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# ON THE PHASE VELOCITY OF THE LARGE MEANDER OF THE KUROSHIO OFF KISYU AND ENSYU NADA — LARGE MEANDER OF THE KUROSHIO IN 1975–1980 (III) —

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**Abstract**

In 1975, the author tried to explain the large meander of the Kuroshio as a stationary Rossby wave using limited observed data obtained from comparatively shallow layers. Recalculation of the phase velocity of the large meander of the Kuroshio by applying Haurwitz's equation for barotropic Rossby waves with finite amplitude in the Kuroshio Current field, and using data from some deep sea serial observations conducted in the period of the large meander of the Kuroshio in 1975–1980, was carried out.

It was reconfirmed that the large meander of the Kuroshio off Kisyu and Ensyu Nada may be regarded as a stationary barotropic Rossby wave with finite amplitude. The slow East-West movement of the large meander in this period is also explained as the motion of the Rossby wave.

## 1. Introduction

After the World War II, the large meander of the Kuroshio off Kisyu and Ensyu Nada occurred three times, in 1953–1955, 1959–1963 and 1975–1980. There were several theories or reports on the occurrence of these large meanders Uda, 1939, 1949; Nan'niti, 1958, 1959; Fukuoka, 1960; Moriyasu, 1961, Yoshida, 1961, Robinson and Taft, 1972; Nitani, 1975; White and McCreary, 1976). However, it seems that there is no complete or established theory yet.

From the results of the oceanographic observations conducted in the first half of 1959, July of which the large meander of the Kuroshio occurred, Moriyasu (1961) and Yoshida (1961) showed that the small- or medium-scale meander of the Kuroshio southeast of Kyusyu propagated eastwards and it grew up abruptly to the large meander immediately after its passing through the Kii Peninsula and fixed soon off Ensyu Nada. Nitani (1975), from the viewpoint of that the fixing of the large meander may be explained by the zero eastward phase velocity of the meander here, attempted to calculate the phase velocity of the large meander off Kisyu and Ensyu Nada regarding the movement of the Kuroshio meander as the barotropic Rossby wave with the finite amplitude in the Kuroshio Current field. He used the equation derived by Haurwitz (1940) in calculation. Conclusion is that in the period of the large meander, the eastward phase velocity of the meander is nearly zero, for example it is 2 cm/s and 1 cm/s in 1955–1957 and 1959–1963, respectively. On the other hand, the mean phase velocity in the period in which the large meander is absent is about 10 cm/s in average (Figure 1).

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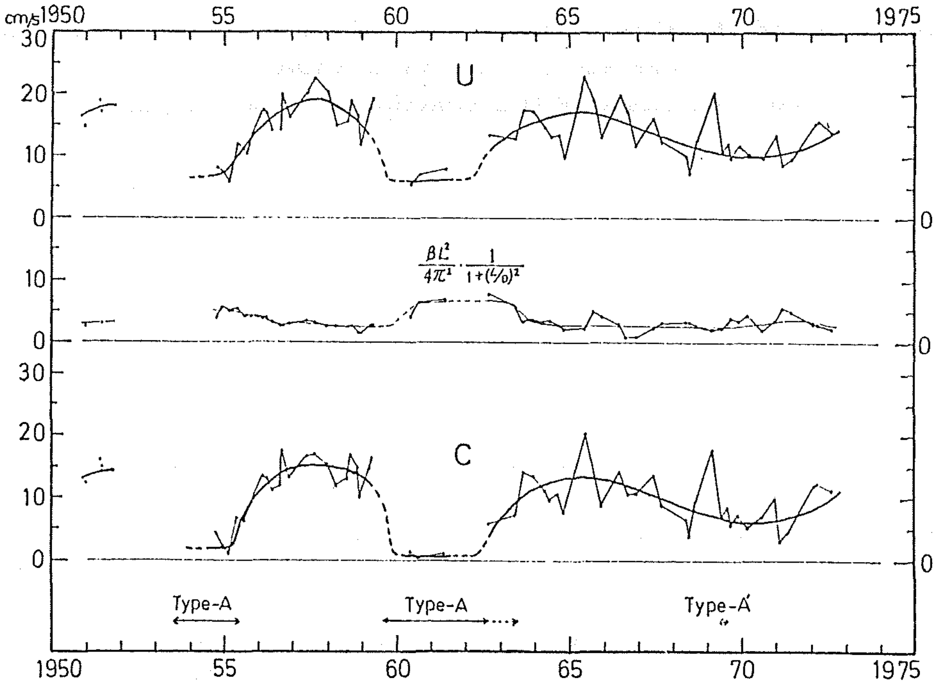


Figure 1 Results of the calculation of the eastward phase velocity, C, of the large meander of the Kuroshio off Ensyu Nada applying the Haurwitz's equation (after Nitani, 1975)

In the calculation of the geostrophic flow in that case, however, two main assumptions were used, because the deepest available serial observation data in this region were obtained from about 1600 db (deci-bar). One was that the level of no motion was estimated tentatively at first as 2300 db, and the other was that the ratio of over-all (horizontally and vertically) mean velocity of the Kuroshio referred to 1000 db to that referred to 2300 db was 1 : 0.60. These assumptions were derived from the apparently reasonable extrapolations of the data obtained at the depths shallower than 1600 db to the deeper portions. Based on the above assumptions and observed phase velocities, it was also suggested that the most probable depths of the layer of no motion in the periods in which the large meander was present and absent were 2750 db and 2250 db, respectively. The confidence of these conclusions or suggestions depends directly on the reliance of these assumptions.

After the occurrence of the large meander of the Kuroshio off Kisyu and Ensyu Nada in August 1975, some deep sea Nansen casts nearly reaching to the bottom were conducted by the Hydrographic Department. In the present paper, the recalculation of the eastward phase velocity of the Kuroshio meander with use of the equation of Haurwitz and the observed deep Nansen cast data is carried out to explain the large meander of the Kuroshio off Kisyu and Ensyu Nada as the stationary barotropic Rossby wave with finite amplitude and to explain its very slow east-west movement in the period of the large meander.

## 2. Method of the calculation

The eastward phase velocity of the Kuroshio meander is calculated with use of the following equation,

$$C=U-\frac{\beta L^2}{4\pi^2}\cdot\frac{1}{1+(L/D)^2} \qquad (1)$$

where, C, U and $\beta$ are the eastward phase velocity, the velocity of the basic eastward current and Rossby factor ($1.9\times10^{-13}\,cm^{-1}sec^{-1}$ at 32.5°N), and L and D are the wave length and the amplitude of the Rossby wave, respectively.

According to our experiences obtained from the deep sea Nansen casts and the direct current measurements, the large meander of the Kuroshio is not only the shallow layer phenomenon but also whole layers one having nearly the same position and the current direction as those of the surface meander. This is the reason to apply the barotropic model in this calculation as the first step, though actual Kuroshio is baroclinic.

In applying the equation (1), L and D are determined as shown in Figure 2, and these values are obtained from the "Prompt Report on the Oceanographic Conditions" issued by the Hydrographic Department in the same period of the observation conducted. U should be as follows,

$$U=\frac{\bar{u}}{\sin\theta}\cdot\frac{L}{L'} \qquad (2)$$

where $\bar{u}$ is the over-all mean velocity component of the Kuroshio perpendicular to the observation line, and $\theta$ is an angle between the axis of the Kuroshio and the observation line. So, $\bar{u}/\sin\theta$ becomes an over-all mean velocity of the Kuroshio along its axis. L′ is the distance along the axis of the actual meandering Kuroshio over a wave length (Figure 2). By multiplication L/L′ by axial over-all mean velocity, we get the mean east component of the velocity of the basic current, U, over a wave length of the meandering Kuroshio. $\bar{u}$ is calculated from the Nansen cast data as the geo-

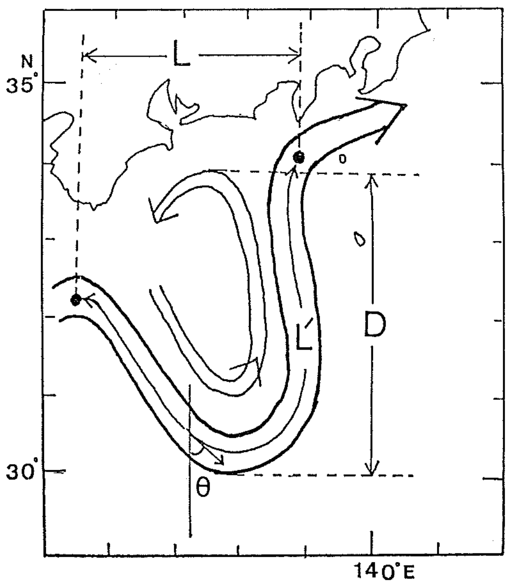


Figure 2 L, L′, D and $\theta$ used in the calculation of the phase velocity

strophic flow, and $\theta$ and L′ are also obtained from the "Prompt Report on the Oceanographic Conditions".

In the calculation of the geostrophic flow, we can use 11 deep sea observation sections from 9 oceanographic cruises. In these sections the sampling depths reach to nearly 4000 db. The extrapolations for the deepest several hundred meters are used in some observation stations where the deepest sampling depth is shallower than 4000 db. In addition to above, 29 sections from 27 cruises whose sampling depth are shallow but not less than 1000 db are used with multiplication by a certain kind of coefficient so that the values from these shallow sections may be used nearly equivalently to those from the deep sea sections.

From the calculation of the geostrophic flow of the Kuroshio referred to 4000 db with use of 11 deep sections, the mean axial velocity at the standard depths and the distribution of the

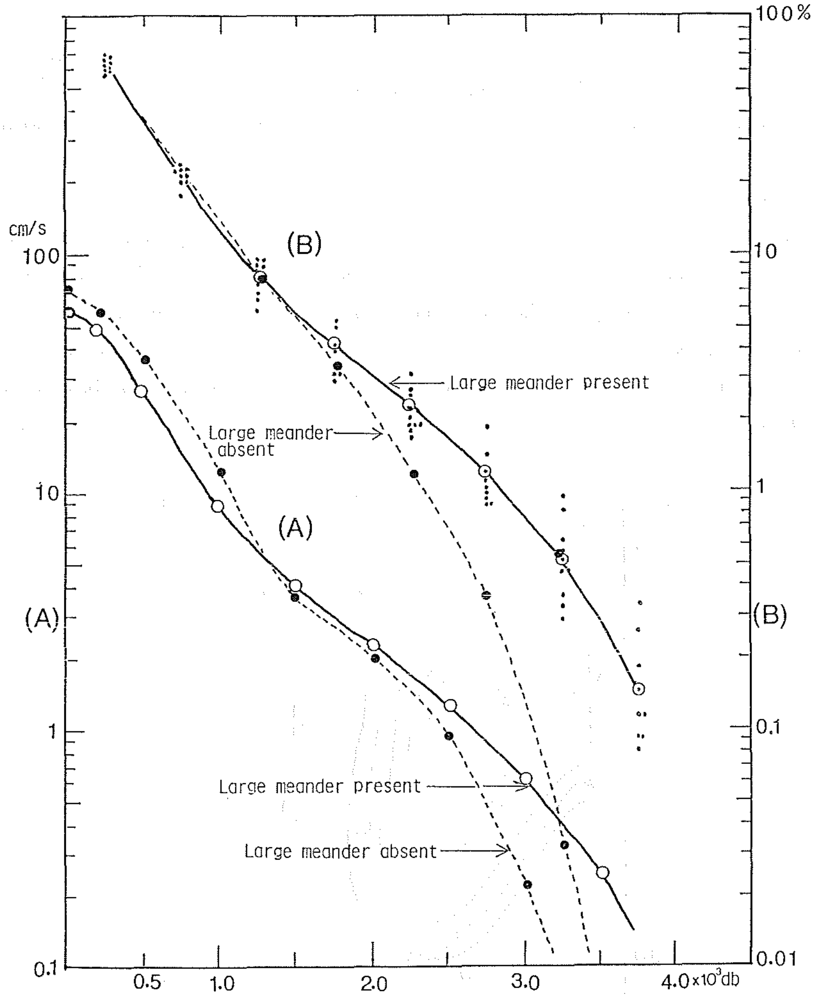


Figure 3 Mean axial velocity at every 500 db depths of the Kuroshio referred to 4000 db (A), and the distribution of the volume transport in each water column of 500 meters long in percentage (B). Thick and dotted lines correspond to the periods of the presence and absence of the large meander.

volume transport in each water column of 500 meters long in percentage are shown respectively in Figure 3. Mean velocity at the depth of 3500 db is only 0.25 cm/s showing the rapid decrease and the volume transport in the column between 3500 db–4000 db is only 0.15°/₀₀ of the whole volume transport from surface to 4000 db. As shown in Figure 4, the ratio of the volume transport of the Kuroshio referred to each standard depth to that referred to 1000 db approaches gradually to the constant value of 1.64 at the depth of 4000 db. Nishida (1982) suggested that in the period of the large meander, the distribution of the temperature at the depth of 3000 db showed the nearly same pattern as the surface one indicating the existing of slow geostrophic current in the deep sea. Considering these phenomena mentioned above and the fact that the mean depth of the bottom in the region of the large meander of the Kuroshio is about 4200 meters, the depth of 4000 db is selected as the level of no motion for the geostrophic calculation.

For the purpose of the present paper only 11 deep sections are not enough in number. It

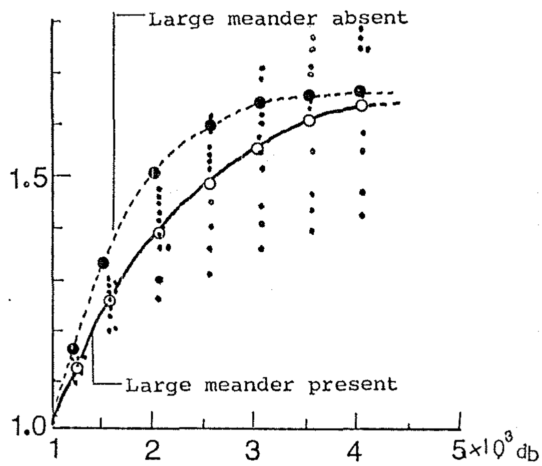


Figure 4 Ratio of the volume transport of the Kuroshio referred to each standard depth to that referred to 1000 db.

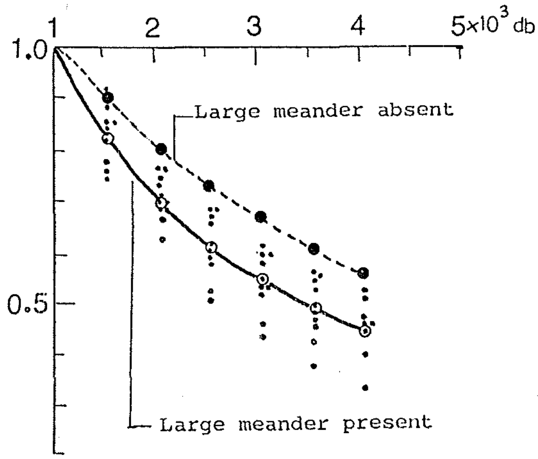


Figure 5 Ratio of the over-all mean velocity of the Kuroshio referred to each standard depth to that referred to 1000 db.

Table Attribute of the observed sections and the results of the calculation

| $R/V$ | Period | Long. of observ. | $L$ (N.M.) | $D$ (N.M.) | $L/L'$ | $U$ (cm/s) | $\beta L^2/4\pi^2\times 1/(1+(L/D)^2)$ (cm/s) | $C$ (cm/s) |
|---|---|---|---|---|---|---|---|---|
| Takuyo | 1974. 5 | 138-139° | 205 | 140 | 0.93 | 10.8 | 2.2 | 8.6 |
| // | 1974. 5 | 137°00′ | 205 | 140 | 0.93 | 12.7 | 2.2 | 10.4 |
| // | 1975. 3 | 137°00′ | 120 | 110 | 0.96 | 14.1 | 1.1 | 13.1 |
| // | 1975. 5 | 137°00′ | 170 | 120 | 0.98 | 12.3 | 1.6 | 10.7 |
| Kaiyo | 1975. 8 | 136°00′ | 195 | 210 | 0.48 | 5.5 | 3.4 | 2.1 |
| // | 1975. 8 | 137°00′ | 195 | 210 | 0.48 | 9.3 | 3.4 | 5.9 |
| Hakuho Maru | 1975.10 | 136-138° | 180 | 240 | 0.45 | 4.5 | 3.4 | 1.1 |
| Ryofu Maru | 1976. 1 | 137°00′ | 210 | 255 | 0.43 | 3.7 | 4.3 | −0.6 |
| Shoyo | 1976. 3 | 135°50′ | 220 | 230 | 0.48 | 5.5 | 4.2 | 1.4 |
| Takuyo | 1976. 5 | 137°30′ | 230 | 320 | 0.48 | 3.2 | 5.8 | −2.6* |
| Ryofu Maru | 1976. 8 | 137°00′ | 220 | 220 | 0.55 | 3.1 | 4.0 | −0.9 |
| Kaiyo | 1976. 8 | 137°30′ | 220 | 235 | 0.54 | 4.4 | 4.3 | 0.1 |
| Shoyo | 1976.11 | 137°30′ | 285 | 295 | 0.55 | 4.4 | 6.9 | −2.5* |
| // | 1976.11 | 135°40′ | 285 | 295 | 0.55 | 8.6 | 6.9 | 1.7 |
| Ryofu Maru | 1977. 1 | 137°00′ | 180 | 200 | 0.37 | 3.0 | 2.9 | 0.0 |
| Shoyo | 1077. 3 | 137°00′ | 160 | 265 | 0.46 | 3.1 | 3.1 | 0.0* |
| Takuyo | 1977. 9 | 136°30′ | 160 | 250 | 0.33 | 3.1 | 3.1 | 0.0* |
| // | 1977. 9 | 135°00′ | 185 | 205 | 0.39 | 4.8 | 3.1 | 1.7* |
| Shoyo | 1977.11 | 136°40′ | 170 | 210 | 0.47 | 4.5 | 2.9 | 1.6 |
| Ryofu Maru | 1978. 1 | 137°00′ | 260 | 260 | 0.41 | 3.5 | 5.6 | −2.0 |
| // | 1978. 2 | 137°00′ | 180 | 240 | 0.51 | 4.2 | 3.4 | 0.7 |
| Shunpu Maru | 1978. 5 | 137°00′ | 260 | 240 | 0.63 | 4.4 | 5.1 | −0.7 |
| Takuyo | 1978. 5 | 136°30′ | 140 | 250 | 0.35 | 2.9 | 2.4 | 0.5 |
| Ryofu Maru | 1978. 7 | 137°00′ | 210 | 250 | 0.43 | 4.2 | 4.1 | 0.2 |
| Shoyo | 1978.11 | 135°30′ | 200 | 250 | 0.50 | 5.0 | 4.1 | 0.9* |
| // | 1978.11 | 137°00′ | 210 | 280 | 0.45 | 3.4 | 4.6 | −1.2* |
| Ryofu Maru | 1979. 1 | 137°00′ | 160 | 240 | 0.34 | 3.1 | 2.9 | 0.2 |
| Takuyo | 1979. 5 | 136°30′ | 120 | 240 | 0.24 | 2.2 | 2.3 | −0.1* |
| Ryofu Maru | 1979. 7 | 137°00′ | 180 | 260 | 0.33 | 2.5 | 3.6 | −1.2 |
| Takuyo | 1979. 8 | 136°50′ | 160 | 160 | 0.49 | 2.8 | 2.1 | 0.7 |
| // | 1979.11 | 138°10′ | 220 | 200 | 0.56 | 5.9 | 3.6 | 2.3 |
| // | 1979.11 | 136°40′ | 220 | 200 | 0.56 | 5.5 | 3.6 | 1.9* |
| Ryofu Maru | 1980. 1 | 137°00′ | 230 | 190 | 0.59 | 7.8 | 3.5 | 4.3 |
| Takuyo | 1980. 5 | 138°10′ | 250 | 190 | 0.66 | 9,5 | 3.8 | 5.7* |
| // | 1980. 5 | 136°40′ | 250 | 190 | 0.66 | 6.5 | 3.8 | 2.8 |
| Ryofu Maru | 1980. 7 | 137°00′ | 250 | 150 | 0.63 | 5.9 | 2.7 | 3.2 |
| Takuyo | 1980. 8 | 138°40′ | 220 | 150 | 0.96 | 8.6 | 2.5 | 6.0 |
| // | 1980. 8 | 137°40′ | 220 | 150 | 0.96 | 11.1 | 2.5 | 8.6 |
| Shoyo | 1980.11 | 137°30′ | 230 | 155 | 0.90 | 14.8 | 2.7 | 12.1* |
| // | 1981. 2 | 138°30′ | 160 | 130 | 0.96 | 11.8 | 1.7 | 10.1 |

The deep sea sections are marked with *.

is necessary to use 29 shallow sections which include the sections observed in the period of no large meander of the Kuroshio. In these case, the geostrophic calculation is referred to 1000 db, and the over-all mean velocity of the Kuroshio is estimated with use of the multiplication factor 0.44 which is the ratio of the over-all mean velocity of the Kuroshio referred to 4000 db to that referred to 1000 db, $\bar{u}_{4000}/\bar{u}_{1000}$, obtained from the result of 11 deep sections mentioned above (Figure 5). The attributes of observed sections are shown in Table together with theresults of calculation.

## 3. Results of the calculation

Results of the calculation for axial over-all mean velocity, $\bar{u}/\sin\theta$, eastward basic current velocity, $U(=\bar{u}/\sin\theta\cdot L/L')$, the second term in the right-hand side of equation (1), $\beta L^2/4\pi^2\cdot 1/(1+(L/D)^2)$ and phase velocity, C are shown in Figure 6.

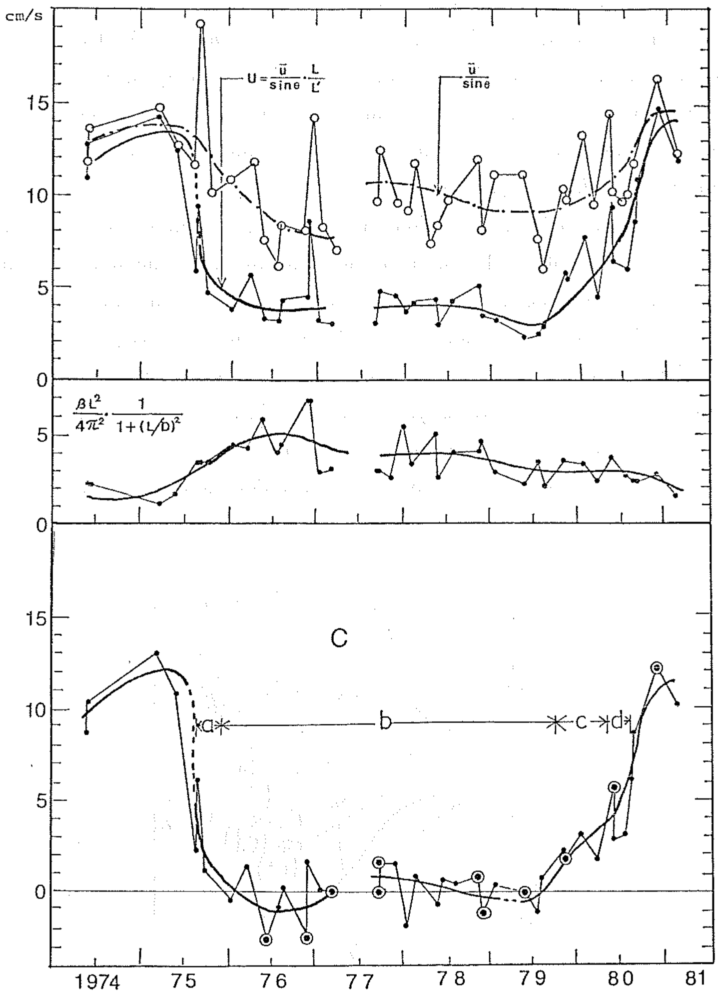


Figure 6 Results of the calculation for the axial over-all mean velocity, the eastward velocity of the basic current, the second term in right-hand side of equation (1) and the eastward phase velocity of the meander of the Kuroshio off Kisyu·Ensyu Nada. In the last calculation, the computed values based on the data from deep sections are marked with ⊙.

In the period in which the large meander is absent, the eastward phase velocity is about 10 cm/s or more in accord with about 5 naut.mile/day of the mean observed phase velocity (Nitani, 1975). In the period in which the large meander is present, on the contrary, $\bar{u}/\sin\theta$ and U become small and $\beta L^2/4\pi^2 \cdot 1/(1+(L/D)^2)$ becomes large a little. As the result of these, the eastward phase velocity becomes nearly zero. An abrupt decrease of the phase velocity appeared in August 1975 when the large meander of the Kuroshio occurred at the offing of the Ensyu Nada.

Even in the period of the large meander of the Kuroshio, the large meander does not fix off Ensyu Nada completely. It moves east and west slowly corresponding to each age of a life of the large meander of the Kuroshio as shown in Figure 7 typically. A life of the large meander of the Kuroshio may be classified into four periods apparently, these are rearing age, prosperous age, decay age and disappearance age, and each period has its own characteristics (Nitani, 1977). In the rearing age (Aug.–Nov. 1975), the large meander moves east with the phase velocity of 2–3 cm/s for some time after the occurrence of it. In prosperous age (Dec. 1975–Oct. 1979), the large meander moves rather west or almost stays having the mean phase velocity of about 0.1 cm/s except three months between May–July in 1977. In these three months, a southern portion of the large cold eddy inside of the large meander was cut off, and the large meander became the small-scale meander at one time (Kamihira *et al.,* 1978). This small-scale meander moved away easterly with fairly large phase velocity as shown in Figure 8. After that the large meander was reformed again by the combination of the separated cold eddy south of the Kuroshio and the new medium-scale meander which came from west. In the decay age (Nov. 1979–Apr. 1980), the large meander moves easterly, reducing its scale, with the phase velocity of 2–3 cm/s. In the disappearance age (May–Aug. 1980), the mean phase velocity increases to about 5 cm/s. After the disappearance of the large meander of the Kuroshio off Kisyu and Ensyu Nada, the phase velocity of the newly occurred small- or medium-scale meander becomes 10 cm/s or more again.

In Figure 8 the observed center of the large meander defined as the center of gravity of

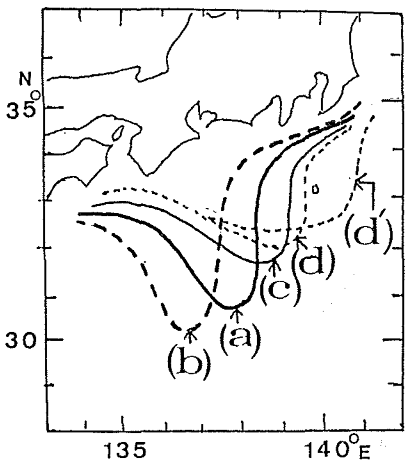


Figure 7 Schematic patterns of the large meander of the Kuroshio in each age of a life of it, rearing age (a), prosperous age (b), decay age (c) and disappearance age (d and d').

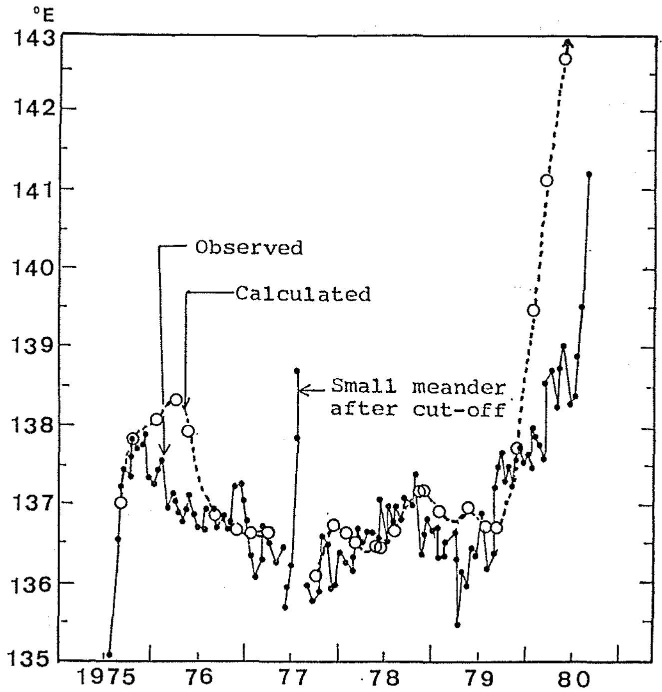


Figure 8 Comparizon between the centers of the large meander of the Kuroshio observed and derived from the calculated phase velocity in Figure 6.

triangle, each apex of which is on the tops of the mountains and valley of the large meander, are shown together with the center calculated based on the phase velocity in Figure 6. The tendency of calculated E-W movement in low frequency area fairly agrees with the tendency of the movement observed. However, the difference in longitudinal positions of both kinds of the centers is conspicuous in the first half of 1976 and after Oct., 1979. In theses periods, the observed centers exist east of 137°–137°30′, and subsequently the center or at least the eastern half of the meander approaches closely to the Izu Ridge. The topographic obstacle of ridge may prevent the eastward movement of the actual large meander. A reason that the calculated movement is behind about 3–4 months than that observed is not clear.

## 4. Concluding remarks

It is reconfirmed more precisely than before (Nitani, 1975), that the large meander of the Kuroshio off Kisyu and Ensyu Nada may be regarded as the stationary barotropic Rossby wave with finite amplitude in the Kuroshio Current field. Subsequently, the slow East-West movement of the large meander in the period of its existence is also explained as the movement of the above Rossby wave, especially for the case in which the large meander is not so close to the Izu Ridge.

According to equations (1) and (2), there are three factors which contribute to making the phase velocity of the large meander nearly zero. The first is the weak axial over-all mean velocity of the Kuroshio, and the second is the sharpness of the shape of the meander expressed by L/L′. These two factors make the eastward velocity of the basic current U small. The third is the largeness of the term $\beta L^2/4\pi^2 \cdot 1/(1+(L/D)^2)$ which is the westward phase velocity of Rossby wave when the basic current is zero. This factor also depends on the shape of the meander. According to Figure 6, an order of the extent of the contribution seems to be the second, the first and the third factors mentioned above.

The second and the third factors are caused by the abrupt glowth of the small- or medium-scale of the Kuroshio, which comes from west with the comparatively small phase velocity than usual in the case of occurrence of the large meander at the offing of Ensyu Nada. The abrupt glowth of the meander here probably due to the instability of the meander of the Kuroshio after passing through the Kii Peninsula. The topography of these regions including the Izu Ridge may play the important role for the abrupt glowth of the meander. Anyway, these factors may be derived from the local topographic effect. On the contrary, the weakness of the axial over-all mean velocity in the period of the large meander may be the phenomenon which relates to the oceanographic conditions of wide area, for instance, those of the northwestern Pacific or at least of the area around the southwestern Japan, because the weakness in the axial mean velocity here occures associating with the small volume transport of the Kuroshio southeast of Yaku Island and the large volume transport in the East China Sea (Nitani, 1972, 1975). However, the physical reasons of the phenomena mentioned above are not clear yet. Also the reason for the slow E-W movement of the large meander of the Kuroshio corresponding to each age of a life of it is unknown. From the investigation of these mechanisms, the mechanism of the disappearance of the large meander of the Kuroshio as well as that of its occurrence will be solved.

According to Figures 3 and 4, in the period of no large meander, the mean geostrophic velocity of the Kuroshio at the depth of 3000 db and the ratio of the volume transport in the water column of 500 meters long in the depth deeper than 3000 db are very small, and the increase of the total volume transport with depth approaches to zero more gradually comparing with those in the period of the large meander, though the deep sea section available for calculation is only one. This means that the velocity of the geostrophic current at the depth deeper than about 3000 db off Kisyu and Ensyu Nada is nearly zero or the depth of the Kuroshio in the period of no large meander is shallower than that in the period of the large meander as already estimated by Nitani (1975) roughly. If this is true, the difference of the depth to which the Kuroshio reach may be one of the important factors to know the mechanism of the occurrence, and subsequently maintenance and disappearance of the large meander of the Kuroshio. The frequent deep sea observations in these regions are desirable in future to confirm the characteristic of the deep portion of the Kuroshio with no large meander.

The author wishes to express his thanks to many scientists who conducted these oceanographic observations, especially to Mr. A. Kosugi, Hydrographic Department, for his leadership for the carrying out of the deep sea oceanographic observation as the routine immediately after the occurrence of the large meander of the Kuroshio in 1975. A part of this observation was carried out as the "Kuroshio Exploitation and Utilization Research (KER)" sponsored by the Science and Technology Agency, and he also thanks to the agency.

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