Journal of the Oceanographical Society of Japan
Vol. 44, pp. 293 to 304, 1988

Variability of Kuroshio Velocity Assessed from the Sea-Level Difference between Naze and Nishinoomote*

Masaki Kawabe†

Abstract: Variations of current velocity of the Kuroshio are examined using the 1965-1983 sea-level difference between Naze and Nishinoomote, located on the offshore and onshore sides of the Kuroshio in the Tokara Strait south of Kyûshû.

Interannual variations of Kuroshio velocity are large, especially at periods longer than five years and around 2.1 years. They are almost determined by those of sea level on the offshore side of the Kuroshio. They are highly coherent with the offshore sea level at periods longer than 1.7 years, and incoherent with the onshore sea level at periods longer than 2.8 years.

The mean seasonal variation averaged for 19 years is at its maximum in July and at its minimum in the second half of October, with a sharp decrease in August and September. However, such a variation does not repeat every year. Amplitude, dominant period and phase are greatly different by year, and they can be roughly divided into four groups: small-amplitude group, semiannual-period group, and two annual-period groups with different phases. The only feature found in almost all years is a weak velocity from September to December.

The amplitude of seasonal variation tends to be large in the formation years of the large meander (LM) of the Kuroshio and small during the LM period. It is also large in the years preceding El Niño, and diminishes remarkably in El Niño years.

Kuroshio velocity in the Tokara Strait is incoherent with position of the Kuroshio axis over the Izu Ridge, but highly coherent with 70-day variations of coastal sea levels which are dominant during the LM period.

1. Introduction

Current velocity and volume transport of the Kuroshio have been examined mostly using surface velocity measured by GEK and geostrophic velocity and transport calculated from hydrographic data. The ship observations by governmental agencies have routinely been conducted each season or each month on several fixed lines around Japan. They are useful for an approximate estimate of Kuroshio velocity and transport, but are too infrequent to assess the Kuroshio variations which occur on a wide range of time scales. A long time series of Kuroshio velocity with a fine time interval is necessary for a good understanding of the variations of the velocity of the Kuroshio.

A direct measurement by moored current meters is a powerful method in order to gain a time series of Kuroshio velocity with a fine time interval (Takematsu *et al.*, 1986). However, it is not easy to get long-time, spatially dense or widely representative data, because mooring works need great labor, time, and expense, and are not always successful.

At present, the sea-level differences between both sides of the Kuroshio are the best information in order to roughly monitor Kuroshio velocity. The difference in daily mean sea level between the two stations is expected to indicate the surface geostrophic transport crossing between the stations, since the daily mean sea level adjusted to barometric pressure is correlated with the dynamic height adjacent to the tide station (*e.g.*, Yosida, 1961; Konaga and Inoue,

---

* Received 25 February 1988; in revised form 31 October 1988; accepted 9 November 1988.

† Ocean Research Institute, University of Tokyo, Minamidai 1-15-1, Nakano-ku, Tokyo 164, Japan.

1973). When a strong current such as the Kuroshio flows between the tide stations, the sea-level difference probably shows the variation of surface transport of the strong current. It is, moreover, expected to show the variation of mean surface velocity of the current, if its width is not significantly variable. Therefore, the surface velocity of the Kuroshio through the Tokara Strait is probably monitored by the sea-level difference between Naze on the south side of the strait and Nishinoomote on the north, Naze minus Nishinoomote (Fig. 1).

Past studies of Kuroshio velocity and transport have mostly focused on mean seasonal variations averaged each season or each month for several years, due to the sparse time interval of GEK and hydrographic data sampling (Masuzawa, 1960, 1961, 1965; Uda, 1964; Nitani, 1969, 1975; Taft, 1972; Nitani *et al.*, 1979; Minami *et al.*, 1979). The analysis of the averaged variation is effective for the variation which shows a similar cycle every year. However, Masuzawa (1960) and Taft (1972) noted that a seasonal cycle repeating every year cannot be found in time series of quarterly GEK data for several years. Exact and detailed studies must be made on variations of Kuroshio velocity, even in terms of seasonal variations.

In this paper, the variations of current velocity of the Kuroshio through the Tokara Strait will be examined in terms of the interannual and seasonal variations and the relations with path of the Kuroshio south of Japan, using the sea-level difference Naze minus Nishinoomote. Only a time variation will be discussed, because absolute values of the sea-level difference cannot be known since the heights of datum lines at the tide gauges have not yet been measured.

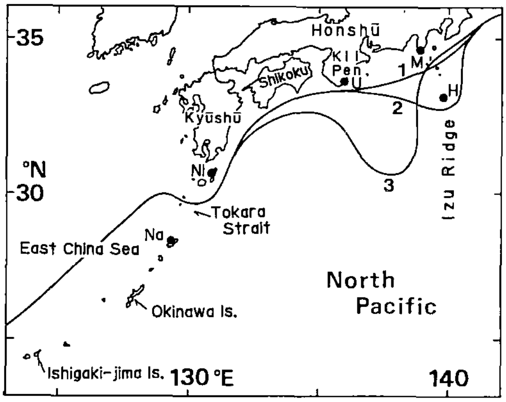

Fig. 1. Locations of tide stations and typical stable paths of the Kuroshio. Tide stations are, Na: Naze, Ni: Nishinoomote, U: Uragami, M: Minami-Izu, H: Hachijô-jima. The three typical paths of the Kuroshio shown by Kawabe (1985) are drawn, 1: nearshore non-large-meander (NLM) path, 2: offshore NLM path, 3: typical large-meander (LM) path.

2. Data

The sea-level difference of Naze minus Nishinoomote from 1965 through 1983 was analyzed. The semimonthly mean values were calculated from daily mean sea levels corrected for barometric pressure based on the hydrostatic approximation. The sea levels at Naze, Nishinoomote, Uragami, Minami-Izu and Hachijô-jima were also used with the barometric pressure correction as well as the removal of 39 major tidal components as in Kawabe (1985, 1986, 1987). The correction for wind stress is not made here, though whether the effect is neglected is not yet known, and must be examined for a quantitative study.

The sea-level data at Naze, Nishinoomote, Minami-Izu and Hachijô-jima were obtained from the Data Report of Hydrographic Observations —Series of Tide issued annually by the Japan Maritime Safety Agency, and those at Uragami were from the Tidal Observations issued annually by the Japan Meteorological Agency (JMA). The barometric pressure data were obtained from the Monthly Report of JMA—Meteorological Observations.

Power spectra and squared coherences of sea levels were computed by the fast Fourier transform method (degrees of freedom=8). The periods used in the calculations are from 22 April 1965 to 2 February 1982 for a long period which includes both non-large-meander (NLM) and large-meander (LM) periods, from 23 April 1965 to 8 August 1975 for the NLM period, and from 22 October 1975 to 31 December 1979 for the LM period.

3. Interannual variations

Long-term variations of tide gauge data may include a vertical variation of the ground which cannot be separated from the observed data. If the linear trends of tide gauge data are caused

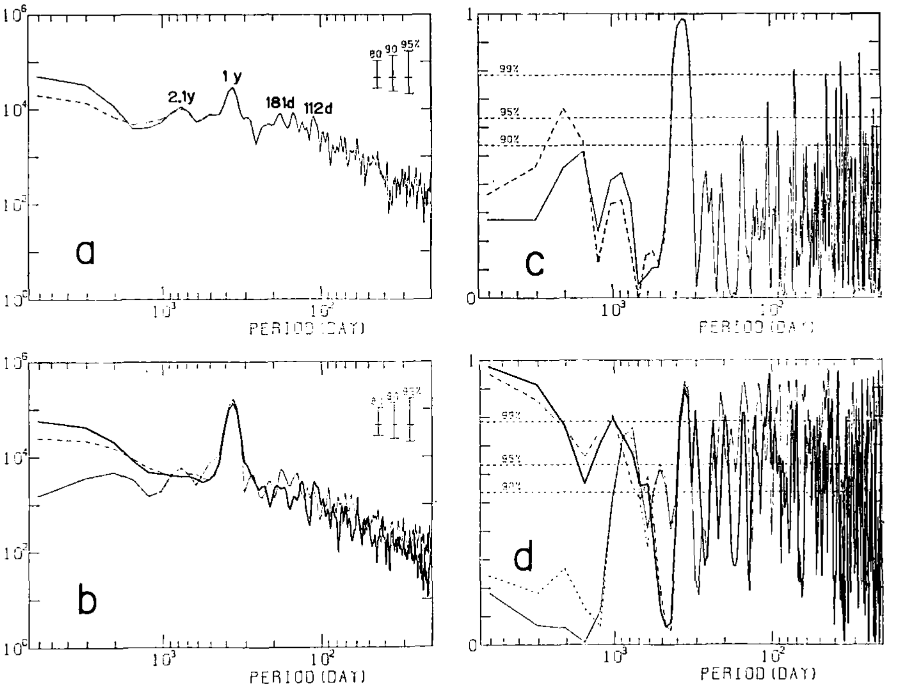

Fig. 2. a: Power spectra (cm^2 day) of the sea-level difference between Naze and Nishinoomote, b: power spectra (cm^2 day) of sea levels at Naze (thick line) and Nishinoomote (thin line), c: squared coherences of sea levels between Naze and Nishinoomote, d: squared coherences of the sea-level difference between Naze and Nishinoomote with sea level at Naze (thick line) and Nishinoomote (thin line). They were calculated using three-day mean values from 22 April 1965 to 2 February 1982. The curves using sea-level data removed the linear trends at each station (0.46 cm·year^{-1} at Naze and 0.04 cm·year^{-1} at Nishinoomote) are shown by broken lines only for longer periods than a year. The curves using non-trend sea levels at Nishinoomote are shown by dotted lines. The dotted line in Fig. 2b overlaps a thin solid line.

by the ground variation, the rates of ground fall are estimated at about 0.46 cm year^{-1} at Naze from 1957–1983 annual mean values and 0.04 cm year^{-1} at Nishinoomote from 1965–1983 values. Spectra and coherences calculated using values removed the linear trends are shown by the broken and dotted lines in Fig. 2. By the removal of linear trends, the power spectra of Naze sea level and the sea-level difference between Naze and Nishinoomote decrease at periods longer than five years. However, the results on the shorter-term variations as well as qualitative results on the whole range of time scales do not significantly change by the removal of linear trends. The unchangeable properties are described here.

The characteristics of interannual variations of sea level are clearly different between Naze and Nishinoomote. First, the power spectral densities of sea level at Naze are much larger than those at Nishinoomote for periods longer than 2.5 years (Fig. 2b). Second, the sea levels at Naze and Nishinoomote are not coherent to each other except for the annual periods (Fig. 2c). The interannual variations of sea level on the offshore and onshore sides of the Kuroshio, thus, are different in amplitude and are not coherent to each other.

The sea-level difference between Naze and Nishinoomote (velocity of the Kuroshio) has a large interannual variability, especially at periods longer than five years and around 2.1 years (Fig. 2a). As a result of the characteristics of sea level noted above, the sea-level difference is coherent with the sea level at Naze at periods longer than 1.7 years with more than 90% confidence and little phase lag, while it is incoherent with the sea level at Nishinoomote at periods longer than 2.8 years with a sharp decrease of the coherence at periods of about 2.5 years (Fig. 2d). The large variations of the sea-level difference with periods longer than five years are entirely due to those of the sea level at Naze, while the variations with the 2.1-year period are due to the sea levels at the both stations. It is concluded that the velocity of the Kuroshio has a large interannual variability which correlates well to that of sea level on the offshore side of the Kuroshio.

4. Seasonal variations

In order to examine a seasonal variation of the sea-level difference Naze minus Nishinoomote, two-month and one-year running means were calculated using semimonthly mean values,

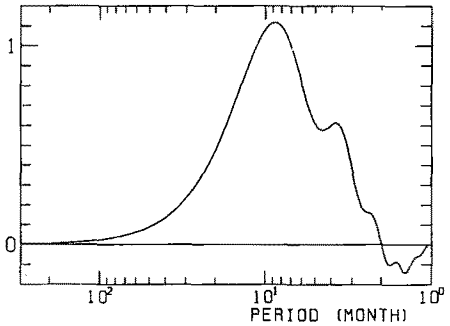

Fig. 3. Relative amplitude transmitted by the simple band-pass filter, two-month running means minus one-year running means.

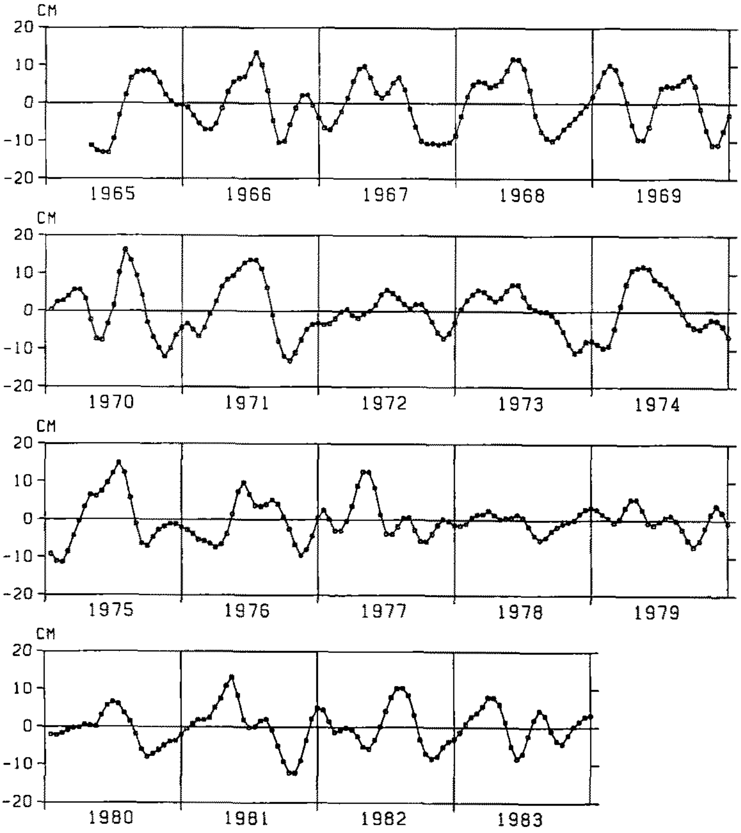

Fig. 4. Time series of residuals after subtracting one-year running means from two-month running means calculated using semimonthly mean values of the sea-level difference Naze minus Nishinoomote. They are thought to show seasonal variations of the sea-level difference.

and the residuals obtained by subtracting the latter from the former were analyzed (Figs. 4 to 7). This procedure is a simple band-pass filter, where the amplitudes are decreased to less than 70% at periods longer than 1.3 years and shorter than 5.5 months (Fig. 3).

The most distinct feature is that amplitude, dominant period and phase of seasonal variation are greatly different from year to year (Figs. 4 to 6). No dominant cycle year to every year, different from a sea-level variation at each station. Only one feature is common to almost all years, which is that the values of sea-level difference are small from September to December (Fig. 5).

Figure 4 shows that the variation is very small in 1972 and from the middle of 1977 to early 1980. In other years, semiannual or annual variation is dominant; semiannual dominates in 1965, 1969, 1970, 1982 and 1983, and annual in other years. The semiannual variations have two maxima between January and April and between July and September, and two minima between April and June and between October and November (Figs. 5 and 6b). The annual variations have various phases and can be classified into two groups; one is large in the first half of the year and small in the second half in 1968, 1973 and 1981 (Fig. 6c), and the other has phase lags of two or three months in 1966, 1967, 1971, 1974, 1975 and 1976 (Fig. 6d). Thus, the seasonal variations of the sea-level difference (Kuroshio velocity) have a large difference year by year and can be divided into the four groups shown in Fig. 6: small-amplitude group, semiannual-period group and two kinds of annual-period group.

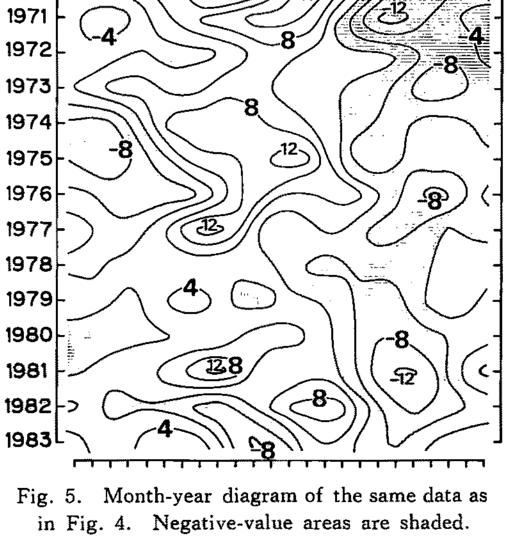

Fig. 5. Month-year diagram of the same data as in Fig. 4. Negative-value areas are shaded.

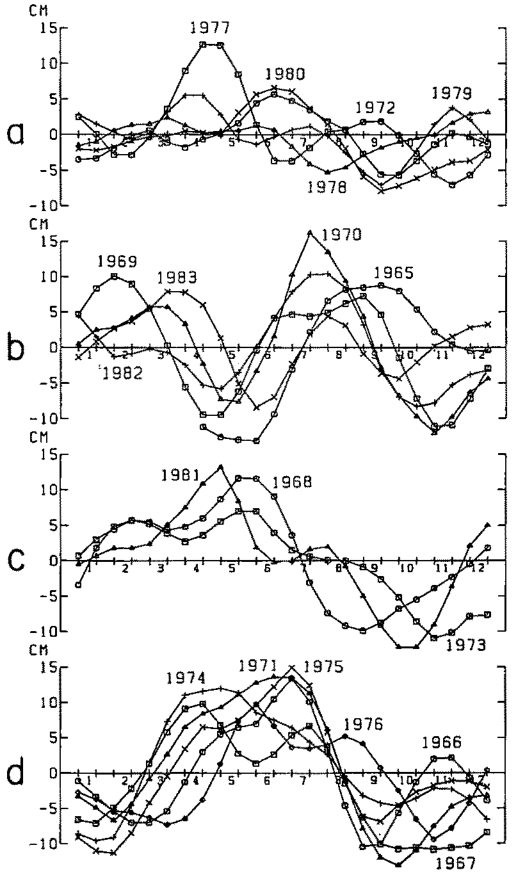

Fig. 6. Classification of seasonal variations of the sea-level difference Naze minus Nishinoomote, shown in Fig. 4, into four groups: a, small amplitude; b, semiannual dominant; and c, d, annual dominant. Groups c and d are different in phases; Group c is like the sine curve with origin at the beginning of the year, and Group d lags by two or three months behind Group c.

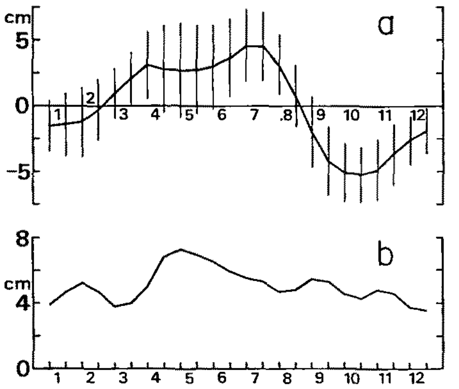

Fig. 7. Mean seasonal variation (a) and standard deviations (b) of the sea-level difference Naze minus Nishinoomote computed in each half month for 19 years from 1965 through 1983 using the Fig. 4 data. Vertical bars in Fig. 7a show 95% confidence intervals.

The difference by year is especially distinct in spring from April to June, during which both the maximum and minimum appear to correspond to the dominance of annual and semiannual variations respectively. The standard deviation is largest during spring, above 6 cm from the second half of April (called April II, hereafter) to June I (the first half of June) (Fig. 7b).

Figure 7a shows the seasonal variation averaged in each half month for 19 years from 1965 through 1983. The sea-level difference (Kuroshio velocity) is large from March to August, small from September to February and reaches a maximum in July I, II and minimum in October II. The sharp decrease in August and September is quite remarkable. The 95% confidence for the semimonthly values in Fig. 7a indicates that the mean values from March II to August I and the values from September I to December I are not significantly different from the maximum in July I, II and the minimum in October II respectively, and the values during the other periods are significantly different. This concludes that, in the mean seasonal variation, the sea-level difference (Kuroshio velocity) is large from March II to August I and small from September I to December I.

The annual range (maximum-minimum) of the mean seasonal variation in Fig. 7a is about 10 cm. This value corresponds to 13 cm sec^{-1} on average for a current width of 100 km. If we assume that the same variation of current velocity extends to a depth of 500 m, it is converted to a volume transport of $6.5\times10^6\ \mathrm{m}^3\ \mathrm{sec}^{-1}$. This implies that the mean seasonal variation of Kuroshio transport may be about ±10% of its mean, since the Kuroshio transport through the Tokara Strait is estimated at about $30\times10^6\ \mathrm{m}^3\ \mathrm{sec}^{-1}$ using CTD and shipboard doppler current profiler data by the Japan Maritime Safety Agency. It should be noted, however, that the annual range in each year is much larger than 10 cm in most years (Fig. 9). The mean of the range in each year between 1965 and 1983 is 20 cm, twice of the annual range of the mean seasonal variation.

5. Comparison with past studies of seasonal variations

One of the most important results of the current study is that seasonal variations of Kuroshio velocity greatly change year by year. This property is not clear from intermittent GEK and geostrophic velocity data, but related descriptions were made by Masuzawa (1960) and Taft (1972). They described that no clear seasonal periodicity could be seen in time series of the maximum GEK velocities of the Kuroshio observed quarterly south of Japan from 1955 to 1959 and from 1956 to 1964. Taft (1972) moreover indicated that the only consistent change that occurs every year is a decrease from summer (1 August to 15 September) to fall (1 November to 15 December). This corresponds to the remarkable feature noted in the present study that weak velocity from September to December is common to almost all years.

Most past studies have treated the mean seasonal variation averaged for several years. Many works have shown that the mean Kuroshio velocity is maximum in summer and minimum in fall, using GEK or geostrophic velocity (Masuzawa, 1960, 1961, 1965; Uda, 1964, for the 139-140°E region; Taft, 1972; Nitani, 1975; Minami *et al.*, 1979). This accords well with the result of the present study, shown in Fig. 7a, and is said to rightly represent the long-time mean characteristics.

It should be noted, however, that different seasonal variations have also been shown in several previous studies. The dominance of a semiannual variation was shown in the 1955-

1962 mean of GEK data taken between 137°E and 139°E (Uda, 1964), in the 1960-1965 mean of GEK data taken around the Izu Ridge (Nitani, 1969), and in long-time mean of ship-drift data taken between 135°E and 140°E (Taft, 1972). Moreover, the velocity variation which is large in spring and summer in the same degree and small in fall and winter was shown for the 130-132°E and 133-135°E regions (Uda, 1964), south of the Kii Peninsula (Nitani, 1969) and the 130-135°E region (Taft, 1972). The various results of mean seasonal variation are thought to be caused by the difference of observational periods of velocity data and by yearly difference of data number. For example, the semiannual variations shown by Uda, Nitani and Taft may be much affected by the years belonging to the semiannual-period group. The other variations mentioned above may be due to the great influence of years in the second kind of the annual-period group and partly due to years in the semiannual-period group.

The yearly difference of seasonal variation requests deliberate attention to equality of sampling time of data for study of spatial phase lag of seasonal variation. Nitani (1969, 1975), Taft (1972), Nitani *et al.* (1979) and so on indicated that phase of mean seasonal variation in an eastern region south of Japan lags behind that in a western region, but yet a spatial difference of phase must be reexamined using time series obtained in different places during the same periods.

6. Relations of the seasonal variations to interannual phenomena

According to Kawabe (1987), annual variations at Naze and Nishinoomote are highly coherent to each other during both the NLM and LM periods, but the phase lag is clearly different between these periods. There is a significant phase lag of one month of Nishinoomote behind Naze during the 1965-1975 NLM period, while there is no significant phase lag during the 1975-1979 LM period. These facts imply that the seasonal variation of the sea-level difference Naze minus Nishinoomote is not large during the LM period, although it is large during the NLM period. Power spectra of the sea-level difference really show no seasonal variation during the 1975-1979 LM period, in contrast to large seasonal variation during the 1965-1975 NLM period (Fig. 8). The low power spectral densities at annual and semiannual periods during the LM period result from a small amplitude of seasonal variation from the middle of 1977 to early 1980, as shown in Fig. 4.

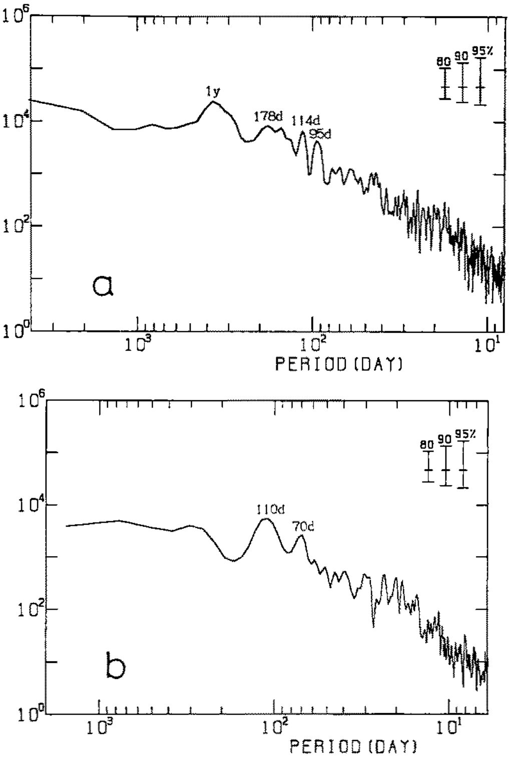

Fig. 8. Power spectra (cm^2 day) of the sea-level difference between Naze and Nishinoomote: a, NLM period (April 1965 to August 1975); b, LM period (October 1975 through December 1979).

Figure 9 shows the time variation of annual range, which is defined as the difference between maximum and minimum in Fig. 4 in each year. Large values above 25 cm are found in four years, 1970, 1971, 1975 and 1981. The last two years correspond to the years during which the Kuroshio large meander was formed. The maximum values in 1975 and 1981 occur prior to formation of the Kuroshio meander, and the four-month period with large values in 1975 corresponds well to the generating stage of the meander (Kawabe, 1980). Small values below 20 cm are seen in nine years, 1972, 1973, 1976-1980, 1982, 1983; the years except for 1972 and

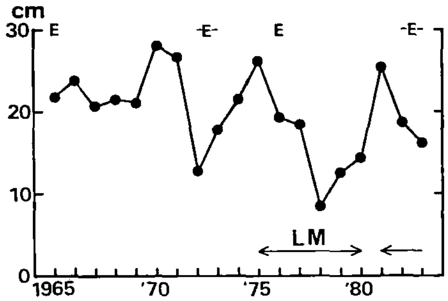

Fig. 9. Variation in annual range of seasonal variations of the sea-level difference Naze minus Nishinoomote shown in Fig. 4. Annual range is the difference between maximum and minimum in each year. Arrows and the symbol E indicate the periods during which the Kuroshio large meander and El Niño occurred, respectively.

1973 belong to the LM period. In addition, small amplitudes in 1955, 1960 and 1961 during the LM period are suggested from time series of Kuroshio velocity measured by GEK shown in Masuzawa (1960) and Taft (1972). Thus, we can see a tendency for the seasonal variation of Kuroshio velocity to be large in the formation years of the Kuroshio large meander and small during the LM period.

Figure 9 also suggests an interesting relation for the occurrence of El Niño, which is a typical interannual phenomenon in the tropics. Striking El Niño events occurred in 1965, 1972–1973, 1976 and 1982–1983. The figure shows extremely large amplitude in the years preceding El Niño occurrences and subsequent sharp decrease of the amplitude. In other words, El Niño occurs after a year with large seasonal variation of Kuroshio velocity, and in the next year during which El Niño occurs the seasonal variation diminishes remarkably.

7. Relations to the sea levels south of Japan

7.1. *To the sea level at Hachijô-jima*

The sea level at Hachijô-jima changes due to the variation of the Kuroshio path over the Izu Ridge (Kawabe, 1985, 1986), and shows a small variation of the LM path over the Izu Ridge and a large variation between the nearshore and offshore NLM paths with periods of 1.6–1.8 years, one year, around 195 days and about 110 days (Kawabe, 1987).

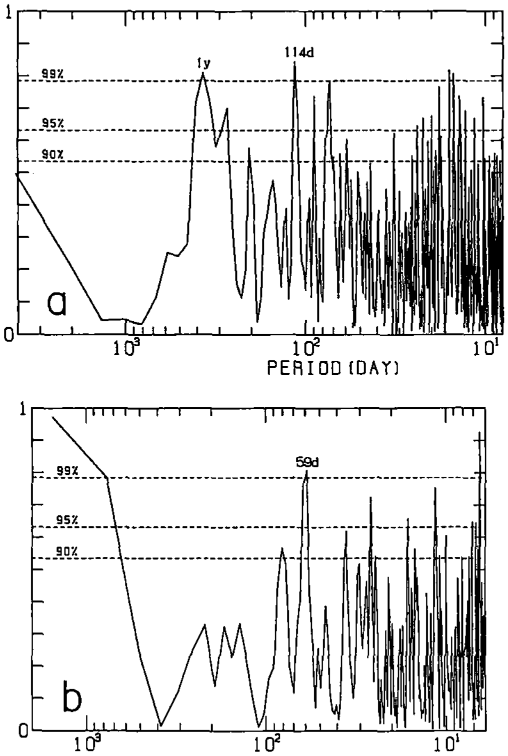

Fig. 10. Squared coherences of the sea-level difference between Naze and Nishinoomote with sea level at Hachijô-jima during the NLM period (a) and the LM period (b).

The sea-level difference between Naze and Nishinoomote is not significantly coherent with the Hachijô-jima sea level at almost all periods during both the NLM and LM paths (Fig. 10). During the NLM period, the sea-level difference has not only large power-spectral density but also significant coherence with Hachijô-jima sea level at annual and 114-day periods (Figs. 8a and 10a). This suggests that there is a relation between the Kuroshio velocity and the NLM path variations with such periods. Still, the 114-day variation may not correspond to the variation of the NLM path with periods of about 110 days (105–111 days) indicated by Kawabe (1987), because there is some, even though little, difference between the periods and no significant coherence between the sea-level difference and Miyake-jima sea level, which also represents the Kuroshio path variations. Accordingly, it is concluded that the Kuroshio velocity south of

Kyûshû is not linearly related to the Kuroshio path variation over the Izu Ridge, except for a possible relation at the annual period during the NLM path.

7.2. *To the 70 and 110-day variations of sea level*

Kawabe (1987) suggested that the 110-day variation of the NLM path results in variations of coastal sea level of the same period between the Kii Peninsula and the Izu Ridge with time lags of nearly one month. The coherence between the sea-level difference between Naze and Nishinoomote and the sea level at Minami-Izu is significant at the 114-day period during the NLM path at the 95% confidence level, but not at the 99% level (Fig. 11a). The roughly 110-day variations of coastal sea level during the NLM path may not be closely related to the 110-day variation of Kuroshio velocity, the same as for the 110-day variation of the NLM path discussed in Section 7.1.

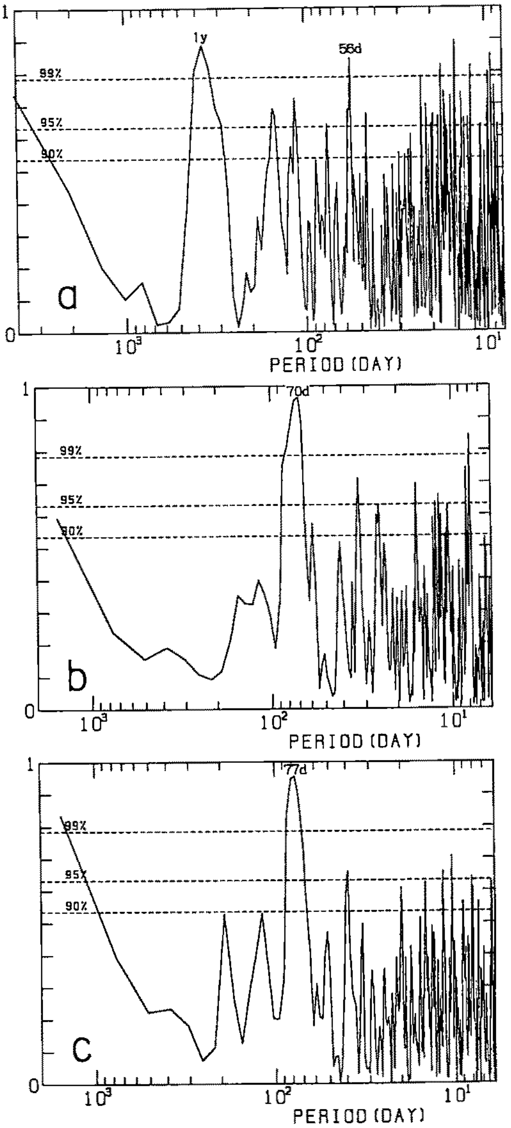

Fig. 11. Squared coherences of the sea-level difference between Naze and Nishinoomote with sea level at Minami-Izu during the NLM period (a) and the LM period (b) and with sea level at Uragami during the LM period (c).

During the 1975–1979 LM period, the sea levels along the south coast of Japan and at Naze and Nishinoomote have large variations with periods of 70 and 110 days; these variations are incoherent between Naze and Nishinoomote, though they are coherent between stations on the south coast of Japan (Kawabe, 1987). This causes a great amplitude of the 70 and 110-day variations in the sea-level difference Naze minus Nishinoomote (Fig. 8b). Figures 11b and c show that the sea-level difference is coherent with the coastal sea levels only at about 70 days, not at 110 days; it is significantly coherent at 67–81 days with Minami-Izu sea level and at 73–85 days with Uragami sea level. There is a small gap of the coherent periods between Uragami and Minami-Izu, the same as the gap in coherence among the coastal sea levels indicated by Kawabe (1987). The about 70-day variations of the coastal sea levels during the LM period are likely related to the velocity variation of the Kuroshio south of Kyûshû, but the 110-day variation is not related.

8. **Summary and discussion**

Sea levels at Naze and Nishinoomote and the sea-level difference Naze minus Nishinoomote from 1965 through 1983 were analyzed. The data indicate the sea levels on the offshore and onshore sides of the Kuroshio south of Kyûshû and the Kuroshio velocity in the Tokara Strait, respectively.

Current velocity of the Kuroshio through the Tokara Strait has large interannual variations, especially at periods longer than five years and around 2.1 years. The interannual variations of Kuroshio velocity are determined mostly by the sea-level variations at Naze on the offshore side of the Kuroshio; the Kuroshio velocity is highly coherent with the sea level at Naze at periods longer than 1.7 years, while incoherent with that at Nishinoomote at periods longer than 2.8 years. This is because the sea-level variations at Naze are larger in amplitude than those at Nishinoomote at periods longer than 2.5 years, and the sea levels are not significantly coherent between both sides of the Kuroshio except for annual periods.

Seasonal variations of Kuroshio velocity have a striking feature that the amplitude, dominant period and phase are greatly different by year; a dominant cycle repeating every year cannot be defined. The difference by year is most distinct in spring from April to June. Small velocity from September to December is the only feature found in almost all years.

The seasonal variations of Kuroshio velocity, however, are not completely random. They can be roughly divided into four groups as follows. One is a small-amplitude variation which appeared in 1972, 1977, 1978, 1979 and 1980 (small-amplitude group). The second is dominated by semiannual variations which have two maxima between January and April and between July and September, and two minima between April and June and between October and November, as seen in 1965, 1969, 1970, 1982 and 1983 (semiannual-period group). The remaining two kinds of seasonal variations have dominant annual variations: one has a large velocity during the first half of the year, as seen in 1968, 1973 and 1981, and the other has maxima in spring and summer, as seen in 1966, 1967, 1971, 1974, 1975 and 1976 (annual-period groups).

The mean seasonal variation averaged for 19 years takes large values from March II (the second half of March) to August I with a maximum in July I and II, and takes small values from September I to December I with a minimum in October II. The velocity sharply decreases in August and September. The difference between maximum and minimum of the mean seasonal variation is about 10 cm in terms of the sea-level difference Naze minus Nishinoomote. This corresponds to 13 cm sec^{-1} of spatially averaged velocity of the Kuroshio with a current width of 100 km.

The amplitude of the seasonal variation tends to be small during the large-meander (LM) period and large in the formation years of the Kuroshio large meander. Moreover, the amplitude is extremely large in the years preceding El Niño events and diminishes remarkably in the years during which the events occur. These relations are interesting and may be important, although it is not easy to find dynamical connections.

Kuroshio velocity through the Tokara Strait is incoherent with meridional variation of the Kuroshio over the Izu Ridge at almost all periods during both the NLM and LM periods, while it is highly coherent with the dominant 70-day variation of coastal sea level during the LM period.

Some characteristics in the mean seasonal variation and interannual variations of current velocity of the Kuroshio seem to be common to the Florida Current through the Straits of Florida. Schott and Zantopp (1985) showed the mean seasonal variation of the sea-level difference across the Straits of Florida averaged between 1965 and 1972, and indicated that the mean seasonal variation of velocity of the Florida Current takes a maximum in July and a minimum in November. This is almost the same as the mean seasonal variation of current velocity of the Kuroshio south of Japan. Moreover, thef characteristics that interannual variations o current velocity are determined mostly by the sea-level variations on the offshore side of the current is also held in the Florida Current through the Straits of Florida, according to a comment in Schott and Zantopp (1985).

The characteristics of interannual variations of sea levels may be explained by thinking of a simple situation where interannual Rossby waves excited by wind variations propagate westward and reflect at the western wall. The sea-level variations propagated by the Rossby waves incident to and reflected from the western wall cancel out each other on the wall, and the interannual variations based on the propagation of Rossby waves disappear on the wall. On the other hand, at points east of the Kuroshio far from the wall, the variations propagated by westward Rossby waves are little changed by those propagated by eastward Rossby waves reflected at the wall, because the reflected Rossby waves decay rapidly due to the short wavelength, and the phases of the incident and reflected waves are not just opposite except at special points. Therefore, interannual variations of sea level are small on the wall (the onshore side of the current) and large at eastern points far from the wall (the offshore side of the current), and are little coherent between the both points. As a result, the sea-level difference between the both sides (current velocity) is determined mostly by the offshore-side sea levels at interannual periods. If this simple speculation is correct, the characteristics of interannual variations of sea level may generally be found in every western boundary region where a strong current flows.

Acknowledgement

I would like to thank Dr. H. Solomon for valuable comments and careful correction of the manuscript.

References

Kawabe, M. (1980): Sea level variations around the Nansei Islands and the large meander in the Kuroshio south of central Japan. J. Oceanogr. Soc. Japan, **36**, 227-235.

Kawabe, M. (1985): Sea level variations at the Izu Islands and typical stable paths of the Kuroshio. J. Oceanogr. Soc. Japan, **41**, 307-326.

Kawabe, M. (1986): Transition processes between the three typical paths of the Kuroshio. J. Oceanogr. Soc. Japan, **42**, 174-191.

Kawabe, M. (1987): Spectral properties of sea level and time scales of Kuroshio path variations. J. Oceanogr. Soc. Japan, **43**, 111-123.

Konaga, S. and T. Inoue (1973): Relations between oceanographic conditions and the mean sea level in the adjacent sea of the Kii Peninsula. Umi to Sora, **49**, 45-49 (in Japanese with English abstract and legends).

Masuzawa, J. (1960): Statistical characteristics of the Kuroshio current. Oceanogr. Mag., **12**, 7-15.

Masuzawa, J. (1961): Recent research on the Kuroshio current. Geogr. studies presented to Prof. Tsujimura in honor of his 70th birthday, 354-364 (in Japanese with English abstract).

Masuzawa, J. (1965): A note on the seasonal variation of the Kuroshio velocity. J. Oceanogr. Soc. Japan, **21**, 117-118 (in Japanese).

Minami, H., E. Kamihira, K. Komura, H. Eguchi and J. Nishizawa (1979): Statistical features of the oceanographic conditions south of Honshu, Japan. Part 2. In spring and autumn off Kii Peninsula. Bull. Kôbe Mar. Obs., **197**, 1-11 (in Japanese with English abstract and legends).

Nitani, H. (1969): On the variability of the Kuroshio in recent several years. Bull. Japan. Soc. Fish. Oceanogr., **14**, 13-18 (in Japanese).

Nitani, H. (1975): Variation of the Kuroshio south of Japan. J. Oceanogr. Soc. Japan, **31**, 154-173.

Nitani, H., S. Yoshida, J. Okumoto and H. Nakamura (1979): Statistics on the currents in the seas adjacent to Japan. Rep. Hydrogr. Res., No. 14, 57-91.

Schott, F. and R. Zantopp (1985): Florida Current: Seasonal and interannual variability. Science, **227**, 308-311.

Taft, B. (1972): Characteristics of the flow of the Kuroshio south of Japan. p. 165-216. *In*: Kuroshio—Its Physical Aspects, ed. by H. Stommel and K. Yoshida, Univ. Tokyo Press, Tokyo.

Takematsu, M., K. Kawatate, W. Koterayama, T. Suhara and H. Mitsuyasu (1986): Moored instrument observations in the Kuroshio south of Kyushu. J. Oceanogr. Soc. Japan, **42**, 201-211.

Uda, M. (1964): On the nature of the Kuroshio, its origin and meanders. p. 89-107. *In*: Studies on Oceanography, ed. by K. Yoshida, Univ. Tokyo Press, Tokyo.

Yosida, S. (1961): On the short period variation of the Kurosio in the adjacent sea of Izu Islands. Hydrogr. Bull., New Ser., **65**, 1-18 (in Japanese with English abstract and legends).

名瀬と西之表の潮位差からみつもった黒潮流速の変動特性

川辺正樹*

要旨：1965年から1983年までの名瀬と西之表の潮位差を使って，トカラ海峡における黒潮の流速変動を調べた．

黒潮流速の経年変動は，5年以上と2.1年付近の周期で特に大きく，ほとんど沖側の潮位変動に支配されている．すなわち，黒潮の沖側（名瀬）の潮位とは1.7年以上の周期で相関が高く，逆に岸側（西之表）の潮位とは2.8年以上の周期で非常に低い．

19年間の平均季節変動では，黒潮流速は7月に最大になり，8月・9月に急激に減少したのち，10月後半に最小となる．しかし毎年の変動をみると，振幅・卓越周期・位相が年によって大きく異なる．おおまかには，振幅小，半年周期卓越，年周期卓越（位相の違いで2つに分けられる）の4種類に分類できる．ほぼ毎年みられる特徴は，9月から12月に流速が小さいということのみである．

季節変動の振幅は，黒潮大蛇行の形成年に大きく，大蛇行期間に小さいという傾向がある．さらに，エル・ニーニョの起きる前年に大きく，エル・ニーニョの年には大きく減少する．

トカラ海峡での黒潮流速は，伊豆海嶺での黒潮の位置とほとんど相関がない．しかし，大蛇行期の日本南岸潮位に卓越する70日周期変動との相関は非常に高い．

---

* 東京大学海洋研究所
〒164 東京都中野区南台 1-15-1