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Tracking a Kuroshio cold ring with a free-drifting surface buoy*

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Abstract—A cyclonic ring formed by the Kuroshio Extension southeast of Japan was observed over a 50-day period in 1976 by XBT (expendable bathythermograph), STD (salinity–temperature–depth recorder), and a free-drifting surface buoy. The ring, estimated to be 4 months old, was 240 km in diameter and extended to a depth of at least 3000 m. The satellite-tracked buoy completed 6.5 revolutions around the ring during 37 days as the ring moved 150 km to the north. At the end of this period, the ring coalesced with the Kuroshio and the buoy was carried downstream, ultimately drifting 3500 km eastward during the next 7 months. As the buoy passed over the Emperor Seamount chain, it began moving in a series of anticyclonic loops which persisted for nearly one month. An analysis of winds along the buoy trajectory revealed two month-long periods when the buoy velocity was significantly correlated with the wind velocity.

INTRODUCTION

THE KUROSHIO and Gulf Stream systems are similar in many respects, including their formation of detached rings from elongated meanders. While cyclonic Gulf Stream rings have been studied extensively during recent years, Kuroshio cyclonic rings have been largely neglected. Little is known of their typical size, distribution, and movement, and the information that does exist is not recent (MASUZAWA, 1957). It is for these reasons that the observations presented here are particularly significant. Three cyclonic rings were located south of the Kuroshio Extension during an airborne XBT survey in October 1976 (Fig. 1); the one nearest Japan was chosen for detailed study. A satellite-tracked drifter was placed in the ring center to follow it for as long as possible.

OBSERVATIONS OF THE RING

The cyclonic Kuroshio ring was initially discovered on 12 October 1976 at 33°00′N, 143°10′E. Twenty-four airborne XBT's dropped in the ring indicated that its overall diameter, defined by the 16°C isotherm at a depth of 300 m, was 240 km. By assuming that the ring's central thermocline had been sinking at a rate of 0.5 m per day (PARKER, 1971; CHENEY and RICHARDSON, 1976), its age was estimated to be approx. 4 months. No previous observations of the ring were found.

Information on the ring's position and size was relayed to USNS *Silas Bent* and more detailed shipboard observations were carried out during 18 to 24 October. An extensive XBT survey was made and 10 STD stations to depths of 3000 m were occupied along a

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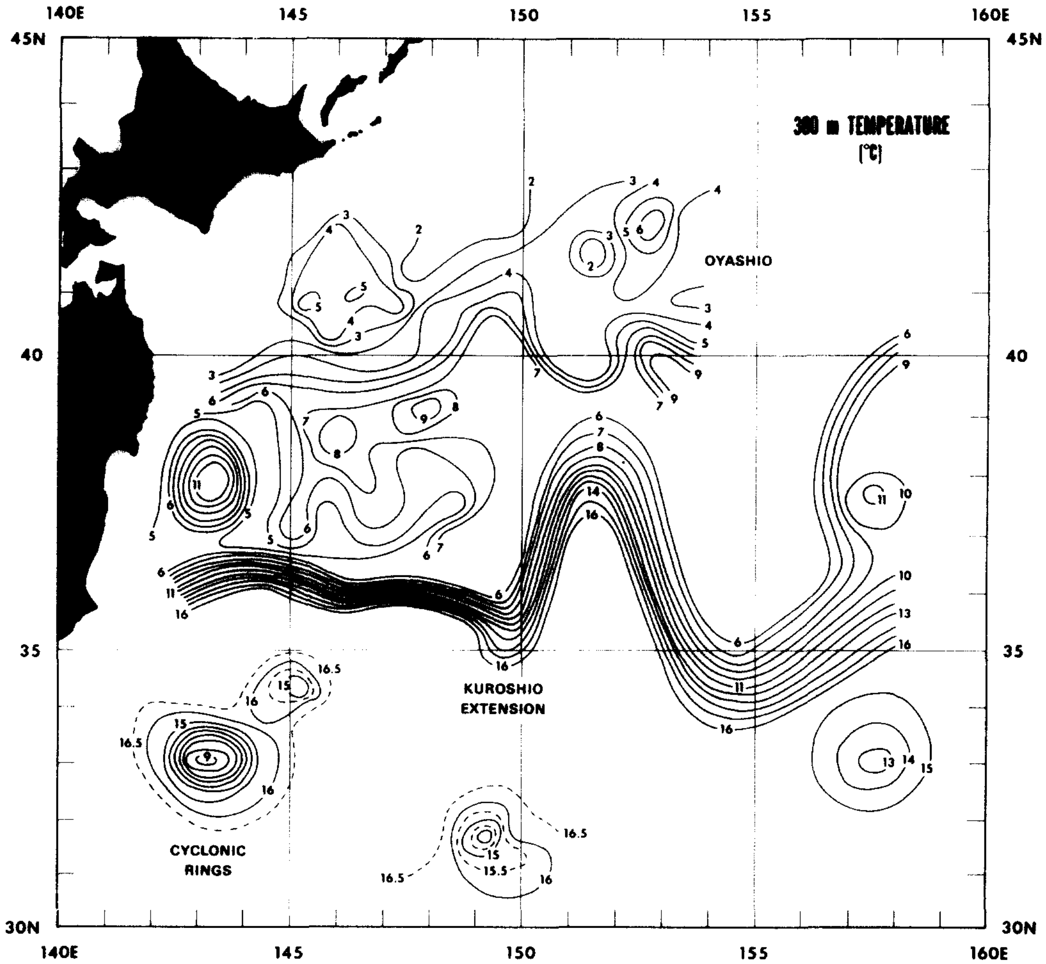

Fig. 1. Temperature at 300 m determined from 280 airborne XBT's, 9–22 October 1976. The westernmost cyclonic ring is the subject of this paper. The smaller feature attached to the northeast edge of the ring is a lens of cooler water confined to depths of 200 to 300 m. It does not appear when temperatures at any other depths are contoured (from CHENEY, 1977).

zonal section through the ring center (Fig. 2). The ring's position remained unchanged during the 9 days between the aircraft and ship surveys. Temperatures at 400 m in the ring's core were 8°C lower than at the same depth outside. Like Gulf Stream rings at similar stages of decay, the Kuroshio ring showed no surface temperature expression, a fact confirmed by airborne radiation thermometer measurements during the initial aircraft survey. The ring therefore was not detectable by satellite infrared imagery. Although the ring's surface layer was isothermal to a depth of 50 m, its subsurface structure was pronounced and extended to at least 3000 m (Fig. 3). The main thermocline was uplifted 300 m in the ring relative to surrounding waters.

Gradient currents were calculated using 3000 dbar as the reference pressure level. The section in Fig. 4 shows maximum current speeds of 60 to 80 cm s^{-1} approx. 60 km from

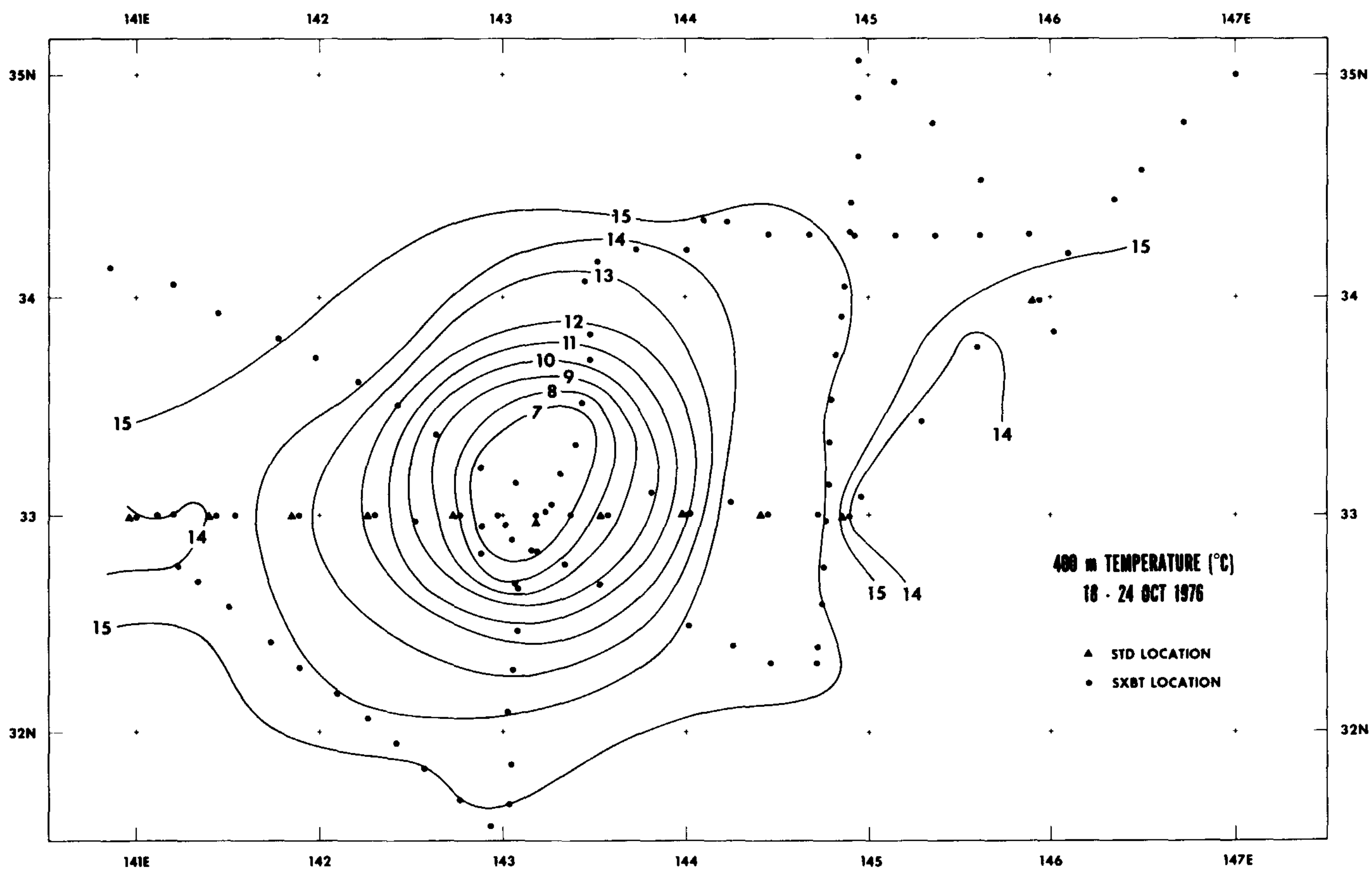

Fig. 2. 400-m temperature in the Kuroshio cold ring, 18–24 October 1976. Locations of XBT's and STD stations are indicated. For complete results of this survey see BLUMENTHAL and CHENEY (1978).

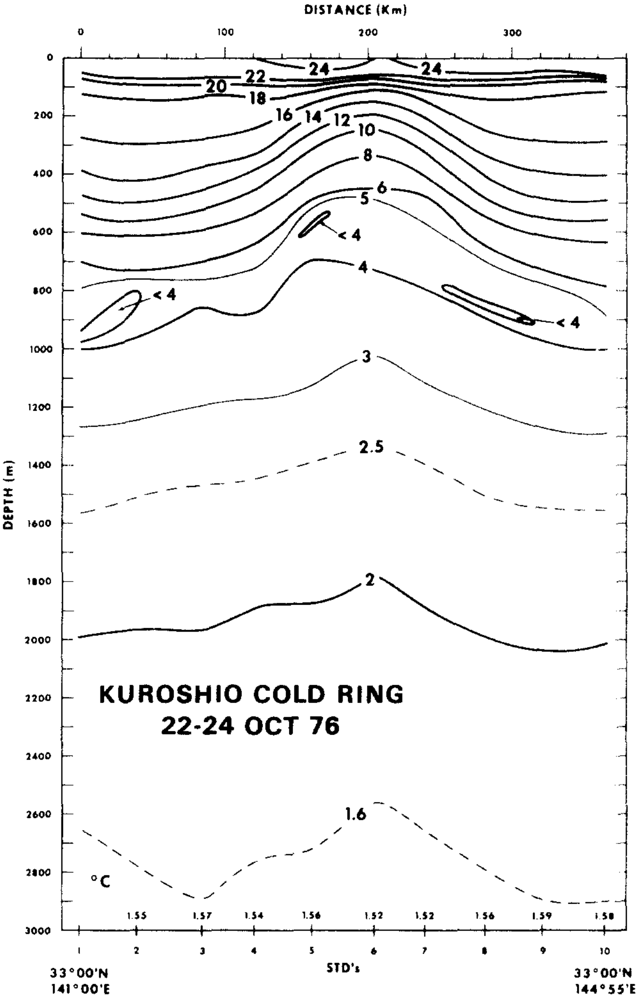

Fig. 3. Deep temperature structure of the Kuroshio cold ring. Isotherms throughout the water column are uplifted 300 m relative to the surrounding North Pacific subtropical water.

the ring center and currents of 10 cm s^{-1} extending as deep as 1200 m. A countercurrent appears in the upper 500 m west of the ring. Average tangential transport is 42×10^6 m^3 s^{-1} and the total kinetic energy of the ring is 3.3×10^{22} ergs. In terms of available potential energy (BARRETT, 1971) the ring represents an anomaly of 1.3×10^{24} ergs.

The cyclonic ring was observed for the third and last time on 31 October by the *Ryofu-Maru*. Eleven XBT's and five hydrographic stations in the ring indicated that it had moved 45 km northward to 33°25'N, 143°00'E. Data obtained the previous day enroute to the ring from Japan also showed that the northwest edge of the ring was only about 75 km from the Kuroshio's offshore edge.

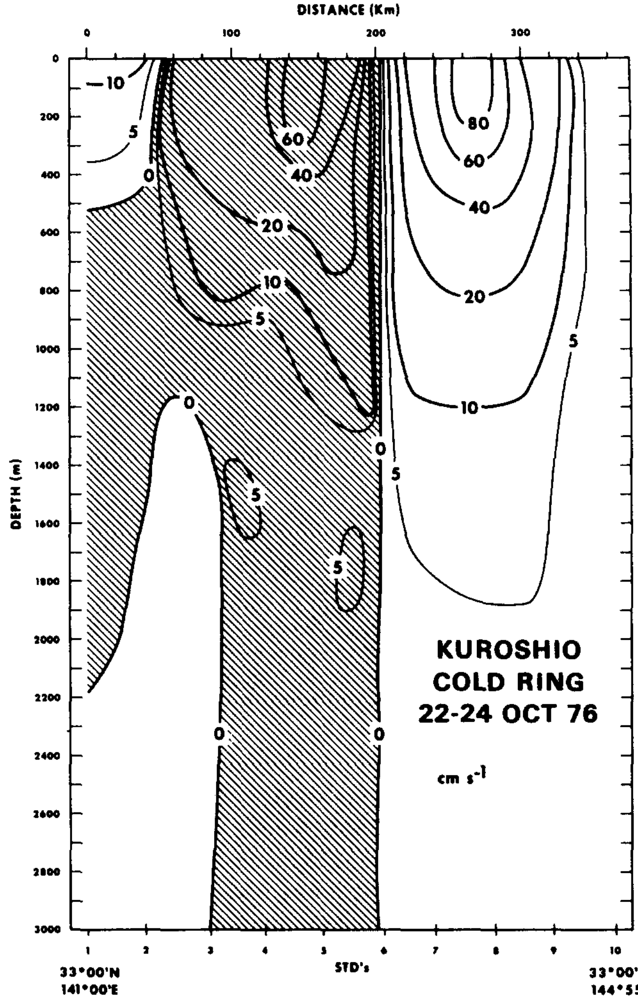

Fig. 4. Gradient currents in the cold ring computed along the zonal STD section. Shaded areas represent southward flow. Maximum current speeds are at a radius of 60 km. Volume transport is 42×10^6 m^3 s^{-1} relative to 3000 m.

BUOY TRAJECTORY IN THE RING

On 23 October (day 297) a satellite-tracked buoy was launched at the ring center in an attempt to track the ring remotely for as long as possible. The buoy, made by Polar Research Laboratory, was 3 m long, weighed 86 kg, and contained batteries for 6 to 8 months of operation. A 1.8 × 13.7-m window shade drogue was attached to the buoy with 200 m of 1-cm dia. nylon line, and a tension sensor enabled us to determine whether the drogue was still attached. The buoy transmitted a 401.2 mHz signal to the *Nimbus* 6 satellite for approx. 1 s each minute. Positions were calculated by the Goddard Space Flight Center from the Doppler shift of the signal as received by the satellite. *Nimbus* 6 is sun-synchronous, passing overhead at local noon and midnight. Typically five fixes per day

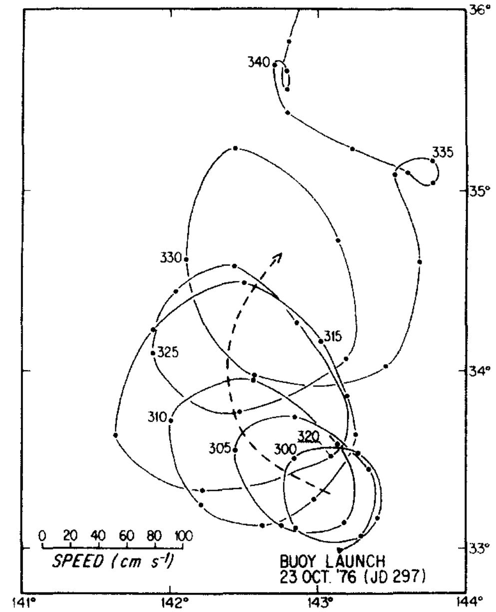

Fig. 5. Buoy trajectory in the Kuroshio ring, 23 October to 8 December 1976. Dots indicate the buoy's daily position, and the scale at lower left is proportional to the distance moved in one day. The dashed line indicates inferred movement of the ring, which apparently coalesced with the Kuroshio in December.

were obtained with an RMS error of about 5 km. In practice the errors of the fixes could be reduced to 1 to 2 km by using the quality parameters provided with the data to eliminate suspect fixes (RICHARDSON, WHEAT and BENNETT, 1979).

The buoy completed 6.5 revolutions around the ring during a 37-day period maintaining an average speed of 60 cm s^{-1} (Fig. 5). The loops had an average diameter of 95 km and period of approx. 6 days. When the loops are analyzed individually, it is seen that the buoy's speed gradually increased from 49 to 62 cm s^{-1} during the first three revolutions as the diameter of the loops slowly expanded from 55 to 90 km (Table 1). The observed outward spiraling indicates an average radial velocity of 2 cm s^{-1} during this time.

Loss of the drogue near the end of the third loop (day 310) corresponded with an abrupt increase in the loop diameter from 90 to 130 km and a slight speed increase to 69 cm s^{-1}. Diameter and speed subsequently decreased during the fifth revolution, but during the last loop a maximum speed of 83 cm s^{-1} was attained. The buoy stopped spiraling outward

Table 1. Summary of the buoy track in the Kuroshio cold ring

Revolution	Period (days)	Average diameter (km)	Speed* (cm s^{-1})
1	4.7	55	49
2	4.6	75	60
3	5.5	90	62
4	7.0	130	69
5	7.0	100	54
6	5.0	120	83

* Speed calculation assumes a circular orbit at the given period and diameter.

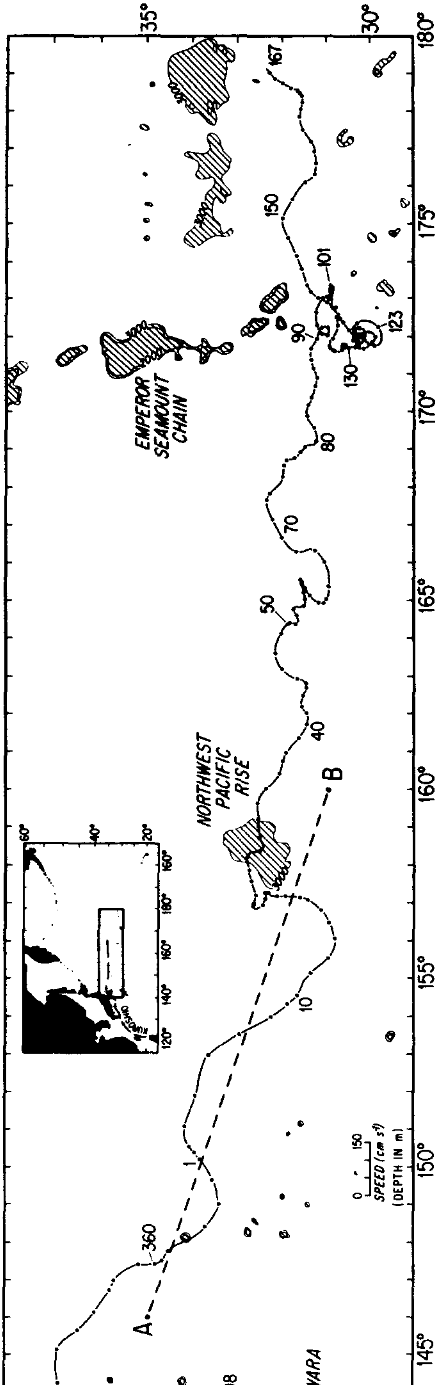

Fig. 6. Buoy trajectory from 23 October 1976 to 16 June 1977. Dots indicate daily positions. Contours show bottom topography shallower than 3000 m. The buoy was entrained in the Kuroshio on day 350 and during the next 7 months moved 3500 km eastward at a net speed of 22 cm s^{-1}.

during revolutions 4 through 6 and stabilized at a radius of approx. 60 km. Both the speed and distance from ring center during the last three loops when compared to the computed velocity cross-section (Fig. 4) indicate that the buoy was being carried in the ring's high-speed core.

Movement of the ring inferred from the buoy trajectory was to the northwest at 5 cm s^{-1} for the first 22 days, then to the north at 8 cm s^{-1} for the next 11 days. Our interpretation of the buoy's final half loop during days 332 to 338 is that the cyclonic ring coalesced with the Kuroshio. This is a common occurrence in the Gulf Stream region, having been observed on many occasions (CHENEY and RICHARDSON, 1976; CHENEY, GEMMILL, SHANK, RICHARDSON and WEBB, 1976; RICHARDSON, CHENEY and MANTINI, 1977; RICHARDSON, 1980). Unlike Gulf Stream rings, which when once detached from the stream can migrate southwestward all the way to Florida, Kuroshio rings are restricted from moving west of 140°E by the Izu-Ogasawara Ridge. The coalescence of rings in this region may therefore occur routinely. Other possibilities are that the undrogued buoy was blown out of the ring by wind, or that the ring merely 'bumped up' against the Kuroshio and during the interaction the buoy was transferred from one current system to the other. However, winds during this time were light (generally less than 5 m s^{-1}) and would have had an insignificant effect on the buoy's movement compared to the strong ring currents. Furthermore, XBT's taken on 30 December in the vicinity of the ring's last known position revealed no anomalous temperatures, nor did a limited XBT search the following February. This evidence, the buoy trajectory, and the ring's accelerating northward movement in late November suggest that the ring did coalesce with the Kuroshio in early December.

BUOY TRAJECTORY IN THE KUROSHIO

The undrogued surface drifter was tracked for 6½ months after it left the ring (Fig. 6). Five-day average speeds for the buoy during its entire lifetime are shown in Fig. 7. During the first two weeks outside the ring the buoy drifted slowly northward along 143°E, reaching a minimum speed of 15 cm s^{-1}. On day 350 the buoy suddenly accelerated to 70 cm s^{-1} and began moving eastward in the swift current of the Kuroshio Extension. During the following month the drifter followed a meandering course that carried it 1400 km downstream with an average speed of 60 cm s^{-1}. We were fortunate on 30–31 December to obtain an XBT section that crossed the buoy's path and cut through the two

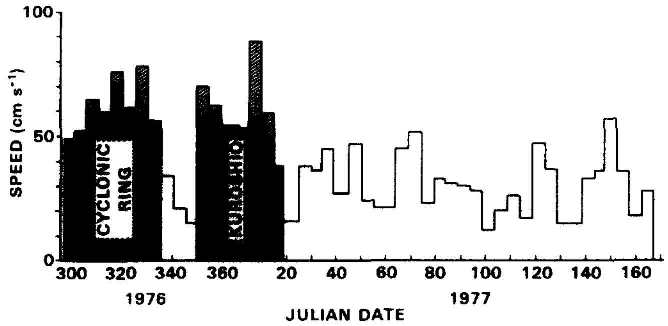

Fig. 7. Speed of the buoy averaged over 5-day intervals.

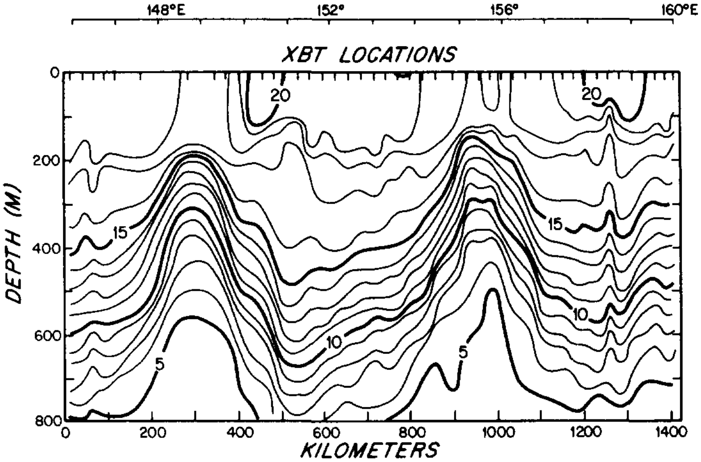

Fig. 8. Temperature section A–B, measured from USNS *Silas Bent* as it crossed the buoy's path during 30–31 December. Additional XBT data obtained by BERNSTEIN and WHITE (1980) show that the cold anomalies are two cyclonic rings interacting with the Kuroshio Extension.

meanders described by the buoy trajectory (section A–B in Fig. 6). The strong horizontal gradients shown by the temperature section in Fig. 8 provide convincing evidence that the buoy was following the Kuroshio Extension during this time.

Additional XBT data corresponding with the buoy's path were collected by BERNSTEIN and WHITE (1980) during the Pacific ship-of-opportunity program. Their maps of 300-m temperature for December and January (Fig. 9) are in excellent agreement with the buoy trajectory during this time. According to the monthly maps, the cold features in the XBT

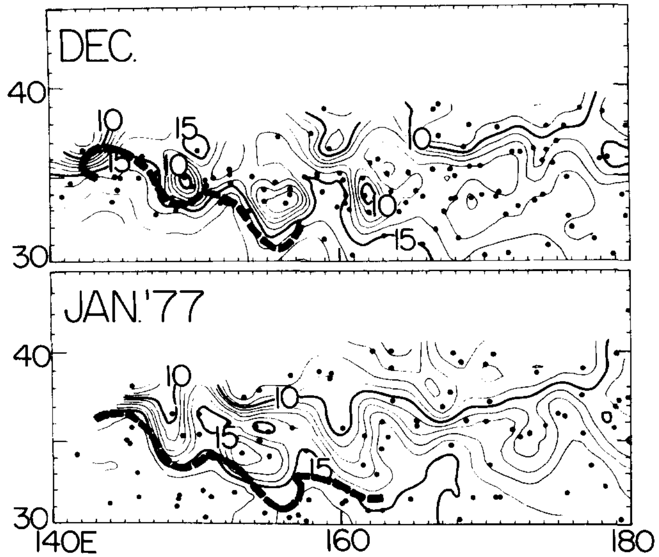

Fig. 9. Temperature at 300 m obtained during the Pacific Ship of Opportunity Program (BERNSTEIN and WHITE, 1980). Superimposed on the December 1976 map is the buoy trajectory from 1 December to 15 January. Trajectory shown on the January map is from 15 December to 15 February.

section appear to be two cyclonic rings imbedded in or interacting with the Kuroshio Extension. The buoy followed the offshore edge of the Kuroshio as it wrapped around both rings and carried the drifter southeastward to 31°N.

For the rest of the buoy's lifetime when no XBT's are available we have tried to assess the effect of wind on the buoy drift. According to Ekman's early work the wind-driven surface current is 45° to the right of the wind in the northern hemisphere. More recent studies have extended Ekman's results by including additional factors such as boundary layers and Stokes drift due to non-linearities of wave motion. Depending on which model is used, the angle between the wind and the surface wind drift current may vary considerably. MADSEN (1977), for example, included a variable vertical eddy viscosity and obtained a surface current that moved 10° to the right of the wind, in agreement with observations of oil slick movements after the *Torrey Canyon* spill (SMITH, 1968). DAVIS, BARNETT and COX (1978) obtained measurements suggesting a drift parallel to the wind, while KIRWAN, MCNALLY, PAZAN and WERT (1979) reported results from undrogued surface buoys that moved 25 to 30° to the right of the wind. Predicting the response of an undrogued buoy to wind is complicated by an unknown amount of "slip" relative to the water due to wind drag acting on the buoy's exposed surface area (KIRWAN, MCNALLY, CHANG and MOLINARI, 1975). Even when wind is not the predominant driving force, small wind components in the presence of large horizontal velocity gradients can drastically alter the long-term trajectory of a surface buoy.

Wind along the buoy trajectory was estimated from ship reports given in National Weather Service charts. Wind vectors were read every 6 h to the nearest 5 knots (2.7 m s^{-1}) and nearest octant and daily averages were computed. Figure 10 shows the wind progressive vector plot from 1 December 1976 (day 336), when the buoy left the cyclonic ring, to 14 June 1977 (day 116). Dots at 10-day intervals give an indication of wind speed according to the scale. The wind vectors were scaled down to 3% of actual speed for comparison with the buoy trajectory. A previous analysis showed this to be the approximate ratio of current speed to wind speed for an undrogued surface buoy in the presence of weak ambient currents (RICHARDSON *et al.*, 1977). Wind was toward the southeast from day 336 to day 60 at speeds of 5 to 13 m s^{-1}, yielding a net vector-averaged

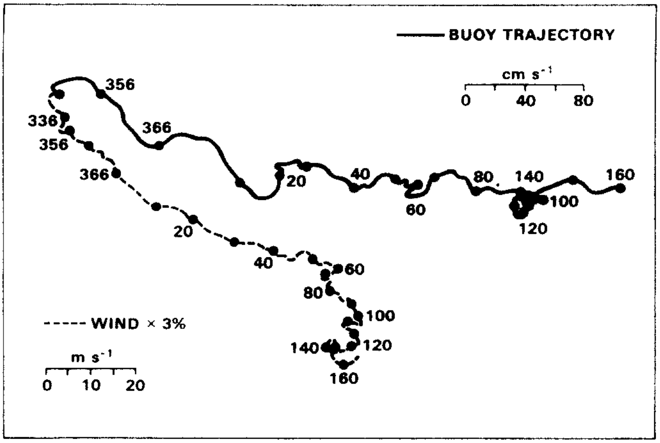

Fig. 10. Comparison between buoy trajectory and wind progressive vector plot. Wind speed has been multiplied by 3%.

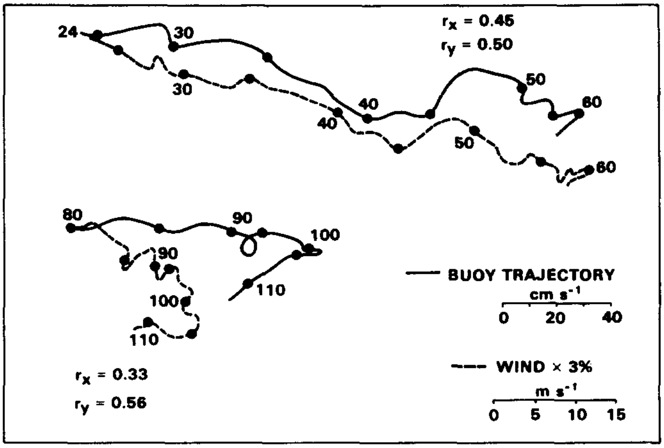

Fig. 11. Buoy trajectory and wind progressive vector plots for two periods with significant correlations (typical correlation values for other periods were $r = 0.15$).

wind speed of 8 m s^{-1} for the period. For the remainder of the time the wind was still in the 5 to 10 m s^{-1} range but much more variable in direction. Averaged over the last 100 days the net wind was southward at only 2 m s^{-1}.

There were two periods when the buoy's velocity appeared to be significantly determined by the wind (Fig. 11). During the first (days 24–62) there was a good correlation between wind and buoy velocities. The wind and buoy plots are essentially parallel, with the buoy moving slightly to the left of the wind. Vector-averaged wind speed was 8.3 m s^{-1} and the buoy drifted at 24 cm s^{-1}, or 3% of the wind speed. The wind analysis thus suggests that the buoy's 38-day drift from 157 to 166°E was due principally to wind. This is the period immediately after the buoy left the high speed current of the Kuroshio Extension (see Fig. 7), an event that also seems to be directly attributable to wind. Two days of strong 18 to 23 m s^{-1} winds toward the southeast corresponded with the buoy's abrupt change in direction toward the east and into a different current regime on day 24.

Another period when the buoy appeared to be largely wind driven occurred during days 80 to 112. The correlation is less striking than during the earlier period, but the gross features are similar. The buoy moved eastward 365 km and then southwestward 150 km. Net displacements of the buoy and wind vector plots at the end of the period were at average speeds of 10 cm s^{-1} and 2.3 m s^{-1}, respectively, yielding a buoy/wind speed ratio of about 4%.

In both cases depicted in Fig. 11 when wind could be identified as a principal driving force the buoy drifted either to the left of or approximately parallel to the wind direction instead of to the right as would be expected. This could be explained by the mean circulation in this region (Wyrtki, 1975), an eastward geostrophic current of a few cm s^{-1}. A net eastward drift was also observed during other periods when wind seemed to have little effect on the buoy trajectory.

Geostrophic currents clearly dominated the buoy's movement between days 63 to 80, when the buoy moved eastward at 40 cm s^{-1} against 9 m s^{-1} winds. Poor correlation between wind and buoy velocities existed during day 113 to 166 after the drifter passed over one of the seamounts in the Emperor Seamount chain at 172°E. During this time the

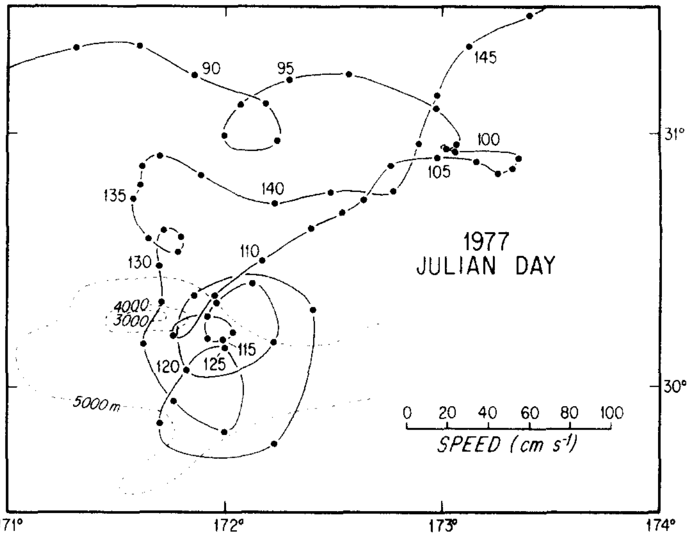

Fig. 12. Buoy trajectory as it crossed the Emperor Seamounts. On day 90 it began a series of anticyclonic loops that persisted for nearly 7 weeks. Average period was approx. 5 days.

character of the trajectory changed into a series of anticyclonic loops, which persisted for nearly one month (Fig. 12). The average period of these loops was approx. 4 days (6 loops in 26 days) and their diameter ranged from 5 to 65 km. A maximum of 70 cm s^{-1} was attained during the largest loop. These motions are less energetic and of smaller scale than those in the cold rings and may be a manifestation of an inertial Taylor column created by eastward flow over a seamount (McCARTNEY, 1975). The meandering wake in such a flow is thought to contain both anticyclonic and cyclonic eddies. Several topographic charts show a large seamount between 30 to 31°N, and 171 to 172°E. Although its size and shape differ on different maps, it seems clear that a seamount extending halfway to the surface from the sea floor at 5000 m could have a profound effect on flow in its immediate area.

The spiraling motion ended abruptly on day 137 and the buoy continued its eastward drift at a net speed of 30 cm s^{-1} until the batteries failed in mid-June 1977. From the time that it was entrained in the Kuroshio Extension off Japan to its final known position, 480 km north of Midway Island, the buoy moved a net distance of 3500 km toward 98°T at an average speed of 22 cm s^{-1}.

SUMMARY AND CONCLUSIONS

A cyclonic Kuroshio ring was located 350 km southeast of Japan during a series of airborne XBT surveys in October 1976. Subsequent shipboard observations revealed that its thermal structure extended to a depth of at least 3000 m. Gradient currents calculated along a zonal section through the ring had maximum speeds of 60 to 80 cm s^{-1} approx. 60 km from the ring center.

The ring was tagged with a satellite-tracked drifting buoy, which provided a good method of measuring the ring's movement as long as the ring remained a detached feature free of the Kuroshio's influence (37 days). During the first four revolutions the drifter spiraled outward with an average radial velocity of 2 cm s^{-1}. Loss of the 200-m drogue after 13 days coincided with a slightly accelerated movement of the buoy away from the ring center, but once the drift reached the radius of maximum current speed (60 km) it appeared to stabilize there. The implication is that a ring's high speed core is a region of surface convergence.

The period of the buoy's movement around the ring was sufficiently short (5 to 7 days) to obtain good estimates of the ring's changing position. Movement of the ring inferred from the buoy trajectory was to the northwest at 5 cm s^{-1} for the first 22 days, then to the north at 8 cm s^{-1} for the next 11 days. Considering the ring's accelerating northward movement, proximity to the Kuroshio, and subsequent entrainment of the buoy unto the Kuroshio Current, it is highly likely that the ring coalesced with the Kuroshio in early December. This conclusion is further supported by XBT surveys in December and February, which failed to find any cyclonic rings in this area.

The undrogued surface drifter was tracked for 6½ months after it left the ring. It followed the Kuroshio Extension 1400 km downstream for one month, averaging 60 cm s^{-1}. The buoy was then blown eastward out of the high speed current by two days of 18 to 23 m s^{-1} winds; during the next month its trajectory was significantly correlated with the wind velocity. For the last few months the buoy movement was alternately controlled by geostrophic currents and wind. However, even when wind seemed to be a primary driving force, the buoy usually moved to the left of the wind direction, suggesting a persistent eastward component of geostrophic velocity. For nearly one month the buoy moved in a series of anticyclonic loops near a seamount in the Emperor Seamount chain, suggesting a Taylor column.

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