Bull. Japan. Soc. Fish. Oceanogr., Vol. 50, No. 1, 1986

Observation of Variability of the Kuroshio Front Using AXBT*

Yoshihiro OKADA**, *** and Yasuhiro SUGIMORI**

Abstract

Two pairs of simultaneous observations using AXBT and SXBT, STD or CTD were made to detect the short-term variability of the Kuroshio Front. Stations across the Kuroshio Front off Cape Iro (March 17–18, 1981), and in the Kuroshio Extension including the Perturbed Area (November 6–9, 1981) were chosen. The measurement of vertical temperature profile in the upper ocean using AXBT was completed in a short period, and SXBT and STD measurements on a vessel were completed in a considerable time later than AXBT measurements. Hence, two vertical temperature profiles determined by these different methods at the frontal zone show a significant difference. It is determined to be caused by fluctuations of the Kuroshio Front in a short period. Horizontal translation speeds of the Kuroshio Front were estimated to be 0.7 m/s for the case of the Kuroshio Front off Cape Iro and 0.3 m/s for the case of warm core ring, which is approximately the same speed observed by MASUZAWA (1958). The translation speed of the Kuroshio Front is estimated to be 0.5 m/s or more, by using several satellite images which were obtained at the same time and area as the second observation on successive days by HIRAI (1984).

1. Introduction

The traditional descriptive image of the Kuroshio Frontal Zone has been based on hydrographic data derived over long periods and at widely spaced points. Consequently, it is hard to determine rapid changes of the frontal structure by vessels. If a method of observation using aircraft could be well-established, instantaneous observations corresponding to the rapid variability of ocean conditions might become possible, from which we could visualize the time-dependence of the front change. It is quite possible to apply AXBT (airborne expendable bathythermography) to observe such rapidly changing ocean phenomena.

Tnere are a few studies of observation by U.S. oceanographers concerned with the problem of the variability of the ocean front, using AXBT. SAUNDERS (1971) observed the variability of the Gulf Stream meander using ART (airborne infrared radiation thermometer) and AXBT. He studied the dynamics of the frontal zone at the stage just after anticyclonic eddies were detached from the Gulf Stream. BRISCOE *et al.* (1974) observed an oceanic frontal zone, east of Malta, by using SXBT, ART, and AXBT, and he presented a synoptic temperature profile over an extensive area. Also, CHENEY (1977) made synoptic thermal measurements using ART and AXBT in the area from 30°N to 45°N latitude and 140°E to 160°E longitude, which coverd the locations of both the Kuroshio and Oyashio Fronts, in October 1976. On this expedition, he determined the synoptic distribution and physical properties of the eddies formed by these fronts through seven flights within two weeks. Therefore, synoptic maps of a frontal zone could be made by AXBT measurements.

In a frontal zone, meanders of the Kuroshio sometimes break out and pinch off warm core rings. Such phenomena have a dominant spatial scale range of hundreds of kilometers. Meanwhile, the time scale of their formation is one to several days, thus it is difficult to trace phenomena only by a few vessels.

* Accepted November 25, 1985

** Faculty of Marine Science and Technology, Tokai University, 3-20-1, Orito, Shimizu, Shizuoka, 424 Japan

*** Present address: Japan Fisheries Information Service Center, Ikenohatanissyoku Bild., 2-9-7, Ikenohata, Taitou-ku, Tokyo, 110 Japan

Studies of the short-term variation of the Kuroshio Front have been made by a few scientists. MASUZAWA (1958), who made the first attempt of repeated hydrographic observation across the Kuroshio axis using several vessels (twice a day during June 23–24, 1957), reported that the Kuroshio Front moved northward by 20 km within twelve hours with a speed larger than 0.4 m/s.

The Japan Hydrographic Office conducted multiple-ship surveys of short-term fluctuation of the Kuroshio current off the Kii Peninsula in 1964 and 1965. They made cross sections every three hours with GEK (geomagnetic electrokinetograph) and BT (bathythermography), and the serial data were analysed by SHOJI and NITANI (1966). They suggested that diurnal fluctuations of the current in the Kuroshio were presented as a predominant phenomena. Based on a multiple-ship survey in the Kuroshio, MASUZAWA (1968) pointed out that diurnal variations might be caused by inertial motion. And moreover, he mentioned that the average speed of the Kuroshio had increased within four or five days. KONAGA *et al.* (1979) reported that the amplitude of diurnal oscillations of the Kuroshio Front seemed to be increased greatly by inertial motion.

On this study, simultaneous observations by aircraft and vessel were made across the Kuroshio Frontal Zone off Cape Iro during 17th to 18th March 1981. And moreover we also made an experiment across the Kuroshio Frontal Zone in the Kuroshio Extension during 6th to 9th November 1981. These are areas of violent oceanic conditions in the Kuroshio Frontal Zone where temperature varies drastically with time and space. The purpose of this paper is to point out the occurrence of the translation with much larger speed of the Kuroshio Front than generally believed by comparing aircraft and ship observations.

2. Observations of the frontal zone

Simultaneous observations by an aircraft and vessel were made twice in the Kuroshio Frontal Zone. The first observation (Case I) was made by a vessel and an aircraft at the Kuroshio Front off Cape Iro, and the second one (Case II) was

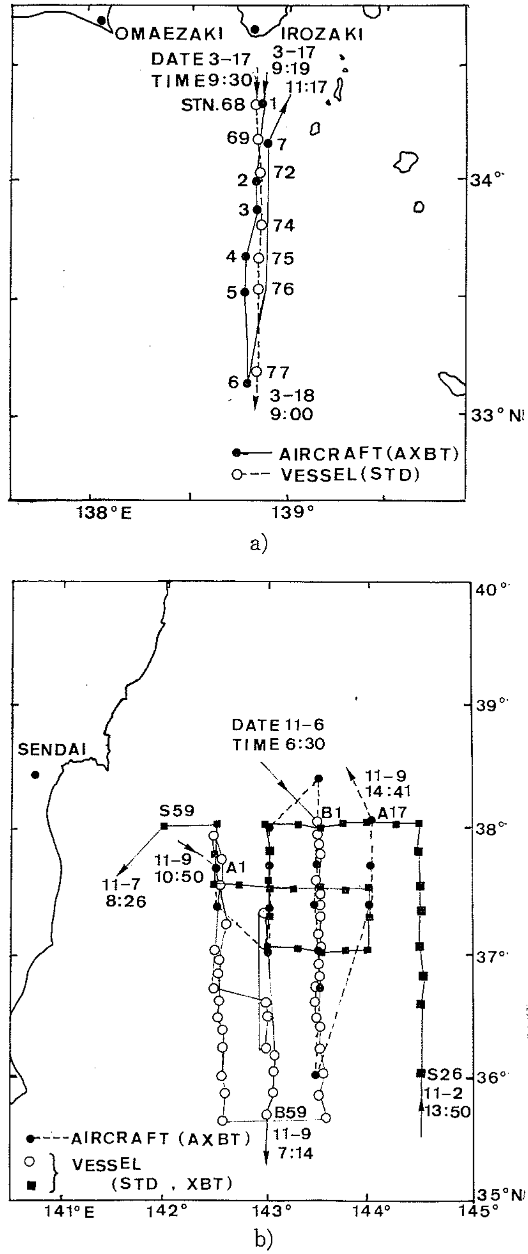

Fig. 1. Courses of aircraft and vessel observations. a) Case I. The solid circles indicate the positions of AXBT measurements, and open circles show the positions of CTD measurements. b) Case II. The solid circles show the positions of AXBT measurements, and the open circles and solid squares show the positions of STD measurements. Start and finish times are given for each course.

performed in the Perturbed Area, north of the Kuroshio Extension. For both observations an improved AXBT system was used. In order to determine the accuracy of the advanced sensor, OKADA and SUGIMORI (1982) made various calibrations and discussed on the total accuracy of the sensor of improved AXBT. From calibration results, accuracies of less than 2% in depth and of less than 0.1°C in resolving temperature were recognized. In Fig. 1 a) and b), the courses of vessels and aircraft in those two pairs of simultaneous observations, for Case I and II, are shown respectively.

2-1. Case I expedition

In Case I (Fig. 1 a)), locations of the stations for AXBT measurements were settled at the same points where the Tokai Regional Fisheries Research Laboratory made measurements of elementary quantam of sardine. In those observations, aircraft measurements began at Station No. 1 at 9:19 on 17th March, 1981, and finished at Station No. 7 at 11:17 on the same day. It took only about 5 minutes per each station for measurement and approximately only 2 hours for the total experiment. Six runs of AXBT were made in total (data at Station No. 2 were not

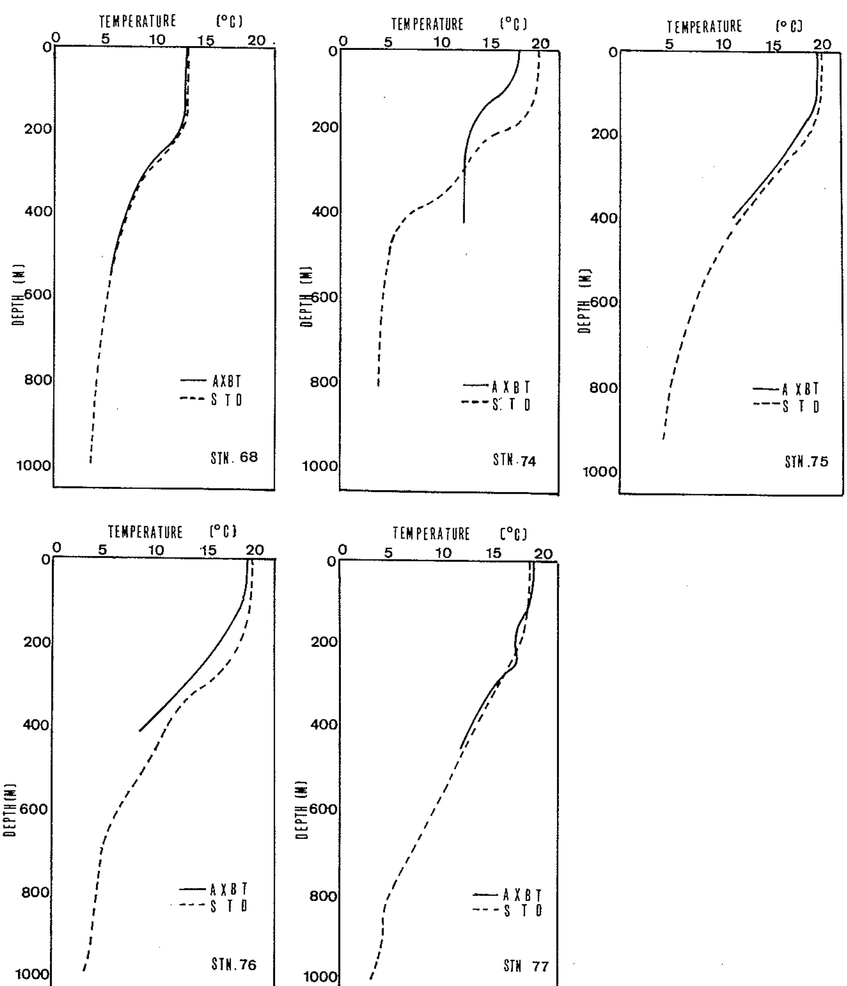

Fig. 2. Comparison of the temperature profiles measured by AXBT and CTD at points from Stations No. 68 to 77, with the simultaneous experiment conducted at Station No. 68. The solid line indicates temperature profiles by AXBT, and the broken line shows temperature profiles by CTD measurements.

obtained, because the AXBT wire might be broken on the way).

On the other hand, the vertical temperature profile at each station across the Kuroshio current was obtained simultaneously by STD and GEK measurements from the Soyo-Maru. The vessel observation began at Station No. 68 at 9:30 on 17th March, 1981, and finished at Station No. 77 at 9:00 on 18th. The vertical temperature and salinity profiles up to about 1,000 m depth were determined by STD, and it took at least 40 minutes for each station. It took about 24 hours to complete the observations for the complete course of 120 nautical miles. On confirmation of accuracy, the AXBT instrument was calibrated at the first station, No. 68, by measuring the temperature profile by STD. Then, the instantaneous data determined by AXBT were compared with the ship data determined slowly by STD.

2-2. Case II expedition

The courses of vessel and aircraft in Case II observations are illustrated in Fig. 1 b). Measurements by aircraft were began at Station No. A1 at 10:50 on 9th November, 1981, and were finished at Station No. A17 at 14:41 on the same day. It took only about 5 minutes for each station and about 4 hours in total. Fifteen runs of AXBT data were obtained in total observations. The average flight altitude of the aircraft was 1,000 ft when data were gathered by AXBT operations.

In order to compare with the AXBT data, the vertical temperature profile at each station was derived by STD and SXBT measurements from the vessel Bosei-Maru II. This expedition took about 3 days to complete observations over the complete course of 280 nautical miles. In this case, vessel observation began at Station No. B1 at 6:30 on 6th November, 1981, and

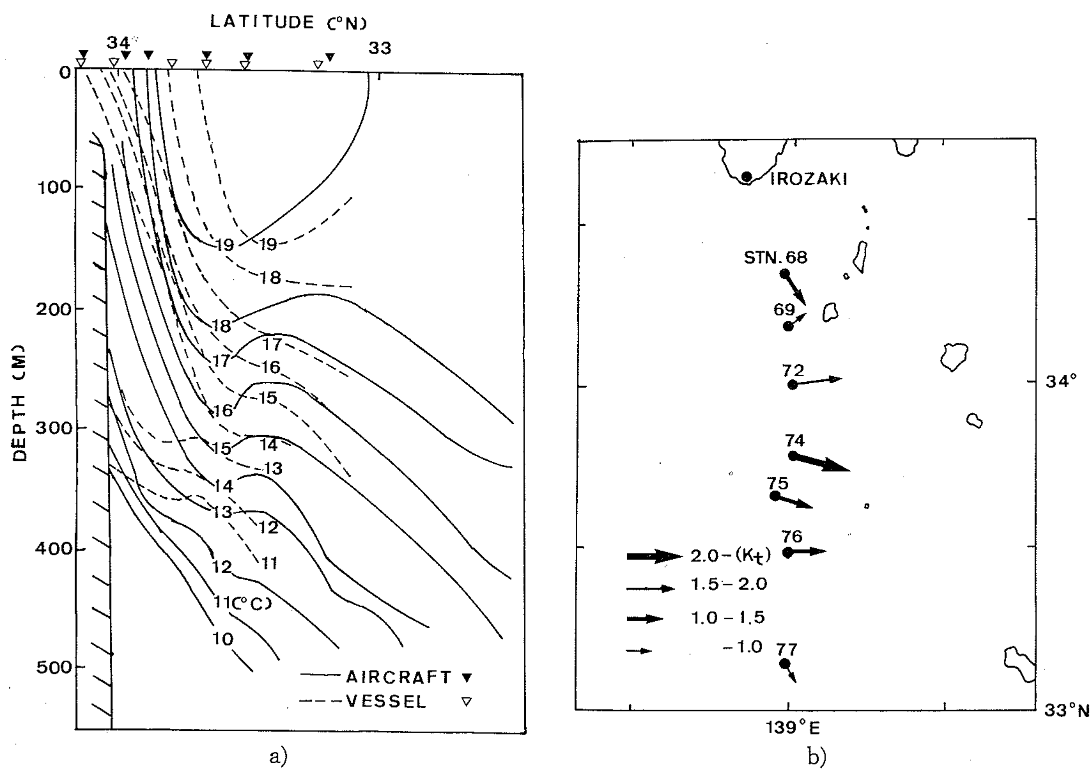

Fig. 3. The results for Case I expedition. a) The thermal sections across the Kuroshio Front measured by aircraft and vessels. The solid line shows the vertical temperature profile by AXBT and the broken line indicates the temperature profile obtained by CTD. b) The current velocity and direction measured by GEK, the Kuroshio flows near 34°N.

was completed at Station No. B59 at 7:14 on 9th November. It took about 2 hours to measure vertical temperature and salinity profiles up to 2,000 m depth using STD. GEK measurement was also made at each station. In addition to the above mentioned experiment, SXBT and DBT (digital bathythermography) observations by the vessel, Shunyo-Maru, were carried out on 2nd through 7th November in the same area by Tohoku Regional Fisheries Research Laboratory.

3. Comparison between AXBT and vessel measurements

Fig. 2 shows the temperature profiles measured by AXBT and STD for Case I expedition. At Station No. 74, the maximum difference between water temperatures measured by AXBT and STD attains +8°C. The average value of the difference between them is 0.7°C for those five stations up to the maximum measuring depth. However the maximum and average values of the difference at Station No. 68, where the observations were carried out simultaneously by both AXBT and STD, were 0.2°C and 0.08°C, respectively. The spatial distance of measurement points between AXBT and STD varied from zero to 3.7 nautical miles, and the average distance was about 2.5 nautical miles.

It should be noticed that at Station No. 74, which was located near the northern front of the Kuroshio (See Fig. 3 a)), the difference of temperature between AXBT and STD measurements was much larger than that of any other station (Fig. 2), through the reason for this temperature difference depended strongly on the time difference (about 10 hours). Meanwhile, the difference of measured temperature (for example at Station No. 77) was rather smaller than that for the station near the front.

4. Thermal section across the Kuroshio Front

Fig. 3 a) shows the thermal section of the Kuroshio Frontal Zone observed by aircraft within 2 hours and vessel within 24 hours, for the Case I expedition. The front seems to exist near Station No. 74. The maximum inclination of 17°C isothermal line across the Kuroshio Front was 1/190 (depth/horizontal distance) for AXBT measurement and 1/200 for STD measurement.

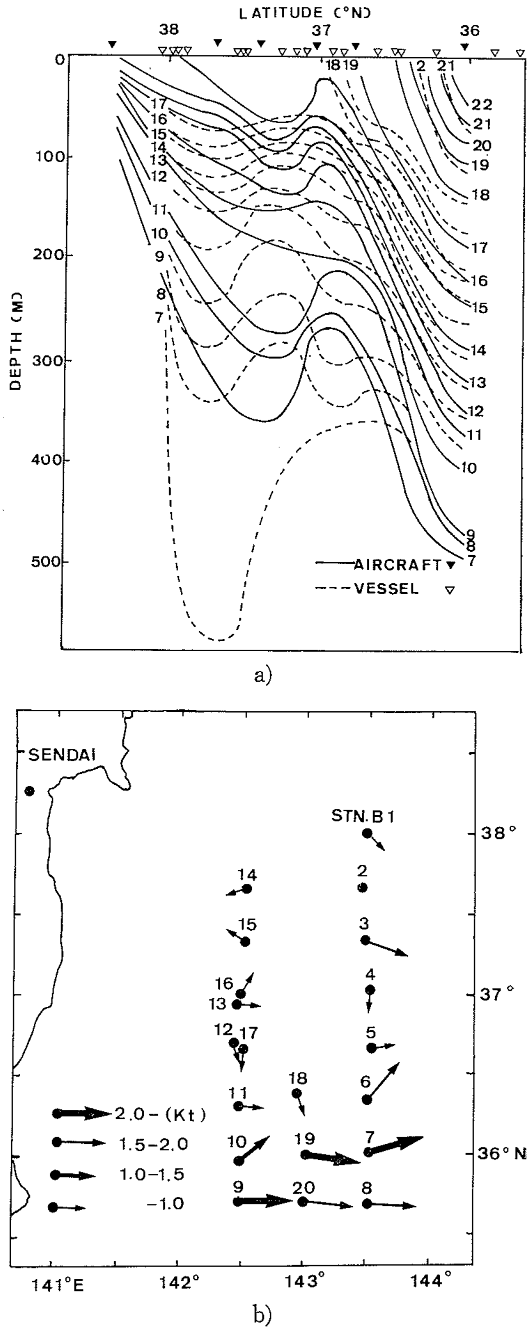

Fig. 4. The result for Case II expedition. a) The section along 143°30′E in the Perturbed Area. The solid line shows the temperature profile by AXBT and the broken line indicates the temperature by STD. b) The current velocity and direction measured with GEK, the Kuroshio flows near 36°N.

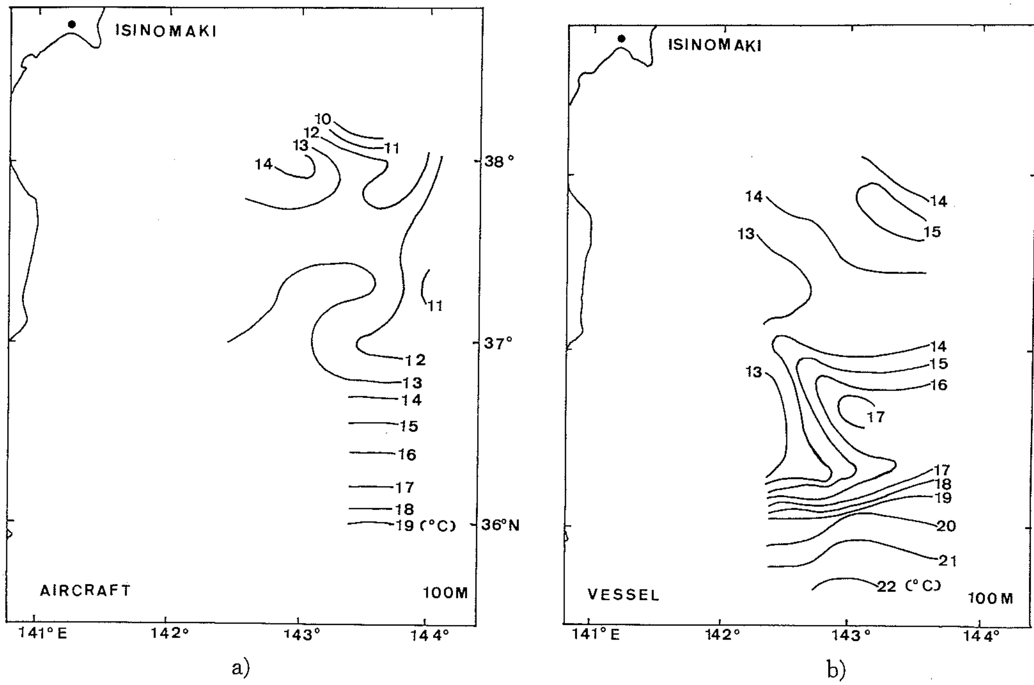

Fig. 5. Horizontal temperature contours at the depth of 100 m for Case II expedition a) by aircraft, b) by vessels.

The results of GEK measurements (Fig. 3 b)) show that the Kuroshio Current flows eastward between 33°40′N and 34°00′N at 139°00′E with an average azimuthal direction of 94° and the front must be north of Station No. 74. Current direction indicates that the observation line is approximately perpendicular to the Kuroshio axis.

Fig. 4 a) shows the thermal section across the Kuroshio Frontal Zone along the longitude 143° 30′E observed with AXBT (full line) within one hour and with vessel measurements (broken line) within 24 hours. The inclination of the 17°C isothermal line was 1/525 for STD and 1/642 for AXBT observations. The results of the GEK measurements (Fig. 4 b)) show that the Kuroshio Front passes near Stations No. 10, 19 and 7. Fig. 5 a) presents the horizontal temperature contours at a depth of 100 m, determined by vessel measurements. A small warm core appears at the area of 37°40′N and 143°30′E, where sea water of about 7°C to 8°C was thickly distributed, from 300 m to 600 m depth (Fig. 4 a)). Fig. 5 b) presents the temperature contours derived by AXBT measurements. This figure also illustrates that the small warm core appeared at 38°00′N and 143°00′E, which was somewhat far from the location determined by the vessel. Therefore, it might be that the warm core ring moved northwestwards with a speed of 0.3 m/s, until AXBT observation was performed three days later after the observation by vessel on 6th of November 1981.

5. Movement of the Kuroshio Front

As mentioned above, the temperature profiles across the Kuroshio Front were simultaneously determined by both observations using AXBT and STD. The temperature gradient derived by STD is modified by a quick movement of the front during ship observation. On the other hand, the temperature profile determined by aircraft observation (AXBT) is considered to be approximately a real structure. In order to calculate the movement speed of the Kuroshio Front, it is assumed that the geometries of the front are maintained and it moves horizontally with speed of U (KAWAI, 1972). In Fig. 6, U denotes the speed of the north-south component of the movement for a given isothermal line. $T(t)$ (heavy line) denotes the isothermal line at

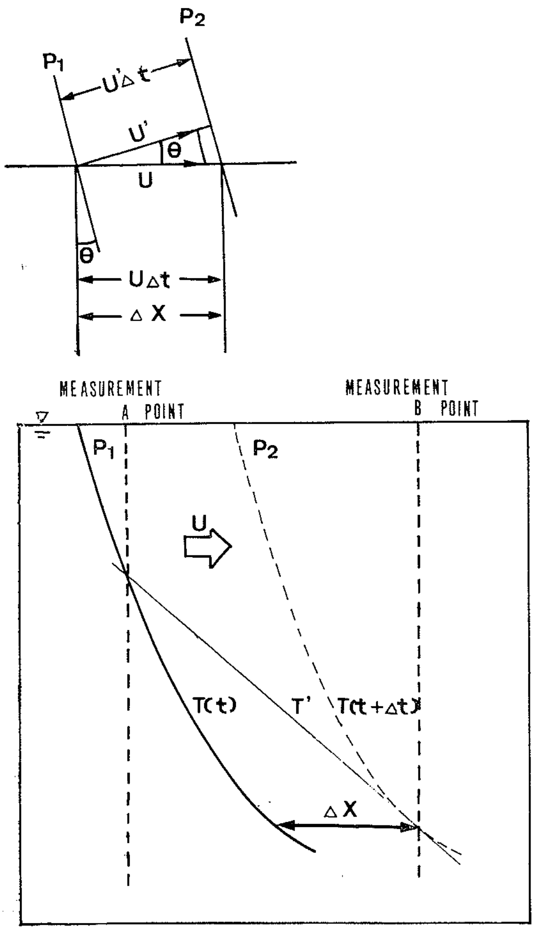

Fig. 6. Illustration of the speed of movement of an isothermal surface. P1 and P2 indicate locations of the isotherms $T(t)$ at time t and $T(t+\Delta t)$. The isotherm T moves at a speed of U from P1 to P2 while the observation vessel moves from observation point A to the next point B. T' that is an apparent isotherm results from the time lag between vessel measurement at point A to B. θ is the angle between the observation line and the direction of horizontal translation of the Kuroshio Front.

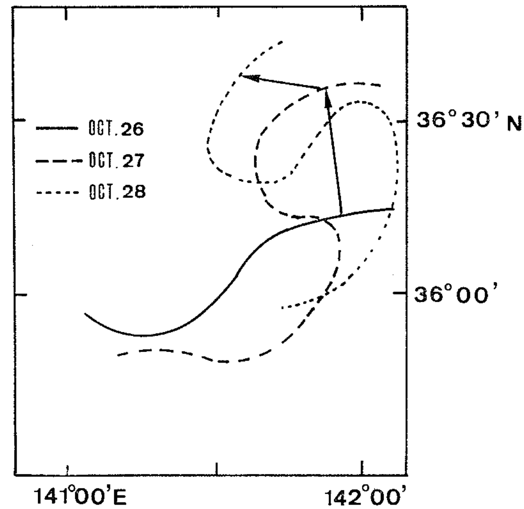

Fig. 7. The movement of the Kuroshio Front obtained by successive day to day satellite thermal images by HIRAI (1984).

moment t, and $T(t+\Delta t)$ (dashed line) denotes the location of this isothermal line at the instant $t+\Delta t$. Δt is the time lag between measurements of vessel at stations A and B, and Δx denotes an amount of movement of the front during the time, Δt, that is the distance $u\Delta t$ between $T(t)$ and $T(t+\Delta t)$. Consequently, an apparent vertical isothermal line T' (fine line) is assumed, and it includes the displacement time Δt. θ is an angle between the observation line and the direction of horizontal movement of the Kuroshio Front. The magnitude of U will be calculated by the ratio of displacement of the isotherm, $\Delta x/\Delta t$, if the STD measurement is perpendicular to the line connecting the two lines $T(t)$ and $T'(\theta=0)$.

In both expeditions of Cases I and II, the courses of aircraft and vessel were almost perpendicular to the Kuroshio Front, and moreover, it can be assumed that structure of the front could be determined instantaneously by aircraft. Whereas the isothermal line obtained by vessel observation must involve the displacement time Δt. Then, movement speed of the Kuroshio Front can be calculated from the difference between both vertical temperature profiles by vessel and aircraft. Finally, the equation for the movement speed can be simply expressed by $U=\Delta x/\Delta t$. However, it is almost impossible to determine Δx and Δt only by the vessel observation without the data of AXBT.

For the Case I expedition, the movement speed of the 17°C isothermal line of the Kuroshio Front was approximately 0.7 m/s. This value is somewhat larger than that derived by MASUZAWA (1958), 0.4 m/s to 0.5 m/s for movement of the Kuroshio Front in the region of the Perturbed Area. Meanwhile, KAWAI (1972) also gave the movement speed of the isothermal surface of 10°C at 200 m depth as 0.1 m/s for the time scale of a few months, using a number of observed data from 1957 to 1960 in the north of Kuroshio Extension. For the expedition of Case II, it was approximately 0.2 m/s, almost the same as the value given by KAWAI. Fig. 7 illustrates the translation speed of the Kuroshio Front by using several successive day to day satellite images by HIRAI (1984), which were obtained at the same time and area as Case II expedition. The translation speed of the warm core ring of the Kuroshio meander is estimated to be about 0.5 m/s or more.

6. Conclusions

The purpose of this study is to make clear the short-term variability of the Kuroshio Front. The results of this study can be summarized as follows:

(1) The maximum and average differences of water temperatures measured simultaneously by AXBT and STD were 0.2°C and 0.08°C, respectively.

(2) Observation by vessel requires a much longer time than that by aircraft. For the expedition of Case I, the aircraft observation using AXBT over the experimental area took only 4 hours, whereas the vessel observation in total, required 3 days in the same area.

(3) It is distinct that the difference of temperature profiles across the Kuroshio Front by aircraft and vessel mainly depends on the difference of time that was required for the observations. In other words, the Kuroshio Front might move within the time of vessel observation.

(4) A speed of movement of the Kuroshio Front in a short-term period was calculated by the difference between vertical temperature profiles determined by aircraft and vessel measurements. For the Case I expedition, the speed of movement of the front was approximately estimated as 0.7 m/s.

(5) The warm core ring, which was observed in the area of the Kuroshio Extension on 6th to 9th November, 1981, moved north-westward, and its speed was 0.3 m/s during the three day period.

(6) The translation speed of the Kuroshio Front is estimated to be about 0.5 m/s or more, by using several successive day to day satellite images by HIRAI (1984), which were obtained at the same time and area as Case II expedition.

(7) In conclusion, it is essentially necessary to use AXBT and satellite images to trace such short-term translations of the fronts in the Kuroshio and warm core rings as mentioned above.

Acknowledgement

The authors thank the staff of Tokai University and Tohoku Regional Fisheries Research Laboratory, who participated in the observations and took an interesting data for this study. The authors also wish to express their thanks to the crew of the Bosei-Maru II for their cooperation in the observations and to the captains and crews of both the Soyo-Maru and the Shunyo-Maru.

A part of this study was supported financially by the Fisheries Agency, Ministry of Agriculture, Forestry and Fisheries.

References

BRISCOE, M.G., O.M. JOHANNESEN and S. VINCENZI (1974) The Maltese oceanic front: A surface description by ship and aircraft. Deep-Sea Res., **21**, 247–262.

CHENEY, R.E. (1977) Synoptic observation of the oceanic frontal system east of Japan. J. Geophys. Res., **20**, 5459–5468.

HIRAI, M. (1984) The movement of a fishery of the saury and the Oyashio. Marine Science Monthly, **16**, 706–712 (in Japanese).

KAWAI, H. (1972) Hydrography of the Kuroshio Extension. *In*, Kuroshio -Its physical aspect, eds. H. STOMMEL and K. YOSHIDA, Univ. of Tokyo Press, 235–352.

KONAGA, S., K. NISHIYAMA and A. WATANABE (1979) Short term fluctuations of current velocities near Oshima Island, Izu District, Japan. Oceanogr. Mag., **30**, 15–29.

MASUZAWA, J. (1958) A short-period fluctuation of the Kuroshio east Cape Kinkazan. Oceanogr. Mag., **10**, 1–8.

MASUZAWA, J. (1968) Cruise report on multi-ship study of short-term fluctuations of the Kuroshio in October to November 1967. Oceanogr. Mag., **20**, 91–96.

OKADA, Y. and Y. SUGIMORI (1982) Experimental

study of the developed air-borne expendable BT. Sora to Umi, No. 5, 43-59 (in Japanese).
SAUNDERS, P.M. (1971) Anticyclonic eddies formed from shoreward meanders of the Gulf Stream. Deep-Sea Res., **18**, 1207-1219.
SHOJI, D. and H. NITANI (1966) On the variability of the velocity of the Kuroshio—1. J. Oceanogr. Soc. Japan, **22**, 192-196.

AXBT による黒潮フロントの変動観測

岡 田 喜 裕*, **・ 杉 森 康 宏*

要旨: AXBT と SXBT, STD または CTD を使用して黒潮フロントの変動性を2種類の手法の同時観測によって検出した。同時観測は黒潮フロントを横切る形で石廊崎沖(1981年3月17日から18日)と，黒潮続流域および東北海区（同年11月6日から9日）において行った。AXBTを使用した上層の鉛直水温断面の観測は短時間で行われるため，AXBT と船舶観測とを並行して行うと，船舶観測では AXBT 観測に比べて時間の遅れが生じて，両者の鉛直水温断面分布に差異が見られ，黒潮フロントの短期変動が示唆された。石廊崎沖での黒潮フロント観測の実験では，その水平移動速度は 0.7 m/s，暖水塊観測の実験では 0.3 m/s であり，MASUZAWA(1958)の結果とほぼ同じ値が得られた。この値に関して平井(1984)の連続した数枚の衛星画像（2度目の観測と同時期，同海域)を解析すると，黒潮フロントの移動速度は 0.5m/s かそれ以上であることが推測された。

* 東海大学海洋学部，〒424 静岡県清水市折戸3-20-1
** 漁業情報サービスセンター，〒110 東京都台東区池之端2-9-7 池之端日殖ビル