shallower than 1000 m. Temperature gradient is found even at deeper layers. This is shown in the temperature distributions at 2000 m, 3000 m and 3500 m in Figure 21. When we calculate the geostrophic velocity at 1000 decibar and 2000

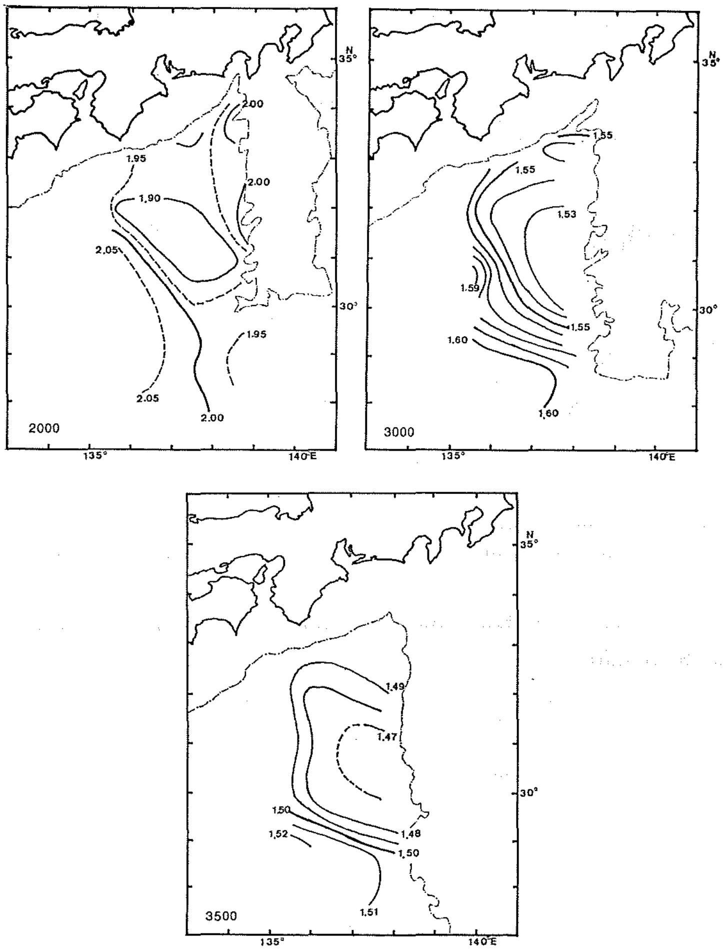

Figure 21 Temperature distributions at 1000 m, 3000 m and 3500 m in November 1976

decibar referred to 3000 decibar, 10 cm/sec and 3 cm/sec are obtained at maximum. This deep temperature gradient continued throughout the meander period. The temperature distribution at 1000 m in September 1979 is shown in Figure 22 as an example of the deep structure near the end of the meander. The temperature near the center of the cold eddy is about 3°C, and sharp temperature gradient is still found.

As is seen in Figure 20, there is a warm eddy off Sikoku. This eddy can not be recognized in the temperature distribution shallower than 200 m because of thick thermostad near the sea surface. The return flow associated with this warm eddy may be large and account for a substantial portion

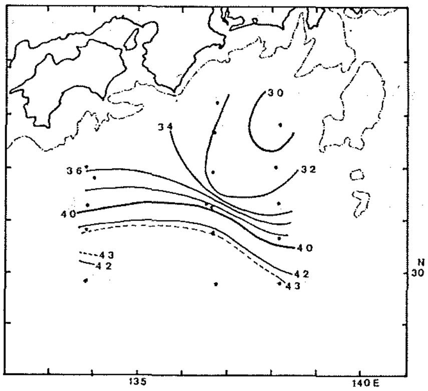

Figure 22 Temperature distribution at 1000 m in September 1979

of the total Kuroshio transport. However, because of the sparsity of data, the role of this warm eddy has not been fully understood. According to Marine Environmental Atlas II (1978) published by Japanese Oceanographic Data Center, the mean position of this warm eddy is 31°N and 136°E during no-meander period. When the Kuroshio meander is present, the mean position of the warm eddy moves to the west. The positions of the warm eddy center during the period from 1975 to 1980 are read from a series of 400 m temperature distribution charts, most of which are prepared by Nishiyama and Ishii (1980). For a half of these charts the center of the warm eddy can be recognized. Table 2 shows all of these positions. The overall mean of them is 30°02′N and 134°18′E. According to Table 2, the warm eddy moved southward in 1977 with the higher temperature value near the eddy center.

There is one more warm eddy which is located over the Izu Ridge. However, it is very scarcely recognized as an eddy because of the lack of data. An example is the 1000 m temperature distribution in May to June in 1978 (Figure 23). As shown in Figure 23, there is a warm area on the

Table 2 Positions of the warm eddy off Sikoku

year	month	lat.	long.	max. temp. at 400 m
1976	May	30°55′	134°05′	17–18°C
	Jul.	30°42′	133°55′	17–18
	Sep.	30°05′	134°00′	17–18
	Oct.	30°25′	134°05′	17–18
1977	Jan.	29°50′	133°40′	16–17
	May	29°22′	134°20′	18–19
	Jul.	29°25′	133°50′	18–19
	Sep.	29°25′	135°00′	18–19
	Oct.	29°20′	133°40′	18–19
1978	Jun.	30°00′	135°20′	18–19
	Nov.	29°05′	133°45′	17–18
	Dec.	30°30′	133°35′	17–18
1979	Mar.	30°00′	134°20′	18–18
	Sep.	31°00′	135°00′	16–17
	Oct.	30°25′	135°50′	16–17
Mean		30°02′	134°18′	

Izu Ridge surrounded by 4.6°C isotherm. This warm eddy is less conspicuous than the one found off Sikoku. According the overall mean dynamic topography in the western North Pacific (JODC, 1975), there is one warm eddy east of the Izu Ridge at about 33°N and 143°E. However, it is not clear whether this eddy shifted westward onto the Izu Ridge or a new eddy was generated there when the large Kuroshio meander occurred.

The change of the positions of the warm eddy off Sikoku from the position in no-meander period to the one in meander period is observed in the generation stage of the Kuroshio meander in 1975. Because the number of deep observations is much less than those of surface or near-surface

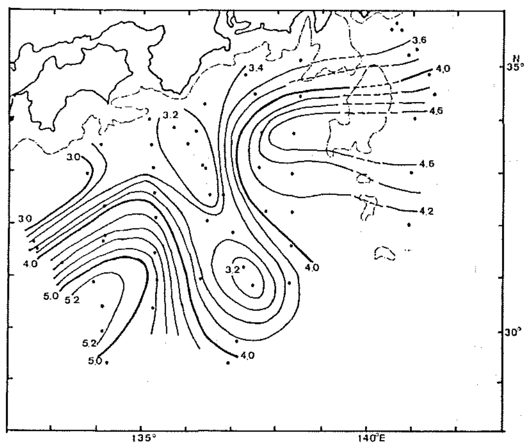

Figure 23 Warm eddy on the Izu Ridge represented by 1000 m temperature distribution in the spring of 1977

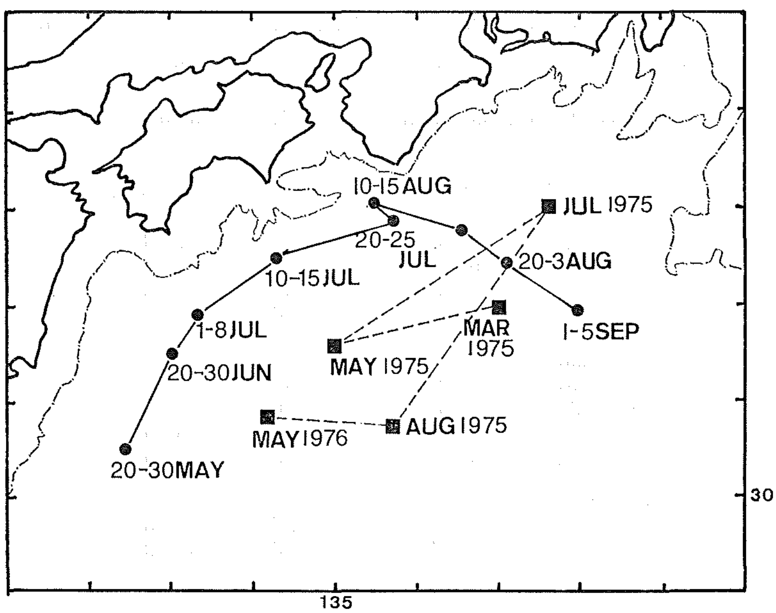

Figure 24 Movement of the warm and cold eddies in the generation stage of the meander. Solid circles represent the center of the cold eddy and solid squares represent the center of the warm eddy.

observations, the center of warm eddy was identified only four times in 1975. Those four positions are shown in Figure 24. The centers of the cold eddy in the same period are also included in Figure 24. According to Figure 24, the warm eddy moved northeastward in May to July along with the cold eddy off Sikoku. However, it seems that the warm eddy moved to the southwest during July and August, being replaced by the cold eddy. Nishiyama *et al.* (1980) suggested that the warm eddy which is found off Omaesaki in July moved away to the east during August, and a new warm eddy came from the west.

Because the eddy structure extends deeper than the sill depth of the Izu Ridge, the deep structure of the cold eddy at the time of C-type Kuroshio meander is very interesting. To our regret, the deep observation of the disappearing stage of the Kuroshio meander is not so dense as to be able to construct a temperature distribution chart in deep layers. However, the fractional evidences in May 1980 indicates that temperature gradient exists in deep layers of the cold eddy on both sides of the Izu Ridge.

7. Water Characteristics of the Cold Eddy

Water characteristics of the cold eddy is analyzed with the use of T-S and T-O_2 relation-

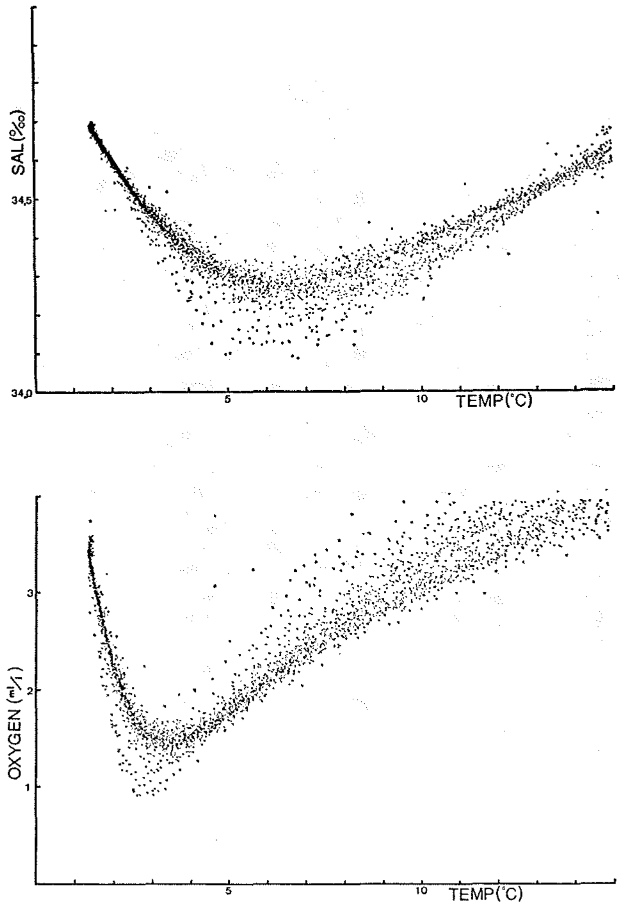

Figure 25 T-S and T-O_2 diagrams for the stations occupied in the area south of Japan during the meander period

ships. T-S and T-O_2 diagrams are constructed using all the serial observation data taken by the Hydrographic Dept. during the period from August 1975 to November 1978 (Figure 25). Station locations of these data are shown in Figure 26. As is seen in Figure 26, the stations are distributed in the area of the cold eddy, the Kuroshio and the south of the Kuroshio. The data of which the temperature is over 15°C are excluded, because those near-surface water is under the influence of the surface disturbances and may not represent the cold eddy adequately. The data used corresponds to the water deeper than 100 m in the center of the cold eddy and deeper than 400 m in the warm eddy. As is seen in Figure 25, all the data fall in the very narrow belt on T-S and T-O_2 diagrams. There are some stations which have lower salinity values at salinity minimum layers and lower oxygen values at oxygen minimum layers. Also, higher oxygen content are often found in the thermocline waters (The water having the temperature value of about 10°C; Masuzawa, 1969). When the stations in the cold eddy and the Kuroshio main current zone are picked up to draw T-S and T-O_2 diagrams (Figure 27), these data fall in even narrower belt, meaning that the stations which have lower salinity value in the salinity minimum layer and higher oxygen content in thermocline waters are all located to the south of the Kuroshio. Therefore the waters which consist of the cold eddy is the same as the water of the Kuroshio main current. As is seen in the north-south temperature

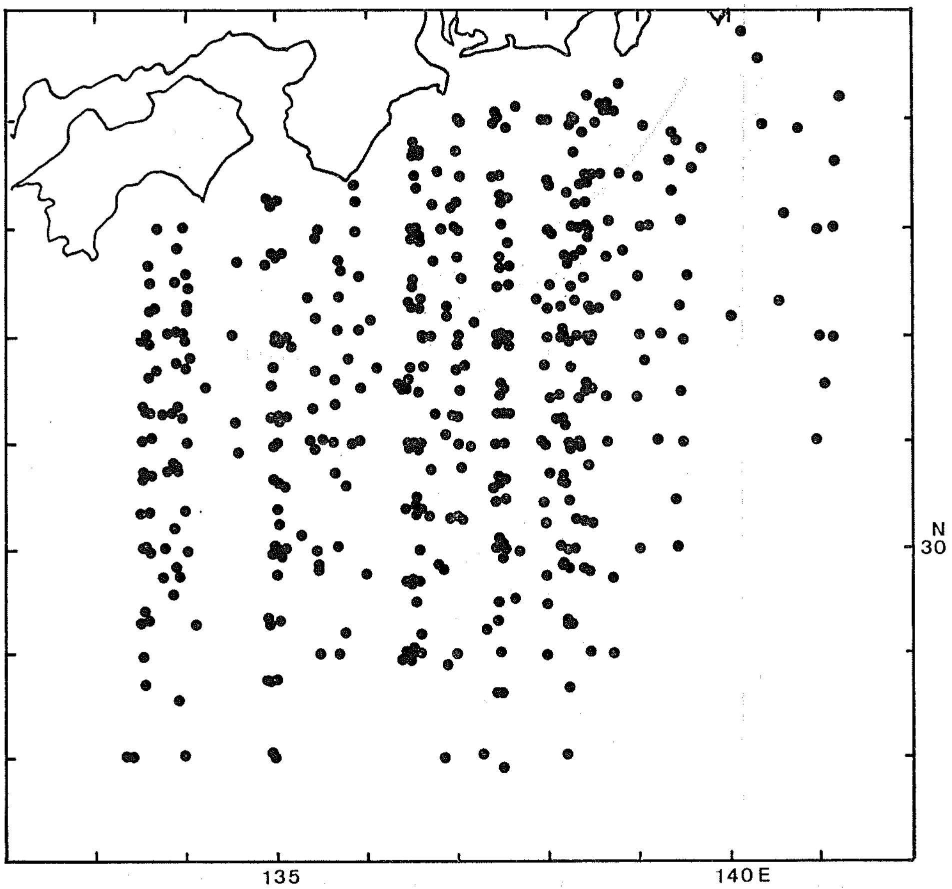

Figure 26 Station locaiton chart for the data in Figure 25

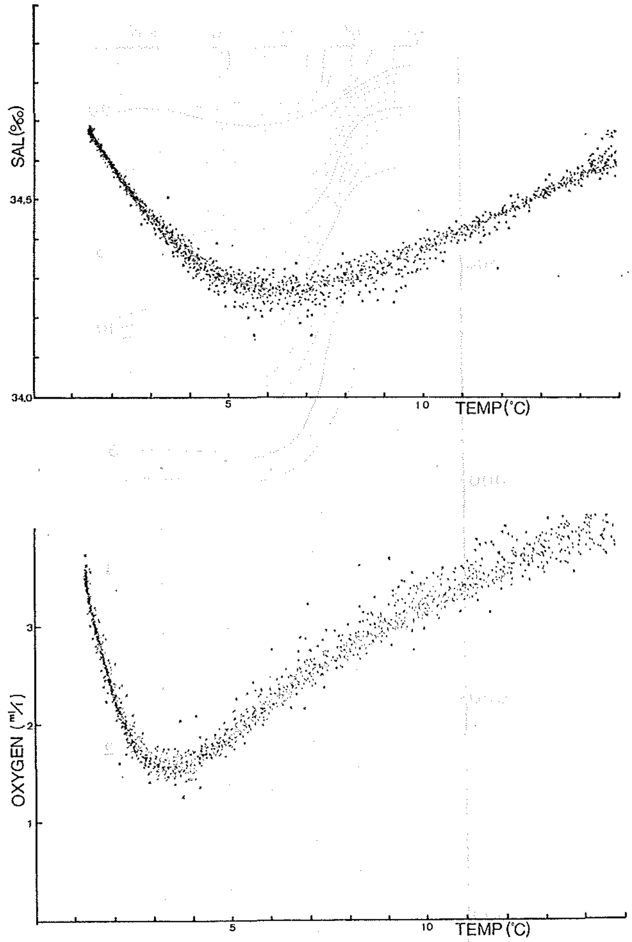

Figure 27 T-S and T-O_2 diagrams for the stations inside the cold eddy and in the Kuroshio main current zone

section which crosses the center of the cold eddy (Figure 28), there is correspondence between the cold eddy water and the Kuroshio water at every depth. This fact indicates that the Kuroshio water upwelled by the amount of 300–400 m at every layer from surface to near bottom. The same result was pointed out for the previous cold eddies, although the observation was rather shallow (Moriyasu, 1954).

Uda (1949) pointed out the good correlation between Oyashio strength and the Kuroshio meander generation, and suggested that Kuroshio cold eddy was caused by Oyashio undercurrent, which flows to the south from the Oyashio region on the east of the Izu Ridge, curls into this region and upwells there. Nan'niti (1958) suggested that the bathymetry south of Japan is favorable for the upwelling of the Oyashio undercurrent. However, the fact that the every layer just below the Kuroshio main current upwelled and became the cold eddy suggests that some dynamical effect is more appropriate for the cause of the occurrence of the cold eddy. Ishii and Toba (1977) suggested that the angle at which the Kuroshio meets the Izu Ridge is essential to the upwelling the Kuroshio water.

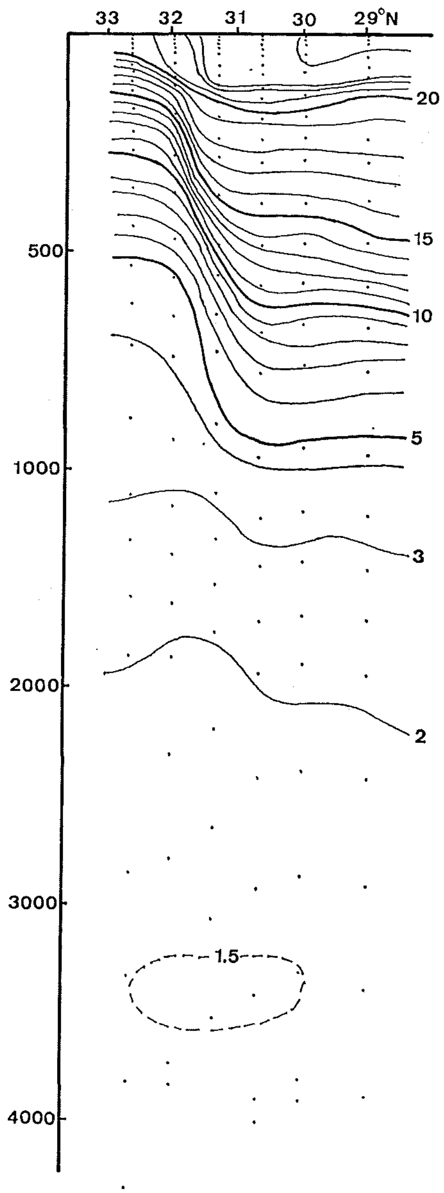

Figure 28 Temperature section along 136°E in November 1976

In May 1980 when the Kuroshio meander takes the C-type, several serial observations were made around the Izu Ridge. Among them, four stations are inside the cold eddy, two of them being to the east of the Izu Ridge and the other two to the west of the ridge. The T-S and T-O_2 relations are plotted in Figure 29. The T-S and T-O_2 curves show that the water deeper than 800 m have different characteristics on both sides of the Izu Ridge, while the shallower waters are the same on both sides. This indicates that when the pattern of the Kuroshio meander changes from A- or B-type to C-type, only the surface pattern moves but the deep waters does not cross the ridge.

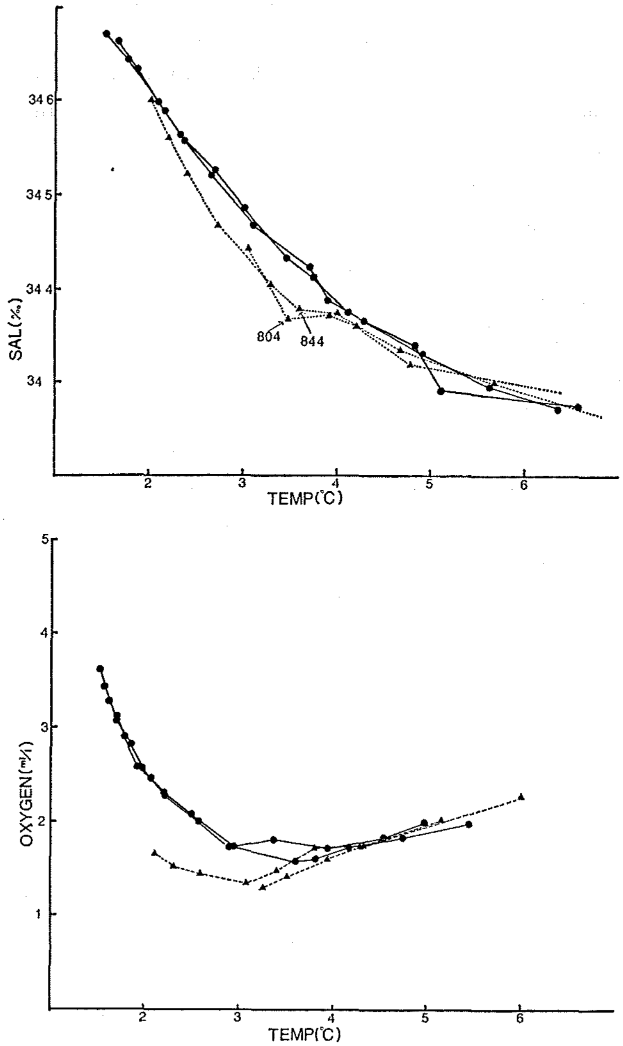

Figure 29 T-S and T-O_2 diagrams for the stations inside the cold eddy at the time of C-type Kuroshio meander. Solid circles represent the stations west of the Izu Ridge and triangles represent the stations east of the ridge.

8. Summary

The large meander of the Kuroshio south of Japan in 1975 to 1980 is described based on the movement of current axis. GEK and BT data from various sources are assembled and the current axises are identified with surface current maximum or temperature gradient maximum at 100 m and 200 m depths. The establishment of the large Kuroshio meander in August 1975 was preceded by the eastward movement of the small meander off Kyusyu and Sikoku. This generation process is very similar to the process in 1959 and 1969. In the latter half of 1975 and throughout 1976, and also in autumns of 1977 and 1978, the meander was very stable, being located off Omaesaki. On the other hand, in the spring and summer of both 1977 and 1979, the meander was rather unstable, being located off Kii Peninsula. During those periods the separation of the cold eddy and the production of a cold ring occurred three times, namely in May 1977, in April 1979 and in August 1979. Among the rings produced above, the one in May 1977, after having moved to the northwest, coalesced in August with the small cold eddy south of Sikoku which was generated in June 1977 to the east of Kyusyu. The typical A-type meander pattern was resumed through this coalescence. Also, in the case of the separation in April 1979, the remaining small meander left by the separation of southern tip returned to its typical A-type through the coalescence with the newly generated meander east of Kyusyu. However, in the case of August 1979, without further supply, the meander remained small and entered into the disappearing stage. In the disappearing stage, the meander moved eastward gradually. Northward flowing portion of the meander on the east side reached the Izu Ridge and crossed the ridge, taking C-type meander pattern. Fluctuation with the period of two or three months overlapped on this gradual eastward movement. Evidences in T-S and T-O_2 diagrams indicate that when the meander crossed the Izu Ridge, the deep water did not cross over the ridge.

The warm eddy, which is located to the south of Kii Peninsula when the meander is absent, was located to the south of Sikoku during the meander period. It moved westward in the generation period, stayed to the south of Sikoku during the meander period and moved back to the south of Ensyunada when the meander ended. One more eddy was found in 1977 and 1978 on the Izu Ridge, where there is no such eddy when the meander is absent.

Analysis of T-S and T-O_2 diagrams indicate that the cold eddy water upwelled by 300 m or 400 m at every layer under the Kuroshio.

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