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Bifurcation Current along the Southwest Coast of the Kii Peninsula

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Along the southwest coast of the Kii Peninsula, a bifurcation current is regularly observed. By using ADCP data taken on board the R/V Wakayama of the Wakayama Prefectural Fisheries Experimental Station, characteristics of this bifurcation current are analyzed. The occurrence frequency of the bifurcation current reaches about 70% in the period from 1988 to 1996. The bifurcation point appears to be changeable and occurs almost evenly between Cape Ichie and Cape Shionomisaki. The current divergence in the alongshore direction was also investigated. Positive divergence values dominated in the whole analyzed area, and an onshore current appears to be dominant along the southwest coast of the Kii Peninsula, except in 1990 when the Kuroshio flowed in a large meandering path.

Keywords:
· Kuroshio,
· large meander,
· bifurcation current,
· current divergence,
· Kii Peninsula,
· Cape Shionomisaki.

1. Introduction

The southwest coastline of the Kii Peninsula is almost straight from Cape Ichie to close to Cape Shionomisaki (see Fig. 1). A bifurcation current is often observed by local fishermen along this coast, and is called the "Furiwake-shio" in Japanese. Sakamoto (1991) discussed the relation between the fish catch and the oceanic structure, and pointed out that successful fishing usually takes place when the bifurcation current appears. One of the authors, Takeuchi, reported in a local fisheries meeting held in 1995 that successful hauls of flying fishes (*Exocoetidae*) occur in the time of the bifurcation current.

It has been believed that the occurrence of the bifurcation current is closely related to the position of the Kuroshio axis off Cape Shionomisaki (T. Sakamoto of the Wakayama Prefectural Fisheries Experimental Station, personal communication), but no detailed investigation has so far been carried out. ADCP was equipped on the R/V Wakayama of the Wakayama Prefectural Fisheries Experimental Station in 1988, and observations of this bifurcation current frequently conducted thereafter. Here we analyze the ADCP data statistically in order to clarify the occurrence frequencies of the bifurcation current.

2. Data Used

The R/V Wakayama of the Wakayama Prefectural Fisheries Experimental Station was equipped in October 1988 with an ADCP made by the Furuno Electric Co. (CI-50). Observations of the bifurcation current were carried out mainly along the 100 m depth contour which runs parallel to the coast in the region under consideration. A typical observation line is shown in Fig. 1, together with the current velocity field measured at a depth of 5 m on June 28, 1991. The current shown flows toward WNW in the western portion, and toward ESE in the eastern portion, and the bifurcation of the current occurs in the vicinity of Susami. In this paper, we call the current structure shown in Fig. 1 as a "Typical Bifurcation Current".

The time required to survey the observation line between Cape Ichie and Cape Shionomisaki was usually less than 2 hours, and the current structure was not significantly influenced by the tidal currents. Even if the current field was somewhat disturbed and the bifurcation point was not so clear, we classify the current pattern into the "Bifurcation Current" when bifurcation trend can be recognized in whole. The term "Bifurcation Current" in the latter discussion includes also the case of the Typical Bifurcation Current.

We analyzed the ADCP data taken in the period from October 1988 to September 1996. We use the data only when the observation line was surveyed approximately along the 100 m depth contour and when the observation range was long enough to cover at least from Cape Ichie to Cape Shionomisaki. The number of the data sets during the period analyzed in this paper is 258. Further only the data measured at the 5 m depth is used in this paper, as the depth of deeper depth is changeable cruise by cruise (20 or 40 m) and the current pattern at the deeper layers usually is identical to that at 5 m.

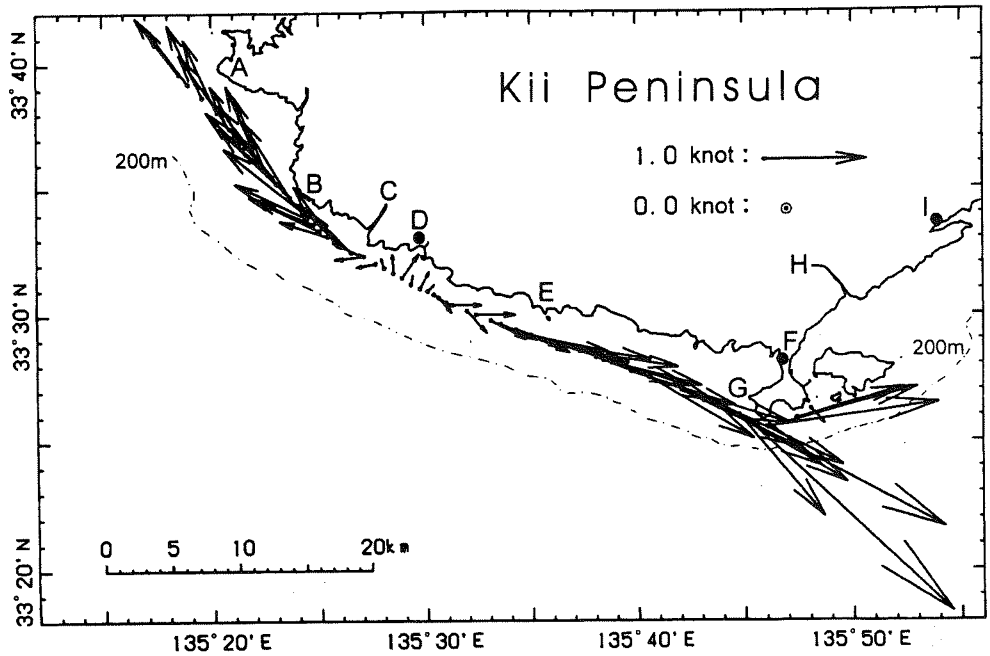

Fig. 1. Location of the Bifurcation Current. A typical ADCP observation line is shown together with current field at a depth of 5 m on June 28, 1991. The observation line was usually selected to follow the 100 m depth contour which runs almost parallel to the coast. The current field shown is a typical example of the Bifurcation Current (the Typical Bifurcation Current). A: Cape Seto, B: Cape Ichie, C: Hiki River, D: Susami, E: Cape Esu, F: Kushimoto, G: Cape Shionomisaki, H: Koza River, and I: Uragami.

3. Classification of the Current Pattern and Occurrence Frequency

Besides the "Bifurcation Current", two other flow patterns are recognized by local fishermen; (1) the Eastward Current called as "Kudari-shio" in Japanese and (2) the Westward Current as "Nobori-shio". ("Nobori" means approaching to the old capital Kyoto, and "Kudari" going away from Kyoto). Typical examples of the Eastward Current and the Westward Current are shown in the top-left and top-right figures of Fig. 2, respectively. Here, we add a further two flow patterns; the Converging Current and the Irregular Current. Typical examples of these current are given in the bottom-left and bottom-right figures in Fig. 2, respectively.

The occurrence frequency of these flow patterns are shown in Fig. 3. The occurrence frequency of the Bifurcation Current is the highest at 69% with that of the Typical Bifurcation Current being 29%. This indicates that the Bifurcation Current is the most common current pattern in this area. However, it should be noted that the frequency of the Convergence Current has also a significant magnitude of 4.3%.

In the case of the Bifurcation Current, the position of the bifurcation point was determined visually from each flow field. In Fig. 4, frequency histograms are given of the position (by longitude) for both the Bifurcation Current (the upper figure: including the Typical Bifurcation Current) and for the Typical Bifurcation Current only (the lower figure). The two figures show an almost identical shape, and a weak peak appears near Cape Ichie in both curves. However, this peak is not significant in yearly frequency histograms (not shown in this paper) except that in 1994 when bifurcation occurred very frequently near Cape Ichie. In Fig. 5, the variation in the bifurcation point position is shown for the observation time on the abscissa and for the Bifurcation Current and the Typical Bifurcation Current, respectively. It is hard to identify the most probable position of the bifurcation point from this figure.

It should be noted that the occurrence of the Bifurcation Current is considerably lower in 1990 than in other years, and that no Typical Bifurcation Current occurred in 1990. During our period of analysis, a long-lasting Large Meander of the Kuroshio occurred only in this year. The relation between the variation of the Kuroshio path and the occurrence of the Bifurcation Current will be discussed later.

The position of the bifurcation point may be affected by the existence of an alongshore coastal current. The effect of the alongshore current would be eliminated if we consider the divergence of the alongshore current component. In the next section, we investigate the current divergence along a standard line which runs approximately along the 100 m depth contour and parallel to the coast line.

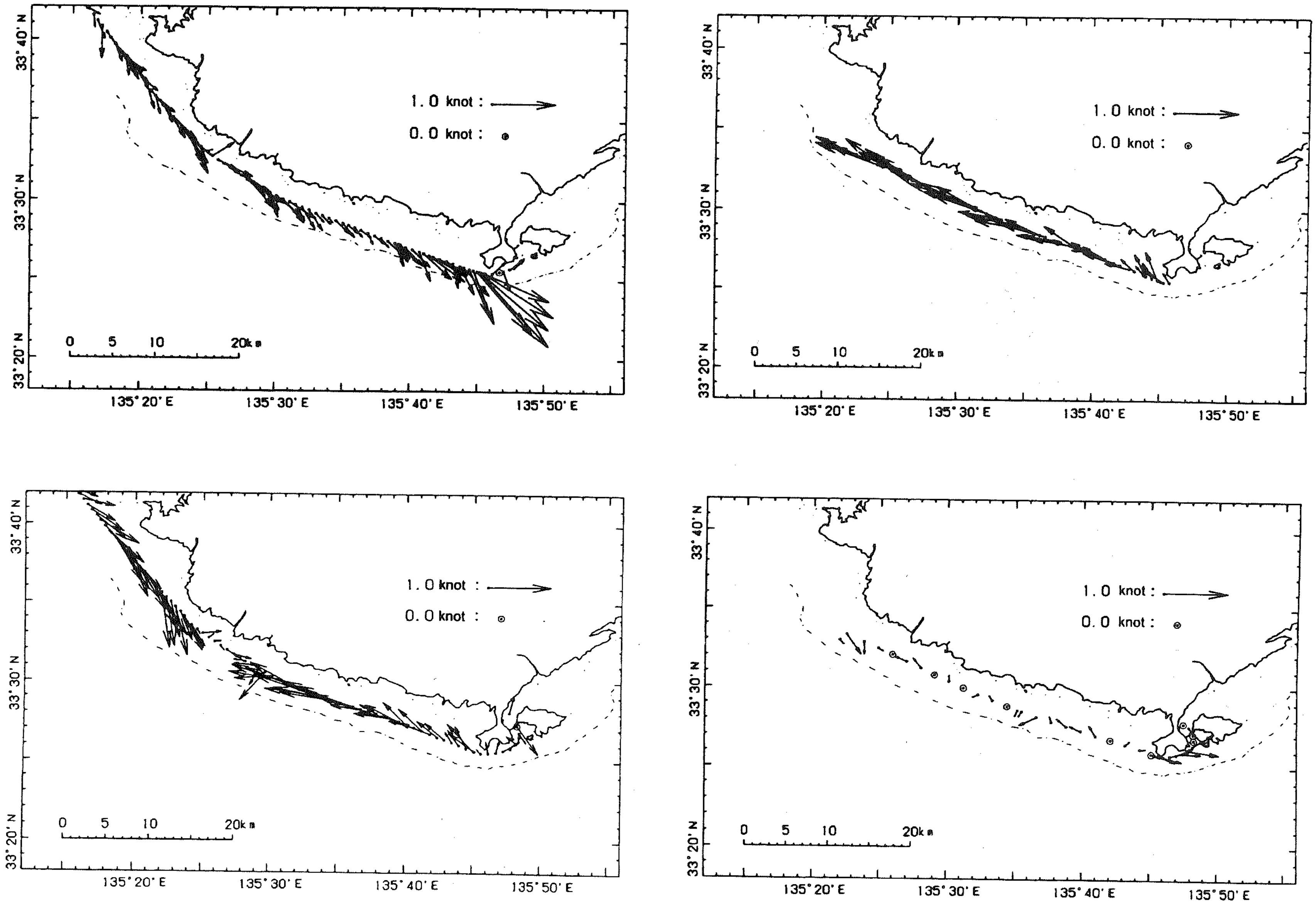

Fig. 2. Typical examples of the Eastward Current (top-left: April 8, 1996), the Westward Current (top-right: December 6, 1993), the Convergence Current (bottom-left: May 9, 1995), and the Irregular Current (bottom-right: February 8, 1990).

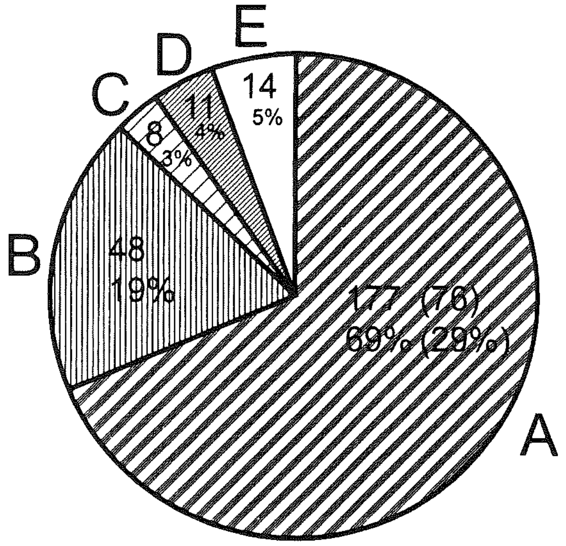

Fig. 3. Occurrence frequency of each flow pattern; A: the Bifurcation Current, B: the Eastward Current, C: the Westward Current, D: the Converging Current, and E: the Irregular Current. The occurrence frequencies are given both by number and by % in each corresponding section (numbers in parenthesis indicate the Typical Bifurcation Current).

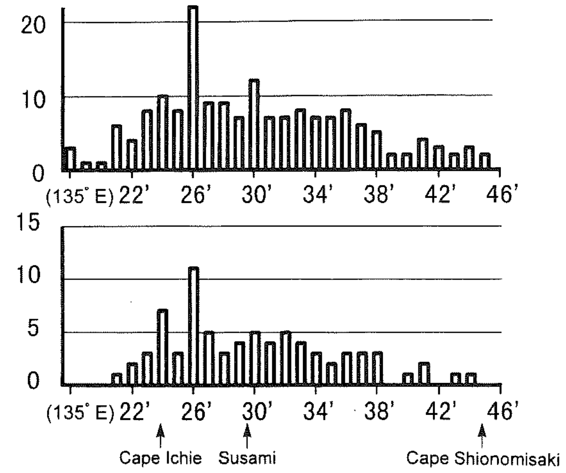

Fig. 4. The frequency histograms against the position (in longitude) are shown for both the Bifurcation Current (upper figure: including the Typical Bifurcation Current) and the Typical Bifurcation Current only (lower figure). Two figures show an almost identical shape, and the weak peak appears near Cape Ichie in each curve.

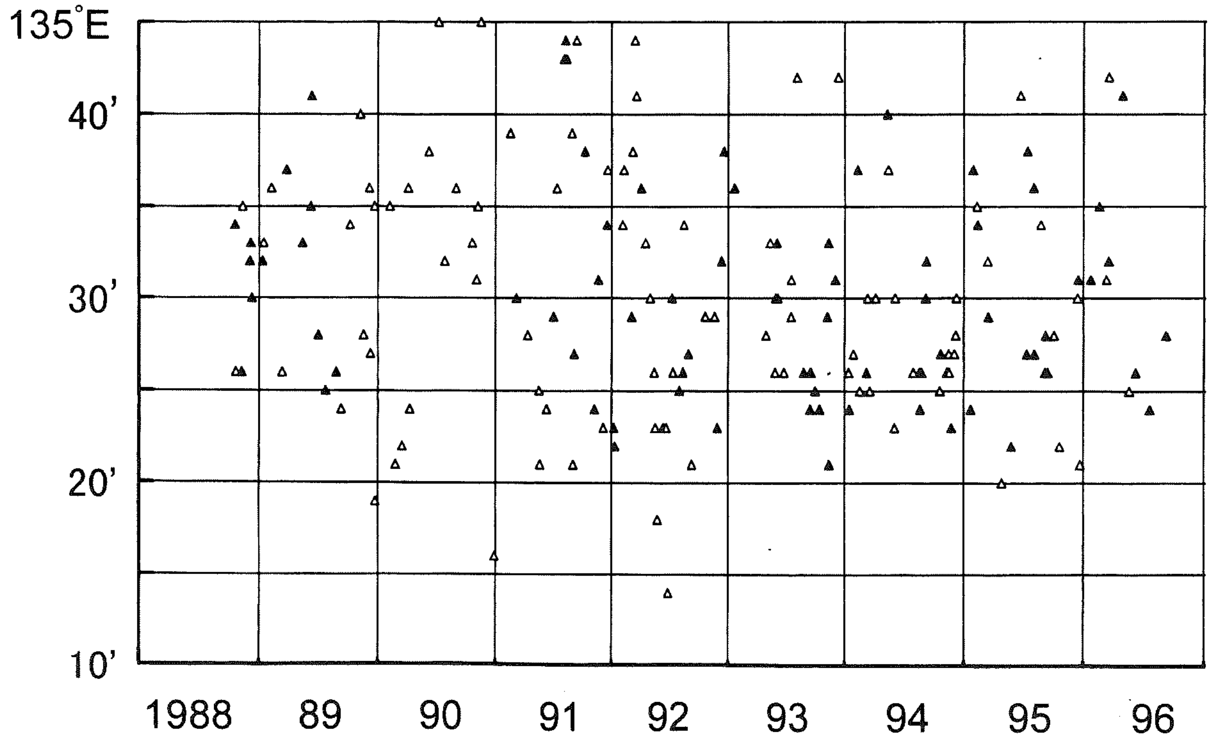

Fig. 5 Scattered nature of the bifurcation position: the observed position in longitude are given on the ordinate, and the observation time on the abscissa. Black triangles indicate the case of the Typical Bifurcation Current. Note that the data points are distributed almost evenly in the region between 135°20′ E and 135°40′ E, and no Typical Bifurcation Current occurred in 1990.

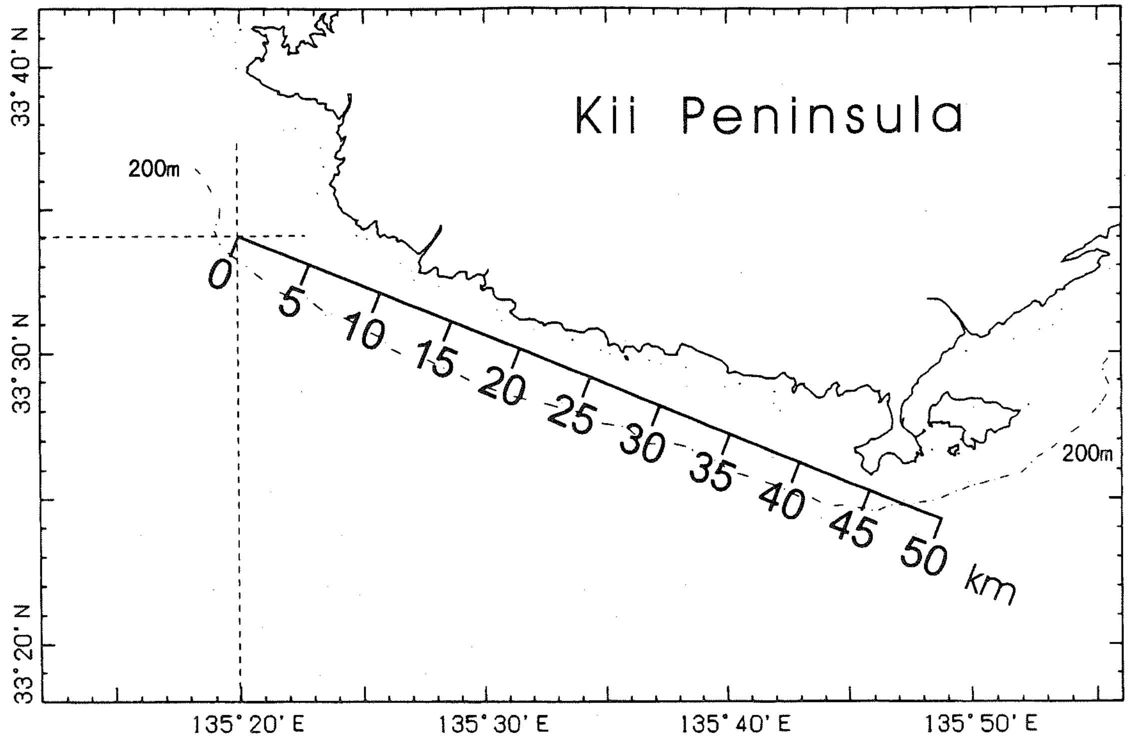

Fig. 6. The standard line where the current divergence was determined.

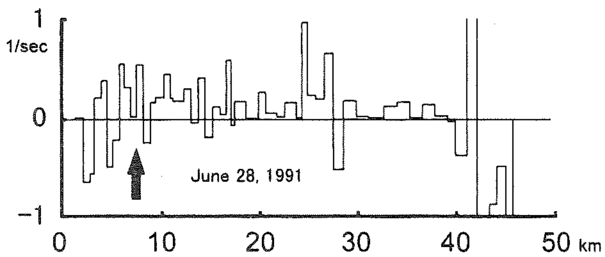

Fig. 7. An example of the distribution of the divergence value (in 1/sec) estimated along the standard line (June 28, 1991).

4. Current Divergence along the Standard Line Parallel to the Coast

4.1 Distribution of the current divergence along the standard line and its yearly variation

Though the ADCP observation lines run approximately following the 100 m depth contour, details of their positions and directions varied between observations. We standardized the line which passes the point (33°34′ N, 135°20′ E) and runs in the direction of 112° from north as shown in Fig. 6. The distance measured from this point along the standard line is used in the following discussions.

Each observation line was projected onto the standard line, and the velocity components along and perpendicular were calculated for each observed velocity datum. Then, the divergence of the alongshore component was calculated by dividing the difference of the current velocity between each successive observation point by the separation distance. An example of the distribution of the divergence values along the standard line is shown in Fig. 7 for the observations made on June 28, 1991.

The obtained divergence values usually fluctuate considerably in both edge regions from 0 to 5 km and from 40 km to 50 km. The coast line runs rather in a north-south direction to the west of Cape Ichie (see Fig. 1), and the observation line also leaves from the standard line in the region between 0 to 5 km. The current structure in the vicinity of Cape Shionomisaki is usually very complex as it receives direct influence from the strong current zone of the Kuroshio. This appears to result in large fluctuations in our estimated divergence in the region to the east of 40 km. Hereafter, we exclude these two edge regions form our discussion.

The position of the bifurcation point determined visually is shown with a bold vertical arrow in Fig. 7. Generally speaking, the bifurcation point does not necessary to coincide with the region where the divergence value is largest, and the divergence value does not show any clear peak, and

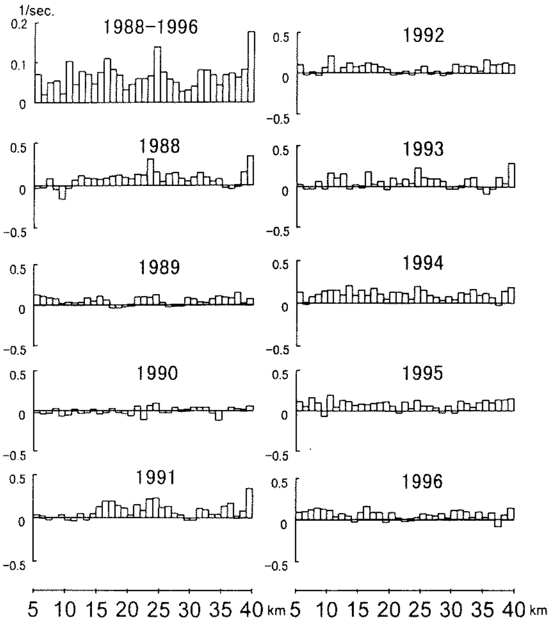

Fig. 8. Distributions of the current divergence (in 1/sec) along the standard line averaged for each year. The distribution averaged for the whole analyzed period from 1988 to 1996 is also given in the first (top-left) figure.

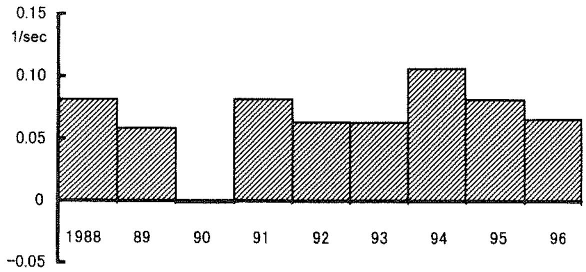

Fig. 9. Temporal variation of the current divergence (in 1/sec) yearly averaged over the standard line.

is distributed almost evenly between 5 and 40 km.

As the observation points are not distributed uniformly, the divergence values were interpolated so as to get data at an equal interval of 1 km. The resultant data set for each of 1 km interval was used in the following analysis.

The distributions of the yearly averaged current divergence along the standard line are shown in Fig. 8 for each year. The distribution averaged for the whole period analyzed from 1988 to 1996 is given in the first (top-left) figure of Fig. 8. Although the distribution is variable between years, positive values are dominant except for 1990 and no conspicuous peak position is observable in these figures. The

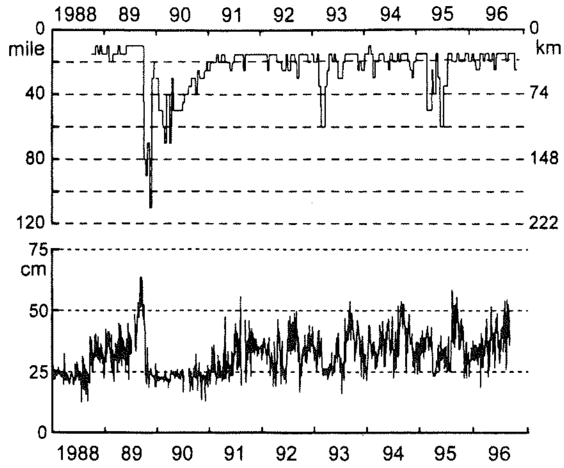

Fig. 10. Temporal variations of the position of the Kuroshio axis measured southward from Cape Shionomisaki (in nautical miles and in km), and the sea level difference between Kushimoto and Uragami (in cm: see Fig. 1 for the positions of these tide gauges). This sea level difference is usually used for monitoring the Kuroshio path off the Kii Peninsula (e.g., Kawabe, 1980).

distribution averaged for the whole period analyzed indicates that a positive divergence value is commonly seen along this coast, and its value is almost in same magnitude from Cape Ichie to the vicinity of Cape Shionomisaki.

The yearly variation of the current divergence averaged over the analyzed region (5–40 km) is shown in Fig. 9. The divergence value for 1990 is very small compared with those for other years and nearly zero (a negative value is seen only for this year). In Fig. 10, temporal variations of the position of the Kuroshio axis measured southward from Cape Shionomisaki and the sea level difference between Kushimoto and Uragami (see Fig. 1 for the positions of these tide gauges). This sea level difference is usually used for monitoring the Kuroshio path off the Kii Peninsula (e.g., Kawabe, 1980): the sea level difference is small when the Kuroshio flows in a meandering path and large when in a straight path. A Large Meander of the Kuroshio occurred during the period from October 1989 to January 1991, so the exceptional nature in 1990 in Fig. 9 seems to be attributed to the Large Meander. A typical Convergence Current observed on May 9, 1995 shown in Fig. 2 is another example of the influence of the Large Meander: the Kuroshio flowed in the meander path at that time though this meander persisted only for a short period (Fig. 10). This also suggests the relation between the current pattern and the flow nature of the Kuroshio. The relation among the current pattern, the averaged current divergence, and the position of the Kuroshio path will be discussed in the following sub-section.

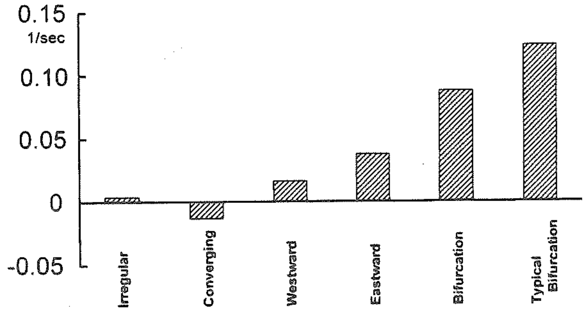

Fig. 11. Current divergence averaged for each flow pattern.

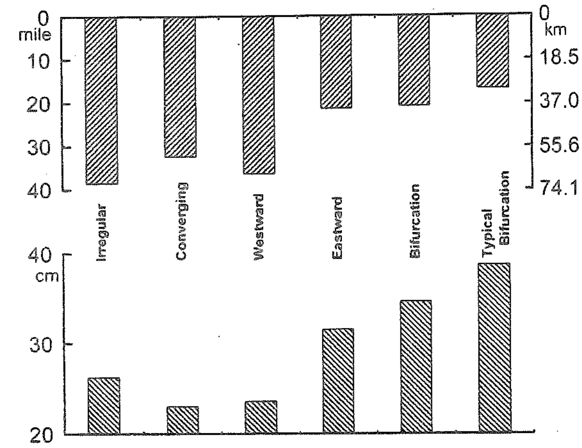

Fig. 12. Position of the Kuroshio axis measured southward from Cape Shionomisaki and the sea level difference between Kushimoto and Uragami for each current pattern.

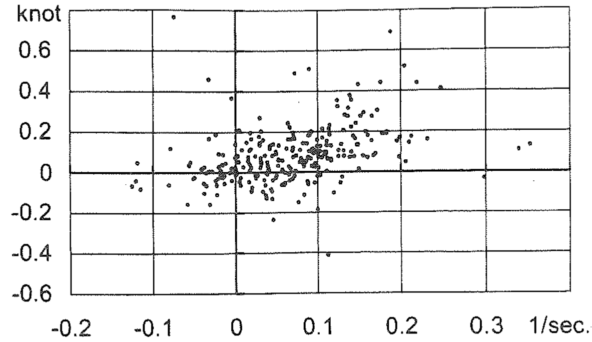

Fig. 13. Scattering diagram between the averaged onshore component (in knot) and the current divergence (1/sec).

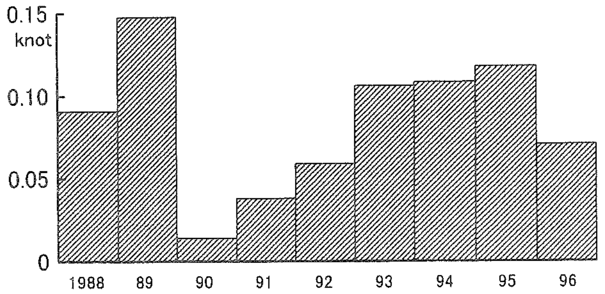

Fig. 14. Temporal variation of the onshore current component (in knot) yearly averaged over the standard line.

4.2 Relation of the current patterns to the current divergence and to the position of the Kuroshio axis

The current divergence was averaged for each flow pattern and shown in Fig. 11. The divergence value is large for the Bifurcation Current (especially for the Typical Bifurcation current). The average values are also positive for the Eastward Current and the Westward Current, although they are considerably smaller. It should be noted that a negative value appears only for the Converging Current. The value is almost zero for the Irregular Current.

The position of the Kuroshio axis measured southward from Cape Shionomisaki and the sea level difference between Kushimoto and Uragami were also averaged for each current pattern and shown in Fig. 12. The results also indicate the close relation of the current pattern to the position of the Kuroshio: the Bifurcation Current and the Eastward Current frequently appear when the Kuroshio is flowing in a straight path, and the Westward Current and the Convergence current when the Kuroshio in a meander path. Judging from Fig. 12, the Eastward Current has a nature similar to the Bifurcation Current, and the Westward Current to the Convergence Current.

5. Onshore-Offshore Current Component

As the current is bounded by the coast line, the positive divergence value suggests the existence of an onshore current. The current component perpendicular to the standard line might be a more direct quantity which determines the current pattern in the nearshore region. We also calculated the onshore component averaged over the region (5–40 km) for each observation.

The correlation between the averaged onshore component and the averaged current divergence is shown in Fig. 13. Although a positive correlation can be seen (the correlation coefficient is 0.36), the data points are widely scattered.

The temporal variation of the yearly average of the onshore current component is shown in Fig. 14. The onshore component is considerably smaller for 1990 than for other years. However, the averaged onshore component varies considerably between years when the Kuroshio flowed in a straight path (all years analyzed except 1990) in comparison with the case of the current convergence along the standard line (Fig. 9). Thus the correlation of the onshore component to the position of the Kuroshio axis is less clear.

Generally, even when the Bifurcation Current was found, offshore currents are frequently observed and the onshore-offshore current component appears very changeable both temporally and spatially. The offshore current component seems to be strongly influenced by the position of the selected standard line. In order to investigate the detailed structure and the variability of the Bifurcation Current, we are planning additional observations by using the R/V Seisui-maru of the Mie University. In a preliminary cruise, we found large vertical shear in the onshore component; the onshore current was observed in the surface layer, but the current near the bottom is offshoreward, while the alongshore component was almost unchanged vertically.

6. Concluding Remarks

We showed that the Bifurcation Current is a common current feature along the southwest coast of the Kii Peninsula, and its occurrence frequency is about 70% in our analyzed period. The current pattern is related to the position of the Kuroshio path, and it is shown that the Bifurcation Current frequently occurs when the Kuroshio flows in a straight path off the Kii Peninsula. The period of the Kuroshio Large Meander is relatively short in our analyzed period, but it appears that the Convergence Current may occur when the Kuroshio flows in a meandering path. The occurrence frequency of the Bifurcation Current might be smaller than the value mentioned above if a much longer meandering period is included in the analyzed period.

The bifurcation position appears to be very changeable, and it occurs at anyplace between Cape Ichie and the vicinity of Cape Shionomisaki. The current divergence along the standard line indicates that the divergent value is usually positive, and its magnitude is distributed evenly along the analyzed coast. More elaborated observations are necessary in order to clarify the structure and variability of the Bifurcation Current

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