La mer 24: 169-176, 1986
Société franco-japonaise d'océanographie, Tokyo

The short-period cold water mass accompanied by large meander of the Kuroshio south of Japan*

Haruo ISHII** and Yoshihiko SEKINE***

Abstract: A cold water mass accompanied by the large meander of the Kuroshio with short lifetime less than one year was observed to the south of Japan. The difference in hydrography between the short-period meander observed in 1969-1970 and long-period meanders observed in 1975-1980 and 1981-1984 is considered. It is shown that there are no apparent differences in the current path pattern of the Kuroshio during the formation process of the large meander between the short-period meander and the long-period meanders. The time variation in temperature at depths of 1,000 m and 1,500 m near the center of the cold water mass with the short-period meander has a tendency to increase in the western side of the Izu Ridge. In the final period of the short-period meander, the center of the cold water mass shifts to the eastern side of the Izu Ridge. Observed current path does not show amplification in the eastern side of the Izu Ridge, which is neither observed in the final period of the long-period meanders. The temperature variation of the cold water mass accompanied with long-period meander is found to repeat its increase and decrease in the western side of the Izu Ridge. However, the decrease in the temperature is not detected in the cold water mass accompanied by the short-period meander. It is suggested that the lifetime of the large meander of the Kuroshio and of the cold water mass is related to the occurrence of temperature decrease of the cold water mass in the western side of the Izu Ridge south of Japan.

1. Introduction

It is well known that a large-scale meander of the Kuroshio appears south of Japan and stays for a long period (e.g., SHOJI, 1972; NISHIDA, 1982). This phenomenon, which is called large meander, is peculiar to the Kuroshio and a similar one has not been observed in other western boundary currents. Since 1950, the large meander of the Kuroshio has been observed six times (see Table 1). We should notice here that the two cases of the large meander, which were formed in 1951 and in 1969, ended with a short lifetime less than one year, whereas the other cases continued more than two years. The difference in lifetime length between both the cases is considered in the present paper.

SEKINE *et al.* (1985) analyzed the time variation of the cold water mass accompanied with the large meander of the Kuroshio formed in 1975. They showed that the temperature at a depth shallower than 1,000 m near the center of the cold water mass takes several repetition of cooling and warming, in which the cooling has a tendency to occur in late spring to summer and the warming in the other seasons. During the cooling periods, the expansion of the low temperature area, which is estimated from a horizontal temperature distribution at a depth of 200 m, is commonly observed, while the shrinking of the low temperature area is observed in warming periods. It is also suggested by SEKINE *et al.* (1985) that the cold water mass of the Kuroshio decays in comparatively short time, three years at most, if the cooling period of temperature does not exist. The occurrence of the cooling of the cold water mass is supposed to be related to the longer lifetime of the cold water mass and the large meander of the Kuroshio.

In the present study, the time variation of the short-period meander and its cold water mass is analyzed from the above viewpoint. Because

* Received March 10, 1986
** Hydrographic Department, Maritime Safety Agency of Japan, Chuo-ku, Tokyo, 104 Japan
*** Institute of Geosciences and Astronomy, The National Defense Academy, Yokosuka, 239 Japan

very little hydrographic data of the short-period meander formed in 1950 is available, the main analysis of the short-period meander is made for that formed in 1969. In what follows, the difference in current path during the formation period of large meander between the short-period meander and the long-period meanders is examined in the next section. In the section three, the time variation in the temperature of the cold water mass of short-period meander is examined and the result is compared with those of long-period meanders formed in 1975 and in 1981. Summary and discussion are made in section four.

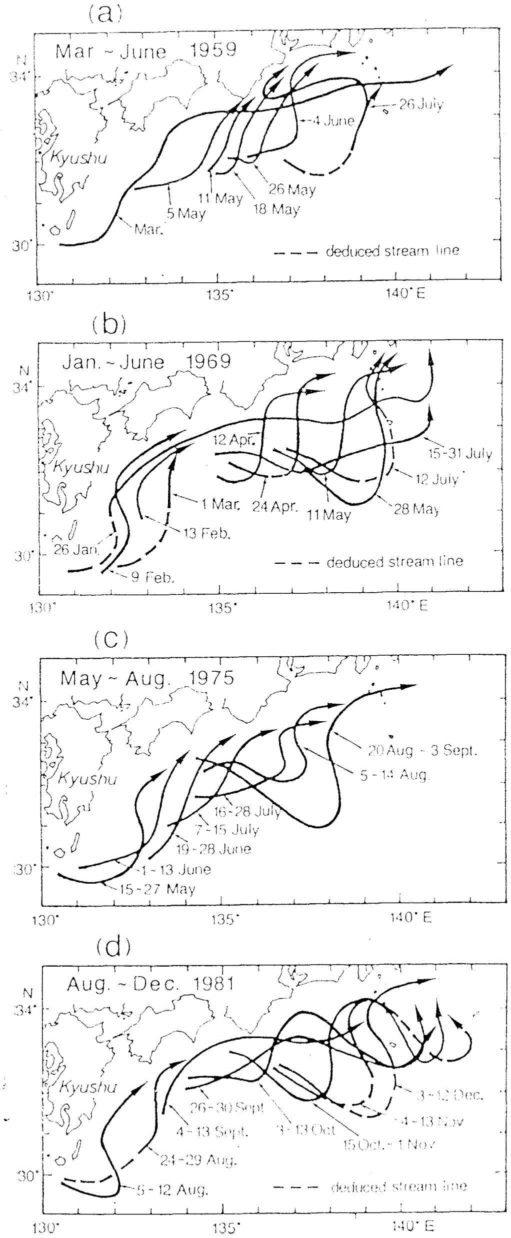


Fig. 1. Change in the path of the Kuroshio during the transition periods from no meander path (a) after YOSHIDA (1961), (b) after SHOJI (1972), (c) after KOSUGI (1978) and (d) based on data of the Hydrographic Department.

2. Time variation in current path during the formation period of the short-period large meander of the Kuroshio

Figure 1 displays the four cases of the time variation of the Kuroshio path during the formation process of the large meander path from no meander path. The case of Fig. 1(b) observed in 1969 is a short-period meander and the other three cases observed in 1959, 1975 and 1981 are long-period meanders (see Table 1). It is found that the variation in current path of the Kuroshio during the transition process is almost common to all the cases; a small meander is generated to the southeast of Kyushu, and it moves eastward. Relatively sudden amplification of the small meander occurs near 137-138°E, which is a final process of the formation of the large meander path of the Kuroshio. It is found from Fig. 1 that there are no apparent differences in the current path pattern in the formation process and in the accomplished large meander path between the short-period meander and the long-period meanders. Although the detailed comparison is difficult due to the lack of the observational data, it is inferred that the lifetime of a cold water mass depends on the process after the accomplishment of the for-

Table 1. Lifetime of the cold water mass of the Kuroshio.

Case no.	Periods of presence of the cold water mass	Lifetime (in years)
I	Aug. 1951-Apr. 1952[a]	0.8
II	Sept. 1953-Dec. 1955[a]	2.3
III	July 1959-Dec. 1962[a,b]	3.5
IV	May 1969-May 1970[b]	1.0
V	Aug. 1975-Aug. 1980[b]	5.0
VI	Nov. 1981-Aug. 1984[b]	2.9

[a] After OKADA and NISHIMOTO (1978).
[b] Based on data from Hydrographic Department of the Maritime Safety Agency of Japan.

mation of the Kuroshio large meander south of Japan.

3. Time variation in temperature of the cold water mass accompanied by short-period meander

The temperature variation in the deep layer near the center of the cold water mass formed in 1969 is shown in Fig. 2. The temperature is estimated as the average of the lowest three temperature data near the center of the cold water mass (for the locations of the lowest three temperature data, see Fig. 3). It is shown that the temperature has a tendency to increase during the total lifetime. The tendency of temperature variation shown in Fig. 2 almost coincides with those of the Gulf Stream cyclonic rings; the warming of the cold dome is found throughout the lifetime (e.g., CHENEY and RICHARDSON, 1976).

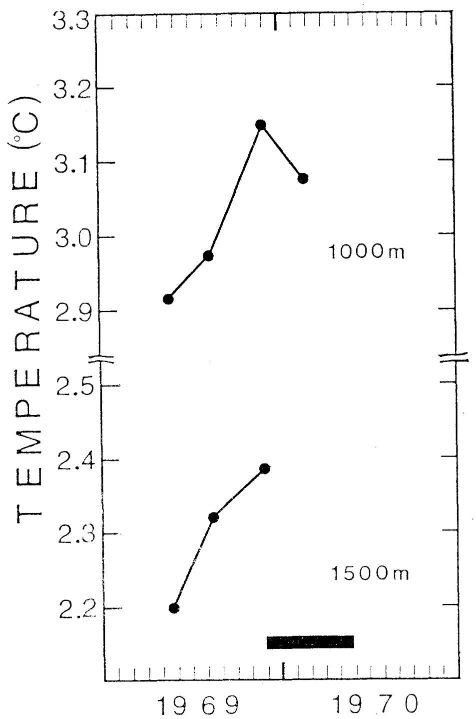


Fig. 2. Time variation of temperature at depths of 1,000 m and 1,500 m in the cold water mass of the Kuroshio. The temperature is defined as the average of the lowest three data near the center of the cold water mass of which locations are shown by larger symbols of station points in Fig. 3. Data sources are Maritime Safety Agency and Japan Meteorological Agency. The black band at the bottom shows the period when the center of the cold water mass exists in the eastern side of the Izu Ridge.

Horizontal distribution of the temperature displayed in Fig. 3 shows that the horizontal scale of the cold water mass diminishes by the lapse of time and the center of the cold water mass shifts to the eastern side of the Izu Ridge. The cold water mass attenuates rapidly in the eastern side of the Izu Ridge and the large meander of the Kuroshio disappears in a short time. The phenomenon that the center of the cold water mass and large meander of the Kuroshio shift to the eastern side of the Izu Ridge in its last stage is common to all the large meanders (e.g. NISHIDA, 1982). Small temperature decrease at a depth of 1,000 m is detected in Fig. 2, after the cold water mass of the Kuroshio shifted to the eastern side of the Izu Ridge. However, the cold water mass may not be intensified in the eastern side of the Izu Ridge.

The temperature variation in the deep layer for the cases of long-period meanders formed in 1975 and in 1981 is shown in Fig. 4(a) and (b), respectively. The temperature tends to increase gradually by the lapse of time, but there exist some cooling periods. The cooling has a tendency to occur in late spring to summer. We should notice here that the decrease in temperature of the cold water mass in the Shikoku Basin (western side of the Izu Ridge) has not been observed in the lifetime of short-period meander formed in 1969 as shown in Fig. 2.

Horizontal distributions of temperature during the cooling periods shown in Fig. 4 are displayed in Fig. 5 and Fig. 6. It is clear that the decrease in temperature of the cold water mass and the expansion of the horizontal scale of the cold water mass of the long-period meander occur in the western side of the Izu Ridge, which is not found in the case of short-period meander shown in Figs. 2 and 3. Because the cooling of a deep layer is caused by the ascent of the isotherms, such a cooling is considered to be a spin-up of the cold water mass (for the detailed description of the cooling period of Fig. 4(a), see SEKINE *et al.*, 1985). From this, no occurrence of the cooling in the western side of

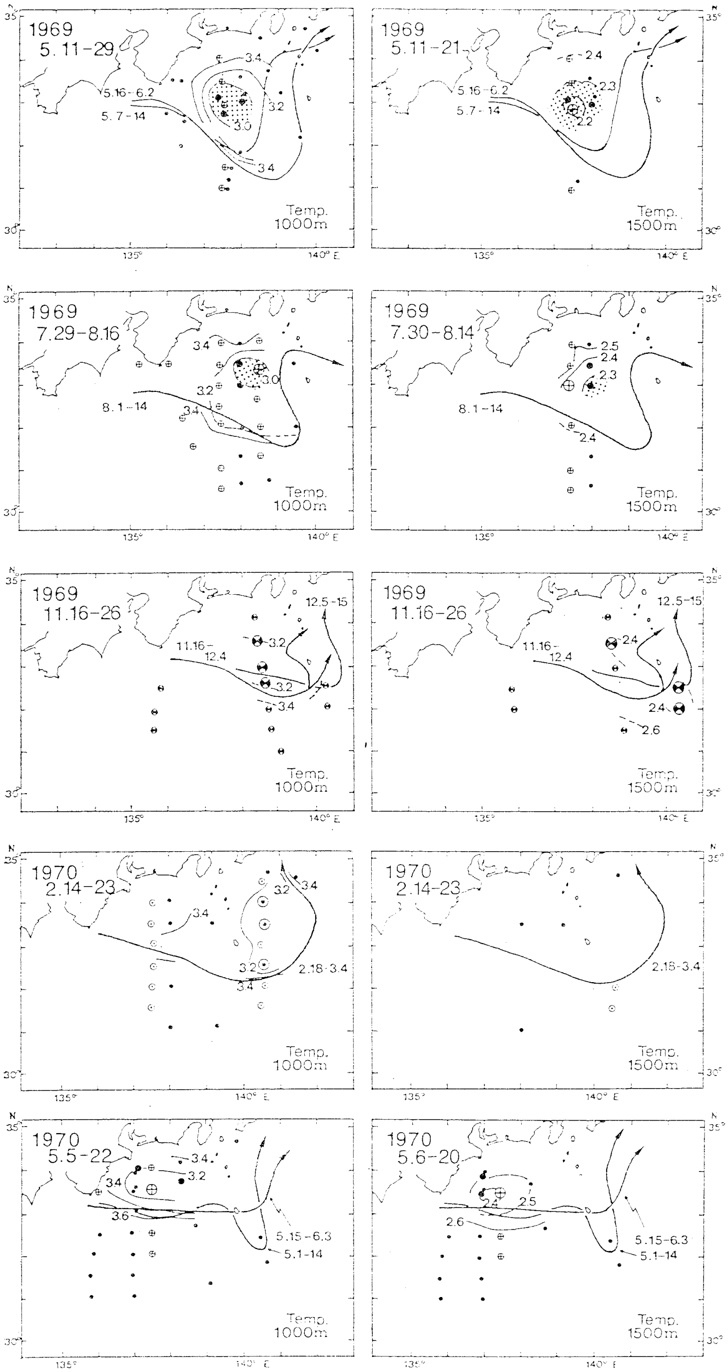
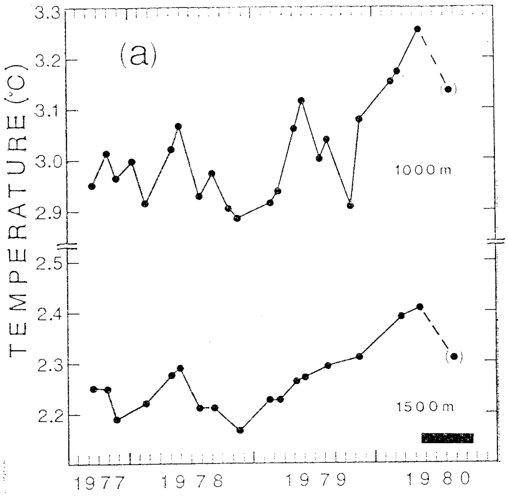


Fig. 3. Horizontal distribution of temperature (°C) at depths of 1,000 m and 1,500 m during the short period meander formed in 1969. Also shown are surface current axes of the Kuroshio (thick lines with arrows) based on the Quick Bulletin of Ocean Conditions published twice a month by Hydrographic Department of Maritime Safety Agency of Japan. Symbols show the observational stations of temperature of Takuyo (●) and Kaiyo (⊗) of Hydrographic Department, and Shunpu Maru (⊕) and Ryofu Maru (◉) of Japan Meteorological Agency. The larger three symbols show stations of the lowest three temperatures, of which averages are displayed in Fig. 2.



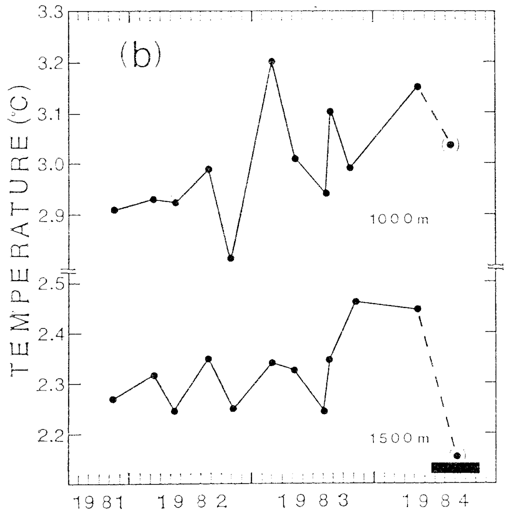


Fig. 4. Time variation of temperature at depths of 1,000 m and 1,500 m in the cold water mass of the Kuroshio accompanied by the long-period large meanders formed in 1975 (a) and in 1981 (b). The temperature is defined as the average of the lowest three data near the center of the cold water mass. Data are provided by Maritime Safety Agency of Japan, Japan Meteorological Agency, Japan Oceanographic Data Center and Fisheries Agency. The black band at the bottom shows the period when the center of the cold water mass exists in the eastern side of the Izu Ridge.

the Izu Ridge indicates no occurrence of the spin-up of the cold water mass accompanied with the short-period meander. In constrast to this, long-period meanders formed in 1975 and in 1981 have spin-up periods of the cold water mass. It is thus pointed out that the occurrence of a spin-up of the cold water mass is associated with the longer lifetime of the large meander of the Kuroshio.

Next we see a critical condition of the shift of the cold water mass to the eastern side of the Izu Ridge, which is commonly observed for the decay period of the cold water mass and large meander of the Kuroshio. The periods when the cold water mass is in the eastern side of the Izu Ridge are displayed by the black bands in Figs. 2 and 4. It is demonstrated from Figs. 2 and 4 that the shift of the cold water mass occurs when the temperature at a depth of 1,500 m near the center of the cold water mass exceeds about 2.4°C. The existence of the critical value of temperature is considered as follows. On the basis of the gradient flow balance on the deep layer circulation of the cold water mass, the larger horizontal gradient of the temperature at a deep level indicates the existence of larger current velocity down to that level, and vice versa. Because the averaged depth of the Izu Ridge is shallower than 1,000 m, the cold water mass is supposed to have a contact with the bottom topography of the Izu Ridge. It is well-known from the theory of the geophysical fluid dynamics (e.g., PEDLOSKY, 1979) that the current in the deep layer has a tendency to flow along the isopleth of the depth. Therefore, the cold water mass with the larger current velocity in the deep layer is not able to go over the Izu Ridge to its eastern side, unless the current velocity in lower layer is weakened. It is thus suggested that the critical velocity which allows the cold water mass to shift to the eastern side of the Izu Ridge is represented by the temperature of about 2.4°C at a depth of 1,500 m, in which averaged temperature at a depth of 1,500 m south of Japan is about 2.6–2.9°C (e.g. TAFT, 1978). However, this critical condition on the shift of the cold water mass should be examined quantitatively by use of simulating model.

4. Summary and discussion

The time variation of the short-period cold water mass accompanied by large meander of

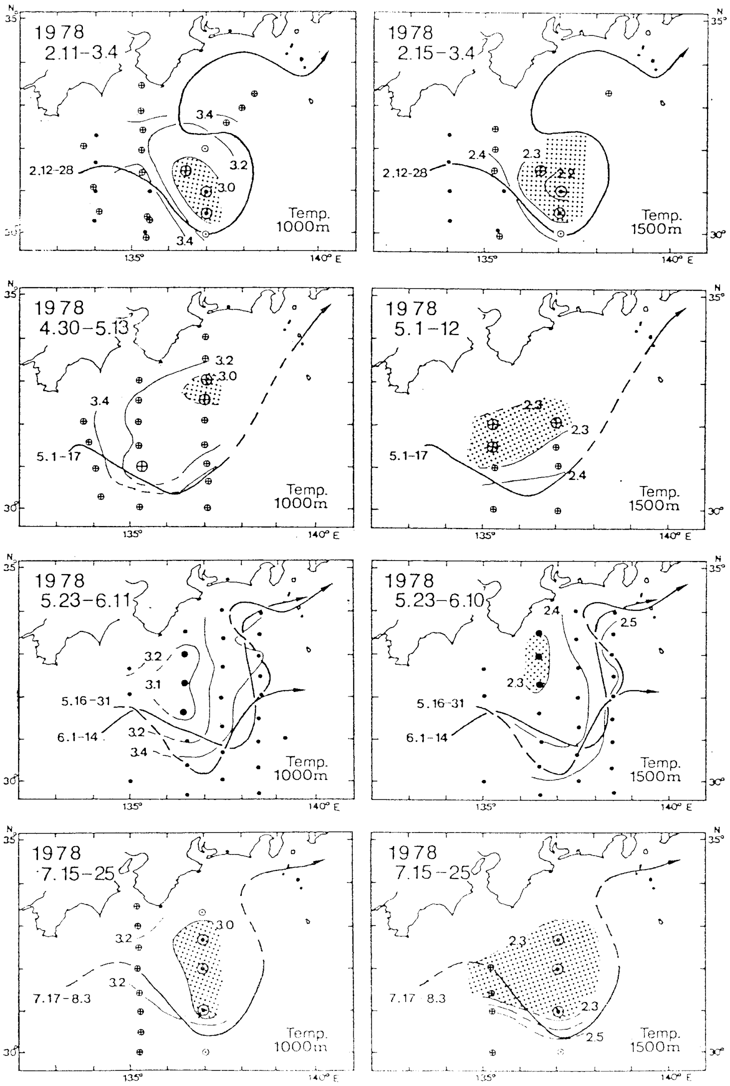


Fig. 5. Horizontal distribution of the temperature during the low temperature period of the cold water mass of the Kuroshio accompanied by the long-period meander formed in 1975. Data sources are the same as in Fig. 4. The symbols of the stations are the same as in Fig. 3.

the Kuroshio formed in 1969 has been studied and the results are compared with those accompanied by the long-period meanders formed in 1975 and 1981. Main conclusions of the present study are summarized as follows:

(1) There exists no apparent difference in current path variations during the formation process of the large meander of the Kuroshio between the short-period meander and the long-period meanders. The lifetimes of the cold water mass and large meander of the Kuroshio are supposed to be due to the process after the accomplishment of the large meander path formation.

(2) The deep layer temperature at depths of 1,000 m and 1,500 m near the center of the cold water mass accompanied by the short-period meander shows no cooling period in the western side of the Izu Ridge. In contrast to this, the cold water mass with the long-period meanders

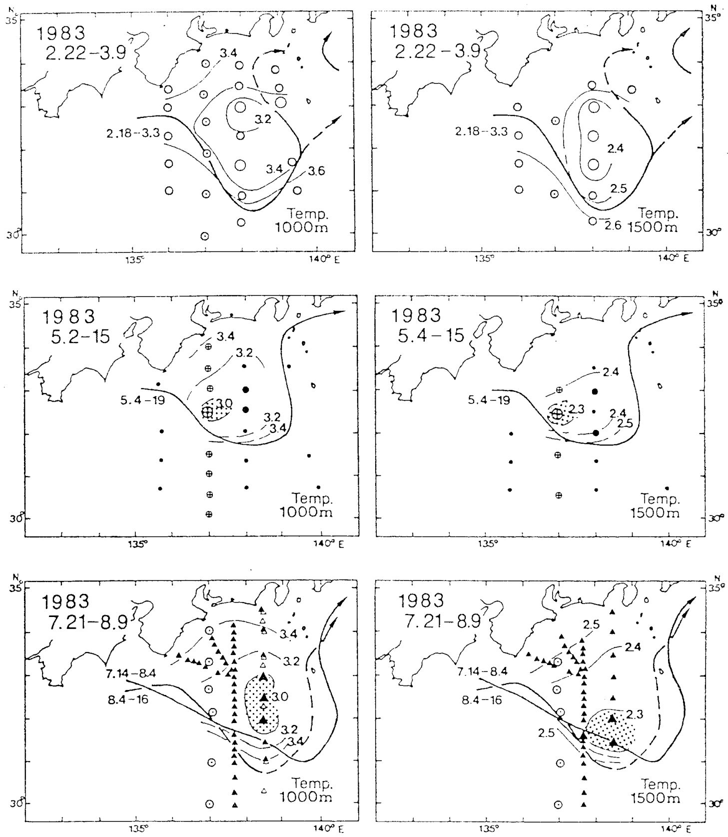


Fig. 6. Horizontal distribution of temperature during the low temperature period of the cold water mass of the Kuroshio accompanied by the long-period meander formed in 1981. Data sources are the same as in Fig. 4. The symbols are the same as in Fig. 3, but for Shoyo (○) of Hydrographic Department, Soyo Maru (▲) and Syunyo Maru (△) of Fishery Agency.

has commonly cooling periods of temperature in the western side of the Izu Ridge. It is suggested that the occurrence of the cooling of the cold water mass has some relationship to its longer lifetime.

(3) Prior to the decay period the large cold water mass and the large meander of the Kuroshio, they shift to the eastern side of the Izu Ridge. It is found that the cold water mass and large meander have a tendency to shift to the eastern side of the Izu Ridge when the temperature at a depth of 1,500 m near the center of the cold water mass exceeds 2.4°C. Because the increase of the lower layer temperature of the cold water mass means the decrease in velocity in the deep layer, this represents a critical condition on the shift of the cold water mass and large meander of the Kuroshio to an eastern side of the Izu Ridge.

Finally, we refer to the occurrence of the spin-up process of the cold water mass of the Kuroshio, which is only observed in the long-period meanders. SEKINE *et al.* (1985) showed that the cooling of the cold water mass formed in 1975 has a tendency to occur in late spring to summer. The similar tendency is found in the temperature variation of the cold water mass formed in 1981 (see, Fig. 4(b)). Therefore, a relationship between the occurrence of the cooling of the cold water mass and the seasonal variation of the Kuroshio flow is suggested. When the cooling of the cold water mass does not occur in this season, there is a possibility that the large meander of the Kuroshio and the cold water mass decay in near future. The dynamics of the cooling of the cold water mass and its relationship to the seasonal variation of the Kuroshio should be investigated in the next stage of this study.

Acknowledgments

The authors would like to express their thanks to Professor Y. TOBA of Tohoku University for his helpful discussions throughout this study. Our thanks are extended to Dr. H. NISHIDA and Dr. M. FUKASAWA for their critical reading of the manuscript with valuable comments.

References

CHENEY, R. E. and P. L. RICHARDSON (1976): Observed decay of a cyclonic Gulf Stream ring. Deep-Sea Res., **23**, 143-155.

FISHERIES AGENCY (1983): The Results of Fisheries Oceanographical Observation. January-December, 1980.

HYDROGRAPHIC DEPARTMENT, MARITIME SAFETY AGENCY OF JAPAN (1969, 1970, 1978, 1981, 1983): The Quick Bulletin of Ocean Conditions. Nos. 10, 11, 16, 23, 24 (1969), No. 5 (1970), Nos. 5, 10-12, 15 (1978), Nos. 16-24 (1981), Nos. 5, 10, 15, 16 (1983).

JAPAN METEOROLOGICAL AGENCY (1971-1972, 1979-1985): The Results of Marine Meteorological and Oceanographical Observations. Nos. 45-47, 61-76.

JAPAN OCEANOGRAPHIC DATA CENTER (1985): Data Report of KER, No. 7.

KOSUGI, A. (1978): The generation process of the Kuroshio large meander and the cold water mass formed in 1975. *In*: The Kuroshio Meander and Cold Water Mass. Rep. of Grant-in-Aid for Cooperative Res., 10-20. (in Japanese)

MARITIME SAFETY AGENCY OF JAPAN (1973-1974, 1980-1986): Data Report of Hydrographic Observation, Series of Oceanography, Nos. 10-11, 17-23.

NISHIDA, H. (1982): Description of the Kuroshio meander in 1975-1980—Large meander of the Kuroshio in 1975-1980 (I). Rep. Hydrogr. Res., **17**, 181-207.

OKADA, M. and K. NISHIMOTO (1978): Mean sea level along the south coast of Japan and large meanders of the Kuroshio from 1894 through 1924. Umi to Sora, **54**, 91-97. (in Japanese with English abstract).

PEDLOSKY, J. (1979): Geophysical Fluid Dynamics. Springer-Verlag, Berlin and New York. 662 pp.

SEKINE, Y., H. ISHII and Y. TOBA (1985): Spin-up and spin-down of the large cold water mass of the Kuroshio south of Japan. J. Oceanogr. Soc. Japan, **41**, 207-212.

SHOJI, D. (1972): Time variation of the Kuroshio south of Japan. p. 217-234. *In*: H. STOMMEL and K. YOSHIDA(ed.), Kuroshio—Its Physical Aspects. Univ. of Washington Press.

TAFT, B.A. (1978): Structure of the Kuroshio south of Japan. J. Mar. Res., **36**, 77-117.

YOSHIDA, S. (1961): On the variation of the Kuroshio and cold water mass off Enshu Nada. Hydrogr. Bull., **67**, 54-57 (in Japanese with English abstract).

日本南岸の黒潮大蛇行に伴なう短期間大冷水塊

石 井 春 雄, 関 根 義 彦

要旨: 日本南岸の黒潮大蛇行に伴なう大冷水塊には，形成されてから1年以内で消滅する短期間のものが観測される。1969年から1970年に存在した短期間の蛇行に伴なう大冷水塊と，1975年から1980年および1981年から1984年に存在した長期間の蛇行に伴なう大冷水塊との違いを調べた。直進流路から大蛇行への移行過程での流路の変動には，両者の間に大きな違いがないことが示された。短期間の蛇行に伴う大冷塊の 1,000 m 深と 1,500 m 深の水温は伊豆海嶺の西側にある時には上昇の傾向を示すのに対して，長期間存在する大蛇行の大冷水塊のそれは伊豆海嶺の西側で上昇したり下降したりする。短期間，長期間の大蛇行ともにその消滅期には冷水塊の中心が伊豆海嶺の東側に移行し，それ以後は双方とも蛇行振幅の増幅は見られない。黒潮大蛇行および大冷水塊の寿命は伊豆海嶺の西側で大冷水塊の水温が低下する現象と関連があることが示唆された。