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The Formation of Thick and Stable Warm Eddies inside the Large Meander of the Kuroshio South of Honshu, Japan

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Abstract : During the period from January 2000 to October 2001, the Kuroshio was flowing in a large meandering south of Honshu, Japan. However, the flow pattern was changeable both in time and space. Two warm eddies both having a long lifetime of about 200 days were observed inside the meandering Kuroshio path, which is usually occupied by a cold-water mass (Large Cold Water Mass). XBT observations conducted on board of the R/V Seisui-maru showed that these eddies had a thick structure of several hundreds meters. Such thick and stable warm eddies have scarcely been reported in the past, except for a report by MINAMI (1989). The evolution of the abnormal warm eddies were analyzed by using the Prompt Report of Oceanic Status in the Sea off Sagami Bay and near the Izu Islands, which is published weekly by the Service Division of the Marine Information Research Center, JHA. It was shown that both warm eddies were generated from a warm-water tongue extending westward from a kink in the Kuroshio off the Izu Peninsula.

Keywords : *warm eddy, Large Meander of the Kuroshio, kink of the Kuroshio path, warm-water tongue, Enshu-nada*

1. Introduction

The Kuroshio has two stable paths while flowing along the south of Honshu, Japan: a straight path and a large meander path (e.g. SHOJI 1972 and TAFT, 1972). Both of the flow patterns are stable and are maintained for several months to several years after being established. In the case of the meandering path, the Kuroshio flows around the Large Cold Water Mass generated off Kumano-nada and/or Enshu-nada (see Fig. 1 for the place names cited in this paper). The usual evolution of a large meander of the Kuroshio is as follows: the meander is generated abruptly to the southeast of the Kii Peninsula (e.g. SHOJI, 1972, KAWABE, 1980, FUJITA *et al.*, 1998 and NAGATA *et al.*, 1999a), and stays for a considerable time as mentioned above. In the last stage, the eastern edge of the meander (or the eastern edge of the cold-water mass) shifts eastward, and after it passes the Izu-Mariana Ridge, the meander decays gradually (e.g. SHOJI, 1972). Other flow types of the path pattern have been discussed and defined by various investigators (e.g., KOBAYASHI *et al.*, 1986, KASAI *et al.*, 1993), however, except for the two basic patterns, the other patterns have a relatively short lifetime.

The Kuroshio took the large meander pattern in January 1999, and the meandering path was maintained until the end of October 2001, but the flow pattern was very changeable in time and space. The patterns, which have been thought to be transient, were often sustained for several months. Warm eddies were often generated inside of Large Cold Water Mass off Enshu-nada. Two of them had a stable nature, and persisted for about 200 days.

Intrusions of the warm Kuroshio Water into Large Cold Water Mass region have often been reported by various investigators (e.g. TAKEUCHI, 1989, MINAMI, 1989, KIMURA and SUGIMOTO, 1990, KASAI *et al.*, 1993, and SEKINE and OKUBO, 2000). However, except for the warm eddy reported off Enshu-nada by

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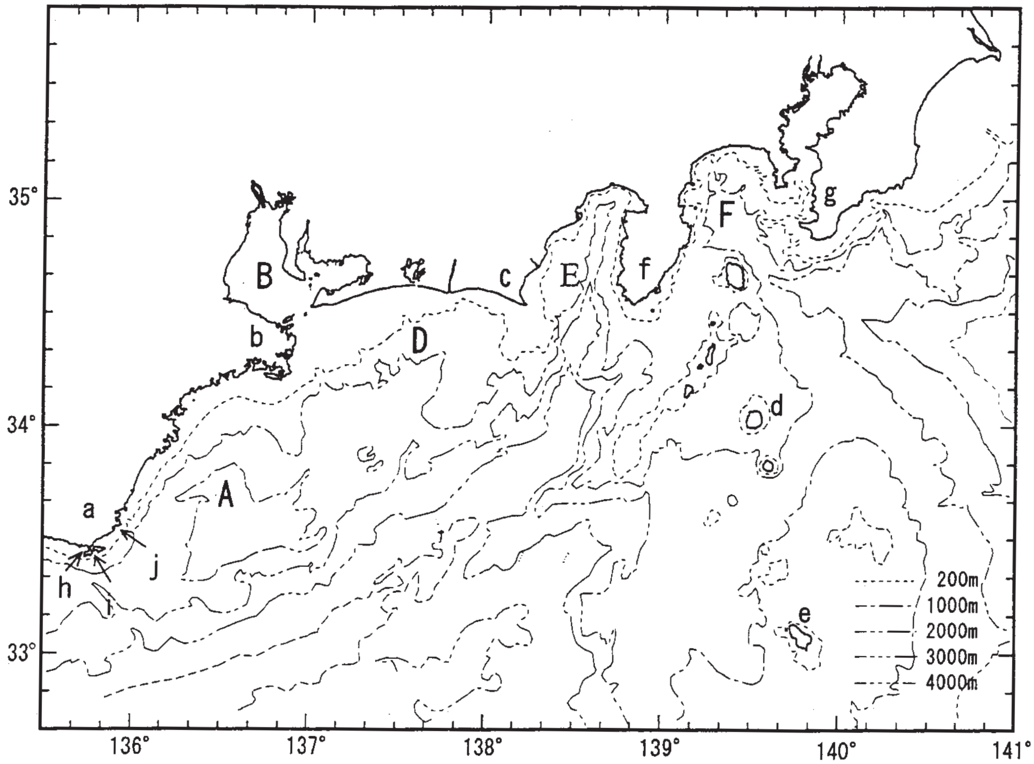


Fig. 1 Names of the locations referred to in this paper: A is the Kumano-nada, B Ise Bay, D the Enshu-nada, E Suruga Bay, F Sagami Bay, and a is the Kii Peninsula (Cape Shionomisaki is the tip of the Kii Peninsula), b Cape Daio, c Cape Omaezaki, d Miyake Island, e Hachijo Island, f the Izu Peninsula, g the Boso Peninsula, h Kushimoto, i Cape Shionomisaki, and j Uragami. Depth contours are also given for several depths.

MINAMI (1989) in 1984, these warm eddies have been shown to have a short lifetime of less than a few weeks, and structurally they were confined to the surface layer shallower than 100 m depth (TAKEUCHI, 1989, and SEKINE and OKUBO, 2000). The warm eddy found by MINAMI (1989) had a thick structure, and the eddy could be identified at least up to the depth of 400 m.

In order to evaluate the vertical structure of the two warm eddies found in 2000 and 2001, we carried out 4 surveys using R/V Seisui-maru of the Mie University to detail the temperature structure of the stable warm eddies. Also, we analyzed the time evolution of the warm eddies by using the Prompt Report of Oceanic Status in the Sea off Sagami Bay and near the Izu Islands, published weekly by the Service Division of the Marine Information Research Center, JHA.

2. Data and materials used

The Service Division of the Marine Information Research Center, JHA publishes weekly the Prompt Report of Oceanic Status in the Sea off Sagami Bay and near the Izu Islands (we shall to refer to this report as the Prompt Report, hereafter). The Prompt Report is compiled by using oceanic data collected by the Hydrographic Department of Japan Coast Guard, and by analyzing the NOAA satellite infrared image, TOPEX/POSEIDON sea level distribution which is provided on a near-real-time base by the Colorado Center for Astrodynamics Research of Colorado University (MAEKAWA *et al.*, 2001), sea level data along the coast, and so on. The Prompt Report

Table 1 List of the warm eddies observed in the period from January 2000 to December 2001. Time of generation indicates the edited date of the Prompt Report in which the isolated warm eddy was first found. Time of disappearance indicates that the warm eddy disappeared. Location of initial path kink is the place where the kink of the current path of the Kuroshio occurred prior to the generation of the warm eddy. See the text for the definition of reinforcement.

No.	time of generation	time of disappearance	period of continuation	initial location of the path kink	reinforcement
I	Feb. 9, 2000	Feb. 17, 2000	9 days	138°E	
II	Mar. 23, 2000	Sep. 21, 2000	183 days	south of Izu Peninsula(139°E)	Jun. 1, 2000
III	Nov. 23, 2000	Dec. 21, 2000	29 days	east of Kii Peninsula(137°E)	
IV	Jan. 18. 2001	Aug. 23, 2001	218 days	south of Izu Peninsula(139°E)	Apr. 19 and Jun. 7, 2001
V	Sep. 20, 2001	Oct. 25, 2001	15～36 days	south of Izu Peninsula(139°E)	
VI	Dec. 26, 2001	Jan. 17, 2002	23 days	138～139°E	

Table 2 XBT observations conducted on board R/V Seisui-maru. The positions of XBT observations are shown. The name of each observation run is shown in the uppermost row, and the date of the observation is shown in the second row. The numbers in the first column are the station numbers.

	XBT 1	XBT 2	XBT 3	XBT 4	XBT 5	XBT 6
date / Sta. #	Aug. 21, 2000	Aug. 30, 2000	Nov. 09, 2001	Jan. 12, 2001	Jan. 30, 2001	Mar. 05–06, 2001
1	34–15.1N 137–00.09E	33–08.35N 136–02.13E	32–59.84N 137–01.01E	34–20.04N 137–19.96E	34–20.02N 137–07.83E	33–34.52N 136–01.48E
2	34–05.00N 137–00.10E	33–14.99N 136–15.38E	33–10.02N 136–59.91E	34–15.07N 137–29.93E	34–10.00N 137–14.26E	33–34.97N 136–10.00E
3	33–55.02N 137–00.01E	33–24.00N 136–31.78E	33–19.93N 137–00.02E	34–10.01N 137–40.01E	33–59.99N 137–20.00E	33–35.13N 136–19.99E
4	33–45.02N 136–59.99E	33–31.94N 136–45.62E	33–29.92N 136–59.98E	34–05.05N 137–50.05E	34–00.01N 137–30.06E	33–35.06N 136–30.00E
5	33–34.99N 137–00.04E	33–41.03N 137–00.57E	33–39.97N 136–59.92E	34–00.19N 138–00.06E	34–00.02N 137–40.03E	33–35.06N 136–40.00E
6	33–25.49N 137–00.18E	33–45.92N 137–10.66E	33–50.40N 137–00.17E	34–00.02N 138–10.04E	33–00.01N 137–50.04E	33–35.11N 136–49.97E
7		33–50.40N 137–19.99E	33–59.97N 137–00.47E	33–59.97N 138–20.08E	33–00.00N 138–00.04E	33–35.00N 137–00.00E
8		33–56.63N 137–30.31E	34–10.00N 136–59.83E	34–00.06N 138–30.25E	34–00.00N 138–10.04E	33–45.02N 137–00.16E
9		34–00.50N 137–40.30E			34–00.05N 138–20.02E	33–55.20N 137–00.37E
10		34–04.50N 137–50.00E			34–04.21N 138–30.00E	34–05.18N 136–59.90E
11		34–09.75N 138–00.21E				34–15.25N 136–59.97E

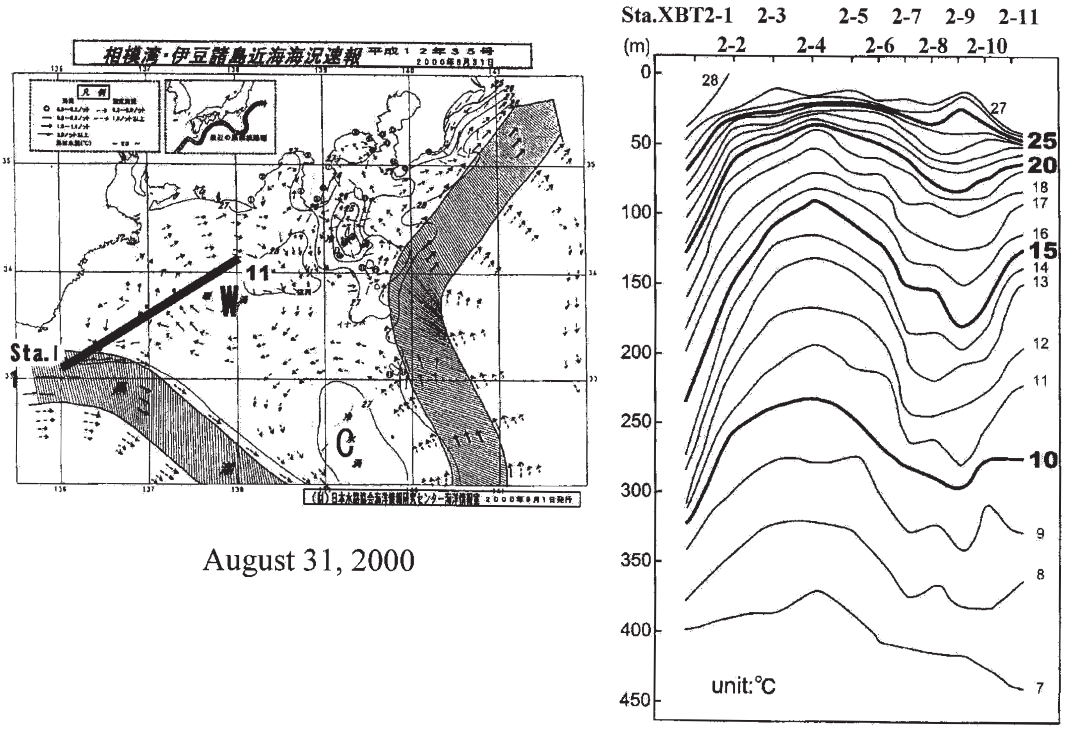


Fig. 2 Temperature cross-section along the observation line XBT2 taken on August 30, 2000 (right figure). Isotherms are given at intervals of 1 ℃, and the station names (see Table 1 for their positions) are given above the upper margin. The position of the observation line is given in the left figure together with the Prompt Report No. 35, 2000 edited on August 31. W and C indicate the warm eddy and the cold eddy (cold-water mass), respectively.

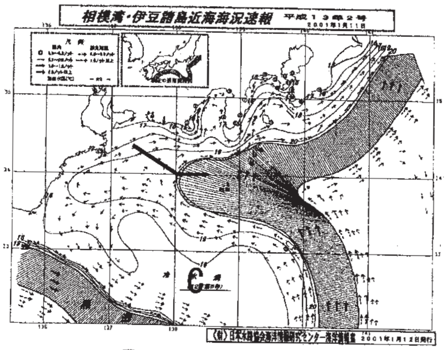
was used to monitor the warm eddies in order to determine the navigation route for the R/V Seisui-maru.

The Prompt Report was also used to determine the duration of the warm eddies inside the Kuroshio Large Meander off Enshu-nada and off Kumano-nada, and their time evolution. The warm eddies found in the period from January 2000 to December 2001 are listed in Table 1.

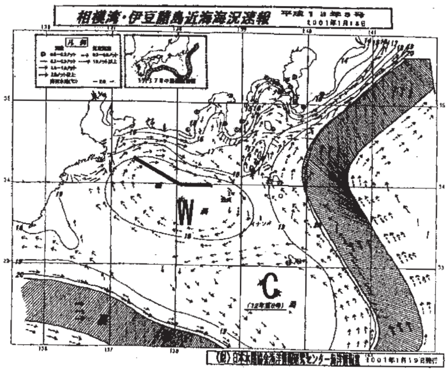
The R/V Seisui-maru of the Mie University was sent a total of 6 times to the area under consideration on ways to or back from the scheduled observation sites, and made XBT observations as shown in Table 2. Among these cruises, the ship course run outside of the warm eddy in the first cruise, XBT1, and the observation XBT3 was conducted at a time when no conspicuous warm eddy occurred inside the Kuroshio Large Meander. So, the observational results of these cruises will not be discussed in this paper.

3. Occurrence of the warm eddy inside the Kuroshio Large Meander in 2000-2001

Warm eddy was observed 6 times during the period from January 2000 to December 2001 as listed in Table 1. Among these eddies, Warm Eddy III (Roman numerals correspond to those in Table 1), and Warm Eddy VI are not so conspicuous and the period of continuation might be overestimated. Warm Eddy I was relatively small but conspicuous. This eddy traveled quickly around the Large Cold Water Mass and disappeared after being absorbed into the Kuroshio just off Cape Shionomisaki. Judging from this nature, the eddy would have had a relatively shallow structure and been carried counter-clockwise around the Large Cold Water Mass. We tried to find a signature of the



January 11, 2001



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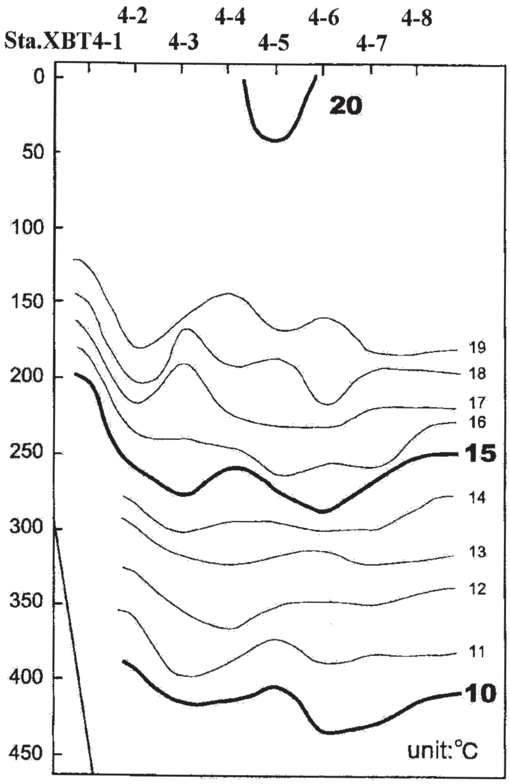

Fig. 3 The same as in fig.2, but for together with the Prompt Report No. 2 edited on January 11 (upper left figure) and No. 3 edited on January 18 (lower left figure).

warm eddies in the TOPEX/POSEIDON sea level distribution which is provided on a near-real-time base by the Colorado Center (MAEKAWA *et al.*, 2001), but no signature was found corresponding to these warm eddies. These warm eddies are considered to have had a similar nature to those reported by various investigators (TAKEUCHI, 1989, KIMURA and SUGIMOTO, 1990, KASAI *et al.*, 1993, and SEKINE and OKUBO, 2000).

In general, a kink in the current path of the Kuroshio occurred before the generation of the warm eddies. The warm-water tongue, which extended from the kink of the current path, penetrated into the cold-water region. The initial position of the kink of the Kuroshio path is shown for each warm eddy in Table 1. The warm eddies with a short lifetime were generated from kinks occurring just to the east of Cape Shionomisaki (the tip of the Kii Peninsula) or at the eastward flowing outer margin of the large meander. On the other hand warm eddies with a long lifetime, *i.e.*, Warm Eddy II and Warm Eddy IV were initiated from kinks just off the Izu Peninsula. The warm eddy with a thick structure reported by MINAMI (1989) was generated just off the Izu Peninsula. Warm Eddy V was also generated at the same position, but its period of continuation was relatively short. This might be attributed to the change of the flow pattern from the meandering path to the straight path, which occurred in October 2001.

4. The vertical structure of the stable warm eddies.

4-1. Temperature cross-section across Warm Eddy II

XBT observations of Warm Eddy II were conducted on August 30, 2000 (XBT2: see Table

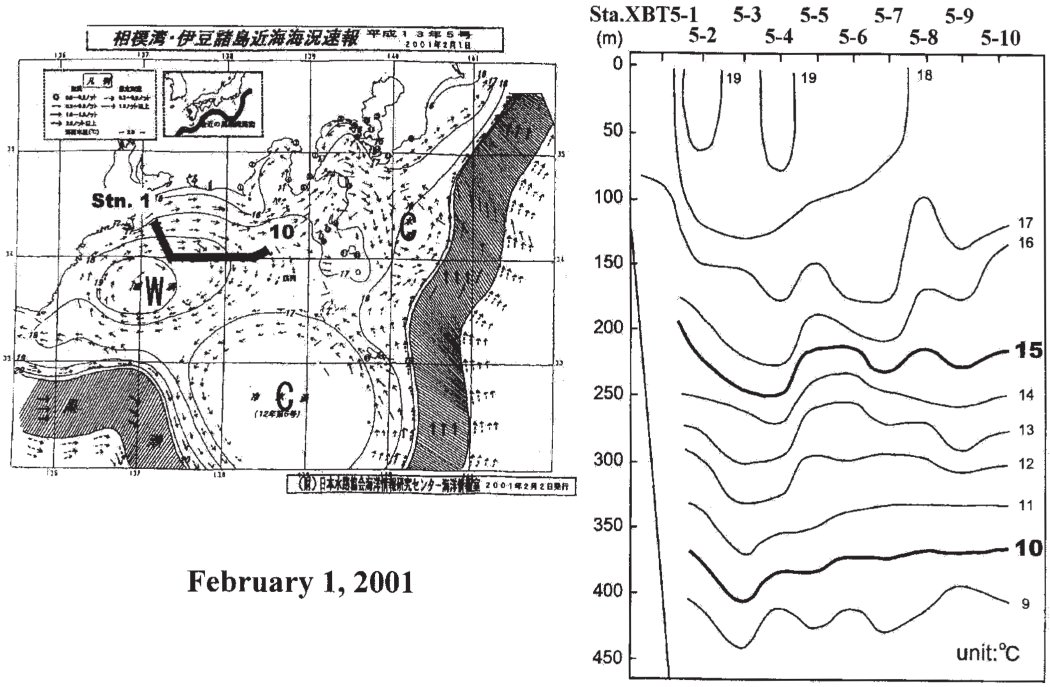

Fig. 4 The same as in Fig. 2 but for XBT5 together with Prompt Report No. 5, 2001 edited on February 1, 2001.

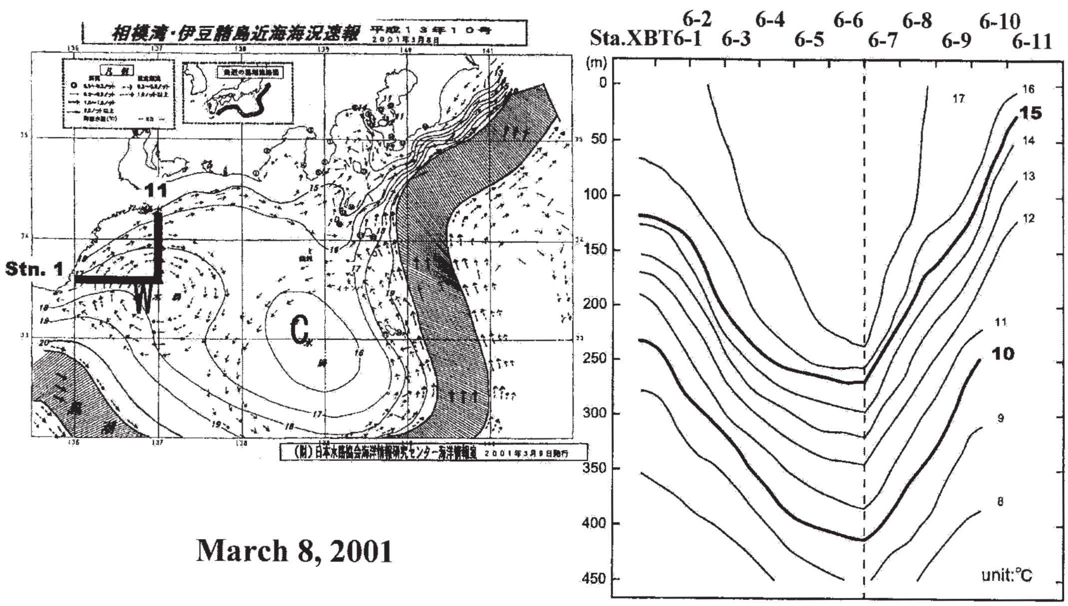

Fig. 5 The same as in Fig. 2 but for XBT6 together with Prompt Report No. 10, 2001 edited on March 8, 2001.

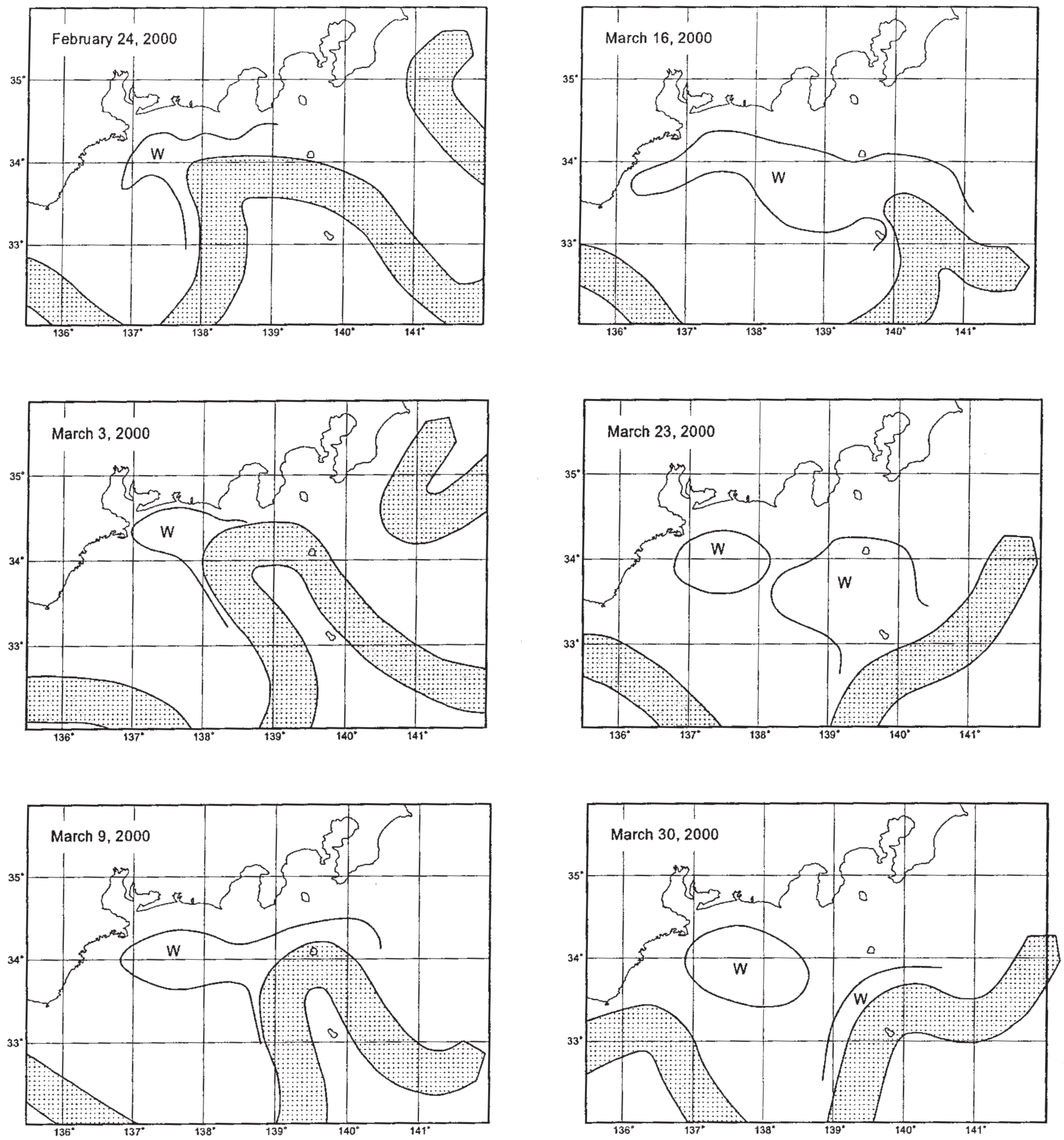

Fig. 6 Evolution of the oceanic state for the generation stage of Warm Eddy II. The current path of the Kuroshio is indicated with a hatched band, and the edges of the relatively warm water areas are shown with bold line. The distributions are derived from the Prompt Reports edited on the date shown in each figure. W indicates the warm eddy or warm area.

2). The observation line of XBT2 is shown with a bold line on the Prompt Report No. 35 edited on August 31 (left figure of Fig. 2: the Prompt Report is usually issued one or two days after its edition, and we show the date of edition here), and the temperature cross-section along the line is shown in the right figure of Fig. 2. The warm eddy is clearly seen off Enshu-nada at the time of the observation.

The sharp temperature gradient between Sta. XBT2-1 and Sta. XBT2-3 corresponds to the current zone of the Kuroshio. Warm Eddy

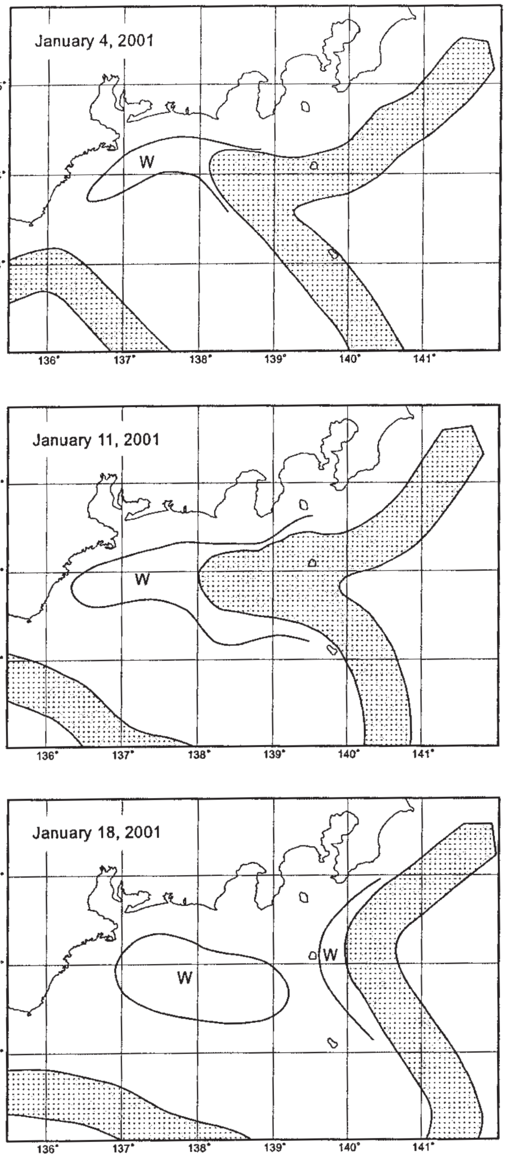

Fig. 7 The same as in Fig. 6 but for Warm Eddy IV.

II is seen between Sta. XBT2-6 and Sta. XBT2-11 as a depression of isotherms below 23 ℃. The depression is recognized to a depth of 300 m or more. Though the observation line may not pass through the center of Warm Eddy II (left figure of Fig. 2), the observed results indicate that Warm Eddy II had a considerably deep structure.

4-2. Temperature structure of Warm Eddy IV

We found a conspicuous kink of the Kuroshio path off the Izu Peninsula on the Prompt Report edited on January 11, 2001 (upper left figure of Fig. 3). The kinked Kuroshio path can be seen from off Sagami Bay to Suruga Bay, and the warm water tongue extended westward from the tip of the kink passing off Ise Bay. We anticipated the generation of a new warm eddy, and sent the R/V Seisui-maru on January 12, 2001 to this area. The Prompt Report edited on January 18 (lower left figure of Fig. 3) indicated the formation of Eddy IV. The position of the observation XBT4 is shown on both of the Prompt Report figures (Fig.3). The temperature cross-section along the line is shown in the right figure of Fig. 3. The line runs through the central part of the warm eddy, and the temperature structure is monotonous except for Sta. XBT4-1, which was located at the edge of the warm eddy. It should be noted that the temperature at 200 m depth is between 17 and 18 ℃. The 15–16 ℃ isotherms at 200 m depth are used as indicators of the position of the current axis of the Kuroshio in the sea to the south of Japan. This high temperature indicates that the Kuroshio Water south of the axis had been brought into Warm Eddy IV.

The second observation (XBT5) of Warm Eddy IV was conducted on January 30. The position of the observation line is shown on the Prompt Report No. 5 edited on February 1, 2001 (left figure of Fig. 4), and the obtained temperature cross-section is shown in the right figure of Fig. 4. Though the observation line appears not to run across the central part of Warm Eddy IV, the temperature at 200 m depth exceeds 15 ℃ at all stations except at Sta. XBT5-1, indicating that the water near the current axis of the Kuroshio was kept inside of the warm eddy.

The third observation (XBT6) of Warm Eddy IV was conducted on March 5–6, 2001. The temperature cross-section is shown in the right figure of Fig. 5, and the observation line is shown in the left figure of Fig. 5 together with oceanic status on March 8. Sta. XBT6-7 appears to be located near to the center of Warm Eddy IV. The stations from Sta. XBT6-1 through Sta. XBT6-7 are aligned from west to east, and the

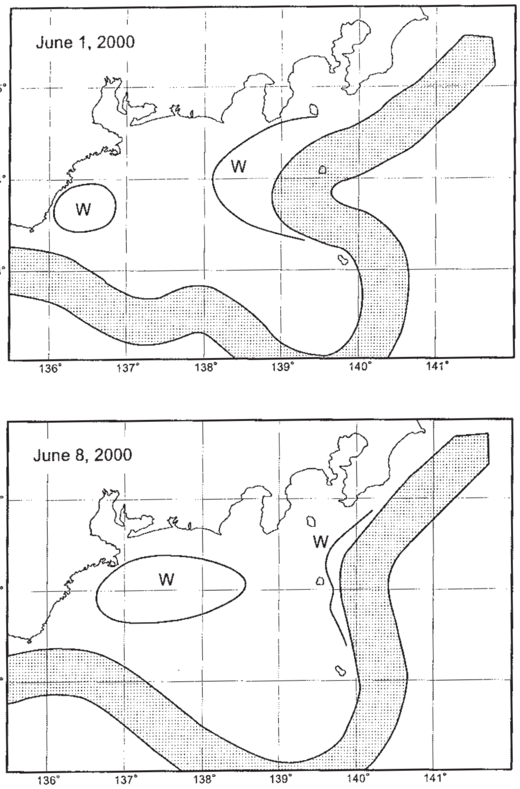

Fig. 8 The same as in Fig. 6 but for the reinforcement stage of Warm Eddy II on June 8, 2000.

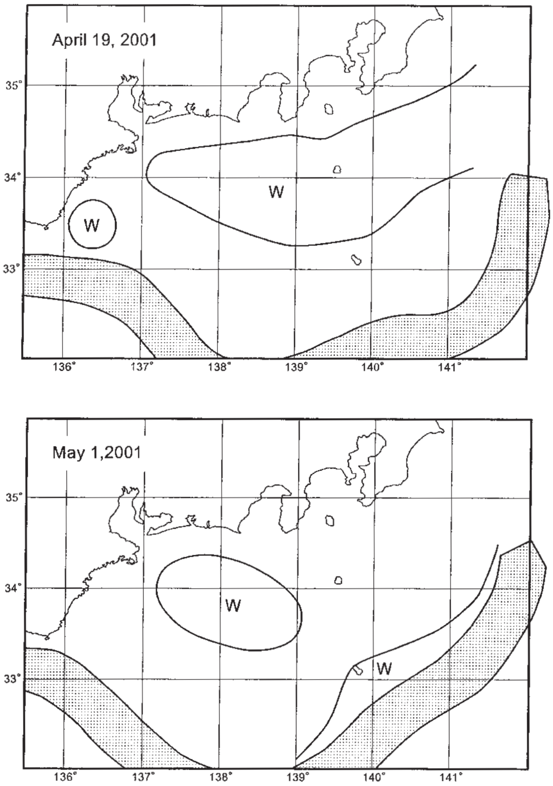

Fig. 9 The same as in Fig. 6 but for the reinforcement stage of Warm Eddy IV on May 1, 2001.

stations from Sta. XBT6-7 to Sta. XBT6-11 aligned from south to north. Judging from the temperature distribution, Sta. XBT6-1 and Sta. XBT6-11 were taken near the edge of Warm Eddy IV. The temperature at 200 m depth at Sta. XBT6-7 exceeds 17 ℃. Though the size of the eddy was significantly decreased by this time, the water at the center of the eddy maintained a high temperature corresponding to the current zone of the Kuroshio.

4-3. Thick structure of the stable warm eddies

As discussed above, both of the stable warm eddies had a thickness of several hundreds meters, and the temperature of the water inside the eddies was very high, and the water inside the eddies is thought to have originated from the Kuroshio current region. Thus, these eddies are sustainable for relatively long period. We shall discuss the generation procedure of these eddies by referring to the Prompt Reports in the next section.

5. Evolution of the oceanic status in the generation stage of the thick and stable warm eddies

The current zone of the Kuroshio is referred to from the Prompt Reports, and the evolution from the generation stage of Warm Eddy II is shown in Fig. 6. The current zone is shown as a hatched zone, and the relatively high temperature area inside the large meander of the Kuroshio is shown with bold lines. On February 24, a cold-water mass was seen to the southeast of the Kii Peninsula, and another cold-water mass to the southeast of the Boso Peninsula. The Kuroshio path shifted northward between the two cold-water masses, and a wide warm water region reached near to the coast. A kink of the Kuroshio path was seen off

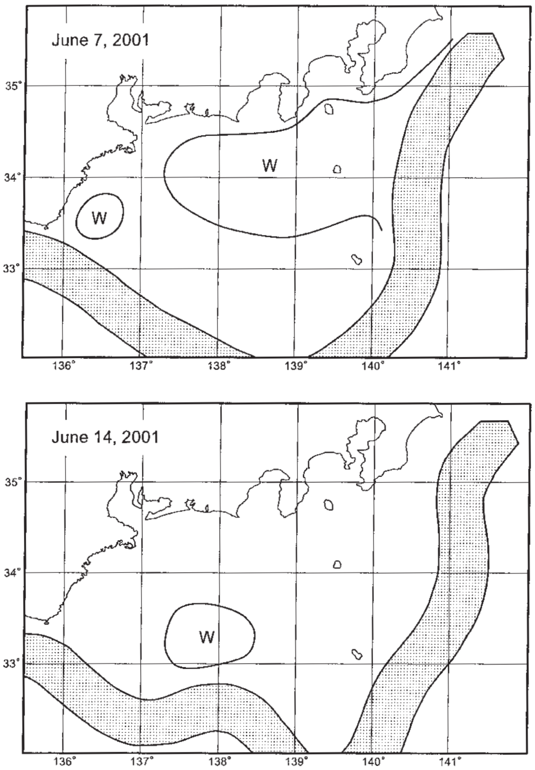

Fig. 10 The same as in Fig. 6 except for the reinforcement stage of Warm Eddy IV on June 14, 2001.

Cape Omaezaki (138° 10′ E), and warm water extended westward to off Ise Bay. A western cold-water mass developed, and its eastern margin shifted to the east from February 24 to March 9. While, the warm water tongue remained almost at the same position, and its east-west length increased gradually. Then, the main path of the Kuroshio retreated southward by March 16. The warm-water tongue widely extended in an east-west direction is seen from the tip of the retreated Kuroshio zone to off Kumano-nada on March 16. On March 23, an isolated warm eddy, Warm Eddy II, was generated off Enshu-nada from the warm-water tongue.

The evolution of the oceanic condition for the generation stage of Warm Eddy IV is shown in Fig. 7 in the same manner of Fig. 6. The Kuroshio path was kinked just off the Izu Peninsula on January 4, 2001 (upper figure), and a large warm-water tongue extending westwards was created on January 11 (middle figure). On January 18, an isolated warm eddy, Warm Eddy IV, was generated (lower figure). The sea level records at Hachijo and Miyake Islands indicated that the Kuroshio path had moved to the east of the Izu Ridge by January 18. The generation process of Warm Eddy IV is very similar to that of Warm Eddy II.

The temperature structure shown in the Prompt Report represents that for the surface layer. Judging from the vertical structure measured by XBT (the previous section), the Kuroshio Water appeared to intrude along the warm-water tongues much more than shown in Fig. 6 and Fig. 7. The origin of the warm water in the thick and stable warm eddies would be brought about by the cut off of the Kuroshio meander.

6. Reinforcement or replacement of thick and stable warm eddies

The thick and stable warm eddies were weakened several times: once on June 1, 2000 for Warm Eddy II and on April 19 and on June 7, 2001 for Warm Eddy IV as indicated in the last column in Table 1. The evolution of the oceanic conditions are shown in Fig. 8, Fig. 9 and Fig. 10, respectively. In each case, the warm eddy was weakened and moved near to the east of Cape Shionomisaki just before its reinforcement event (upper figures in Fig. 8, in Fig. 9 and in Fig. 10). At the same time, a warm-water tongue intruded from the east into the area under consideration. Then, one week later, the strengthened warm eddy was established off Enshu-nada.

The disappearance stage of the thick and stable warm eddies were not clear, but the weakened warm eddies shown in these upper figures resembles the situation of the disappearance stage. So, the reinforcement event shown here might be understood as the replacement of the old eddy by a newly generated warm eddy. If so, the period of continuation shown in Table 1 might be overestimated, but it is hard to conclude from the limited available data.

7. Sea level difference between Kushimoto and Uragami

The position of the Kuroshio axis off Cape Shionomisaki can be monitored by the sea level difference between Kushimoto and Uragami. KAWABE (1980) showed that the sea level difference (the sea level at Kushimoto minus that at Uragami) is small and is stable when the Kuroshio takes a typical meandering path and is large and very variable when the Kuroshio takes a straight path. FUJITA (1997) analyzed the correlation between the sea level difference between these two stations and the separation distance of the Kuroshio axis measured southward from the tip of the Kii Peninsula (Cape Shionomisaki) (see Fig. 11 of NAGATA *et al.*, 1999b) . When the Kuroshio takes a straight path and the distance is smaller than 50 km, the sea level difference is higher than 25 cm. While, when the Kuroshio takes a meandering path and the distance is larger than 50 km, the sea level difference is almost constant and less than 25 cm. (Here, the reported sea level values are used, and a 25 cm difference corresponds to a zero difference in absolute sea levels). FUJITA (1997) discussed about the half-month averaged values. TAKEUCHI *et al.* (1998) and NAGATA *et al.* (1999b) discussed the detailed oceanic structure in the vicinity of Cape Shionomisaki and clarified why the sea level difference is well correlated to the separation distance of the Kuroshio, and UCHIDA *et al.* (2000) indicated that the similar correlation is found even if daily averaged values are used.

However, a good correlation between the sea level difference and the separation distance of the Kuroshio could not be found in the period from January 2000 to May 2001 as shown in Fig. 11. The separation distance was very changeable, but the sea level difference was almost steady during this period. It is plausible that the appearance of the thick and stable warm eddies influenced the sea level at Uragami to minimize the sea level difference.

8. Concluding remarks

Two thick and stable warm eddies were found in 2000 and in 2001 inside the Kuroshio Large Meander. The period of continuation of these two warm eddies were 183 days and 218 days, respectively. These eddies were formed from warm-water tongues extending westward from the kinked current path of the Kuroshio off the Izn Peninsula, and contained the warm Kuroshio water up to several hundred meters in depth. The warm eddy reported by MINAMI (1989) would be very similar to these stable warm eddies, though its detailed nature was not fully clarified due to the limited observational data.

Another warm eddy (Warm Eddy V) was formed on September 20, 2001 in a similar formation processes, but it had relatively short lifetime. The flow pattern of the Kuroshio was changed from the meandering path to straight path at the decaying stage of Warm Eddy V. If the warm eddy approaches to the current zone of the Kuroshio, strong current shear would be

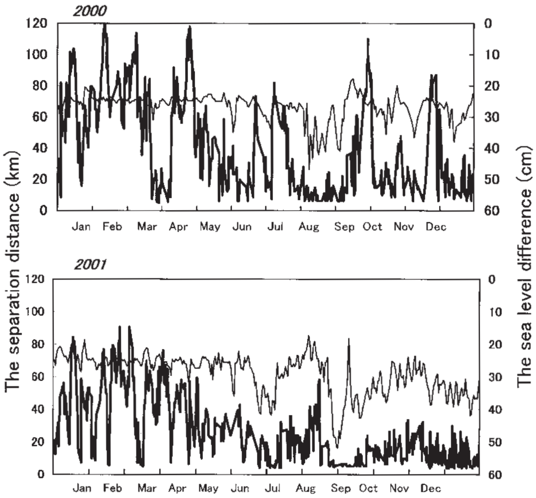

Fig. 11 Variations of the separation distance of the Kuroshio measured southward from the tip of the Kii Peninsula (Cape Shionomisaki) (bold line: the scale of distance is given on left side of the figure in km) and of the sea level difference between Kushimoto and Uragami (thin line: the scale is given on right side of the figure in cm) in the period from January 2000 to December 2001 (after J. Takeuchi of the Wakayama Research Center of Agriculture, Forestry, and Fisheries). Note that the scale of the sea level difference is given inversely.

generated and the warm eddy would become unstable. So, the stable warm eddy would be well separated by cold-water mass from the current zone of the Kuroshio. It is understandable that the stable warm eddy is usually from the warm-water tongue extended westward from off the Izu Peninsula, as the intruded warm water would be well separated from the current zone of the Kuroshio in such condition. Also, when the straight path is established, there would not be enough space to create a stable warm eddy off Enshu-nada.

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