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Bottom Trapped Cyclonic Eddy Southwest of Kyushu Revealed by Field Observation

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Abstract

A bottom trapped cyclonic eddy was detected over the trough southwest of Kyushu in the hydrographic and current observations during June 6-18, 1997. Successive satellite images of sea surface temperature between May 20 and June 17 indicate its formation process as follows. A cyclonic circulation is initially induced at the continental shelf break region by the Kuroshio instability. It propagates northeastward along the Kuroshio, and then it is trapped at the mouth of the trough southwest of Kyushu. After its detachment from the Kuroshio, a cyclonic eddy moves northward along the trough while the Kuroshio moves southward significantly. The hydrographic observation indicates that the cyclonic eddy reaches the depth deep enough to be affected by side walls of the trough. These observational results suggest that 1) the blocking effect of the bottom topography southwest of Kyushu plays an important role in the detachment of the cyclonic eddy initially induced by the Kuroshio instability, and 2) the interaction between the detached eddy and the Kuroshio causes the Kuroshio meander with a large meridional amplitude.

1. Introduction

The Kuroshio flows northeastward along the continental shelf break through the East China Sea. After the Kuroshio changes its direction to the east and leaves from the continental shelf break northwest of the Amami-oshima Island, it exits through the Tokara Strait (Fig. 1). Owing to the Kuroshio meander and shed-off eddies, the flow field in the region between the turning point of the Kuroshio and the Tokara Strait is more complicate than the continental shelf break region. The variation range of the Kuroshio meander is smaller than 30 km in the continental shelf break region while it is larger than 50 km in the region between the turning point and the Tokara Strait (Yamashiro et al., 1993). The dominant periods of the variation in the Tokara Strait are known to be one month, two months, and 4.6 months (Yamashiro and Kawabe,

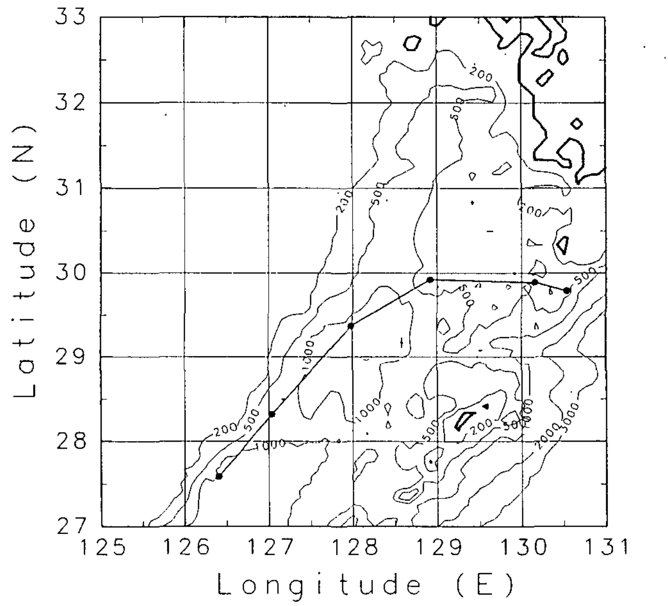

Fig. 1. Map of the East China Sea. Bold solid line indicates climatological annual mean position of the Kuroshio quoted from Table 2 in Yamashiro et al. (1993). Data of bottom topography are the TerrainBase Global Land and Ocean Depth (5×5 min) provided by the National Geophysical Data Center.

1996). A large anticyclonic warm eddy detached from the Kuroshio meander has been often observed at the head of the trough west of Kyushu (Huh, 1982; Tawara and Fujiwara, 1985; Muneyama et al., 1984; Qiu et al., 1990). An anticyclonic sense of circulation in the trough is also verified by the climatological mean surface currents derived from geoelectrokinetograph (GEK) data (Hsueh et al., 1996). However, cyclonic eddies have been hardly found in the trough except for a clear evidence shown by a trajectory of a satellite-tracked drifter in Lie and Cho (1994) (see Fig. 9 in their paper). The dominance of the anticyclonic eddy in this area may be explained by an idea proposed by Yamagata and Kamachi (1989). Using a simple numerical model representing the bottom topography by the bottom friction, they showed that the cyclonic eddy evolves the anticyclonic eddy.

The formation mechanisms of the Kuroshio meander and shed-off eddies southwest of Kyushu have been examined from the point of view of the Kuroshio instability. Qiu et al. (1990) suggested that fluctuations of the surface temperature front (called the Kuroshio Front) are generated at the continental shelf break region by the Kuroshio instability, and propagate downstream to the Tokara Strait, evolving rapidly and forming warm filaments and shed-off eddies. The statistical analyses of Qiu et al. (1990) and Maeda et al. (1993) indicated that the variation of the Kuroshio-front meander is closely related to the meridional shift of the Kuroshio in the Tokara Strait. This suggests that the Kuroshio meander in the Tokara Strait is caused by the Kuroshio instability. However, the dynamics making the strong relationship between them are not obvious, because the Kuroshio front is characterized in the shallower layer than the approximate 200-m depth while the Kuroshio current has the deep structure over the entire main thermocline (Nakamura et al. 1997). An effect of the bottom topography southwest of Kyushu is thought to be the blocking of the northward Kuroshio current along the continental shelf break. Using a conceptual model with an idealistic bottom topography, Hsueh et al. (1996) suggested that the blocking effect separates an in-shore part of the Kuroshio from its main stream. However, there is no study about the effect of the bottom topography southwest of Kyushu on the propagation of the Kuroshio-front fluctuations accompanied by shed-off eddies and on the meridional shift of the Kuroshio meander.

In order to investigate flow fields related to the bottom topography southwest of Kyushu, the hydrographic and current observations were carried out by T/V Keitenmaru during June 6–18, 1997. A bottom trapped cyclonic eddy was observed in the trough southwest of Kyushu. This paper examines hydrographic and current structures of the eddy by field data and its formation and evolution by successive satellite images of sea surface temperature between May 20 and June 17, 1997. A primary objective of this paper is to propose a formation mechanism of the cyclonic eddy in the trough southwest of Kyushu. This paper is arranged as follows. The observation and data processing are mentioned in section 2. The formation and evolution of the cyclonic eddy revealed by successive satellite images of sea surface temperature are presented in section 3. The vertical structure of the cyclonic eddy obtained by hydrographic and current data are shown in section 4. In section 5, observational results are summarized, and the possible topographic effects on the formation of the cyclonic eddy are discussed.

2. Observation and data processing

Hydrographic observations with XBT, CTD with RMS, and current observation with the shipboard ADCP were carried out around the trough southwest

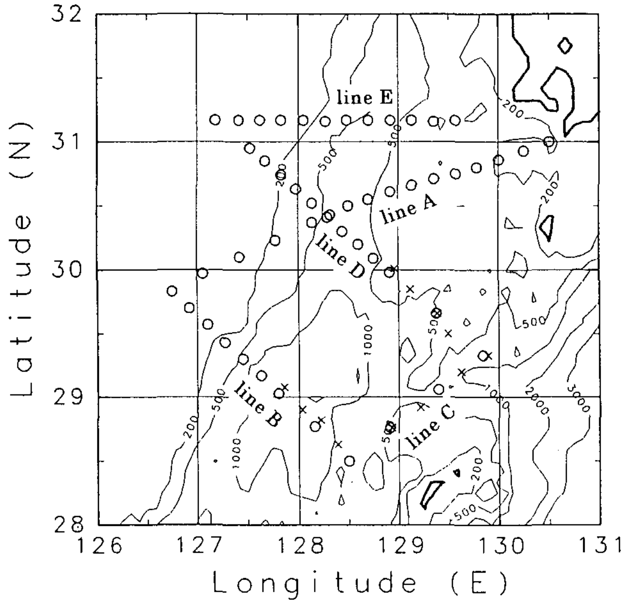

Fig. 2. XBT stations (crosses) and CTD stations (circles). Bottom topography is the same as in Fig. 1.

of Kyushu by T/V Keitenmaru of Kagoshima University. The observation was performed along five lines shown in Fig. 2 during June 6-18, 1997 (JST). Hereafter, each line is called line A-E, which are denoted in Fig. 2. The XBT observations were performed basically to 750-m depth and the CTD observations to the bottom (to 1500-m depth when the bottom is deeper than 1500 m). Current data with ADCP were obtained basically at 5-m, 50-m and 100-m depths with every minute. Date and time of the observation on each line are summarized in Table 1.

XBT data were arranged in every 5-m interval by using a gausian filter with the 5-m e-falling scale, after removing unusual values over 3 σ to mean values averaged within every 10-m interval. CTD salinity data were calibrated through the following processes. The conductivity measured by CTD was corrected by salinity of 42 bottle samples at specific depths on the upcast. Samples were analyzed with the AUTOSAL 8,400 B salinometer, referenced to the IAPSO standard sea water (batch number, P 129). The best quadric coefficients to make CTD salinity equal to bottle salinity were determined by the least square method for 28 bottle salinity data. The standard deviation of corrected CTD salinity from bottle salinity was 0.0027 psu. CTD temperature

Table 1. Survey periods (JST) on each observational line.

	Start	End
line A	17 : 34, June 6, 1997	20 : 48, June 7, 1997
line B	20 : 48, June 7, 1997	14 : 50, June 8, 1997
line C	14 : 50, June 8, 1997	00 : 52, June 9, 1997
line D	00 : 52, June 9, 1997	08 : 39, June 10, 1997
line E	07 : 53, June 17 1997	00 : 47, June 18, 1997

and salinity were arranged in every 1-m interval, adopting the method that decreases the number of density inversions caused by the difference of response times between temperature and conductivity sensors. Thirty-minute mean absolute velocity of ADCP was calculated at 5-m, 50-m and 100-m depths as a vector sum of the detected Doppler current velocity relative to the ship and the ship velocity determined by GPS.

3. Satellite observation

Figure 3 shows successive satellite IR images received at Kagoshima University between May 20 and June 17, 1997. The images are made to emphasize the structure of surface temperature fronts at the in-shore side of the Kuroshio, so gray scales indicate the different temperature ranges in each picture. In the images, darker areas indicate warmer water and brighter areas colder water. Both the sharp front and weak front connecting with the sharp front can be regarded as the front of the surface Kuroshio current. In this paper, the front detected by this method is called the Kuroshio front. Large meandering features of the Kuroshio front and its small fluctuations associated with filaments and eddies can be detected well in all images. These structures derived from Fig. 3 are superimposed on the bottom topography in Fig. 4. Hatched shading in Fig. 4 indicates the area where a cyclonic circulation is identified as a cold water pool.

1) On May 20 (Fig. 4a), a crest of the Kuroshio-front meander is located at 128.86°E, 30.34°N. A cyclonic circulation pulling warm water filaments exists in the upstream side of the crest of the Kuroshio-front meander.

2) On May 27 (Fig. 4b), the crest of the meander moves northeastward to the approximate location of 129.47°E, 30.55°N, together with the cyclonic circulation.

3) On June 6 (Fig. 4c), the crest of the Kuroshio front moves eastward

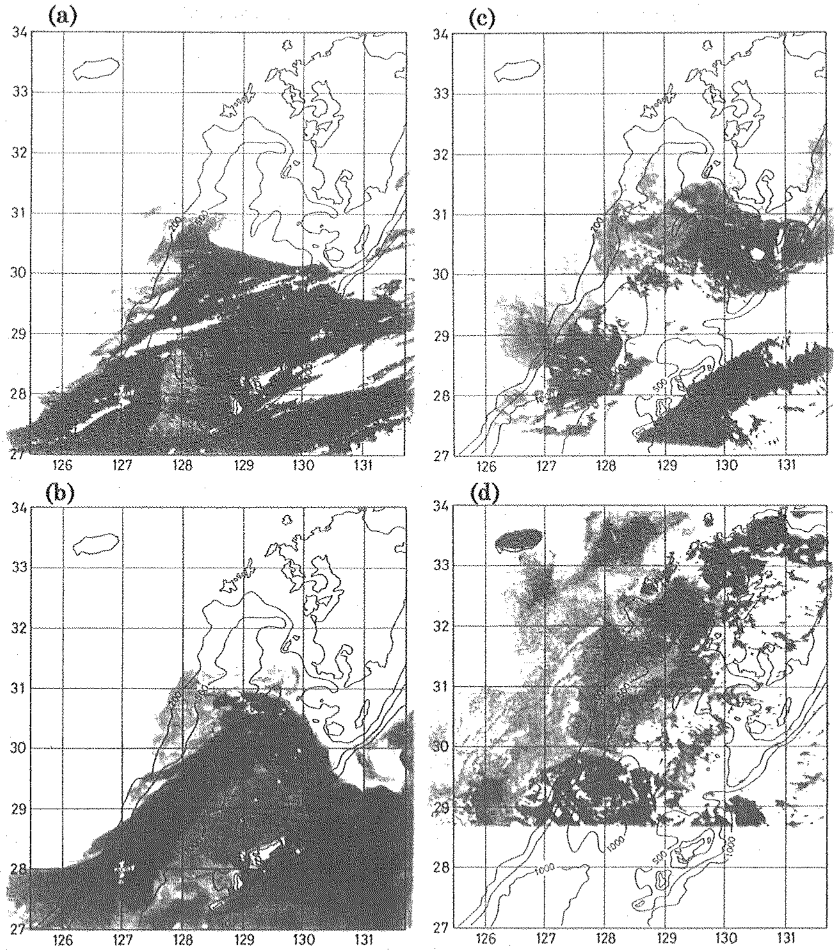

Fig. 3. Successive satellite IR images received at Kagoshima University on (a) May 20 (at 0642 JST), (b) May 27 (0217), (c) June 6 (0208), and (d) June 17 (1451), 1997.

holding the northernmost position. On the other hand, the cyclonic circulation moves northeastward along the Kuroshio front and located just at the mouth of the trough southwest of Kyushu. At this stage, the cyclonic circulation seems to be trapped at the mouth of the trough and have the structure of the cyclonic eddy.

4) On June 17 (Fig. 4d), the cyclonic eddy is detached from the Kuroshio front and moves northward along the trough. On the other hand, the Kuroshio

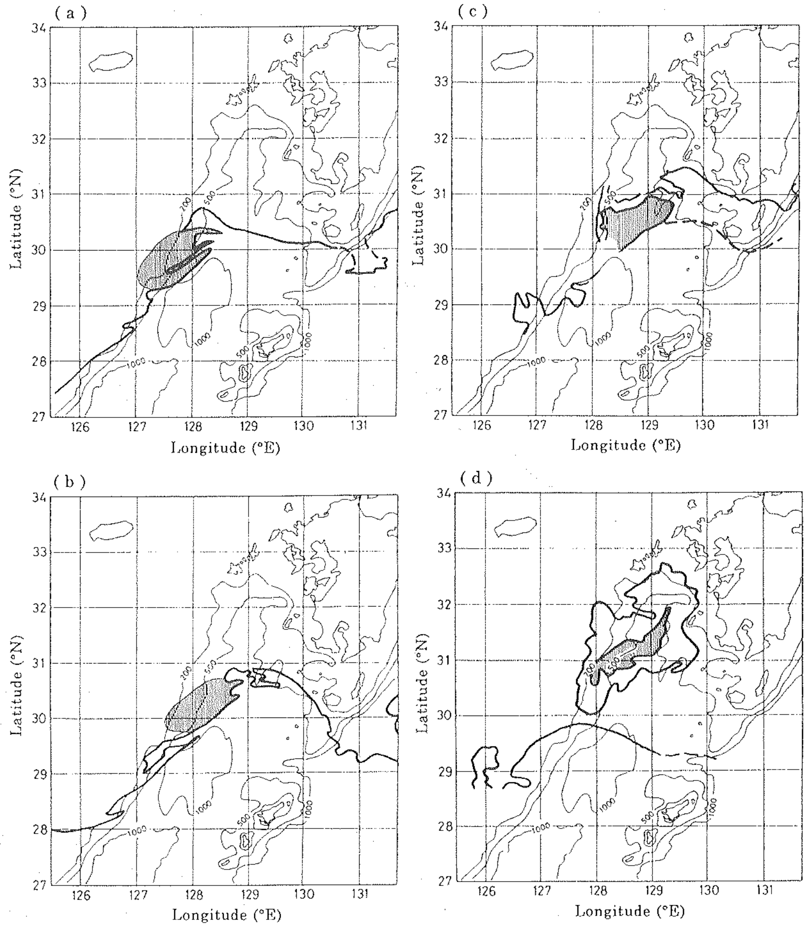

Fig. 4. Evolutions of the Kuroshio meander and the cyclonic eddy deduced from the satellite IR images between May 20 and June 17, 1997. (a) May 20 (at 0642 JST), (b) May 27 (0217), (c) June 6 (0208), (d) June 17 (1451). Hatched shading indicates the location of the cyclonic eddy. Bottom topography based on the TerrainBase Global Land and Ocean Depth is improved by observed data.

front moves southward significantly, and a new crest of the Kuroshio-front meander is formed in the upstream side of the Kuroshio near the continental shelf break. The cyclonic eddy pulls much warm water of the Kuroshio along its perimeter, and the warm water pools at the head of the trough.

Figure 5 summarizes migrations of both the Kuroshio front and the cyclonic eddy. The cyclonic circulation propagates northeastward along the Kuroshio front with an approximate speed of 7.8 cm/s between May 20 and May 27, and

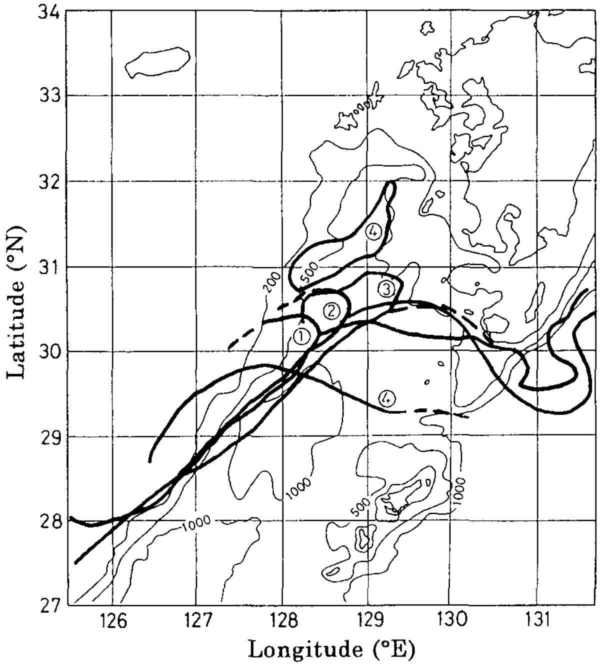

Fig. 5. Superimposition of positions of the Kuroshio meander and the cyclonic eddy between May 20 and June 17, 1997. Bottom topography is the same as in Fig. 4. Numbers in figure represent stages on May 20, May 27, June 6 and June 17 in turn.

also with an approximate speed of 7.5 cm/s between May 27 and June 6. After the cyclonic eddy is detached from the Kuroshio front, the eddy moves northward with an approximate speed of 8.1 cm/s along 129°E while the Kuroshio front moves southward with an approximate speed of 10.9 cm/s along 129°E.

4. Hydrographic and current observations

The hydrographic and current observations were carried out along lines A, B, C, and D during June 6-10 1997 (JST), and along line E during June 17-18 1997. Satellite images of sea surface temperature were fortunately obtained at both periods. Figure 6 shows a temperature distribution at the 200-m depth, which is a composite drawing of all data during June 6-18. It should be mentioned that Fig. 6 primarily shows the temperature distribution on June 6-10 except for the region adjacent to line E. Open circles in Fig.6 indicates the climatological annual mean position of the Kuroshio axis detected by the temperature indicator of 17.2°C at the 200-m depth in the Yamashiro et al. (1993). The cyclonic eddy

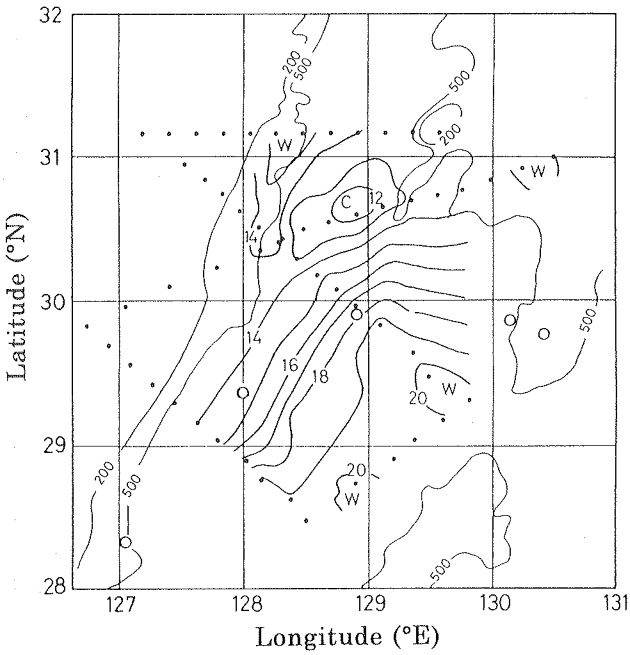

Fig. 6. Horizontal distribution of temperature at 200-m depth. Dots indicate observation points. Open circles indicate climatological annual mean positions of the Kuroshio axis quoted from Table 2 in Yamashiro et al. (1993). Bottom topography is the same as in Fig. 4.

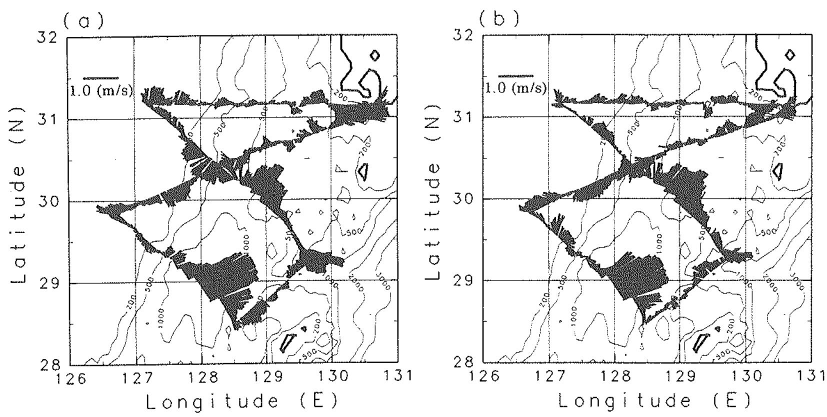

Fig. 7. Horizontal distributions of ADCP velocity at (a) 5-m depth and (b) 50-m depth. Sticks are drawn with every 5-minute interval. Bottom topography is the same as in Fig. 1.

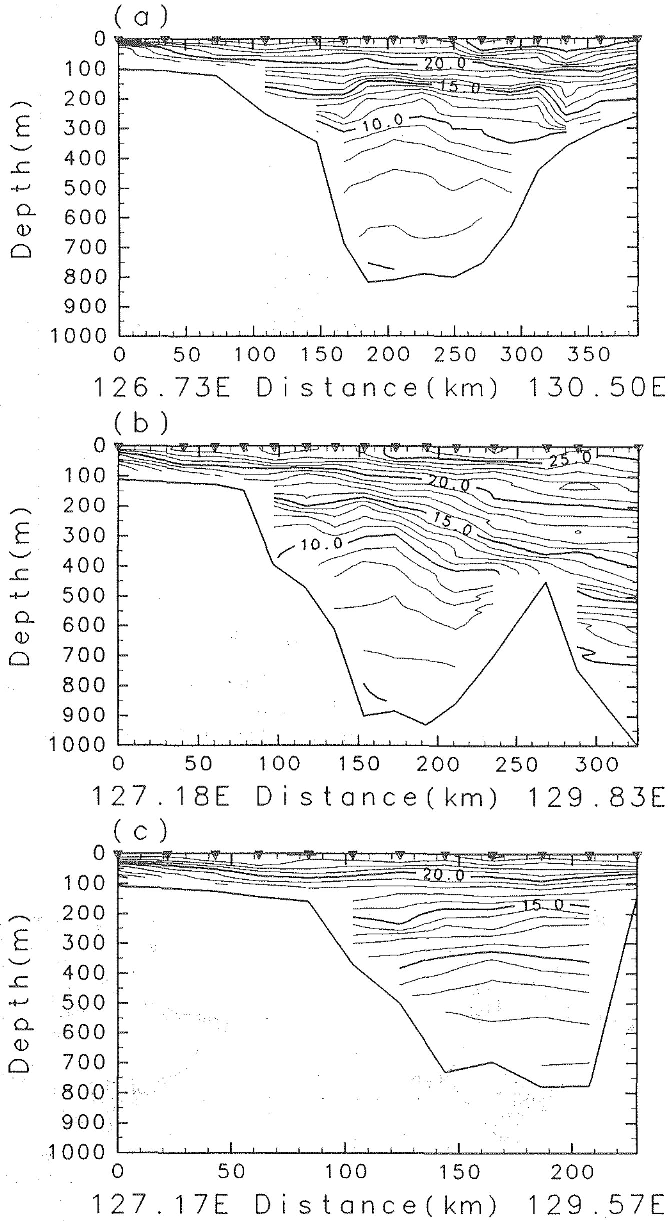

Fig. 8. Cross-sections of temperature along (a) line A, (b) line D, and (c) line E. Contour interval is 1.0°C.

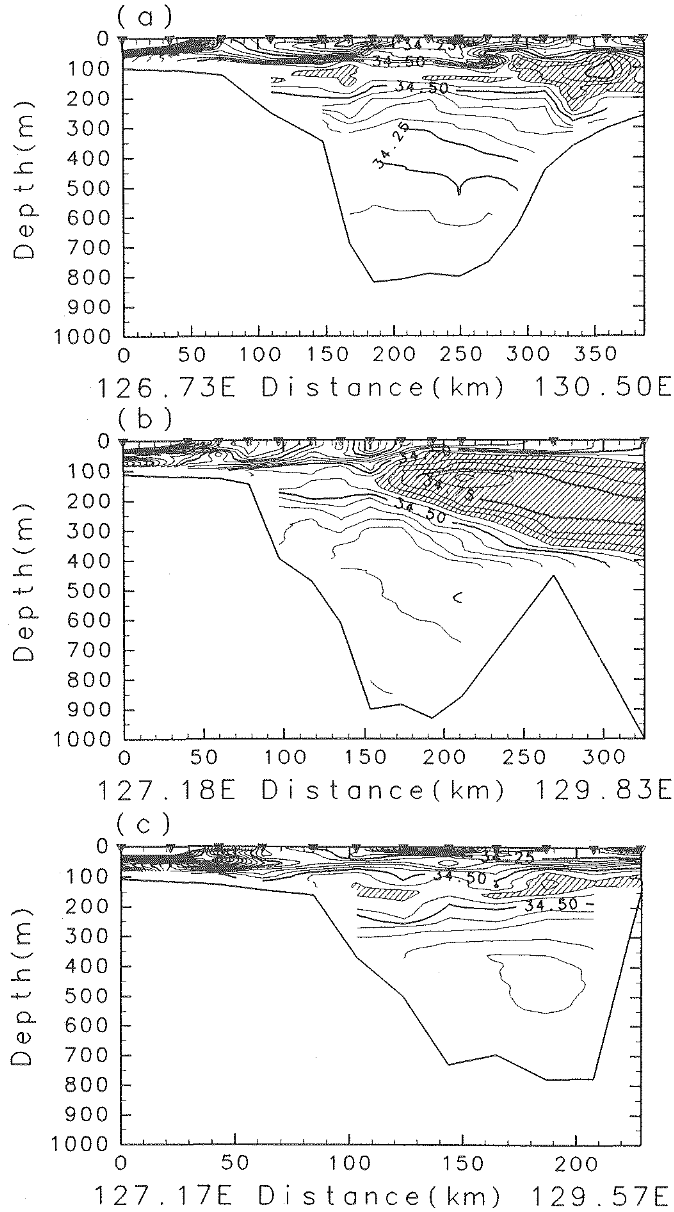

Fig. 9. Cross-sections of salinity along (a) line A, (b) line D, and (c) line E. Contour interval is 0.005 psu. Hatched shading indicates higher salinity water than 34.60 psu.

exists just at the mouth of the trough southwest of Kyushu. The location of the eddy exactly corresponds to that detected by the satellite image on June 6 (Fig. 4c). The position of the Kuroshio axis on 128.9°E, using the temperature indicator of 17.2°C at the 200-m depth, almost corresponds to the mean position of the Kuroshio axis.

Horizontal distributions of ADCP velocity at 5-m depth and 50-m depth are shown in Fig. 7a and 7b, respectively. Both velocity fields show centers of the cyclonic eddy at 128.77°E, 30.57°N on line A, and at 128.55°E, 30.25°N on line D. The location of the center on line A almost corresponds to that of the cyclonic eddy in the temperature distribution at 200-m depth (Fig. 6) and also in the satellite image on June 6 (Fig. 4c). However, velocity vectors on line E do not indicate a cyclonic eddy. The satellite image on June 17 indicates that line E crosses the cyclonic eddy in a narrow area north of its center. This may result in the cyclonic sense of circulation being weak near the surface north of its center. The Kuroshio axis in ADCP velocity field geographically corresponds to that in the temperature distribution at 200-m depth. The velocity vectors showing the southwestward flow of the cyclonic eddy between 200-m and 500-m isobaths on line D are rotating at 5-m depth while not 50-m depth. The rotating feature of the velocity fields is thought to be due to the internal tide.

As shown in Fig. 6, line A approximately crosses the center of the cyclonic eddy. The vertical temperature distribution on line A (Fig. 8a) shows a typical temperature pattern of the cyclonic eddy. The pattern is apparent from 200-m to 600-m depths between both side-walls of the trough. This indicates that the cyclonic eddy is trapped in the trough southwest of Kyushu. Line D, as shown in Fig. 6, crosses both the southwestern corner of the cyclonic eddy and the Kuroshio. The temperature distribution on line D (Fig. 8b) shows that the temperature pattern due to the Kuroshio is remarkable on the southeastern side of the cross-section while the temperature pattern with a character of the return flow is apparent from 200-m to 600-m depths near the western side-wall of the trough. The temperature distribution on line E (Fig. 8c) does not show the apparent structure of the cyclonic eddy in the shallower layer than 300-m depth while shows the pattern in the deeper layer than 300-m depth. This corresponds to the fact that ADCP surface velocity on line E does not indicate the cyclonic sense of circulation. The temperature distributions on line A, line D and line E indicate that the structure of the cyclonic eddy is remarkable in the deeper layer than the approximate 200-m depth.

The vertical salinity distribution on line A (Fig. 9a) shows that the higher salinity water than 34.60 psu at the subsurface is divided into two parts near the

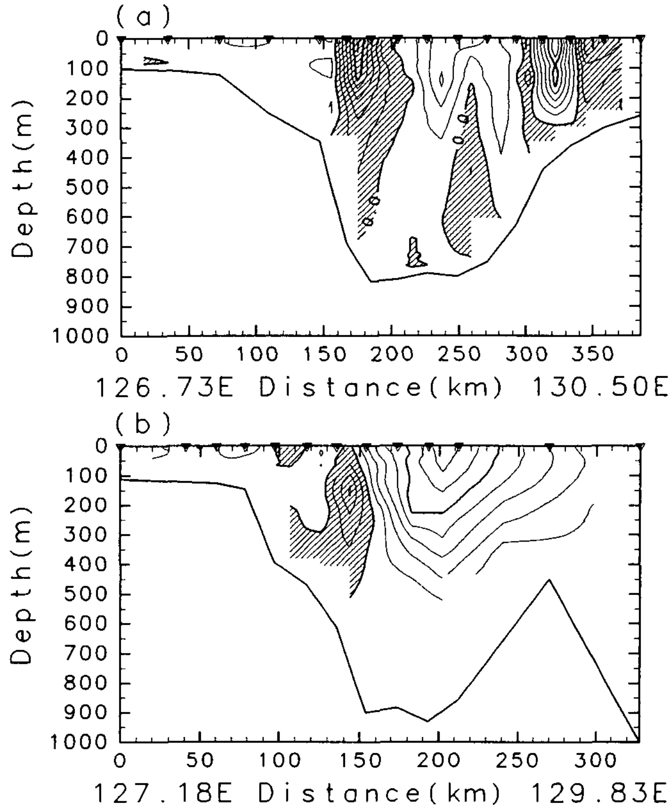

Fig. 10. Cross-sections of geostrophic velocity shear referring to the bottom along (a) line A and (b) line D. Contour interval is 0.1 m/s. Hatched shading indicates negative velocity. Velocity convention: the flow direction of the Kuroshio is positive.

eastern and western shelf breaks. The salinity of the high-salinity water near the eastern shelf break is higher than that near the western shelf break. This indicates that the cyclonic eddy pulls the Kuroshio saline and warm subsurface water along its perimeter. The same feature as line A is found on line E (Fig. 9c) while not on line D (Fig. 9b). The fact that the high-salinity water is not found near the western side-wall of the trough on line D indicates that the cyclonic eddy pulls the Kuroshio saline subsurface water from its eastern side.

It is possible to derive distributions of absolute geostrophic velocity from density and ADCP velocity. As mentioned in the former part of this section, ADCP velocity near the continental shelf break, however, includes noises mainly due to the internal tide. The absolute geostrophic velocity is not calculated in this paper, because it is difficult to remove noises. The geostrophic velocity shears referring to the bottom on line A and line D are shown in Fig. 10a and Fig. 10b, respectively. The return flow due to the cyclonic eddy on line D (hatched shading in Fig. 10b) has almost the same geostrophic shear as the in-shore edge of the Kuroshio, except for the shallower layer than 150-m depth. The geostrophic shear of the cyclonic eddy on line D is also similar to that on line A under 150-m depth, although the southward flow due to the cyclonic eddy on line A has a little strong shear. The geostrophic velocity shears at the shallower layer than 150-m depth are different between the in-shore edge of the Kuroshio and the cyclonic eddy, and also in some places of the cyclonic eddy. The difference of the geostrophic shears in the shallow layer may be ascribed to the complicated spread of the Kuroshio subsurface warm water intruding along the perimeter of the cyclonic eddy.

5. Summary and discussion

A cyclonic eddy was observed in the trough southwest of Kyushu on June 1997 by the hydrographic survey and successive satellite images of sea surface temperature. The evolution of the cyclonic eddy was first examined by successive satellite images. A cyclonic circulation initially induced at the continental shelf break region propagated northeastward along the Kuroshio front with an approximate speed of 7-8 cm/s (May 20 and 27), and then it was trapped at the mouth of the trough southwest of Kyushu (June 6). After the cyclonic circulation was detached from the main current, the cyclonic eddy moved northward along the trough, pulling the Kuroshio subsurface warm water along its perimeter (June 17). A speed of the northward migration of the cyclonic eddy was approximately 8 cm/s. At the same time, the crest of the Kuroshio-front meander south of the trough shifted southward significantly with an approximate speed of 11 cm/s, and a new crest was formed in the upstream side of the Kuroshio near the continental shelf break (June 17). The vertical structure of the cyclonic eddy was examined by the hydrographic and current data during June 6-10 and 17-18. Before the detachment of the cyclonic eddy, the Kuroshio axis south of the mouth of the trough was located near its climatological annual mean position (June 6-10). The structure of the cyclonic eddy was more remarkable at the deep layer ($\geq$200m) than the shallow layer ($\leq$200 m).

Qiu et al. (1990) showed that the Kuroshio-front fluctuation with horizontal scales of 100 to 150 km and speeds of 20 to 25 cm/s is formed along the continental shelf break. Recently, using a spectral model with the realistic background state of the Kuroshio, James et al. (1997) showed that the generation mechanism of the fluctuations is the baroclinic-barotropic mixed type of instability of the Kuroshio. It is considered that the cyclonic circulation analyzed in this paper was formed at the continental shelf break region by this type of instability. The observed cyclonic circulation had an approximate horizontal scale of 120 km and a propagation speed of 7-8 cm/s. Although the horizontal scale is similar to that reported in Qiu et al. (1990), the speed is less than a half. The cyclonic circulation propagating eastward south of the trough was blocked by the ridge south of Kyushu, i.e. the eastern side-wall of the trough southwest of Kyushu, and then detached from the main current. The slow propagation of the cyclonic circulation may be caused by the blocking effect of the ridge south of Kyushu. Furthermore, it is considered that the blocking effect plays an important role to the detachment of the cyclonic eddy from the Kuroshio. The Kuroshio axis was located near its mean position before the detachment of the cyclonic eddy. This suggests that the detachment of the cyclonic eddy can often occur in this region, when the cyclonic circulation induced by the Kuroshio instability passes. The detached cyclonic eddy moved northward along the trough while the Kuroshio front moved southward significantly with almost the same speed as the eddy. This suggests that the interaction between the Kuroshio current and detached cyclonic eddy causes the Kuroshio meander with a large meridional amplitude.

Many previous studies reported that an anticyclonic warm eddy exists at the head of the trough west of Kyushu (Huh, 1982 ; Tawara and Fujiwara, 1985 ; Muneyama et al., 1984 ; Qiu et al., 1990 ; Hsueh et al., 1996). Yamagata and Kamachi (1989) proposed that the anticyclonic warm eddy in the trough is formed through the evolution of the cyclonic eddy initially induced by the Kuroshio instability. The satellite IR image on June 17 (Fig. 3d) showed that the Kuroshio subsurface warm water pooled north of the cyclonic eddy. This image may indicate the process that the cyclonic eddy evolves the anticyclonic eddy, pulling the surrounding Kuroshio subsurface warm water (see Fig. 1b and Fig. 5 in Yamagata and Kamachi (1989)).

In order to clarify the dynamics of the Kuroshio meander and shed-off eddies between the turning point of the Kuroshio and the Tokara Strait, it is necessary to examine the blocking effects of the bottom topography on the propagation of fluctuations initially induced along the continental shelf break. The convenient way to examine this effect is to use a numerical model, which has the resolution high enough to generate the instability, and to represent the realistic bottom topography.

Acknowledgments

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