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Variations of the Kuroshio in the Southern Region of Japan: Conditions for Large Meander of the Kuroshio

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Conditions for the formation of large meander (LM) of the Kuroshio are inferred from observational data, mainly obtained in the 1990s. Propagation of the small meander of the Kuroshio from south of Kyushu to Cape Shiono-misaki is a prerequisite for LM formation, and three more conditions must be satisfied. (1) The cold eddy carried by small meander interacts with the cold eddy in Enshu-nada east of the cape. During and just after the propagation of small meander, (2) the Kuroshio axis in the Tokara Strait maintains the northern position and small curvature, and (3) current velocity of the Kuroshio is not quite small. If the first condition is not satisfied, the Kuroshio path changes little. If the first condition is satisfied, but the second or third one is not, the Kuroshio transforms to the offshore non-large-meander path, not the LM path. All three conditions must be satisfied to form the large meander. For continuance of the large meander, the Kuroshio must maintain the small curvature of current axis in the Tokara Strait and a medium or large range of velocity and transport. These conditions for formation and continuance may be necessary for the large meander to occur. Moreover, effects of bottom topography on position and structure of the Kuroshio are described. Due to topography, the Kuroshio changes horizontal curvature and vertical inclination of current axis in the Tokara Strait, and is confined into either of two passages over the Izu Ridge at mid-depth. The former contributes to the second condition for the LM formation.

Keywords:
- Kuroshio,
- conditions for large meander,
- eddy interaction,
- current axis curvature,
- current velocity,
- bottom topography,
- Tokara Strait,
- Izu Ridge.

1. Introduction

The subtropical ocean gyre in the North Pacific circulates clockwise and flows strongly in the northwestern part, where the current from east of Taiwan to the separation from the Japanese coast is called the Kuroshio. After passing east of Taiwan, the Kuroshio flows along the continental shelf in the East China Sea with much less variability in the current path than downstream. The variability of path of the Kuroshio increases just after leaving the continental shelf, becomes significant in the Tokara Strait, and is large in the southern region of Japan.

Variations of the Kuroshio path south of Japan seem complicated at first sight, but are comprehensively described by three typical paths and their cycles (Kawabe, 1985, 1986, 1995). The typical paths at the sea surface are drawn schematically in Fig. 1. One is the large meander (LM) path, which flows off Kyushu and Shikoku, turns south off the Kii Peninsula, and is located to the extreme south of Enshu-nada when changing the current position greatly (Yoshida, 1964; Masuzawa, 1965; Taft, 1972; Kawabe, 1985). The other two are non-large-meander (NLM) paths, called the nearshore and offshore NLM paths, which are steadily close to the Japanese coast from south of Kyushu to Cape Shiono-misaki and different in the eastern region around the Izu Ridge. The nearshore and offshore NLM paths at the sea surface are located around Miyake-jima (Sta. 8 in Fig. 1) and south of Hachijo-jima (Sta. 9), respectively.

The three typical paths alternate with the basic cycle shown in the lower panel of Fig. 2 (Kawabe, 1986, 1995). The LM path forms from the nearshore NLM path and, after lasting for several years, transforms into the offshore NLM path. The Kuroshio during the NLM periods takes the nearshore and offshore NLM paths alternately.

In the NLM to LM transition, i.e. the formation stage of the large meander, a characteristic phenomenon occurs: a small-scale displacement of the Kuroshio called the small meander is generated south or southeast of

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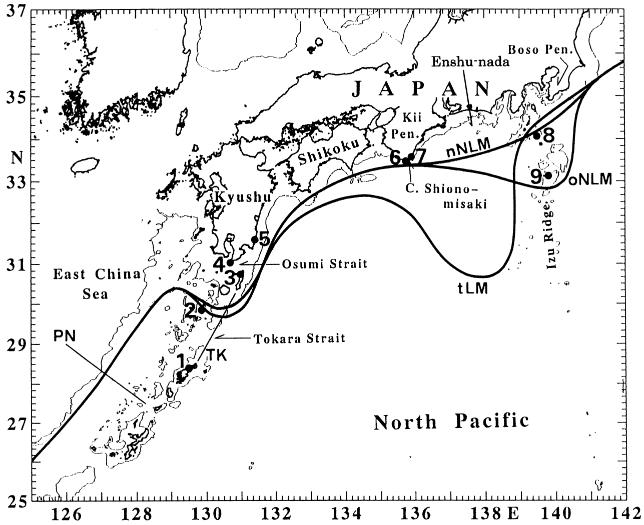

Fig. 1. Typical paths of the Kuroshio, nNLM: nearshore non-large-meander (NLM) path; oNLM: offshore NLM path; tLM: typical large-meander (LM) path. Tide stations are Naze (1), Nakano-shima (2), Nishino-omote (3), Odomari (4), Aburatsu (5), Kushimoto (6), Uragami (7), Miyake-jima (8), and Hachijo-jima (9). The PN and TK lines are CTD lines of the Japan Meteorological Agency. Thin lines show isobaths of 500 m (Kawabe, 1995).

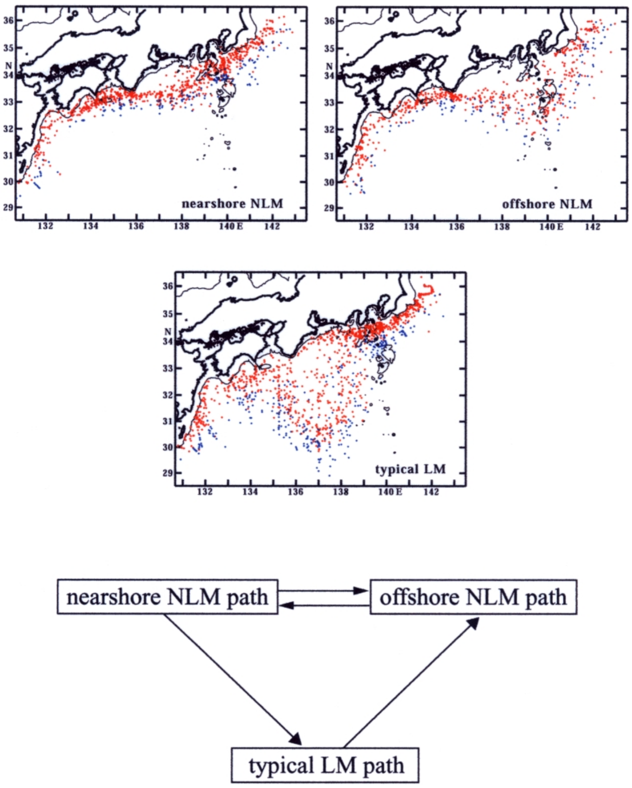

Fig. 2. Upper panels: Points of 15°C at a depth of 200 m (red) and 13°C at 400 m depth (blue) during 1971–80, indicating the Kuroshio axis at sea surface and mid-depth, respectively. The panels are for the three typical paths of the Kuroshio: the nearshore and offshore NLM paths and the typical LM path. Lower panel: Cycle of the three typical paths of the Kuroshio.

Kyushu and propagates eastward to Cape Shiono-misaki, taking about four months. On the other hand, the reverse transition, i.e. the decay stage of the large meander, is difficult to be detected from the path variations in the southern region of Japan, because of a gradual change without any characteristic phenomenon (Yoshida, 1972). The detection of the LM decay stage was made possible by the recent studies of the Kuroshio in the Tokara Strait as follows.

Using the Kuroshio Position Index (KPI) defined with sea levels at Naze, Nakano-shima, and Nishino-omote (Stas. 1–3), it has been clarified that the Kuroshio axis in the Tokara Strait shifts from north (south) to south (north) about four months before the LM decay (formation) and maintains the new location during the transition (Kawabe, 1995; Yamashiro and Kawabe, 1996). The LM decay (formation) stage therefore begins at the southward (northward) shift of the Kuroshio axis in the Tokara Strait and ends at attachment (detachment) of the Kuroshio to (from) the Japanese coast between southeast of Kyushu and Cape Shiono-misaki.

As is well known, the LM period can be detected by the sea level difference between Kushimoto (Sta. 6) and Uragami (Sta. 7) (Moriyasu, 1958, 1961; Tsumura, 1963; Kawabe, 1980, 1985, 1995; etc.). This period includes the LM decay stage defined above, and should be called the LM period in a broad sense. The LM (NLM) period in a narrow sense can be defined as the period removing the LM decay (formation) stage from the broad-sense LM (NLM) period. Therefore, the LM decay and formation stages as well as the narrow-sense LM and NLM periods are clarified with the sea level difference and the KPI. Section 2 describes the current axes of the Kuroshio at sea surface and mid-depth for the narrow-sense LM and NLM periods, and the effects of bottom topography on the Kuroshio.

The primary subject of this paper is the conditions governing the occurrence of the large meander of the Kuroshio. According to Kawabe (1995), volume transport and current velocity of the Kuroshio are small or medium during the 1963–75 NLM period, and are medium or large during the 1975–91 LM-dominant period. In medium or large range of transport and velocity, the position and curvature of the Kuroshio axis in the Tokara Strait change about four months prior to the LM formation and decay. Therefore, the large meander occurs when the Kuroshio takes the northern position and small cur-

Table 1. Long-term conditions for continuance of the large-meander (LM) and non-large-meander (NLM) paths of the Kuroshio, according to Kawabe (1995) and Yamashiro and Kawabe (2002).

Current velocity and volume transport of the Kuroshio		Curvature of the Kuroshio axis in the Tokara Strait	
		Small (located north)	Large (south)
Large	LM, NLM →	LM	NLM
Medium	LM, NLM →	LM	NLM
Small	NLM →	—	NLM

vature of the surface axis in the Tokara Strait in medium or large range of Kuroshio transport and velocity (Table 1). These may be necessary conditions for continuance of the large meander.

Section 3 shows that transport and velocity of the Kuroshio continued to be medium or large after 1991, and the Kuroshio axis was sometimes located north in the Tokara Strait. However, the large meander of the Kuroshio has never occurred since 1991, at least until 2003*. Reasons for no occurrence of the large meander in 1990s are inferred in Section 3, and conditions for the large meander are discussed in Section 4.

2. Effects of Bottom Topography on the Kuroshio

The typical LM path corresponds to the high sea-level state at Hachijo-jima and Miyake-jima during the narrow-sense LM period, and the nearshore and offshore NLM paths correspond to the high and low sea-level states during the narrow-sense NLM period, respectively. The three typical paths at sea surface and mid-depth (about 500-m depth) are shown with red and blue points in Fig. 2, respectively. They are slightly different from the figures for the broad-sense periods in Kawabe (1985). For example, the nearshore NLM path in Fig. 2 does not include the offshore points off Kyushu and Shikoku, which are due to the small meander in the LM formation stage.

At mid-depth, the nearshore NLM path passes through the gap between Miyake-jima and Hachijo-jima, while the offshore NLM path passes through the deep region south of Hachijo-jima (Fig. 2; Kawabe, 1985). The distinction between the nearshore and offshore NLM paths is due to the difference in current passage at mid-depth over the Izu Ridge. As a result, the distance between them reaches about 1.5° latitude over the ridge, which is almost the same as the distance between the two passages at mid-depth. The typical LM path passes through the northern gap, like the nearshore NLM path. Thus the bottom topography of the Izu Ridge fixes the Kuroshio at mid-depth in either of the two passages, based on a selection of the passage by the Kuroshio. This effect makes the Kuroshio less variable over the ridge and seems to regulate it into the typical paths.

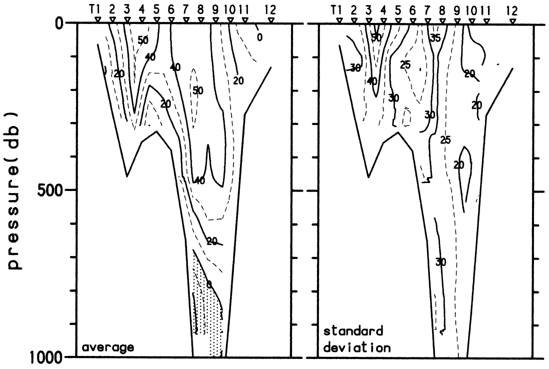

Fig. 3. Vertical distribution of average and standard deviation of geostrophic velocity (cm s^{-1}) at the TK line during 1987–97. Positive values show southeastward current. Station T1 is located at 30°15′ N, 130°50′ E, and T12 is at 28°35′ N, 129°45′ E (Oka and Kawabe, 2003).

Another topographic effect on the Kuroshio occurs in the Tokara Strait, in particular due to the projection of continental shelf shallower than 500 m at the TK line to the south of Yaku-shima and Tanega-shima (Fig. 1; Nakano and Kaneko, 1990; Oka and Kawabe, 2003). Part of the Kuroshio deeper than about 400 m must pass through the deep channel south of the projection of continental shelf, while the shallower part of the Kuroshio can largely move meridionally (Fig. 3).

The Kuroshio in the surface layer has two current cores on average to the north and south of the seamount located in the southernmost part of the shallow projection. The northern core is often strong but disappears occasionally and has large standard deviation of current velocity, while the southern core is permanently present (Fig. 3). The bottom topography affects the structure of the Kuroshio in the Tokara Strait.

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*Note added in proof: The large meander of the Kuroshio began in early July 2004, three months after this paper had been accepted for the Journal of Oceanography. The non-large-meander period lasted for thirteen and a half years from January 1991 through June 2004.

During the LM period, the Kuroshio surface axis in the Tokara Strait, particularly at the projection of continental shelf, is located farther north and has smaller curvature than that during the NLM period (Fig. 4; Kawabe, 1995; Yamashiro and Kawabe, 1996, 2002). The curvature of the Kuroshio axis in the Tokara Strait is a significant factor for the Kuroshio path south of Japan (Kawabe, 1996). The surface axis position and curvature in the Tokara Strait are almost determined by which is the surface axis, the northern core or the southern core.

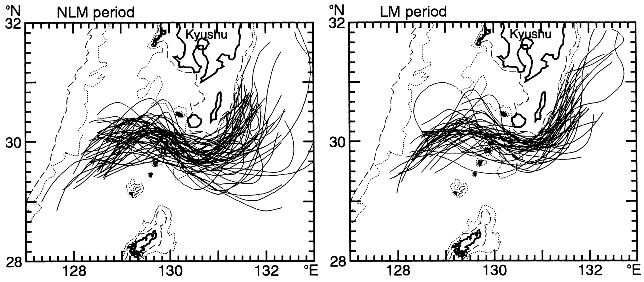

Fig. 4. Curves of the surface axis of the Kuroshio (17°C isotherms at a depth of 200 m) south of Kyushu for the NLM (left) and LM (right) periods during 1964–95. Broken and dotted lines indicate isobaths of 200 m and 500 m, respectively (Yamashiro and Kawabe, 2002).

The Kuroshio axis is located farther offshore in deeper layer, and the line connecting the axis downward in a vertical section inclines offshore (Masuzawa, 1954; Masuzawa and Nakai, 1955). Kawabe (1985) indicated that the vertical inclination of current axis for the typical LM path is more than twice of that for the NLM path. The large (small) inclination during the LM (NLM) period can be attained in the Tokara Strait, due to the surface axis in the northern (southern) position and the mid-depth axis fixed in the southern channel. The difference in the vertical inclination between LM and NLM may originate in the Tokara Strait and continue to the east.

The selection of the mid-depth passage in the Izu Ridge and the vertical inclination of the Kuroshio axis determine the location of the Kuroshio surface axis around the Izu Ridge. Comparison between the typical LM path and the nearshore NLM path shows that the surface axis of the typical LM path is located farther north on average and closer to the Japanese coast over the Izu Ridge, though both the paths pass through the common passage at mid-depth (Fig. 2; Kawabe, 1985). This is because the LM path has a larger vertical inclination than the NLM path. Due to the approach to the coast, the Kuroshio taking the

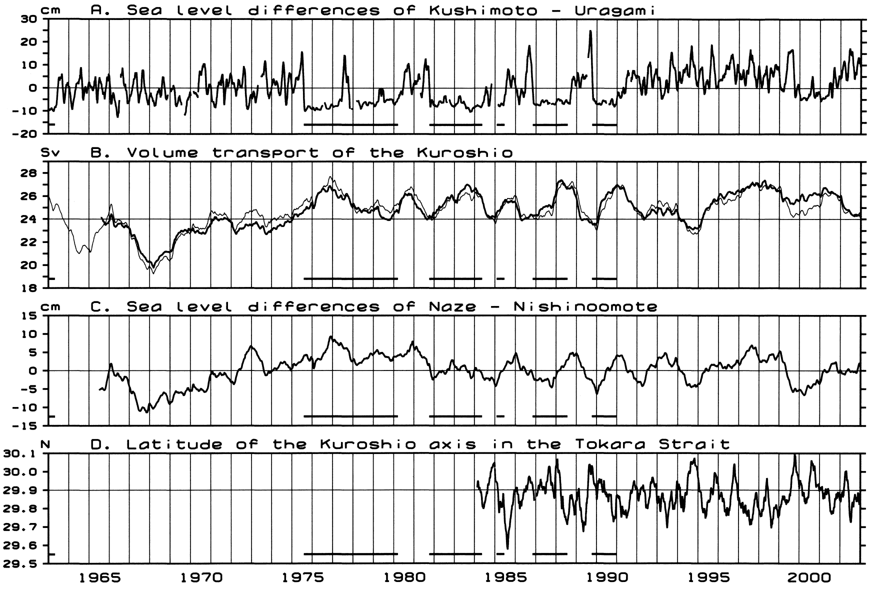

Fig. 5. Low-passed time series of daily mean values from 1963 through 2002, with horizontal lines showing the LM periods; A. Sea level difference of Kushimoto minus Uragami (40-day running mean), index of the large meander of the Kuroshio, B. Volume transport of the Kuroshio in the East China Sea (1-year running mean), estimated from sea levels at Naze, Nishino-omote, and Odomari (thick line) and Naze and Aburatsu (thin line) by the method of Kawabe (1995) with the fitted relation to the Kuroshio transport at the PN line, C. Sea level difference between Naze and Nishino-omote (1-year running mean), indicating surface velocity of the Kuroshio in the Tokara Strait, D. Latitude of the surface axis of the Kuroshio in the Tokara Strait (80-day running mean), estimated by the method of Yamashiro and Kawabe (1996) using sea levels at Naze, Nakano-shima, and Nishino-omote. The mean value during 1963–2002 is taken as the zero point in A and C.

typical LM path carries the Kuroshio water into the coastal area, the water expands into the Sagami and Suruga Bays due to coastal currents, eddies, and waves, and the water masses and flow patterns around there are changed (Kawabe and Yoneno, 1987; Matsuyama, 1992). This must significantly influence fishery and living marine resources.

3. Conditions for the Kuroshio Large Meander—Why did not It Occur in 1990s?

Figure 5A shows the sea level difference between Kushimoto and Uragami, an excellent index for the large meander of the Kuroshio. The Kuroshio takes the LM path predominantly from 1975 to 1991, and takes the NLM path from 1963 to 1975 and from 1991 to the present. The large meander is a bi-decadal phenomenon with primary periods of about 20 years (Kawabe, 1987).

The large meander occurs when the Kuroshio takes the northern position and small curvature of surface axis in the Tokara Strait in medium or large range of transport and velocity (Kawabe, 1995; Table 1). This is based on the observed relations before 1992. Looking at the later period after 1991, the Kuroshio has similar transport and velocity to the values during 1981–91 in the LM-dominant period and is sometimes located north in the Tokara Strait (Fig. 5). The necessary conditions for continuance of the large meander in Table 1 are satisfied several times in 1990s. However, the large meander of the Kuroshio has never occurred since 1991, at least until 2003. Why did the large meander not occur in the 1990s?

The large meander of the Kuroshio formed in November 1986 and October 1989, just after the sharp decrease of the sea level difference between Kushimoto and Uragami (Fig. 6A). The sharp decrease occurs when the small meander coming from south of Kyushu reaches Cape Shiono-misaki. Figures 7a and 8a show that the small meander propagates eastward south of Shikoku in 1986 and east of Kyushu in 1989 before it reaches the cape. This is the state at the maximum of the sea level difference. The Kuroshio is still located close to Cape Shiono-misaki, and a cold eddy exists in Enshu-nada. In 1989, cold eddies were present in and around Enshu-nada, and are generically called "cold eddy in Enshu-nada" hereafter.

When the small meander passes the cape, the sea level difference between Kushimoto and Uragami decreases sharply. Just after the decrease to the minimum level, the Kuroshio takes the initial state of a large meander, which embraces a cold eddy with minimum temperature of 11 or 13°C at 200-m depth (Figs. 7b and 8b). This

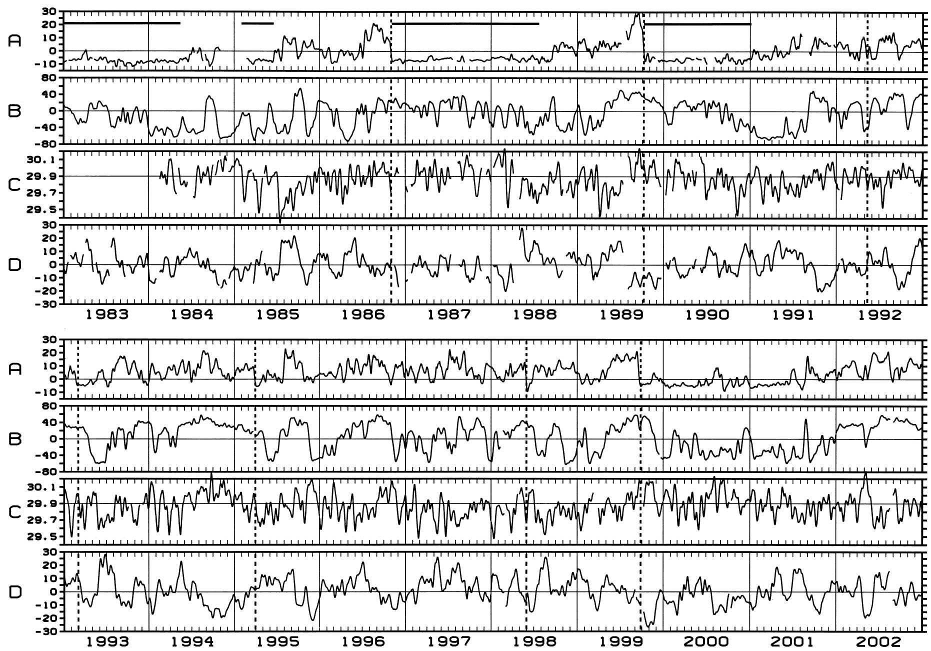

Fig. 6. Time series of 10-day running means of daily mean values from 1983 through 2002; A. Sea level difference (cm) between Kushimoto and Uragami, indicating the LM periods with the horizontal lines, B. Sea level (cm) at Hachijo-jima, C. Latitude (°N) of the surface axis of the Kuroshio in the Tokara Strait, estimated by the method of Yamashiro and Kawabe (1996), D. Sea level difference (cm) between Naze and Nishino-omote, indicating surface velocity of the Kuroshio in the Tokara Strait. The mean value during 1963–2002 is taken as the zero point in A, B, and D. The times at which the Kuroshio small meander reached Cape Shiono-misaki are shown with vertical broken lines.

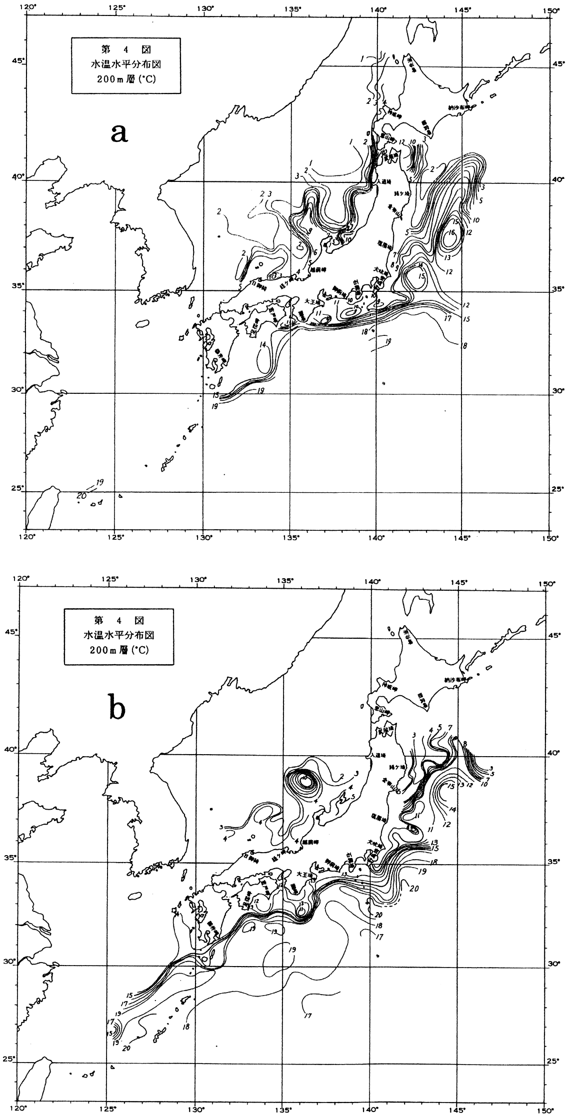

Fig. 7. Horizontal distribution of water temperature at a depth of 200 m during 3–17 September 1986 (a) and 5–19 November 1986 (b) (*Quick Bulletin of Oceanographic Conditions* issued semimonthly by the Hydrographic and Oceanographic Department, Japan Coast Guard). The period of (a) corresponds to that of the maximum of the sea level difference between Kushimoto and Uragami, and (b) corresponds to the period just after the sharp decrease of the sea level difference to the minimum level.

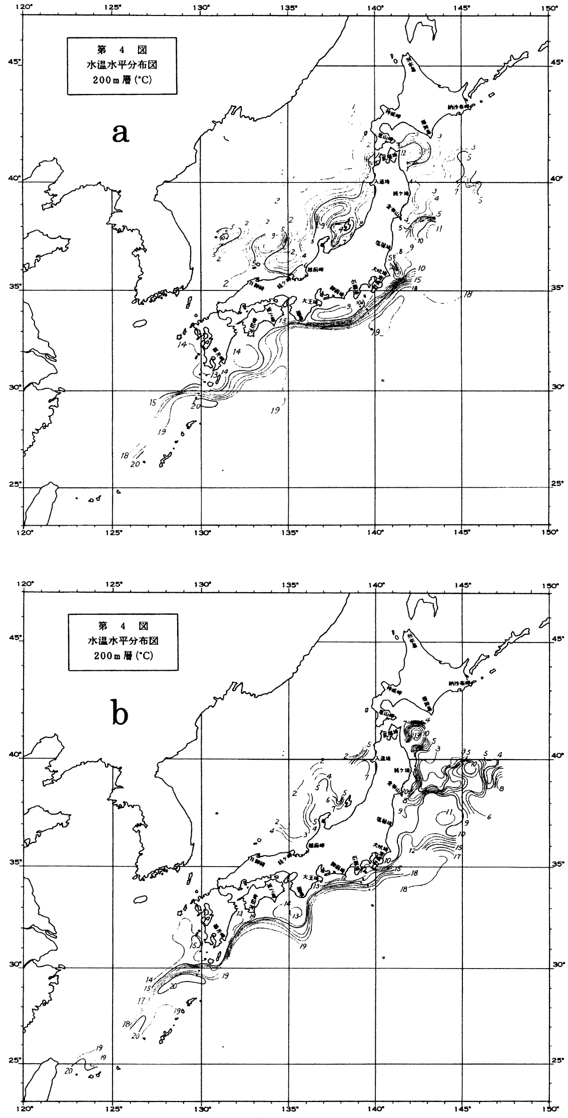

Fig. 8. As Fig. 7 but for 31 August–13 September 1989 (a) and 19–31 October 1989 (b).

temperature is intermediate between those of the cold eddies in the small meander (~14°C) and Enshu-nada (9 or 10°C). The cold eddies accompanied by the small meander and existing in Enshu-nada may interact with each other during the decrease of the sea level difference, namely, between Figs. 7a and 7b and between Figs. 8a and 8b, so that the cold eddy in the large meander may be formed.

In the LM formation stage in 1953, 1959, and 1975, the Kuroshio continued to take the nearshore NLM path (Kawabe, 1985), and the cold eddy remained in Enshu-nada as in 1986 and 1989. However, in 1969 and 1981, the Kuroshio began the transition from the nearshore NLM path to the offshore NLM path during the propagation of small meander (Kawabe, 1986). The cold eddy in Enshu-nada had moved to east before the small meander reached Cape Shiono-misaki, and seems to have shifted to east of the Izu Ridge in 1969 and remained to the west in 1981. As a result, significant interaction between the cold eddies may not have occurred in 1969, and may have occurred in 1981 further east than usual. This may be a reason why the large meander did not form in 1969, and oc-

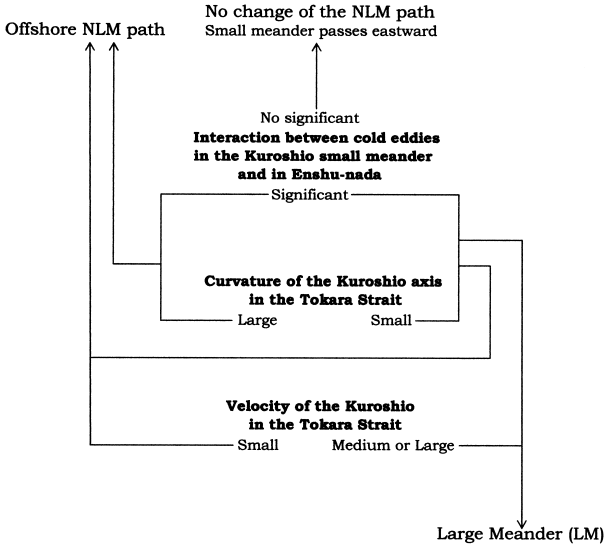

Fig. 9. Conditions for formation of the large meander of the Kuroshio during and just after the propagation of small meander to Cape Shiono-misaki.

curred in 1981 at a location further east than the "normal" large meander.

Moreover, a large amplitude of the cold eddies may be necessary for significant interaction between them. Nitani (1977) examined six small meanders between 1959 and 1975, and indicated that the small meander was so large as to reach south of 32°30′ N at 135°E in the LM-formed cases. This suggests that the cold eddy in the small meander must be strong for a significant interaction to occur between the cold eddies. Similarly, the cold eddy in Enshu-nada may also have to be strong. The sea level difference between Kushimoto and Uragami is quite large, with a significant peak just before the LM formation (Kawabe, 1980). The peak may imply that the sea surface height on the Kuroshio axis decreases greatly downstream, and the Kuroshio accelerates greatly at the south of Cape Shiono-misaki (Kawabe, 1990). As a result, the cold eddy in Enshu-nada may be strengthened by large velocity of the Kuroshio just before the small meander reaches Cape Shiono-misaki.

During 1990s, significant small meanders of the Kuroshio reached Cape Shiono-misaki in 1992, 1993, 1995, 1998, and 1999 (Fig. 6). Except for 1992, the sea level at Hachijo-jima is high during and just after the propagation of the small meander; that is, the Kuroshio continues the nearshore NLM path like the "normal" cases of LM formation. On the other hand, the sea level at Hachijo-jima falls in the case of 1992; that is, the Kuroshio transforms from the nearshore NLM path to the offshore one during the propagation of the small meander. The cold eddy in Enshu-nada shifted to the east side of the Izu Ridge as in 1969, according to the *Quick Bulletin of Oceanographic Conditions*. This suggests that no significant eddy interaction occurred. This may explain why the large meander did not form in 1992.

In the cases of 1993, 1995, and 1998, the sea level difference of Kushimoto minus Uragami is not very large (Fig. 6A), and the cold eddy in Enshu-nada may not develop extremely. In addition, the Kuroshio axis in the Tokara Strait is located far south, at least temporarily during and just after the propagation of the small meander (Fig. 6C). The meridional position is correlated with the curvature of the Kuroshio axis; the southern position means large curvature (Yamashiro and Kawabe, 2002). Large curvature in the Tokara Strait causes the Kuroshio to approach to the Japanese coast of Kyushu and Shikoku, and leads to the NLM path. This was concluded by Kawabe (1996) using a steady model, but such a tendency probably also appears in a transient state. This may be a reason why the Kuroshio failed to take the LM path, maybe together with the moderate strength of the cold eddy in Enshu-nada. To form the large meander, the surface axis of the Kuroshio may have to maintain the northern position and small curvature in the Tokara Strait during and just after the propagation of the small meander.

In the case of 1999, all these conditions are satisfied, like the LM-formed cases, but the large meander did not form. What is the difference from the LM-formed cases? Figures 6A and D show that current velocity of the Kuroshio was extremely small just after the arrival of a small meander at Cape Shiono-misaki in 1999. The Kuroshio velocity in October and November 1999 was the lowest in the whole record since 1965, being comparable to that from October to December in 1967. Kawabe (1995) pointed out that Kuroshio velocity in the LM formation stage, except for 1975, retains small values after a peak at the generation of small meander, but the velocity in 1999 is much smaller than that in the LM formation stage (Fig. 6D). In terms of the interannual components, the Kuroshio velocity is small from 1999 to 2000 and decreases nearly to the range of the small velocity for which the large meander has never occurred (Fig. 5C). A small velocity of the Kuroshio may be a reason why the large meander did not form in 1999.

The small meanders in 1993, 1995, 1998, and 1999 brought about the offshore NLM path one month after the sharp decrease of the sea level difference between Kushimoto and Uragami (Figs. 6A and B). This corresponds to the high correlation of the sea level difference with Hachijo-jima sea level during the NLM period, with a phase lead of 35 days in which the nearshore NLM path transforms to the offshore NLM path (Kawabe, 1986, 1989, 2003).

4. Conclusion and Discussion

First of all, we have described how the Kuroshio is strongly affected by bottom topography in the Tokara Strait and the Izu Ridge. In the Tokara Strait, the continental shelf projects southward with a seamount on the southernmost part, and a deep channel exists to the south. Due to this topography, the Kuroshio in the surface layer changes the position of its surface axis meridionally and forms double current cores, while the mid-depth and deeper part of the Kuroshio are confined in the southern deep channel. The northern position of the Kuroshio surface axis in the Tokara Strait, characterizing the large-meander (LM) path, causes large vertical inclination of the Kuroshio axis. This may bring about a larger vertical inclination of the LM path than the NLM path in the southern region of Japan.

Moreover, the Kuroshio at mid-depth is restricted by the Izu Ridge to two passages, the northern gap between Miyake-jima and Hachijo-jima and the southern deep region south of Hachijo-jima. Around the Izu Ridge, the position of surface axis of the Kuroshio may be determined by the mid-depth passage of the Izu Ridge and the vertical inclination of the Kuroshio axis. The typical LM path approaches the Japanese coast near the surface, since it passes through the northern gap of the Izu Ridge at mid-depth with large vertical inclination of current axis.

Next, the conditions for formation of the large meander of the Kuroshio were discussed. As is well known, a small meander of the Kuroshio generates south or southeast of Kyushu, propagates eastward, and reaches Cape Shiono-misaki prior to the LM formation. This is prerequisite for LM formation but does not always bring about the large meander. More conditions must take effect for the LM formation.

Three conditions are inferred from the small meanders occurred in 1990s, as summarized in Fig. 9. First, the cold eddy carried by the small meaner of the Kuroshio interacts significantly with the cold eddy existing in Enshu-nada. The significant interaction may occur when the cold eddies are strong, and the cold eddy in Enshu-nada does not move to the east. Second, the Kuroshio axis in the Tokara Strait almost maintains the northern position and small curvature during and just after the propagation of a small meander to Cape Shiono-misaki. Third, current velocity of the Kuroshio is not quite small during and just after the small-meander propagation.

If the first condition is not satisfied, the small meander just passes eastward, and the non-large-meander (NLM) path of the Kuroshio does not significantly transform. If the first condition is satisfied, but the second or third one is not, the Kuroshio taking the nearshore NLM path does not form the large meander and transforms to the offshore NLM path. The large meander of the Kuroshio seems to develop only when all the three conditions are satisfied.

These are short-term conditions for the LM formation, which must be satisfied during and just after the formation stage. In a long-term view, the large meander exists while the velocity and transport of the Kuroshio are medium or large, and the curvature of the Kuroshio surface axis in the Tokara Strait is small (Kawabe, 1995). These two conditions are long-term conditions for long-time continuance of the large meander. Since the large meander of the Kuroshio lasts for years and is not temporal, both the short- and long-term conditions are necessary for occurrence of the large meander. The large meander would fail to continue in the case of 1969, even if the LM formation process were normally completed, because Kuroshio transport was quite small during 1964–74.

The position and curvature of the Kuroshio axis in the Tokara Strait contribute to both the short-term and long-term conditions, and the northern position and small curvature are necessary for both the formation and continuance of the large meander. This condition, however, may be a stricter requirement for the formation than the continuance, because once the large meander occurs, it exists stably even if the Kuroshio in the Tokara Strait shifts southward and has large curvature during less than 20 days (Yamashiro and Kawabe, 1996).

Bottom topography in the Tokara Strait is associated with the conditions for the LM formation and continuance, because of the effect on position and curvature of the Kuroshio axis. The Izu Ridge may contribute to the LM continuance by regulating the path of the Kuroshio at mid-depth.

In the present paper, three conditions occurring during and just after the propagation of small meander are inferred to be necessary for the LM formation. This inference needs examining by dynamics studies. Whether or not the short- and long-term conditions are sufficient also needs to be examined. The dynamics studies based on the present result may lead to an understanding of the dynamic mechanism underlying the occurrence of the large meander of the Kuroshio.

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