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Sea Level Variations along the South Coast of Japan and the Large Meander in the Kuroshio*

Masaki KAWABE**

Abstract: Sea level variations from 1974 through 1976 at 9 stations on the south coast of Japan (from west to east, Aburatsu, Tosa-shimizu, Muroto-misaki, Kushimoto, Uragami, Owase, Toba, Maisaka and Omaezaki) were analysed in relation to the large meander in the Kuroshio.

From May to July in 1975, a small maximum in sea level variation was observed at every station west of Cape Shionomisaki from Aburatsu to Kushimoto. It propagated eastward along with the eastward propagation of a small meander in the Kuroshio until it reached Kushimoto, when the sea levels at Uragami and Owase started to rise sharply. This remarkable rise appeared at all stations in August when a large meander in the Kuroshio was established. The mean sea level at the stations east of Cape Shionomisaki from Uragami to Omaezaki rose by about 10 cm. The difference in sea level variations between the regions east and west of Cape Shionomisaki, which had been present before the rise, disappeared. A similar characteristic of sea level variation was also found in the generation stage of the large meander in 1959.

The sea level variations along the south coast of Japan indicate that, prior to the generation of the large meander, the small meander in the Kuroshio was generated southeast of Kyushu and propagated eastward and that, just when this meander reached off Cape Shionomisaki, a large scale oceanic event covering over the whole region of the south coast of Japan occurred. This large scale event seems to be one of the necessary conditions for the generation of the large meander in the Kuroshio off Enshû-nada.

1. Introduction

It is known that the path of the Kuroshio south of Japan can be classified into two stable types both of which persist for several years; one is the straight path parallel to the coast of Japan (Fig. 1a), and the other is the meandering path which accompanies a large cold eddy with a diameter of about 200 km off Enshû-nada and Cape Shionomisaki (Fig. 1b).

UDA (1937) studied the large meander off Enshû-nada which appeared in 1934 and considered it to be an abnormal state of the path of the Kuroshio. Since then, the subject has been of great interest to oceanographers; reviews of these studies are given by MASUZAWA (1965), NITANI (1972) and YOSHIDA (1972). The large meander in the Kuroshio occurred 4 times after 1934: from 1934 to 1944, from 1953 to 1955, from 1959 to 1963 and from 1975 to the present.

In the case of the meander from 1959 to 1963 YOSHIDA (1961) traced the change of the path of the Kuroshio prior to the generation of the large meander by using hydrographical data and found that a small meander was first generated southeast of Kyûshû, moved eastwards, grew rapidly after passing Cape Shionomisaki, and then became stationary off Enshû-nada. However, the time interval of available hydrographical data was not short enough to investigate details of the generation stage of the large meander.

To obtain supplementary information on variation of the path of the Kuroshio, continuous data of coastal sea level from tide gauges were used by several investigators (MORIYASU 1961; TSUMURA 1963; KONAGA 1968). They found that a significant difference exists between the sea level variation west of Cape Shionomisaki and that east of the cape when the Kuroshio takes its straight path, whereas no difference is seen when the Kuroshio takes its meandering

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** Geophysical Institute, University of Tokyo, Bunkyô-ku, Tokyo 113, Japan

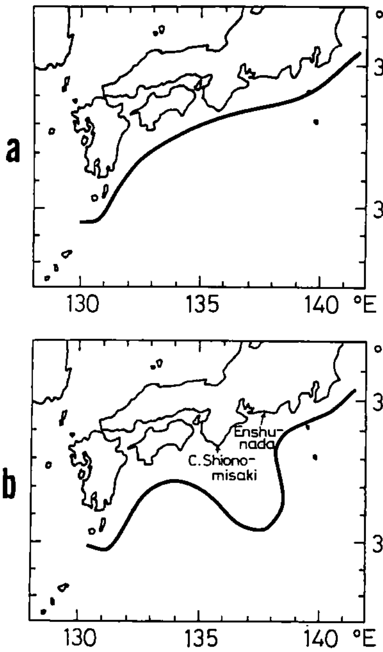

Fig. 1. The two types of path of the Kuroshio south of Japan; a. the straight path, b. the meandering path.

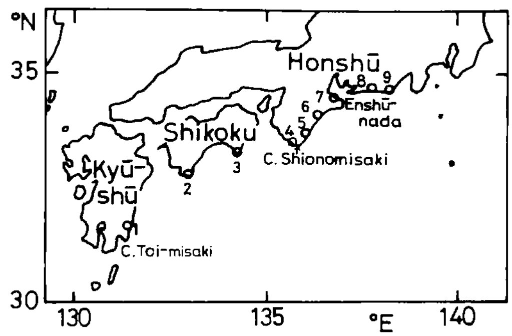

Fig. 2. Locations of the tidal stations; 1. Aburatsu, 2. Tosa-shimizu, 3. Muroto-misaki, 4. Kushimoto, 5. Uragami, 6. Owase, 7. Toba, 8. Maisaka, 9. Omaezaki.

path off Enshû-nada. They suggested that the presence of the large meander in the Kuroshio could be detected using sea level data from the south coast of Japan. Thus we can expect that a detailed analysis of sea level data should give us some useful information on the generation of the large meander.

In this paper, sea level data at 9 tidal stations from 1974 through 1976 are analysed together with hydrographical data. Differences in sea level variation before and after the generation of the large meander are analysed, and sea level variations in the generation stage of the large meander are examined in detail.

2. Data

Data of sea level at 9 tidal stations on the south coast of Japan from 1974 through 1976 were used. Four stations: Aburatsu, Tosa-shimizu, Muroto-misaki and Kushimoto, are lotated west of Cape Shionomisaki, and the rest: Uragami, Owase, Toba, Maisaka and Omaezaki, are located east of the cape (Fig. 2). In the present paper, the former stations are referred to as the western stations, and the latter as the eastern stations. I used daily mean values (mean of 24 hourly readings) in the Tidal Observations published annually by the Japan Meteorological Agency.

Values of sea level were corrected for barometric pressure based on hydrostatic approximation. Values of barometric pressure were obtained from the Monthly Report of the Japan Meteorological Agency. The values of sea level were referred to the Mean Sea Level of Tokyo Bay (T.P.) under a barometric pressure of 1,000 mb. In order to exclude seasonal and fortnightly variations in sea level, anomalies of corrected sea level from predicted values were calculated.

I divided each month into six intervals of five days. The values of daily mean sea level were averaged for each interval, although the number of days for the last interval is different each month. I refer to this average as the 5-day mean for simplicity. These intervals were used for easy comparison of the sea level data with semimonthly hydrographical data. The running mean of five successive values of the 5-day mean were then calculated, and are referred to as the 25-day running mean.

3. Sea level variations along the south coast of Japan from 1974 through 1976

The variations of daily mean sea level anomalies at 9 tidal stations on the south coast of Japan from 1974 through 1976 are shown in Fig. 3. The rise and fall of sea level is often simultaneous along the south coast of Japan, and we can expect that these simultaneous

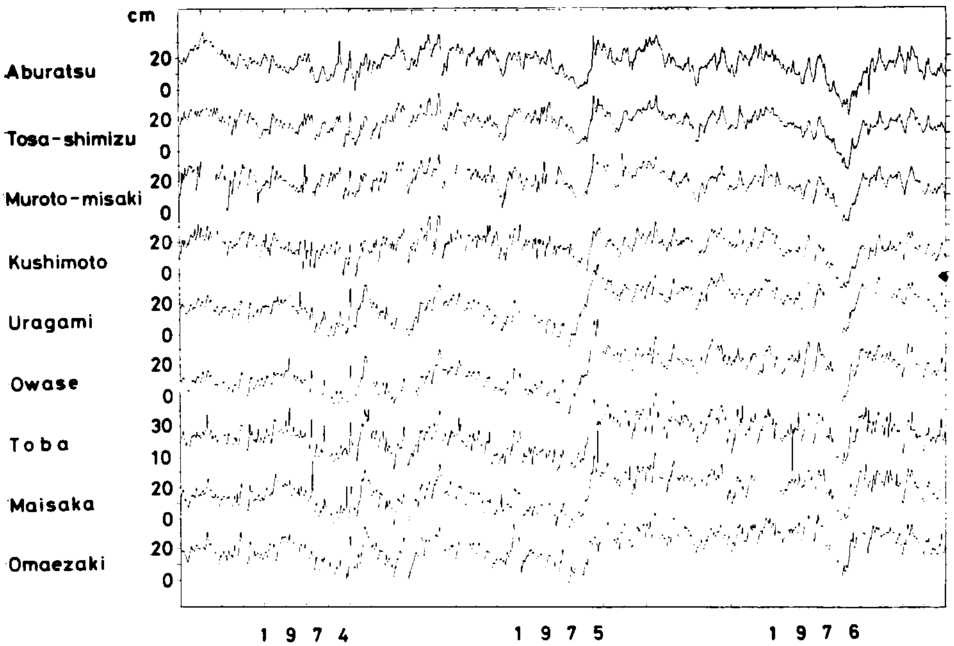

Fig. 3. Variations of daily mean sea level anomalies on the south coast of Japan from 1974 through 1976 referred to T.P. under a barometric pressure of 1,000 mb.

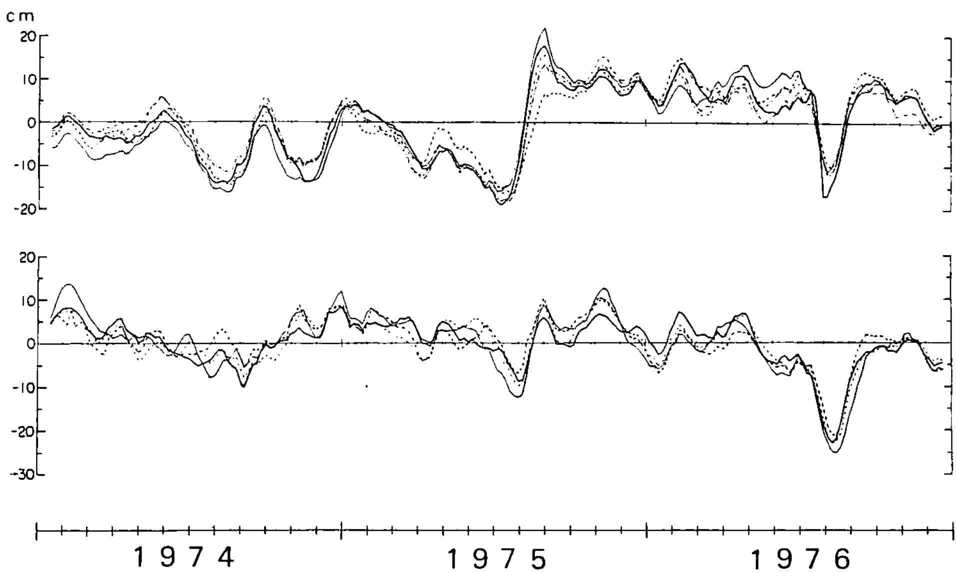

Fig. 4. Variations of 25-day running means of the sea level anomalies on the south coast of Japan from 1974 through 1976. Upper: eastern (━━ Uragami, —— Owase, —·— Toba, ---- Maisaka, ······ Omaezaki). Lower: western (—— Aburatsu, ---- Tosa-shimizu, ······ Muroto-misaki, ━━ Kushimoto). The mean value of each curve for the whole three-year period is taken as the zero point of the ordinate.

Table 1. Maximum cross correlation coefficients of 5-day means and 25-day running means of the sea level anomalies from the predicted values between Tosa-shimizu and Kushimoto, Kushimoto and Uragami, and Uragami and Toba.

		Jan., 1974 ~Jul., 1975	Aug., 1975 ~Dec., 1976	Jan., 1974 ~Dec., 1976
Tosa-shimizu—Kushimoto	5-day mean	0.805	0.940	0.893
	25-day running mean	0.822	0.964	0.922
Kushimoto—Uragami	5-day mean	0.535	0.901	0.463
	25-day running mean	0.505	0.884	0.349
Uragami—Toba	5-day mean	0.930	0.834	0.928
	25-day running mean	0.941	0.879	0.952

variations represent an oceanic phenomenon of very large horizontal extent. Several prominent events can be found common to all the records: for example, the rise in sea level in early August, 1975 and the drop in sea level in August, 1976. The former is most interesting, because the variation after this rise looks somewhat different from that before this rise, and because a large meander in the Kuroshio was formed off Enshû-nada immediately after this rise. Another notable feature in Fig. 3 is the similarity of the variation among the records at the four western stations from Aburatsu to Kushimoto, and among the records at the five eastern stations from Uragami to Omaezaki. Kushimoto is located just west of Cape Shionomisaki, and the distance between Kushimoto and Uragami is only about 15 km. On the other hand, the distance between Aburatsu and Kushimoto is about 450 km and that between Uragami and Omaezaki is about 250 km.

To show the characteristics mentioned above, the 25-day running mean of the sea level anomalies for each station is plotted in Fig. 4. The similarity in variations can clearly be seen among the eastern and western stations, respectively. The notable differences between the two groups are;

(1) The rise in early August, 1975 is much larger for the eastern stations than for the western stations.

(2) The mean levels after this rise are about 10 cm higher than those before the rise for the eastern stations, while no such difference in height can be seen for the western stations.

(3) Before the rise, sea level variations with periods of 102 days and 1 year are dominant for the eastern and the western stations, respectively. After the rise, variation with a period of about 70 days is dominant for all stations.

Maximum coefficients of cross correlation for 5-day means and 25-day running means of the sea level anomalies between Tosa-shimizu and Kushimoto, between Kushimoto and Uragami and between Uragami and Toba were calculated (Table 1). No significant time lag is found between any pair of these. Generally speaking, the coefficient is high between the stations in the same group, but is low between the stations in different groups. TSUMURA (1963) already noted a distinct difference in the variation of monthly mean sea level from 1950 to 1962 between the stations east and west of Cape Shionomisaki. However, it should be noted that the coefficient between Uragami and Kushimoto is high if we consider the period after the rise in sea level in early August, 1975 alone. This suggests that, except for the difference in the mean level, the variations of all the stations from Aburatsu to Omaezaki are very similar when the large meander is present off Enshû-nada.

The rise of mean sea level at the stations east of Cape Shionomisaki at the time of generation of the large meander off Enshû-nada in May, 1959 has been discussed by numerous investigators (*e.g.*, MORIYASU 1961; TSUMURA 1963; KONAGA 1968). They mainly analysed the sea level difference between two near-by stations, Kushimoto and Uragami, as the effect of meteorological disturbances on sea level could then be ignored. Recently, OKADA and NISHIMOTO (1978) analysed tidal records along these lines and inferred the presence of a large meander from 1906 to 1912, and from 1917 to 1922, although no other oceanographic data were available for these periods.

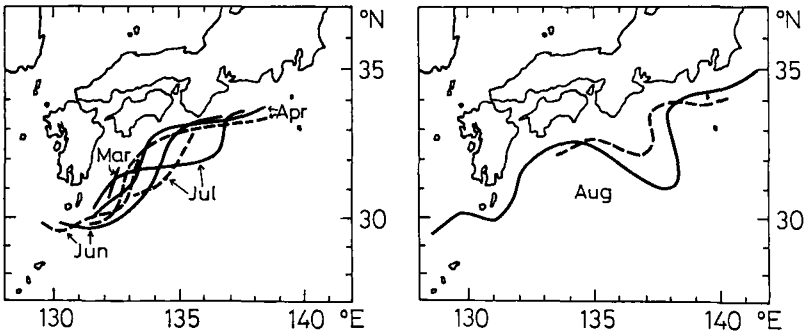

Fig. 5. Change of path of the Kuroshio south of Japan from March to July (left) and in August (right), 1975. Broken line and solid line indicate the path in the first half and the second half of each month, respectively.

4. Sea level variations in the generation stage of the large meander off Enshû-nada in 1975

Fig. 5 shows the change of path of the Kuroshio south of Japan from March to August, 1975 based on the Oceanographic Observation Report issued semimonthly by the Japan Maritime Safety Agency. The path of the Kuroshio in the first half of April shows that a small meander is generated southeast of Cape Toimisaki. The position of the small meander shifts gradually eastward, and its front passes Cape Shionomisaki before the second observation in July. The meander takes up the position of the stationary large meander off Enshû-nada in the first half of August and grows larger in the second half of August. The remarkable rise in early August found in the records of sea level anomalies corresponds to the time just before the large meander is formed off Ensuû-nada.

The curves of the 25-day running mean of sea level anomalies at all the stations are presented in Fig. 6 from April to September, 1975. The most prominent features commonly seen in these records are the sharp rise in sea level in early August and the maximum (marked by × in the figure) in the sixth interval of August. Another maximum (marked by ●) can be seen for every record in late April. The relative height of the former to the latter is larger for the eastern stations than for the western stations. This reflects the greater rise in sea level at the eastern stations than that at the western stations during the period of presence of the large meander off Enshû-nada. The time of the minimum (marked by ○) between these two maxima varies: occurring at the sixth interval of July for the western stations, the second interval of July for the 2 central stations and the fourth interval of July for the 3 easternmost stations.

Another notable difference in the shape of the curves between the western and eastern stations lies between the maximum in late April and the minimum in July. A monotonous decrease in sea level is seen for the eastern stations, while a secondary maximum appears for the western stations as shown by vertical arrows in the figure. This secondary maximum clearly travels from west to east. OKADA (1977) analysed values of 5-day mean sea level from May to August, 1975 and pointed out that the highest sea level among the western stations moved eastward with the front of the meander in the Kuroshio. The secondary maximum in Fig. 6 corresponds roughly to the peak in spatial variation curves of 5-day means discussed by OKADA (1977). Movement of the disturbance accompanying the secondary maximum in sea level may be one of the reasons for the large variability in the time of the minimum in July. Note that the time of the minimum is later for the western stations than for the eastern stations. The shape of the disturbance in curves of coastal sea level accompanied by the small meander in the Kuroshio should be determined by differences between the eastern and western stations if the long-term background variations were common to all the stations. The difference in the 25-day running mean of sea level anomalies between Kushimoto and Uragami is given by the bottom curve in Fig. 6. The portion where the difference is larger than that in April and May is hatched, and this portion may represent the temporal pattern of the disturbance at Kushimoto. Although such an estimate for the disturbance is very crude and gives only an outline of it, the magnitude of the disturbance is only about 1/3* of that of the rise in sea level for

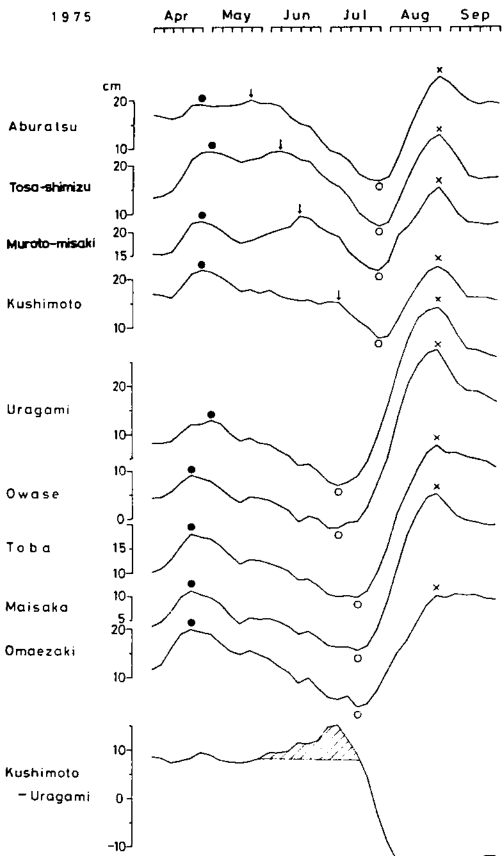

Fig. 6. Variations of 25-day running means of sea level anomalies on the south coast of Japan and of the difference in these values between Kushimoto and Uragami from April to September in 1975 referred to T. P. under a barometric pressure of 1,000 mb. ×, ●, ○ and ↓ point to maxima and a minimum in sea level discussed in the text, and see the text about the hatched portion.

* Since the difference in the predicted sea level between Kushimoto and Uragami itself varies by about 10 cm between maximum and minimum, the estimate for the magnitude of the disturbance is not precise.

the eastern stations during the period when the large meander is present.

The sea level difference between Kushimoto and Uragami is often used to detect the presence of the large meander off Enshû-nada, because it may reflect the rise in sea level east of Cape Shionomisaki when the large meander is present (for example, KONAGA 1968; OKADA and NISHIMOTO 1978). Fig. 6 leads to a conclusion that the transition from "non-meandering" to "meandering" occurred in the period from the second interval of July to the fourth interval of August in 1975. However, the first half of the decrease from the second interval to the sixth interval of July represents not only the rise in sea level at Uragami but also the fall in that at Kushimoto. Therefore, if the difference in the time of the minimum in the two curves at Kushimoto and Uragami was caused by a moving disturbance, the disturbance would have the effect of exaggerating the negative slope of the curve of sea level difference. On the other hand, in the latter half from the sixth interval of July to the fourth interval of August, the rise in sea level at Kushimoto should have the effect of decreasing the negative slope of the curve of sea level difference. The difference in daily mean sea level between Kushimoto and Uragami increases remarkably just before the transition from mid-July to early August, and, therefore, the transition is exaggerated (Fig. 7). The remarkable increase just before the transition is probably caused by the moving disturbance as discussed above. Another prominent feature is the very small variability of the curve after the transition. This suggests that

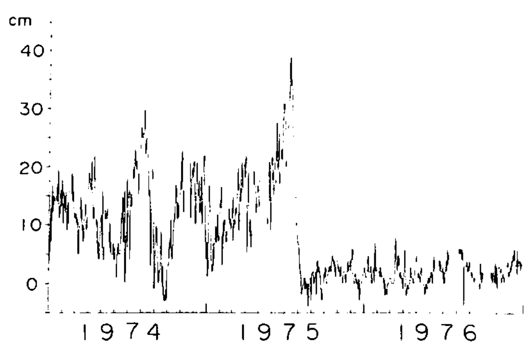

Fig. 7. Variation of the difference in daily mean sea levels between Kushimoto and Uragami from 1974 through 1976.

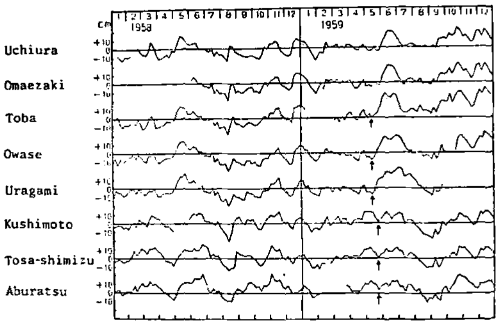

Fig. 8. Variations of the 5-day mean sea level anomalies on the south coast of Japan from 1958 through 1959 (after OKADA, 1977). Arrows point to falls in sea level discussed in the text.

the variations of sea level at Kushimoto and Uragami are very similar to each other when the large meander is present off Enshû-nada.

It was also found that in the case of the generation stage of the large meander in May, 1959, the rise in sea level occurred not only east of Cape Shionomisaki but also west of the cape, though the magnitude of the rise at the latter was much smaller than that at the former (Fig. 8). The time of the minimum (marked by arrows) prior to the rise occurred considerably later for Aburatsu, Tosa-shimizu and Kushimoto than for Uragami, Owase and Toba. This difference may be due to some disturbance which raises sea level at the western stations only.

OKADA and NISHIMOTO (1978) analysed sea level differences between Kushimoto and Nagoya from 1913 through 1976 and between Kushimoto and Aburatsubo from 1895 through 1976 and detected the occurrence of a large meander off Enshû-nada six times during the analysed period.* They pointed out that the transition from "non-meandering" to "meandering" was always defined clearly in the curves of sea level difference, while the transition from "meandering" to "non-meandering" was usually vague and sometimes hard to be detected from the curves of sea level difference. This suggests that a disappearance of a large meander in the Kuroshio is not led by such a moving disturbance as has been shown in the generation stage of the large meander in 1975.

5. Discussion—Conditions for the generation of the large meander off Enshû-nada

It is concluded that the small meander generated southeast of Kyûshû travels eastward and reaches the region off Cape Shionomisaki just before the large meander off Enshû-nada is generated. However, it is hard to conclude that the cause of the generation of the large meander can be attributed to the small meander generated off the coast of Kyûshû alone, as the event such as found in early August, 1975, which is characterized by a remarkable rise in sea level, is observed almost simultaneously at all the stations along the south coast of Japan. It should also be noted that the moving disturbance west of Cape Shionomisaki has a limited horizontal scale, while the rise in sea level which occurs simultaneously at the eastern stations when the disturbance reaches the region off Cape Shionomisaki has a large horizontal extent. Therefore, it may be possible to consider that an oceanic condition of such a large extent is a cause of the generation of the large meander. The disturbance traveling along the coast west of Cape Shionomisaki probably acts only as a trigger for the transition.

The rise in sea level as seen in early August, 1975 presumably represents some large scale oceanic condition capable of generating the large meander off Enshû-nada. Such a large scale oceanic condition would provide an appropriate environment for the small traveling meander to grow into the large stationary meander off Enshû-nada on passing Cape Shionomisaki. The large meander generated then maintains the rise in sea level along the coast east of Cape Shionomisaki. If no such oceanic condition exists south of Japan, the small meander will not grow but will continue traveling eastward or die out. If, on the other hand, such an oceanic condition exists but no small meander is formed, the sea levels after the rise in early August, 1975 should return quickly to their height before the rise.

Since we have no idea of the physical nature of "the large scale oceanic condition capable of

* Besides the six occurrences of the large meander, they also detected three occurrences of a semi-large meander, the life time of which is at most about one year. The arguments presented here are also applicable to these semi-large meanders.

generating the large meander" at the present stage, we cannot give any conclusive remarks on the generation of the large meander off Enshû-nada. However, I hope that my results will give some useful information to those who investigate the generation mechanism of the large meander in the Kuroshio.

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日本南岸の潮位変動と黒潮大蛇行

川 辺 正 樹*

要旨: 日本南岸の9地点（西から，油津，土佐清水，室戸岬，串本，浦神，尾鷲，鳥羽，舞阪，御前崎）における1974年から1976年までの潮位変動を解析し，黒潮大蛇行との関係を考察した．

1975年5月から7月にかけて，串本以西にのみ潮位の小さなピークがみられ，黒潮の小蛇行の東進とほぼ一致して西から東に伝播した．ピークが串本に到達すると，浦神と尾鷲の潮位は急激に上昇し始めた．この上昇は，大蛇行の形成された8月には全地点でみられ，それ以後，浦神以東の平均潮位は約10cm高まり，串本・浦神間にあった潮位変動の相違はなくなった．こうした潮位変動の特性は，1959年の大蛇行形成時にも見出すことができる．

日本南岸の潮位記録は，1975年8月の大蛇行の発生に先立って小蛇行が九州沖から東進し，潮岬沖に達した時に，日本南岸全域にわたる大規模な海況変動のあったことを示している．この大規模な海況変動は，黒潮大蛇行の形成に必要な条件の一つと考えられる．

* 東京大学理学部地球物理学教室
〒113 東京都文京区弥生 2-11-16