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On the Nature of the Kuroshio Waters off the Kii Peninsula and Its Relation with the Kii Bifurcation Current and Coastal Sea Level

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Abstract. The detailed nature of the Kuroshio Waters and its relation with the Kii Bifurcation Current and the sea level difference between Kushimoto and Uragami are discussed by using the recent observations and referring the recent investigations conducted by our group. The current zone of the Kuroshio touches the coast and the bottom just off Cape Shionomisaki at the time of the straight path of the Kuroshio. The current zone separates the coastal water to the west of Cape Shionomisaki from that to the east. The warm Kuroshio Water intrudes well into the coastal region to the west, but the water to the east remains to be occupied by the relatively cold and original coastal water. Resulted contrast between the coastal waters produces the large sea level difference between Kushimoto and Uragami, which are separated only by 14 km. The Kii Bifurcation Current, which is often found along the southwest coast of the Kii Peninsula at the time of the straight path of the Kuroshio, appears to be related to the mechanism to draw the Kuroshio Water into the coastal region. Even though the current zone intrudes into the shelf region near the Shionomisaki, it leaves the shelf just to the east of the cape. The centrifugal force, which would be produced if the current follows bottom contours, would give an explanation why the current leaves the shelf.

INTRODUCTION

One of the peculiarities of the Kuroshio is that it has two stable path patterns at the south of Honshu, Japan: a straight path and a large meander path (Fig. 1). Each of the pattern persists from several months to several years when it takes place (e.g., Shoji, 1972; Taft, 1972). It was shown that the flow pattern of the Kuroshio can be monitored by watching the sea level difference between two tide gauge stations, Kushimoto and Uragami (e.g., Kawabe, 1980), which are located only 14 km apart to each other (see Fig. 5 for the locations of these tide stations and see Fig. 3 for the region under consideration). Fujita (1997) and Sekine and Fujita

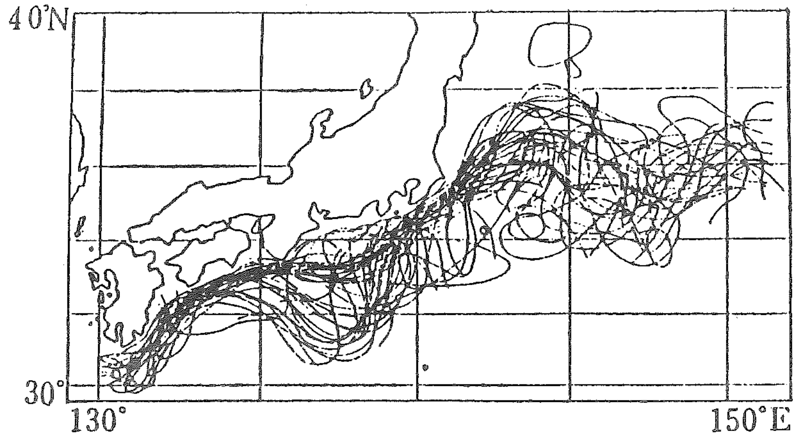

Fig. 1. Position of the Kuroshio axis measured in the period from 1955 to 1964 (Masuzawa, 1965). The positions of the Kuroshio axis are determined from that of the isotherms of 15°C. The two stable paths of the Kuroshio are seen to the south of Honshu.

(1999) analyzed the data taken at two routine observation stations (Sta. 25 just off Kushimoto and Sta. 31 just off Uragami: see Fig. 5 also their locations) of the Wakayama Prefectural Fisheries Experimental Station (its present name is the Wakayama Research Center of Agriculture, Forestry and Fisheries). He calculated the sea level difference between these two oceanic stations (taking the reference level at 300 m depth) by using temperature and salinity data, and compared with the sea level difference between the two tide gauge stations. The result of their analysis is shown in Fig. 2, which shows that the variation of the sea level difference between the tide gauge stations can be explained quantitatively by that of the oceanic structures of the surface 300 m layer. Fujita (1997) also investigated the relation of the sea level difference to the position of the Kuroshio axis: He determined the distance of the Kuroshio axis measured due south from Cape Shionomisaki by using the Prompt Report of Oceanographic Condition published bimonthly by the Hydrographic Department of the Maritime Safety Agency of Japan and calculated the bimonthly averaged sea level difference between Kushimoto and Uragami. He found that the Kuroshio takes the large meander path when the sea level difference is near or smaller than 25 cm (this value would be affected by selection of the reference levels of two tide gauge stations, but here we used simply the sea level values reported by Japan Meteorolgy Agency). Note that tidal components of the variations had not removed, but that the tidal components are very similar to each other and do not affect the results. The Kuroshio takes the straight path when the sea level difference is larger than this threshold value of 25 cm. However, it had not been clarified why and how such a sharp contrast of the oceanic condition is created between two adjacent points: the distance between Kushimoto and Uragami is only about 14 km.

Recently, a group which consists of the researchers belonging to Wakayama Prefectural Fisheries Experimental Station, Mie University, Marine Information

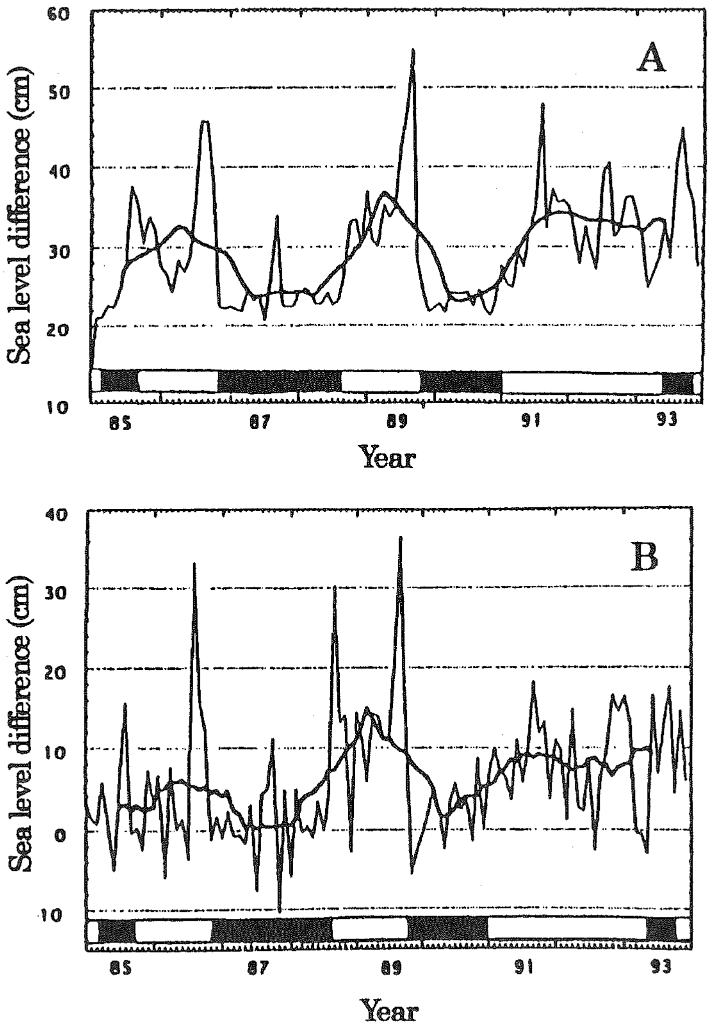

Fig. 2. The variations of the sea level difference between two tide gauge stations at Kushimoto and Uragami (upper figure: A) and those between two oceanic observation stations, Stas. 25 and 31, of Wakayama Prefectural Fisheries Experimental Station (lower figure: B) during the period from 1985 to 1993 (Fujita, 1997; Sekine and Fujita, 1999). Thin line in A indicates the bimonthly averaged value and that in B at each observation time (the stations are occupied basically once a month). Bold lines are the 12.5 months running averaged curves. The black bars and white bars shown in the both figures indicate the times of the large meander and the straight path of the Kuroshio, respectively.

Research Center of Japan Hydrographic Association, and Fisheries Research Center of Mie have made several detailed observations and analyses of the oceanic conditions in the vicinity of the Kii Peninsula and investigated their relations to the flow nature of the Kuroshio just off Cape Shionomisaki (the tip of the Kii Peninsula). The main results are:

(1) The transition from the straight path to the large meander path occurs usually abruptly. It has been believed that small-scale meanders of the Kuroshio

generated often near the southern tip of Kyushu travels eastward along the south coast off Shikoku and Honshu, and that some of them develop abruptly just after they pass by Cape Shionomisaki and form the steady Kuroshio Large Meander off Enshu-nada (see Fig. 3 for these locations). However, this is not correct in details. The small-scale meander generated off Kyushu usually increases its east-west width, and only the eastern edge travels to east. Just after the eastern edge of the elongated meander passes by Cape Muroto, the eastern portion of the meander is separated and a new small-scale meander is generated just off the Kii Channel. This new meander is rapidly developed there and then passes by Cape Shionomisaki to form the Kuroshio Large meander (Fujita *et al.*, 1998; Nagata *et al.*, 1999a).

(2) Along the southwest coast of the Kii Peninsula, a bifurcation current (the Kii Bifurcation Current) often appears, and its occurrence frequency is about 70% in the period from 1988 to 1996. Its occurrence frequency is especially high when the Kuroshio takes the straight path (Takeuchi *et al.*, 1998a, 1998b).

(3) Structure of the Kii Bifurcation Current and its short-period variation were examined. The Kii Bifurcation Current is very stable when the current zone of the Kuroshio touches the coast and bottom slope just off Cape Shionomisaki. The current is weakened when the current zone leaves the coast even tentatively, according to the passage of small-scale meanders (or eddies) by Cape Shionomisaki. This variation nature can be monitored by the daily averaged sea level difference between Kushimoto and Uragami, and the threshold value of 25 cm is also applicable for the short-period variation having the time scale from a few days to several days. (It was suggested that even the hourly variation of the sea level difference may indicate the sea state variation just off Cape Shionomisaki to a certain extent.) It was observed that, when the daily sea level difference dropped tentatively below 25 cm, the Kii Bifurcation current disappeared (Uchida *et al.*, 2000).

(4) The detailed oceanic observation was carried out in the vicinity of Cape Shionomisaki when the Kuroshio took the typical straight path. It was shown that the current zone of the Kuroshio touched the coast and bottom slope just off Shionomisaki, and that the coastal water to the west of the cape was completely separated from that to the east. It was also observed that the offshore warm Kuroshio Water penetrated into the coastal area to the west of the cape. These oceanographic features seems to explain why the flow path of the Kuroshio can be monitored by the sea level difference between Kushimoto and Uragami though the distance between these tide gauge stations is only 14 km. The Kuroshio flows out eastward into the open ocean after passing by Cape Shionomisaki, even though the strong current of the Kuroshio extends to the bottom slope off Cape Shionomisaki and though the conversation law of vorticity may require the barotropic flow to follow the bottom contours. The reason why the Kuroshio flows into the shelf region and leaves there was investigated by Nagata *et al.* (1999b).

In this paper, we shall introduce the interesting current natures in the vicinity of Cape Shionomisaki, mainly based on Nagata *et al.* (1999b).

FLOW NATURE OF THE KUROSHIO IN THE VICINITY OF THE KII PENINSULA AT THE TIME OF THE STRAIGHT PATH OF THE KUROSHIO (JUNE 11–14, 1996)

The dense CTD and XBT observations were carried out in the Kuroshio area in the vicinity of Cape Shionomisaki, the tip of the Kii Peninsula, on board the

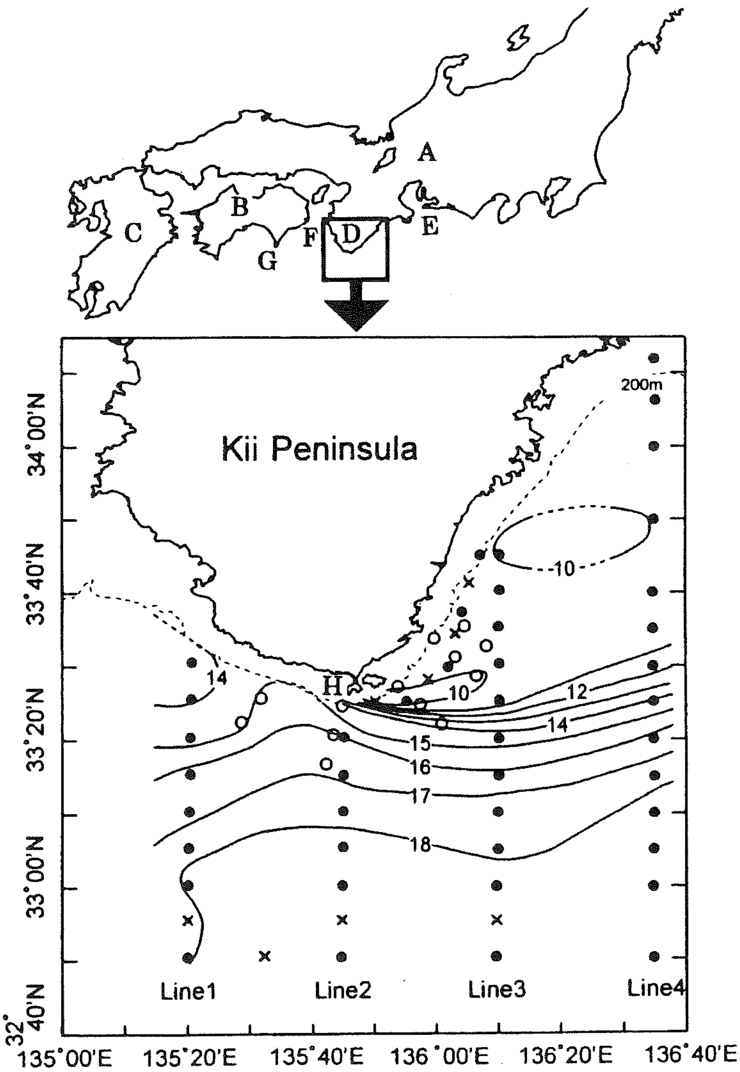

Fig. 3. Observation sites of the R/V Seisui-maru of Mie University on June 11–14, 1996 and of the R/V Wakayama of Wakayama Prefectural Fisheries Experimental Station on June 11–12. The CTD observation points by the R/V Seisui-maru and by the R/V Wakayama are indicated with black circles and white circles, respectively, and the XBT observation points by R/V Seisui-maru with ×. The horizontal temperature distribution (in °C) at 200 m depth is also shown (Nagata *et al.*, 1999b). A: Honshu, B: Shikoku, C: Kyushu, D: Kii Peninsula, E: Enshu-nada, F: Kii Channel, G: Cape Muroto, and H (lower figure): Cape Shionomisaki.

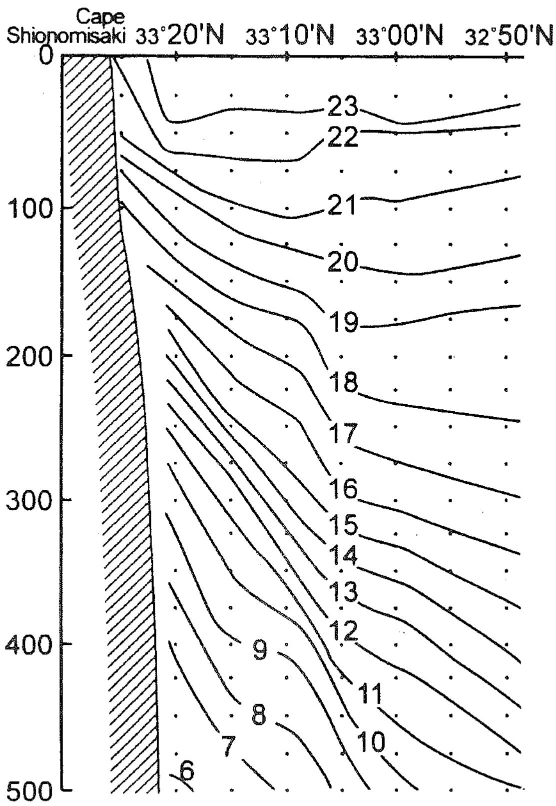

Fig. 4. Temperature cross-sections (in °C) along the north-south line (Line 2 in Fig. 3) just south of Cape. Dots indicate the data points used for this analysis (Nagata *et al.*, 1999b).

R/V Seisui-maru of Mie University on June 11–14, 1996. Due to an obstacle of the ADCP, no direct current information was available in this cruise. In the same period (on June 11–12), the R/V Wakayama of Wakayama Prefectural Fisheries Experimental Station occupied its routine observation lines in the vicinity of the Kii Peninsula, and CTD and ADCP observations were conducted. The observation points of these cruises are shown in Fig. 3 together with the obtained temperature field at the depth of 200 m (the position of the isotherm of 15°C at 200 m depth is the measure of the Kuroshio axis in this region). The temperature cross-sections along the north-south lines extending from Cape Shionomisaki (Line 2) is shown in Fig. 4.

The high temperature gradients is seen just near Cape Shionomisaki in Figs. 3 and 4, indicating that the strong eastward current of the Kuroshio was located very near to the cape. The temperature cross-section along Line 2, which runs in the north-south direction from just off Cape Shionomisaki, indicates that the strong current zone of the Kuroshio touched the coast and bottom slope just off Cape Shionomisaki. The surface current field at the depth of 5 m is shown in Fig. 5. The current field at the depth of 50 m is almost identical to that at 5 m. The current velocities at 100 m are a little smaller than those at 5 m (up to about 10%).

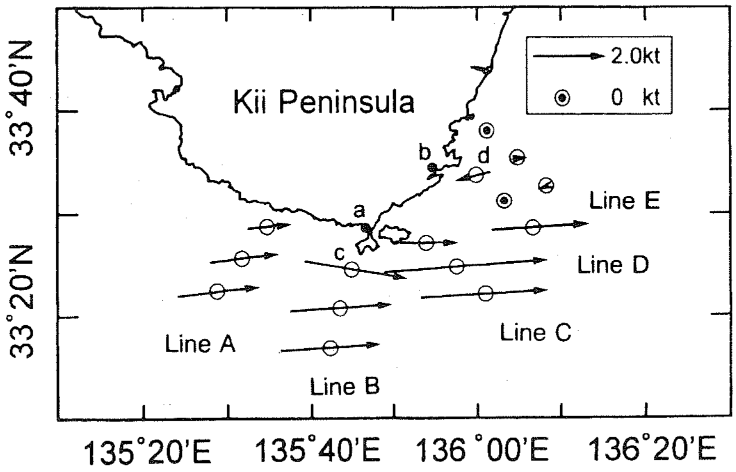

Fig. 5. Surface velocity field measured by ADCP of the R/V Wakayama on June 11–12, 1996 (Nagata *et al.*, 1999b). The locations of tide gauge stations Kushimoto and Uragami are shown with a and b, and the routine observation stations of Sta. 25 and Sta. 31 of Wakayama Prefectural Fisheries Experimental Station with c and d, respectively.

It is hard to estimate the current velocity just above the bottom, but, if we simply extrapolate the measured current profile, the current velocities at 200 m or 300 m depths would exceed 1.0 m/s, and the vertically averaged velocity would reach 1.5 m/s in the strong current zone of the Kuroshio. These also indicate that the current zone of the Kuroshio touched the coast near Cape Shionomisaki, and that the Kuroshio current is quai-barotorpic and reaches the bottom.

It should be noted in Fig. 3 that the Kuroshio in the vicinity of Cape Shionomisaki has a big east-west contrast in isotherm density, the densest portion of which corresponds to the current zone of the Kuroshio. To the east of the cape, the horizontal temperature gradient associated with the current zone is very sharp, and a clear shadow zone of the current is formed just east of Cape Shionomisaki, while the temperature field to the west of the cape is rather diffused. The temperature gradient across the Kuroshio increases from west to east in our observation area. The acceleration of the flow velocity of the Kuroshio near Cape Shionomisaki is also seen in the current field shown in Fig. 5. The temperature field west of the cape suggests that the Kuroshio water intrudes well into the shelf region, and that the Kuroshio water covers almost whole coastal region southwest of the Kii Peninsula. This situation seems to be related to the Kii Bifurcation Current often found in this region as discussed later.

The situation shown in Fig. 3 seems to be a representative feature of the Kuroshio when it takes the straight path, and the coastal waters to the west of Cape Shionomisaki is completely separated from that to the east. This separation would be essential to create the sea level difference between Kushimoto located to the west of the cape and Uragami located to the east of the cape.

LEAVE OF THE KUROSHIO CURRENT ZONE FROM THE COAST TO THE EAST OF CAPE SHIONOMISAKI

The temperature field in Fig. 3 and the current field in Fig. 5 indicate that the current zone of the Kuroshio extends due eastward from the tip of the Kii Peninsula (Cape Shionomisaki), and leaves the shelf and continental slope. It is curious as a geostrophic flow which touches the bottom is generally forced to follow bottom contours due to the vorticity conservation law.

The coastline in the vicinity of Cape Shionomisaki is shown together with 200 m bottom contour in Fig. 6. The bottom contour to the west of the cape is straight, but that to the east has a large curvature. The 200 m bottom contour to the east of the cape is approximated by a circle arc as shown in the figure. The radius of the circle is 25.9 km. If we assume the current velocity just above the bottom is 1.0 m/s or the vertically averaged velocity is 1.5 m/s as estimated in the previous section, the centrifugal force would become 0.39×10^{-4} m/s^2, or 0.87×10^{-4} m/s^2 when the current is trapped by bottom contours to the east of the cape. The corresponding Coriolis forces at 35.5°N (the pressure gradient force is hardly estimated without the knowledge of bottom pressure field, but it would be comparative to the Coriolis force due to the geostrophic nature of the Kuroshio) for these velocity values are 0.77×10^{-4} m/s^2 or 1.15×10^{-4} m/s^2, respectively. Thus, if the current follows the bottom contours, the centrifugal force becomes comparative to Coriolis force for the observed range of current speeds, and the current is hardly to able to follow the bottom contours. This gives the reason why the Kuroshio leaves the shelf and slope regions to the east of Cape Shionomisaki.

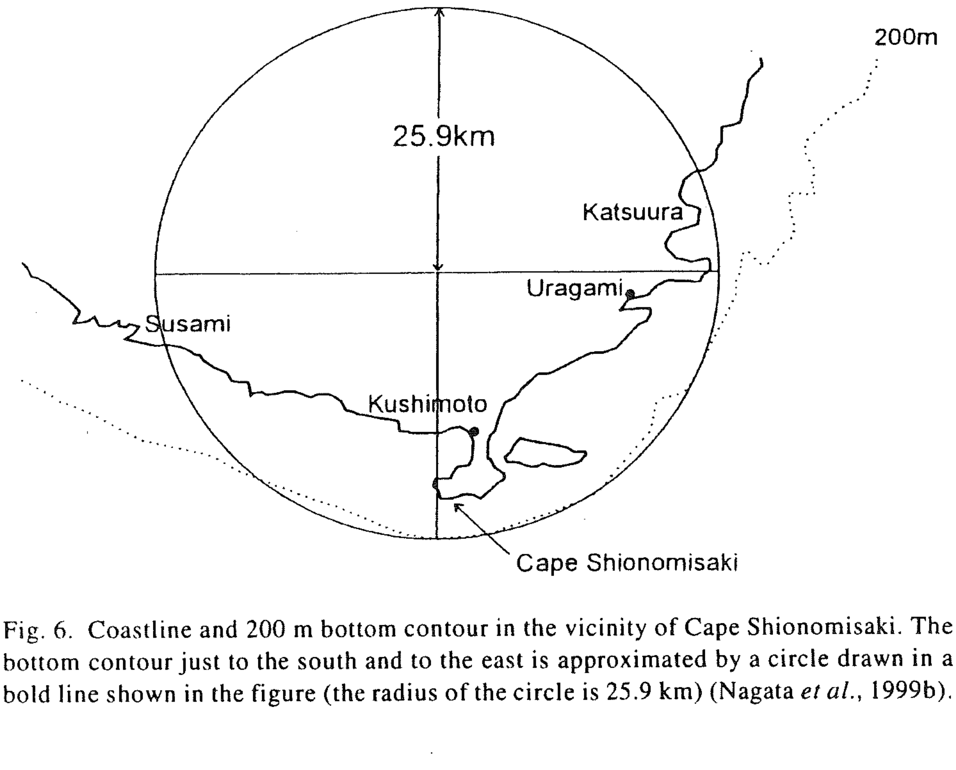

Fig. 6. Coastline and 200 m bottom contour in the vicinity of Cape Shionomisaki. The bottom contour just to the south and to the east is approximated by a circle drawn in a bold line shown in the figure (the radius of the circle is 25.9 km) (Nagata *et al.*, 1999b).

THE KII BIFURCATION CURRENT AND INTRUSION OF THE KUROSHIO WATER INTO THE COASTAL REGION TO THE WEST OF CAPE SHIONOMISAKI

As discussed in Section 2, there is a big contrast in oceanic features between the areas to the west and to the east of Cape Shionomisaki. This phenomenon has not been intensly investigated, but such contrast is usually seen when the Kuroshio takes the straight path (Takeuchi, personal communication).

Along the southwest coast of the Kii Peninsula, the Kii Bifurcation Current is often observed. Takeuchi *et al.* (1998a) showed that the Kii Bifurcation Current was found about in 70% of the 258 ADCP sections taken in the period from 1988 to 1996 by the R/V Wakayama. It was also shown that the occurrence frequency is high at the time of the straight path and low at the time of the large meandering path of the Kuroshio.

An example of the horizontal structure of the Kii Bifurcation Current observed on board the R/V Seisui-maru on June 24–25, 1997 is shown in Fig. 7 (velocity field) and in Fig. 8 (temperature distribution at 200 m depth) (Takeuchi *et al.*, 1998b; Uchida *et al.*, 2000). Along the line A, the along-line component of the current changes its sign near Susami, indicating the existence of the bifurcation current. As seen in this figure, the eastward flowing portion of the Kii Bifurcation Current near Cape Shionomisaki is considered to be the coastal edge part of the strong current zone of the Kuroshio.

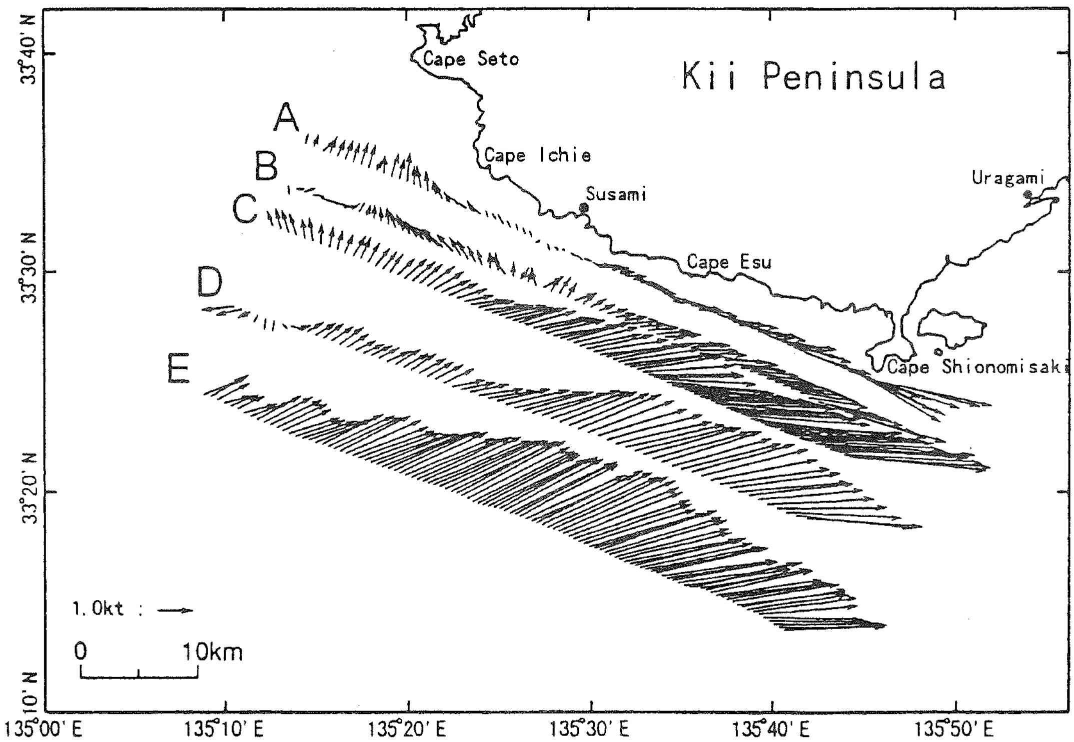

Fig. 7. Current field measured at 5 m depth on board the R/V Seisui-maru from 22:44 on June 24 to 15:45 on June 25, 1997 (Takeuchi *et al.*, 1998b; Uchida *et al.*, 2000).

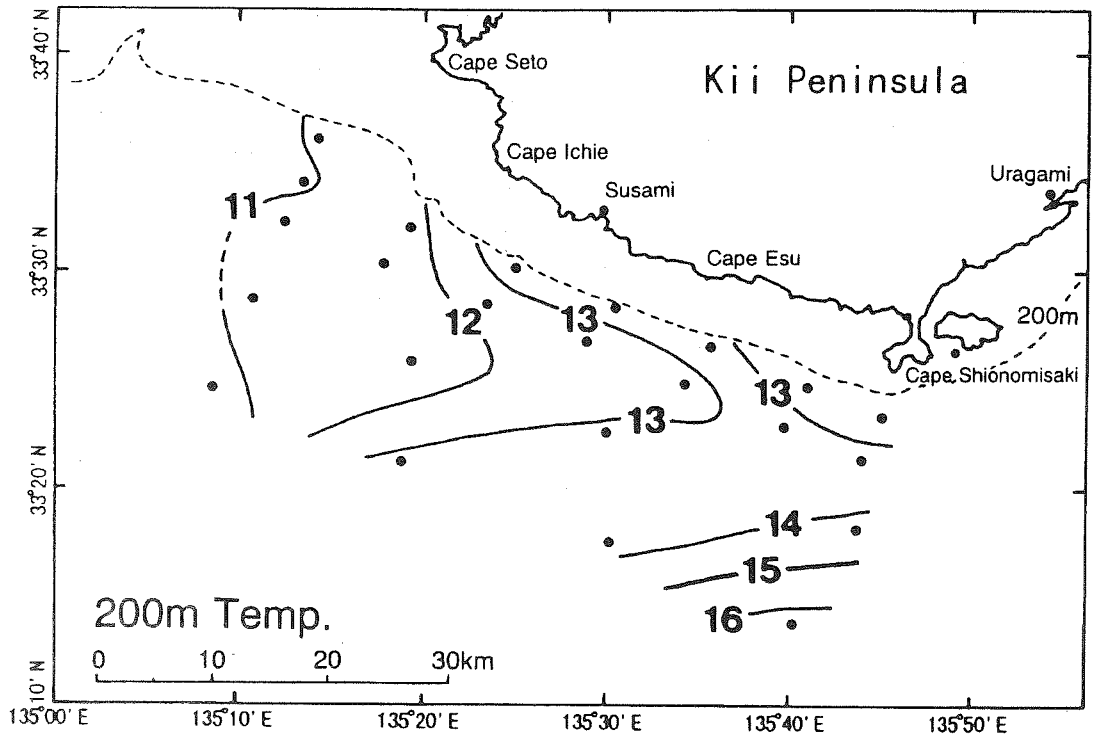

Fig. 8. The same as in Fig. 6 except for the temperature field at 200 m depth.

The westward flowing portion to the west of Susami may be related with a counter-clockwise eddy in the Kii Channel (Fujita *et al.*, 1998; Nagata *et al.*, 1998), which is often observed when the Kuroshio takes the straight path. However, the relation has not been clarified yet, as only one observation line of Wakayama Prefectural Fisheries Experimental Station runs in north-south direction along the center of the Kii Channel, and as the structure and its variation of the eddy cannot be deduced from such limited observations. It would be highly possible that the westward current of the western portion of the Kii Bifurcation Current is enhanced if the counter-clockwise eddy is strengthened.

The temperature field at 200 m depth (Fig. 8: see the configuration of 13°C isotherms) also indicates that a branch current of the Kuroshio is intruding into the coastal region, and suggests the existence of the Kii Bifurcation Current. Takeuchi *et al.* (1998a) reported that, though the onshore-offshore component of the current is changeable in time, the alongshore current usually diverges along the Line A (they call the line the standard line) in the region from Cape Ichie to the vicinity of Cape Shionomisaki when the Kii Bifurcation Current (or the Eastward Current) is observed. The divergence value averaged over the standard line is well correlated to the flow patterns not only along the standard line but also to the path nature of the Kuroshio. This suggests that the offshore Kuroshio water is flowing into the coastal region southwest of the Kii Peninsula at the time of the straight path.

As discussed above, since the current speed of the Kuroshio is relatively weak to the west of the cape and increases from west to east in the vicinity of the cape, it is not feasible that the inertia force due to the strong Kuroshio current sends the Kuroshio water into the shallow shelf region against the law of the vorticity conservation. It would be reasonable to think that the counter-clockwise eddy in the Kii Channel is strengthened and the Kuroshio current zone approaches to Cape Shionomisaki at the time of the straight path, and that the resulted Kii Bifurcation Current draws the offshore Kuroshio water into the coastal region. Or, if the Kuroshio water intrudes into the coastal region to the west of Cape Shionomisaki due to some reason, the Bifurcation Current would be generated and the eddy in the Kii Channel might be strengthened.

The tide gauge station at Kushimoto is located to the west of the land passage which connects Cape Shionomisaki to the main part of the Kii Peninsula. At the time of the straight path, the region just off the Kushimoto tide gauge station is covered with the Kuroshio water, while that off the Uragami tide gauge station is covered with the relatively cold and heavy coastal water (existence of the current-shadow zone of the Kuroshio to the east of Cape Shionomisaki would enhance this tendency). Thus, the large sea level difference is created between two tide gauge stations. There is no reason that such difference occurs at the time of the large meander path, as the coastal water to the west of the cape would have the similar nature to that to the east of the cape.

DISCUSSION

The detailed oceanic structure in the vicinity of Cape Shionomisaki, the tip of the Kii Peninsula, was discussed mainly for the time of the straight path. Similar detailed observations in this area would be needed also at the time of the large meander path. However, the oceanographic condition in the coastal region at the time of the large meander path would be simpler, by judging from the variation nature of the sea level difference between Kushimoto and Uragami: the difference is very changeable at the time of the straight path in comparison with that at the time of the large meander path (see for example figure 7 of Kawabe, 1980). As discussed before, Fujita (1997) investigated the correlation between the position of the Kuroshio axis measured due southward from Cape Shionomisaki (in km) and the sea level difference between the Kushimoto and Uragami (in cm) (Fig. 9). Although considerable scattering of the data points is seen, it is clear that the sea level difference at the time of the large meander path is smaller (generally smaller than 25 cm) regardless to the large variability in the distance of the Kuroshio axis from the coast (ranging from 40 to 320 km). On the other hand, at the time of the straight path, the distance is nearly constant and is from 30 to 50 km, but the sea level difference is very variable and ranges from about 25 to 55 cm. This appears to support our results that the strong current zone of the Kuroshio touches the coast and bottom slope just off Cape Shionomisaki at the time of the straight path, and that the resulted separation of the coastal water to the west of the cape from that to the east causes the relatively large sea level difference between the two tidal stations, which are separated by only 14 km.

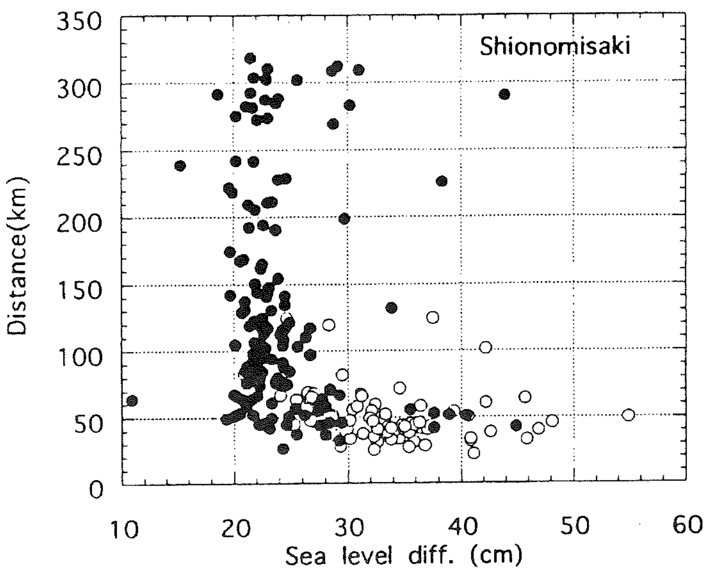

Fig. 9. Correlation between the position of the Kuroshio axis measured due southward from Cape Shionomisaki (in km) and the sea level difference between Kushimoto and Uragami (in cm). The distance was determined from Prompt Report of the Oceanographic Condition published bimonthly by Hydrographic Department, Maritime Safety Agency of Japan, and the sea level difference averaged for each half month is used. Black circles indicated the data which were taken at the time of the large meander and white circles those taken at the time of the straight path (Fujita, 1997).

The intrusion of the offshore Kuroshio water into the coastal region to the west of the cape (namely, off the Kushimoto tide gauge station) would enhance the sea level difference. However, the short-time leave of the current zone of the Kuroshio from the coast may allow water exchange between the coastal regions to the west and to the east of the cape in some degree. The large scattering of the sea level difference at the time of the straight path suggests that the separation of the coastal waters may be partly destroyed depending on the current structures very near to the cape. It is very understandable that the large sea level difference is not created if the Kuroshio axis is apart far enough from the coast so as that the water exchange of the coastal waters between to the west and to the east of the cape takes place. Uchida *et al.* (2000) discussed the structure and its variability of the Kii Bifurcation Current with reference to the short period (a few days to several days) variability of the sea level difference between Kushimoto and Uragami, and gave an evidence of water exchange between the coastal waters to the east and to the west of Cape Shionomisaki at the time of the straight path of the Kuroshio.

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