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Monitoring of Position of the Kuroshio Axis in the Tokara Strait Using Sea Level Data

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Properties of the index of position of the Kuroshio axis in the Tokara Strait, named the Kuroshio position index (KPI), were examined using sea-level data during 1984–92. The index is KPI = $(X + M_x)/(Y + M_y)$ where $X(Y)$ is the anomaly of sea-level difference of Nakanoshima (Naze) minus Nishinoomote from the 1984–92 mean $M_x(M_y)$. The correlation with the latitude of the Kuroshio axis in the Tokara Strait concluded that the KPI with $M_x/M_y = 0.83$ and realistic M_y (100 ± 40 cm) best indicates the position of the Kuroshio axis in the strait. The KPI with $M_x = 83$ cm and $M_y = 100$ cm was newly called the KPI as the best index. Using daily values of this KPI, the relation between the position of the Kuroshio in the strait and the large meander of the Kuroshio shown by Kawabe (1995) was confirmed and studied in detail. A large meander forms (ends) 3.3 (5.1) months after a northward (southward) shift of the Kuroshio in the Tokara Strait. Yet, a temporary southward shift with a duration of ten to twenty days does not finish the large-meander (LM) path. At the LM formation, a small meander southeast of Kyushu begins to move eastward associated with the northward shift. The processes of LM formation and decay are started by the meridional move of the Kuroshio axis in the Tokara Strait. The Kuroshio axis at the FES line during the LM path is located farther north by 7′ latitude than that during the non-large-meander (NLM) path. The latitude during the LM formation (decay) stage is a little higher (lower) than that during the LM (NLM) period, though the Kuroshio still takes an NLM (LM) path.

1. Introduction

The Kuroshio in the North Pacific flows from the East China Sea into the southern region of Japan, passing through the Tokara Strait between Amami-oshima and Tanegashima. The Kuroshio south of Japan takes three typical paths alternately, the typical large-meander (LM) path and the nearshore and offshore non-large-meander (NLM) paths, and the transitions between them are characterized by the property that the typical LM path is formed from the nearshore NLM path and is transformed into the offshore NLM path (Kawabe, 1985, 1986, 1995) (Fig. 1). The Kuroshio in the Tokara Strait changes the position of the current axis meridionally, and the north-south move of the Kuroshio axis is closely related with the variation of path of the Kuroshio between LM and NLM paths, together with volume transport and current velocity of the Kuroshio; the LM path occurs when the Kuroshio is located north in the Tokara Strait during the periods of large volume transport and current velocity (Kawabe, 1995). Moreover, the transitions from the NLM path to the LM path and from LM to NLM are associated with the northward and southward shifts of the Kuroshio axis in the strait, respectively. The meridional move of the Kuroshio axis in the Tokara Strait seems to be one of the essential factors for

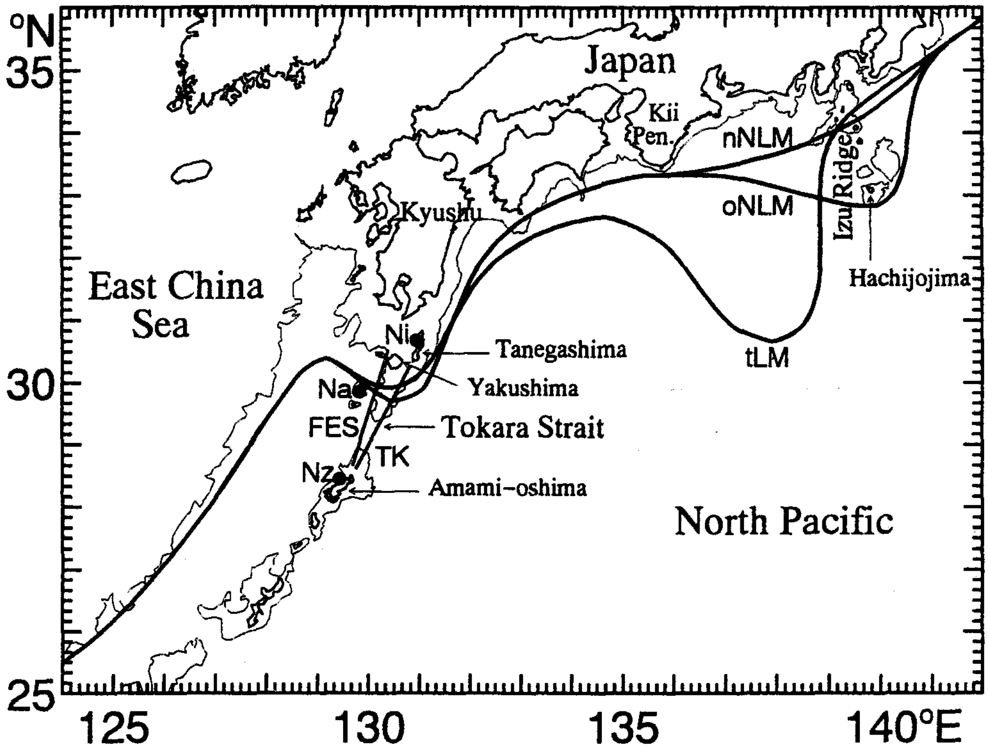

Fig. 1. Tide stations at Naze (Nz), Nakanoshima (Na) and Nishinoomote (Ni), and typical paths of the Kuroshio (Kawabe, 1985): nNLM. the nearshore non-large-meander (NLM) path, oNLM. the offshore NLM path, tLM. the typical large-meander (LM) path. The FES and TK lines crossing the Tokara Strait are the lines of hydrographic observation of the Kagoshima Prefectural Fisheries Experimental Station and the Nagasaki Marine Observatory, respectively. Thin lines indicate isobaths of 500 m.

determining the current path of the Kuroshio south of Japan, and its monitoring is important for the study of the Kuroshio.

Kawabe (1995) introduced an index of position of the current axis of the Kuroshio in the Tokara Strait, named the Kuroshio position index (KPI). It was defined by the ratio of the sea-level difference of Nakanoshima minus Nishinoomote to that of Naze minus Nishinoomote, namely

$$\mathrm{KPI} = \frac{X + M_x}{Y + M_y} \tag{1}$$

where X is the anomaly of the sea-level difference of Nakanoshima minus Nishinoomote from the long-term average, Y the same as X but for Naze minus Nishinoomote, M_x and M_y the long-term average of the respective sea-level differences. The denominator of KPI is expected to indicate a surface volume transport of whole of the Kuroshio, while the numerator is that of the northern part of the Kuroshio north of Nakanoshima since the Kuroshio flows around this island. Therefore, the KPI is the ratio of the northern part to the whole of surface transport of the

Kuroshio and is expected to indicate the position of the Kuroshio axis approximately. The normalization by the whole of surface transport of the Kuroshio is a devised point of this index.

A serious problem to estimate the KPI is an estimate of the absolute values of the sea-level differences, because the datum-line heights of tide gauges at the islands are unknown. In other words, the absolute values of the long-term means M_x and M_y in Eq. (1) cannot be estimated. Kawabe (1995) assumed M_x and M_y as 50 cm and 100 cm, respectively, and confirmed that the KPI with these values is well correlated with the latitude of the Kuroshio axis at the TK line (Fig. 1). However, the characteristics of KPI are not yet examined in detail about the dependence on the values of M_x and M_y and how better than the sea levels or sea-level differences in the Tokara Strait.

The present paper clarifies the characteristics of KPI and provides the best index of position of the Kuroshio in the Tokara Strait (Section 3). Furthermore, using daily values of the best index, the position of the Kuroshio axis is examined in detail in terms of the relation with the occurrences of large meander of the Kuroshio (Section 4). In the other sections, the data and data procedures are described (Section 2), and the results are summarized (Section 5)

2. Data

Hourly data of sea level at Naze, Nakanoshima, and Nishinoomote from 1984 through 1992 were used (Fig. 1). The short-term components of periods less than 30.3 hours were filtered out by a digital filter designed on a basis of Thompson (1983) without any change of long-term components more than 97.3 hours (Fig. 2). Daily means were calculated from the filtered hourly data and corrected for barometric pressure. The anomalies of daily-mean sea levels from the average between 1984 and 1992 were analyzed.

The sea levels are measured by the Hydrographic Department, Japan Maritime Safety Agency, and the data were supplied by the Japan Oceanographic Data Center. Daily mean data of barometric pressure at Naze and Tanegashima were obtained from the Monthly Report of the

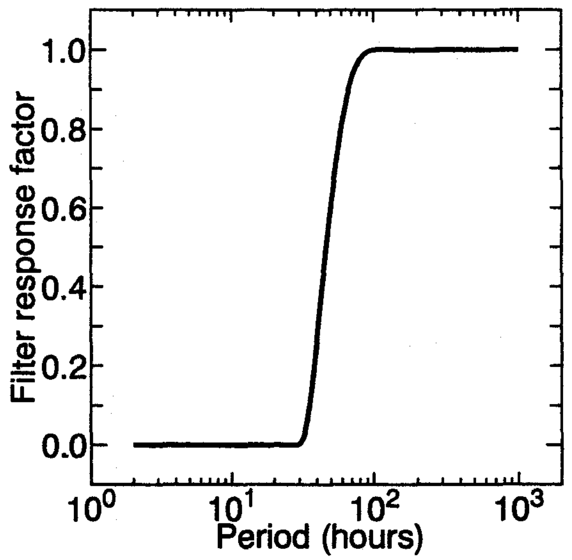

Fig. 2. Response factors of the digital filter used for the sea levels with respect to periods of variation. The power is full at periods longer than 97.3 hours and zero at periods shorter than 30.3 hours.

Meteorological Observation issued by the Japan Meteorological Agency and were used for the correction of sea level at Naze and Nishinoomote, respectively. Daily mean barometric pressures at Naze were also used for sea levels at Nakanoshima.

To detect the position of the Kuroshio axis at the sea surface in the Tokara Strait, we used the data of water temperature at a depth of 200 m at the FES and TK lines (Fig. 1) taken quarterly by the Kagoshima Prefectural Fisheries Experimental Station (KPFES) during 1984–91 and by the Nagasaki Marine Observatory during 1987–92, respectively. The data were obtained from the Annual Reports of Fishery Division, KPFES and the Oceanographic Prompt Report of the Nagasaki Marine Observatory.

The knowledge of periods during which the Kuroshio was taking an LM path is important for this study and should be noted at the early part of this paper. The LM periods during 1981–92 are 6 Oct. 1981 – 15 May 1984, 1 Feb. – 18 Jun. 1985, 5 Nov. 1986 – 22 Jul. 1988, and 9 Oct. 1989 – 5 Jan. 1991 (Kawabe, 1995).

3. Best Index of Position of the Kuroshio Axis

Water temperature of 17.2°C at a depth of 200 m is an indicative temperature of the Kuroshio axis at the sea surface in the Tokara Strait and the East China Sea (Yamashiro *et al.*, 1993). Figure 3 shows a distribution of position of the Kuroshio axis at the FES and TK lines determined with this indicative temperature. The Kuroshio axis at the FES line is always located near Nakanoshima between 29°27′ N and 30°14′ N with the mean position at 29°55′ N, a little north of this island. The position at the TK line is between 29°31′ N and 30°05′ N with the mean of 29°48′ N. The north-south move of the Kuroshio axis at the TK line is less than that at the FES line. This is probably because the shoal extending around Yakushima and Tanegashima prevents the Kuroshio at the TK line from shifting to far north. The mean latitude of the Kuroshio axis at the TK line is farther south by 7′ latitude than that at the FES line; the Kuroshio in the Tokara Strait flows east-southeastward on average.

The position of the Kuroshio axis at the FES line is little correlated with sea level at Nishinoomote and is more correlated with those at Nakanoshima and Naze (Table 1). The highest correlation is for Nakanoshima, since the Kuroshio always flows around this island. However, much higher correlation is obtained for the sea-level differences between Naze and Nakanoshima and between Nakanoshima and Nishinoomote, because the seasonal variation of sea level is almost eliminated in the sea-level differences. The correlation of the Kuroshio position with the sea-level difference of Naze minus Nakanoshima is negative, while that with Nakanoshima minus Nishinoomote is positive. This is consistent with the comprehensive character that the mean surface velocity north (south) of Nakanoshima increases (decreases), as the Kuroshio axis shifts northward (Maeda *et al.*, 1993). Particularly high correlation is obtained for the sea-level difference between Naze and Nakanoshima (Fig. 4).

The Kuroshio position index (KPI) defined by Eq. (1) is expected to be a better index than the sea-level differences, since it takes the variation of strength of the whole Kuroshio into consideration. However, the KPI includes an ambiguity of M_x and M_y, since their exact values are unknown because of no measurement of the datum-line heights of tide gauges at the islands. Then the dependence of KPI on M_x and M_y is examined first. The correlation of KPI with latitude of the Kuroshio axis at the FES line, determined with the indicative temperature, increases largely as M_y increases from 20 cm to 40 cm but little changes for larger M_y (Fig. 5). In particular, the correlation in case of M_y more than 60 cm is almost constant for M_x/M_y more than 0.5. Since a realistic range of M_y (the sea-level difference across the Kuroshio current) is 100 ± 40 cm, the

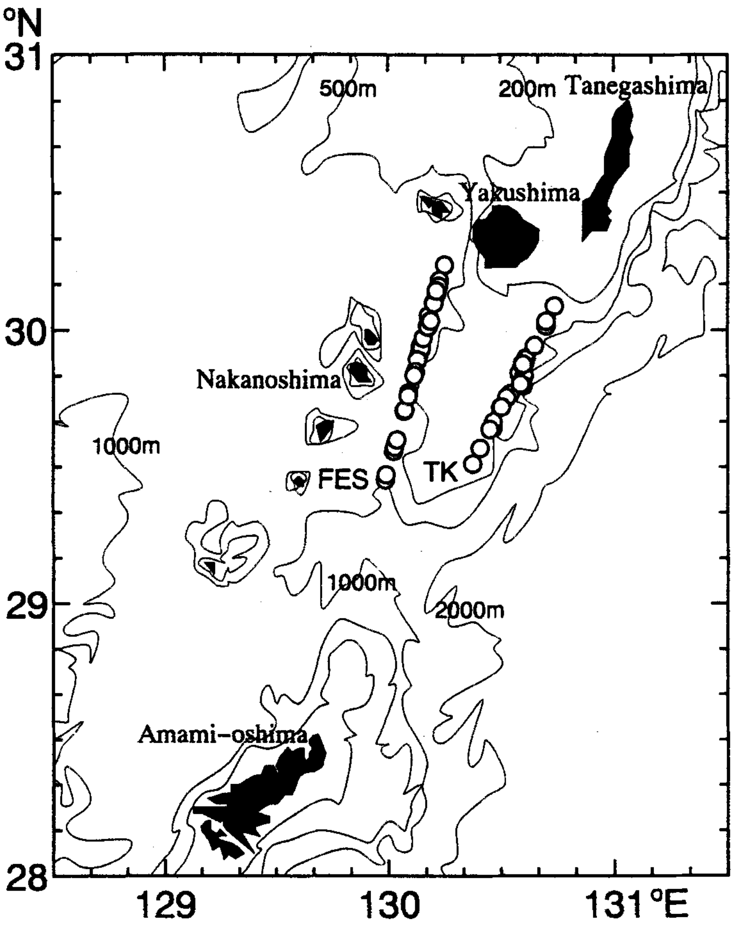

Fig. 3. Plots of current axis of the Kuroshio at the sea surface during 1984–91 at the FES line and during 1987–92 at the TK line. The positions are determined with the indicative water temperature of 17.2°C at a depth of 200 m.

Table 1. Correlations of sea levels and the Kuroshio position index (KPI) with the latitude of the Kuroshio axis at the FES and TK lines in the Tokara Strait. The sea levels are those at Nishinoomote, Nakanoshima and Naze, and their differences of Nakanoshima minus Nishinoomote and of Naze minus Nakanoshima. The KPI is defined by Eq. (1) with M_x = 83 cm and M_y = 100 cm. Numerals in parentheses are numbers of data.

	FES line	TK line
Nishinoomote	–0.16 (30)	0.23 (24)
Nakanoshima	0.47 (30)	0.44 (24)
Naze	–0.40 (30)	–0.16 (24)
Nakanoshima-Nishinoomote	0.62 (30)	0.34 (24)
Naze-Nakanoshima	–0.84 (30)	–0.62 (24)
Kuroshio Position Index (KPI)	0.86 (30)	0.61 (24)

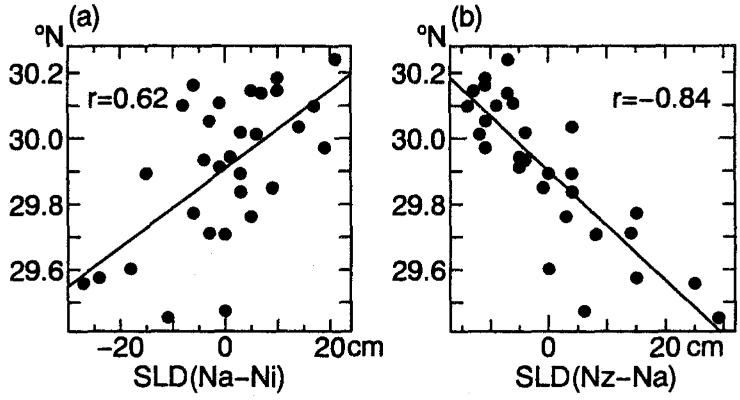

Fig. 4. Correlation diagrams between the latitude of the Kuroshio axis at the FES line and the daily-mean difference in sea level of Nakanoshima minus Nishinoomote (a) and Naze minus Nakanoshima (b). The regression lines computed by the least squares method and the correlation coefficients (r) are shown in the diagrams.

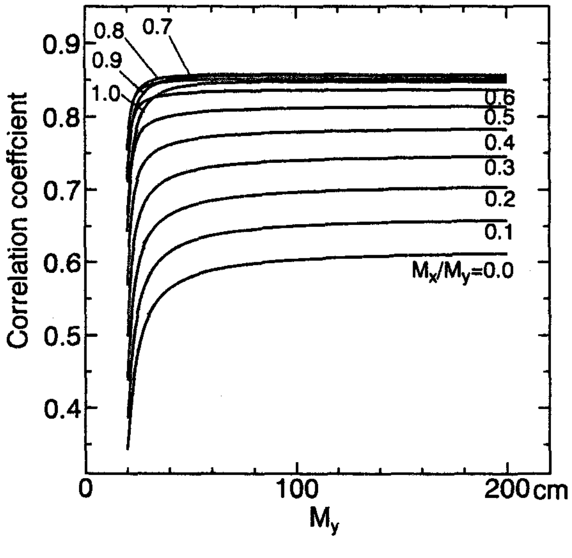

Fig. 5. Correlation coefficients between the Kuroshio position index (KPI) and the latitude of the Kuroshio axis at the FES line, with respect to M_y between 20 and 200 cm and M_x/M_y between 0 and 1.

KPI for M_x/M_y more than 0.5 does not depend on M_y in the realistic range. Figure 5 also shows that the KPI with $M_x = 50$ cm and $M_y = 100$ cm, used in Kawabe (1995), is not best but quite good.

In order to find the best KPI, the correlation between the KPI and the latitude of the Kuroshio axis is calculated for various M_x/M_y in realistic cases of $M_y = 60$, 80, and 100 cm (Fig. 6). The results for $M_y = 120$ and 140 cm are not shown, because they are almost the same as that for $M_y = 100$ cm. All the results for realistic M_y are similar, and are almost the same for M_x/M_y more than 0.6. The correlation is maximum for $M_x/M_y = 0.83$. This is consistent with the distribution of Kuroshio axis in Fig. 3 showing that the Kuroshio axis is located north of Nakanoshima on

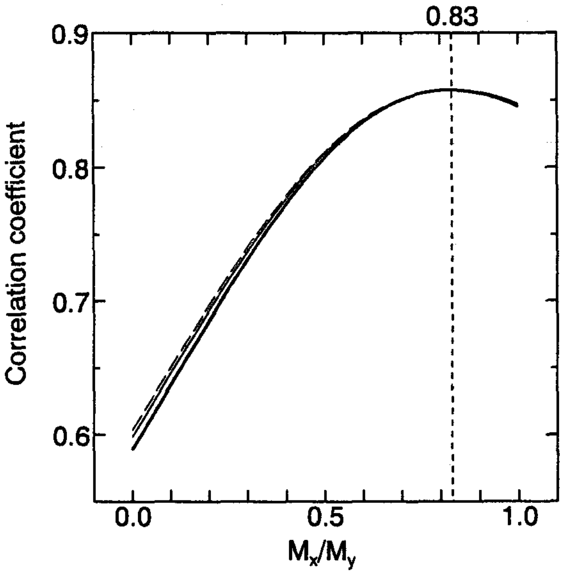

Fig. 6. Correlation coefficients between the KPI and the latitude of the Kuroshio axis at the FES line for M_y = 60 cm (thick line), 80 cm (thin line) and 100 cm (broken line), with respect to M_x/M_y. The correlation is maximum at M_x/M_y = 0.83 for the cases.

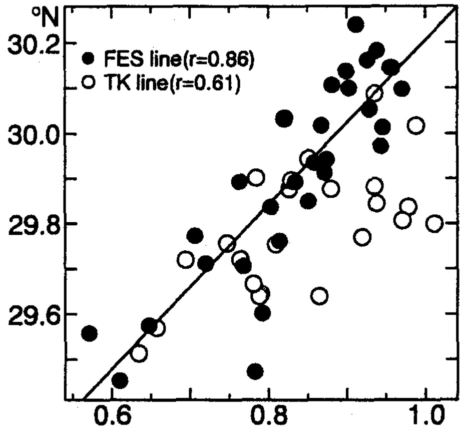

Fig. 7. Correlation diagram between the KPI (M_x = 83 cm, M_y = 100 cm) and the latitude of the Kuroshio axis at the FES line (dots) and the TK line (open circles). The values of r are the correlation coefficients. The solid line is the regression line for the FES-line plots.

average. Thus, the best KPI is obtained for M_x/M_y = 0.83 and realistic M_y within 100 ± 40 cm. The values of M_x and M_y can be 83 cm and 100 cm, respectively. The KPI with M_x = 83 cm and M_y = 100 cm is most correlated with the latitude of the Kuroshio axis at the FES line, as the correlation coefficient is 0.86 (Fig. 7, Table 1), and is the best index of position of the Kuroshio axis at the FES line. The regression equation is

$$Z = 1.8165\text{KPI} + 28.389, \quad (2)$$

where Z is the latitude (°N) of the Kuroshio axis at the FES line, and KPI is the value of the KPI with $M_x = 83$ cm and $M_y = 100$ cm. This KPI is newly called the KPI hereafter.

The sea-level difference of Naze minus Nakanoshima is correlated with the Kuroshio position as high as the KPI. However, it may not be valid as an index of the Kuroshio position if the sea-level difference between Naze and Nishinoomote, i.e., the surface transport of whole of the Kuroshio, changes greatly. During the analyzed period 1984–92, the variations of sea level at Nishinoomote and Naze are quite similar to each other, so that the variation of their difference is relatively small. The sea-level difference of Naze minus Nakanoshima may be less useful than the KPI for the period during which the sea-level difference between Naze and Nishinoomote changes largely.

The position of the Kuroshio axis at the TK line brings about similar results, except for low correlation with sea level at Naze (Table l); its correlations with the KPI and the sea-level difference between Naze and Nakanoshima are higher than those with the other sea levels. However, the correlation coefficients are smaller than those at the FES line, since the plots at the TK line in Fig. 7 are similar to those at the FES line in case of KPI less than 0.9, but deviate southward from the FES-line plots for larger KPI. This southward deviation of the Kuroshio axis seems to be caused by the shoal around Yakushima and Tanegashima (Fig. 1).

4. Variations of Position of the Kuroshio Axis in the Tokara Strait

Figure 8 shows variations of daily latitude of the Kuroshio axis at the FES line in the Tokara Strait calculated from Eq. (2). The Kuroshio axis is located between 29.29°N and 30.52°N with the mean of 29.90°N. The latitude of the Kuroshio axis takes minima and maxima in time intervals of one, two, or three months. The variations are relatively large at periods between about 20 and 80 days with power spectral peaks around one month and two months, together with a period of 4.6 months (Fig. 9).

Kawabe (1995) concluded that a northern (southern) position of the Kuroshio axis in the Tokara Strait is highly correlated with an LM (NLM) path with time lead of about four months. Figure 8 confirms this conclusion and shows its details as follows. The Kuroshio took a northern position stably from 25 September 1984, 29 July 1986, and 22 July 1989. Since the LM paths began in early February 1985, on 5 November 1986, and 9 October 1989 (Kawabe, 1995), the time leads of the northward shift of the Kuroshio are 4, 3.2, and 2.6 months, respectively. On the other hand, the Kuroshio in the Tokara Strait returned to a southern position on 5 February 1985, 7 March 1988, and 26 June 1990 (Fig. 8). The LM paths finished on 18 June 1985, 22 July 1988, and 5 January 1991 (Kawabe, 1995), and the time leads of the southward shift are 4.4, 4.5, and 6.3 months, respectively. On average, the Kuroshio axis in the Tokara Strait shifts northward 3.3 months earlier than the formation of large meander and returns southward 5.1 months prior to its end.

Figure 8 shows another interesting fact that an LM path is not ended by a temporary southward shift of the Kuroshio axis with a duration of ten to twenty days. Such a temporary shift to a southern position occurred several times during the LM paths but did not affect the life of LM path. This suggests that the persistence of the Kuroshio large meander is not largely affected by the temporary southward shift of the Kuroshio axis in the Tokara Strait. Such a great stability of the large meander may be caused by an interaction with the warm and cold eddies developed inside the large meander.

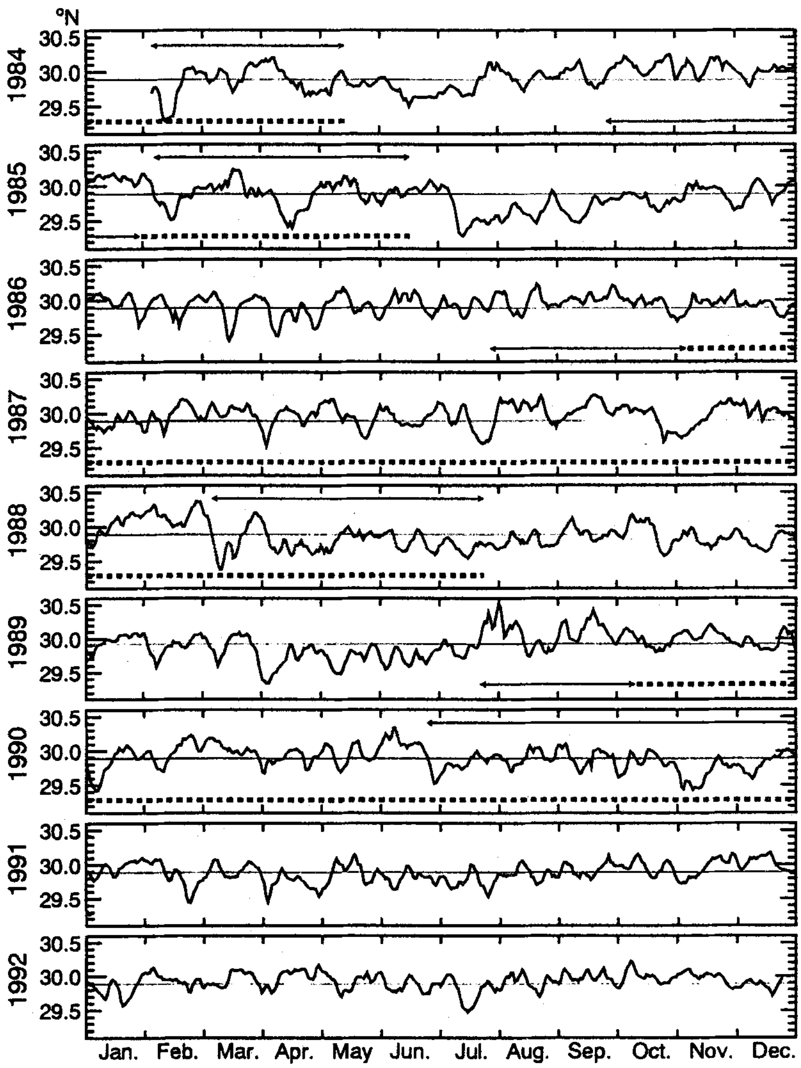

Fig. 8. Time series of the latitude of the Kuroshio axis at the FES line in the Tokara Strait from 1984 through 1992 calculated from Eq. (2) with the KPI. Thin horizontal lines indicate the mean latitude (29.90°N) of the Kuroshio axis. Dotted horizontal lines show the periods of large meander of the Kuroshio from Kawabe (1995). The horizontal arrows below and above the time-series curve show the LM formation and decay stages, respectively.

According to the Quick Bulletins of Ocean Conditions issued semimonthly by the Japan Maritime Safety Agency, a small meander existed just east of the Tokara Strait in the second half of September 1984 and the first halves of July 1986 and July 1989, and started to move eastward in the next half month. In comparison with the time of the northward shift of the Kuroshio axis in the Tokara Strait, a small meander has already formed and begins to move at the time of the northward shift. Therefore, the northward shift of the Kuroshio axis does not seem to be a major cause for the generation of small meander, unlike the inference in Kawabe (1995). On the other hand, the simultaneous occurrence of the northward shift and the small-meander propagation

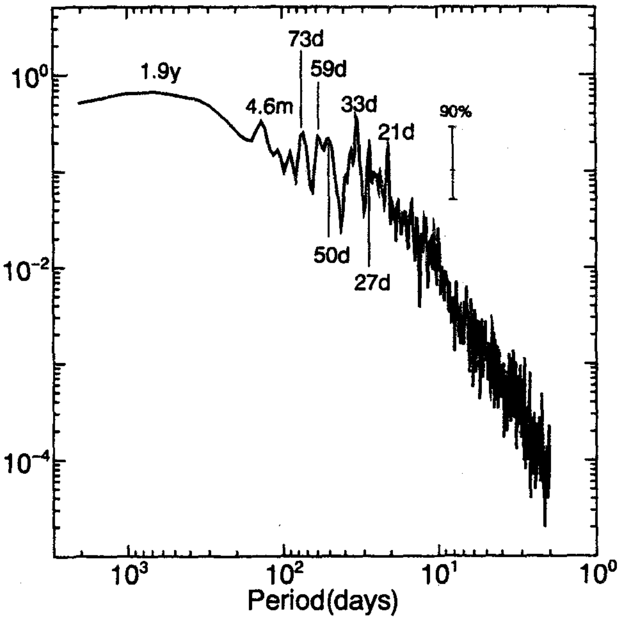

Fig. 9. Power spectra of the KPI from 4 Feb. 1984 to 12 Sep. 1989 computed by the fast Fourier transform method (degrees of freedom = 8). The 90% significant interval is shown in the figure.

Table 2. Periods of LM formation (Formation), LM decay (Decay), LM except the LM-decay stage (LM), and NLM except the LM-formation stage (NLM). The beginnings of the LM and NLM periods are from Kawabe (1995), and those of the LM formation and decay stages are determined from the KPI in Fig. 8.

Formation	LM	Decay	NLM
		2/ 4, 84–5/15, 84	5/16, 84– 9/24, 84
9/25, 84– 1/31, 85	2/1, 85–2/ 4, 85	2/ 5, 85–6/18, 85	6/19, 85– 7/28, 86
7/29, 86–11/ 4, 86	11/5, 86–3/ 6, 88	3/ 7, 88–7/22, 88	7/23, 88– 7/21, 89
7/22, 89–10/ 8, 89	10/9, 89–6/25, 90	6/26, 90–1/ 5, 91	1/ 6, 91–12/24, 92

shown by Kawabe (1995) is confirmed again; that is, the eastward propagation of small meander seems to be associated with the northward shift and the persistence of the northern position of the Kuroshio axis in the Tokara Strait.

In the decay process of large meander in 1988, the southward shift of the Kuroshio axis occurred on 7 March in the Tokara Strait (Fig. 8) and in early June over the Izu Ridge (Fig. 5 of Kawabe, 1995). In 1990, it occurred on 26 June in the Tokara Strait, while it began in September and developed in November over the Izu Ridge. Thus, the Kuroshio moves to the south of Hachijo-jima over the Izu Ridge three months or a little more after the Kuroshio shifts to a southern position in the Tokara Strait. Then a few months later, the Kuroshio approaches to the coast of the Kii Peninsula and finishes the LM path by being in an offshore NLM path (Kawabe,

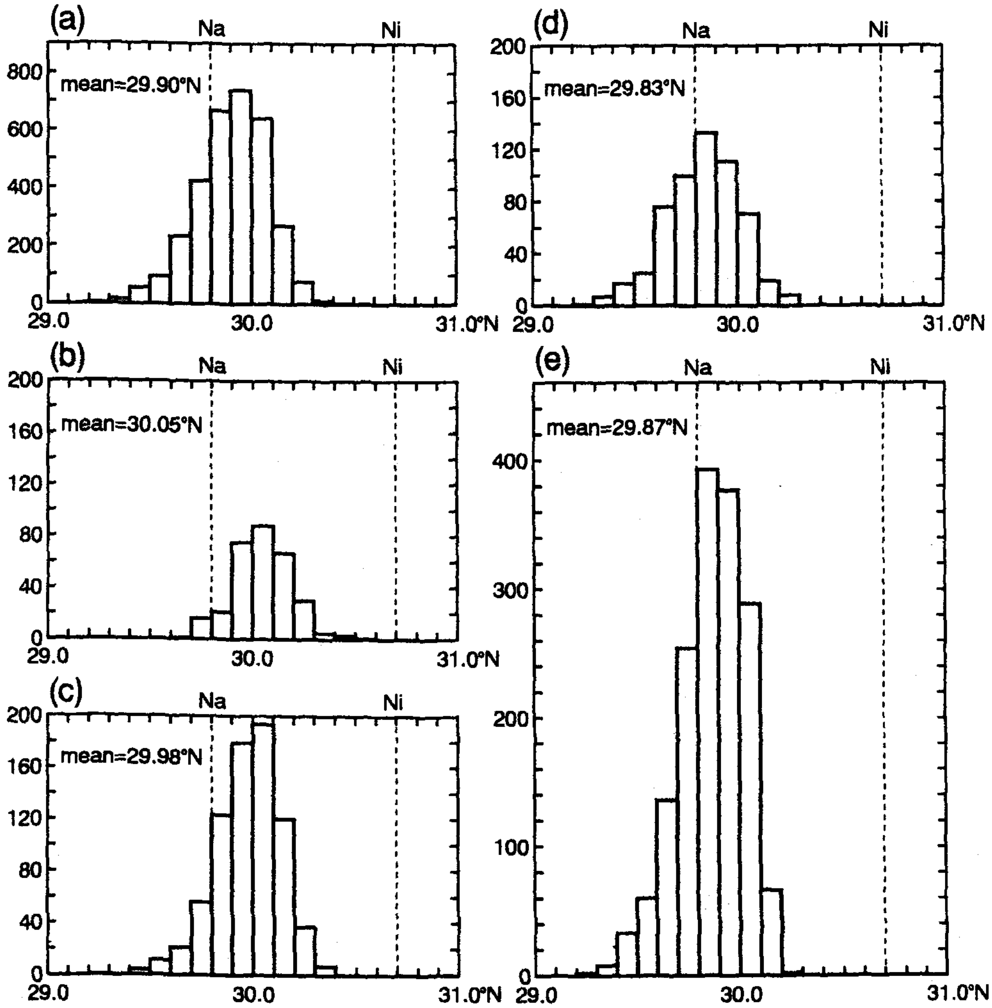

Fig. 10. Histograms of the latitude of the Kuroshio axis at the FES line in the Tokara Strait during the total period between 4 Feb. 1984 and 24 Dec 1992 (a), the LM formation stage (b), the LM period except the LM-decay stage (c), the LM decay stage (d), and the NLM period except the LM-formation stage (e). The periods tabulated in Table 2 are used for (b) to (e). It should be noted that the ordinate of (a) is different from the others.

1986, 1995). The decay process of large meander seems to start from the southward shift of the Kuroshio axis in the Tokara Strait.

Accordingly, the beginning days of the formation and decay processes of large meander of the Kuroshio can be detected by the KPI and are determined by the day in which the Kuroshio axis passes its mean latitude (29.90°N) with a significant meridional shift (Fig. 8). The final days of these processes are determined by Kawabe (1995). Table 2 shows the periods of LM formation, LM decay, LM except for its decay stage, and NLM except for the LM formation stage. The latter two periods are called the LM and NLM periods hereafter.

The Kuroshio at the FES line during the LM period is located farther north by 7′ latitude than the NLM period; the band with the highest frequency is between 30.0°N and 30.1°N during the

LM period and between 29.8°N and 29.9°N during the NLM period (Fig. 10). The latitude of the Kuroshio axis during the LM formation stage, although the Kuroshio still takes an NLM path, has the highest frequency at the same band as that during the LM period, and its mean is rather a little higher than that during the LM period. In a similar way, the occurrence of latitude during the LM decay stage is most frequent at the same band as that during the NLM period with a little lower mean latitude, although the Kuroshio still takes an LM path. The frequencies during the 1984–92 total period show nearly a Gaussian distribution with a single maximum between 29.9°N and 30.0°N.

5. Summary and Discussion

Using the data from 1984 through 1992 of sea levels at the islands in the Tokara Strait (Naze, Nakanoshima, and Nishinoomote) and water temperatures at the FES and TK lines, the characteristics of the Kuroshio position index (KPI) defined by Eq. (1) were examined. The KPI is an index of position of the Kuroshio axis in the Tokara Strait introduced by Kawabe (1995). The dependency of the KPI on M_x and M_y in Eq. (1) was clarified. The KPI for M_x/M_y more than 0.5 does not depend on M_y in a realistic range of 100 ± 40 cm. The correlation of the KPI with the latitude of the Kuroshio axis is highest for $M_x/M_y = 0.83$. The KPI with $M_x/M_y = 0.83$ and realistic M_y best indicates the position of the Kuroshio axis in the Tokara Strait. Then the KPI with $M_x = 83$ cm and $M_y = 100$ cm was newly called the KPI, namely

$$\mathrm{KPI} = \frac{X + 83\mathrm{cm}}{Y + 100\mathrm{cm}},$$

where X and Y are the same as in Eq. (1). The latitude of the Kuroshio axis at the FES line is obtained by this KPI and Eq. (2).

The meridional move of the Kuroshio axis in the Tokara Strait and its relation with the large-meander (LM) and non-large-meander (NLM) paths of the Kuroshio south of Japan were examined in detail by using daily values of the KPI. Then the following facts were clarified.

(1) On average, a large meander of the Kuroshio forms 3.3 months after the Kuroshio axis in the Tokara Strait shifts to a northern position, while it ends 5.1 months after the Kuroshio shifts to a southern position.

(2) The formation and decay processes of large meander are started by the shift of the Kuroshio axis in the Tokara Strait to northern and southern positions, respectively. In the formation process, a small meander generated southeast of Kyushu begins to propagate eastward associated with the northward shift of the Kuroshio axis in the Tokara Strait, although the small meander seems to have already been formed before the shift of the Kuroshio axis. In the decay process, the southward shift of the Kuroshio over the Izu Ridge occurs three months or a little more after the southward shift in the Tokara Strait, and then the decay is completed a few months after the southward shift over the Izu Ridge.

(3) The decay process of large meander seems to start from a southward shift of the Kuroshio axis in the Tokara Strait, but a temporary southward shift with a duration of ten to twenty days does not terminate the large meander. The southward shift at least longer than twenty days may be necessary for advancing the decay process of large meander.

(4) The Kuroshio axis at the FES line is located between 29.29°N and 30.52°N with the mean of 29.90°N. Its position during the LM period (LM period except for the LM decay stage) is farther north by 7′ latitude on average than that during the NLM period (NLM period except

for the LM formation stage). The position during the LM formation (decay) stage is almost the same as that during the LM (NLM) period and rather slightly farther north (south) on average, although the Kuroshio is still in an NLM (LM) path.

The above results show that the sea-level data from tide gauges are very useful to monitor the position of the Kuroshio. However, such use of tide-gauge data as in this paper is limited to the regions at the Tokara Strait and the Izu Ridge. Satellite altimetry data may be able to complement the tide-gauge data for this purpose. The present study provides an idea for utilization of altimetry data.

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