Tracking a Gulf Stream Ring with a Free Drifting Surface Buoy[1,2]

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ABSTRACT

A newly developed buoy which is free drifting and tracked by satellite was successfully used to measure the movement of a Gulf Stream ring. The buoy, launched in a young ring at 36°15′N, 58°00′W, looped around its center with a period of 54 h, radius of 25 km and speed of 75 cm s^{-1}. For two months the ring moved rapidly and consistently to the northeast with an average speed of 9 cm s^{-1}. An airborne XBT survey and satellite infrared radiometry measurements provided evidence that the ring coalesced with the Gulf Stream near 53°W. This study presents the most convincing evidence yet that a ring can coalesce with the Gulf Stream. When this result is combined with the results of other studies, there is a suggestion that rings may coalesce with the Gulf Stream more frequently than previously believed.

1. Introduction

Despite a considerable effort to study cyclonic Gulf Stream rings, their trajectories or paths in the ocean remain largely unknown due to lack of a suitable long-term tracking technique. Only once has a ring been continuously and unambiguously followed for as long as six months (Fuglister, 1977); in this case a ring was tracked with surface buoys, ship and airplane. This experiment gave the first evidence that surface buoys would stay within a ring for long periods of time. Only recently, however, with the development of an expendable satellite-tracked buoy by the National Data Buoy Office, has there been a relatively inexpensive method for the real-time, continuous and long-term tracking of a surface buoy. Positions of this satellite buoy are determined by NASA twice a day with an accuracy within 5 km. This buoy provided us with an instrument with which to resolve the surface motion of a ring and to measure its long-term movement. The value of such a technique, in addition to measuring ring trajectories, was that we could return to a ring at intervals of several months in order to make repeated measurements of its physical, chemical and biological characteristics and thus gain an understanding of the decay processes within a ring. In October 1974 we attempted to use SOFAR floats in order to follow a ring but the floats came out of the ring after only a few months (Cheney *et al.*, 1976). In December 1975 we began an experiment using one of the satellite buoys to follow a ring. The results presented in this paper show that the buoy worked well; it followed the ring and provided a good tracking technique. With these encouraging results several scientists have begun an experiment (December 1976) to follow a newly formed ring with satellite buoys through its life and to measure its changes with time.

Gulf Stream rings are examples of the largest oceanic eddies; they have overall diameters of 200–300 km and are formed from Gulf Stream meanders (Fuglister, 1972). Approximately ten cyclonic rings exists at a time and their mean life is thought to be about two years. The general movement of rings in the Sargasso Sea is toward the southwest based on an analysis of historical data (Parker, 1971; Lai, 1976) plus attempts to track a few individual rings (Richardson *et al.*, 1973; Fuglister, 1972). However, this movement is mainly inferred. The only ring whose path was continuously followed (Fuglister, 1977) moved in a complicated trajectory consisting of large loops; its mean speed of movement over six months, approximately 1 cm s^{-1}, was small compared to its excursions about the mean. We have little actual data on the mean movement of rings.

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[2] Contribution No. 79 from the Mid-Ocean Dynamics Experiment (MODE).

Recent evidence suggests two modes of ring behavior. The first is a movement of a few centimeters per second to the southwest toward Florida where rings may coalesce with the Gulf Stream. During their life of a few years these rings decay slowly (Chaney and Richardson, 1976). The second mode consists of a relatively short life (several months) in which rings coalesce with the Stream, or are captured by a meander. The coalescence of a cyclonic ring with the Stream has been observed on one occasion (Cheney *et al.*, 1976) and in several other cases a ring has been seen to move toward the Stream and subsequently disappear. Coalescence of the Stream and ring is the simplest and we believe correct explanation of the disappearance of these rings. This explanation is supported by the present experiment which is the clearest example of a ring coalescing with the Stream.

2. The buoy

The buoy was designed by W. Richardson at Nova University and was purchased from the National Data Buoy Office. It is a 4.5 m long PVC tube with a foam-filled flotation collar (Hall and Kerut, 1975). It was strengthened by the addition of four 1.2 cm concrete reinforcing rods fiberglassed to the PVC tube. Sensors on the buoy measured wind speed 1.5 m above the sea surface, temperature 1.8 m below the sea surface and drogue tension. The drogue was a window shade type whose width was 1.7 m, length 14.6 m and weight 40 kg in water. The material was dacron sailcloth fastened securely all along its perimeter to rigid bars along top and bottom and steel shrouds along the edges. The drogue was attached to the buoy by a 200 m length of 1.9 cm diameter nylon line and the evidence is that it worked well until it came off after two months.

The buoy's transmit terminal sends a signal for approximately 1 s each minute. Signals consist of buoy identification number and sensor data. The position is calculated by NASA from the Doppler shift of the signal as it is received by the Nimbus 6 satellite. A comparison of 12 good fixes and the known location of the buoy ashore suggests an accuracy of 1.2 km and a precision (rms scatter about the mean) of ± 0.9 km, well within the design limits of the system (± 5 km). Position errors are introduced from several sources including weak signals, low number of signal transmissions received, low or high angle of satellite pass, unknown velocity of the drifter and errors of the satellite position. In practice it was found that

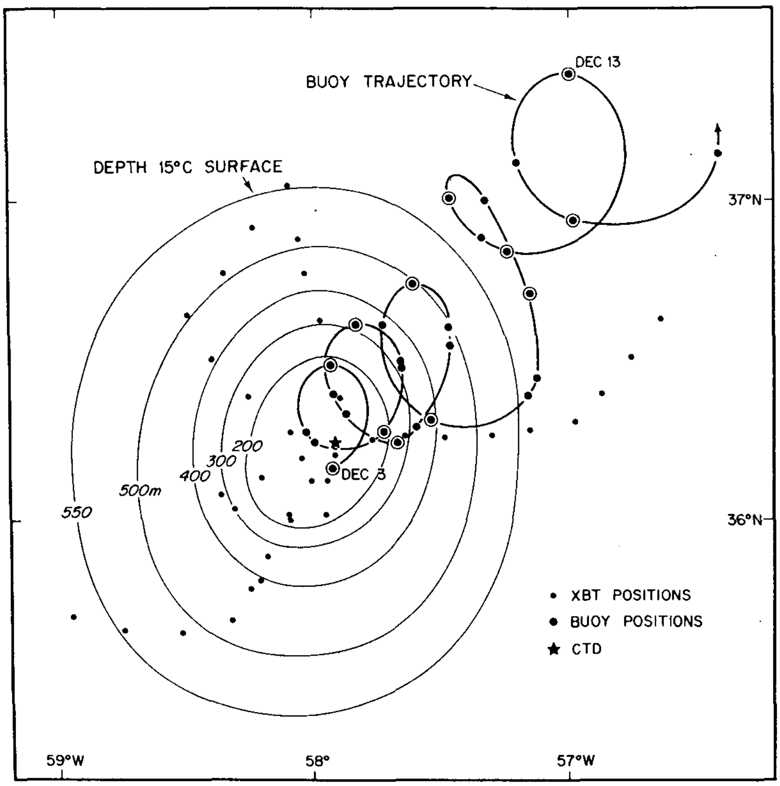

FIG. 1. Location of Gulf Stream ring and first 12 days of the buoy trajectory. Contours are depths of the 15°C isothermal surface. XBT locations from 3–4 December 1975 were adjusted to remove the effect of ring movement during the survey. Circled buoy positions are the daily 1400 GMT fixes.

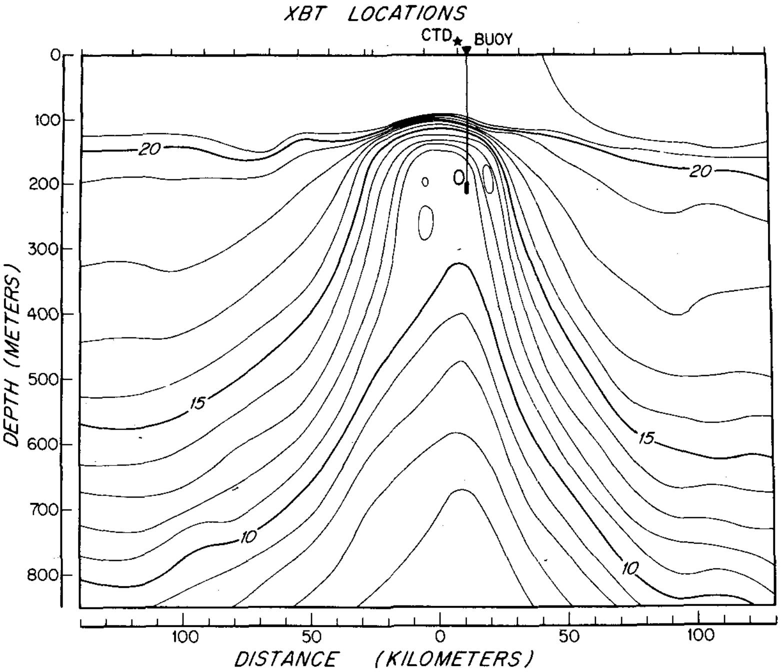

FIG. 2. XBT section through the ring. Buoy position at launch and CTD station are shown. Temperature inversions are associated with *T-S* anomalies (see Fig. 3).

those fixes with a low error index (<40), high angle of satellite pass (>87.5°) or with few messages reeived by the satellite (<7) were frequently off the inferred trajectory and therefore were discarded. Error index is calculated by NASA to estimate the error in fitting the theoretical Doppler curve to data received by satellite.

On the average, 1.6 fixes per day were obtained; they were spread over the time 0200–1600 GMT. Since fixes were most frequently obtained near 1400 GMT, this time was chosen for the daily position of the buoy and was used to compute daily averages of wind, sea surface temperature and velocity. Occasionally daily positions were not received and the trajectory of the buoy was extrapolated based on its path before and after the missing data.

3. The ring

The ring was located and surveyed by XBT on R/V *Trident* cruise TR-175 during 3 and 4 December 1975; its center was near 36°15′N, 58°00′W (Fig. 1). The diameter of the ring based on the intersection of 15°C isotherm and 500 m was 130 km but its overall size was larger, 200 km, as can be seen on the XBT section (Fig. 2). Evidence suggests that the ring had completely separated from the Gulf Stream although no concurrent measurements were made in the Gulf Stream nor could the Stream be seen on satellite IR photos for this period. A CTD-O_2 profile was made near the ring center and when the station is compared to another outside of the ring, the fresher and oxygen-rich water of the ring core, indicative of Slope Water, can be seen (Fig. 3). That such cold temperatures and strong anomalies were found at the ring center suggests that the ring had recently formed. Older rings have a deeper thermocline and smaller anomalies (Cheney and Richardson, 1976).

4. Buoy trajectory

The buoy was launched near the center of the ring and appeared to follow it very well for 2.5 months (Fig. 4). The buoy trajectory clearly shows the cyclonic circulation of the ring plus its translational velocity. Buoy fixes and the inferred trajectory during the first two weeks of drift are shown in Fig. 1, superimposed on the ring at the time of launch. The size of the loops about the ring was small compared to the overall size of the ring, assuring us that the buoy remained in the core of the ring as it moved through the ocean. The surprising result is that the ring moved consistently northeastward. From early December to mid-February the buoy continued to execute cyclonic loops about the ring with a period of about 54 h and radius of 25 km. During this period movement of the ring as inferred from the looping trajectory of the buoy was toward 54° with an average velocity of 8 km day^{-1} and with a peak speed of 18 km day^{-1} over 11 days. This rapid movement was against the mean wind vector which was from the north at a mean speed of 6 kt during the 11 days.

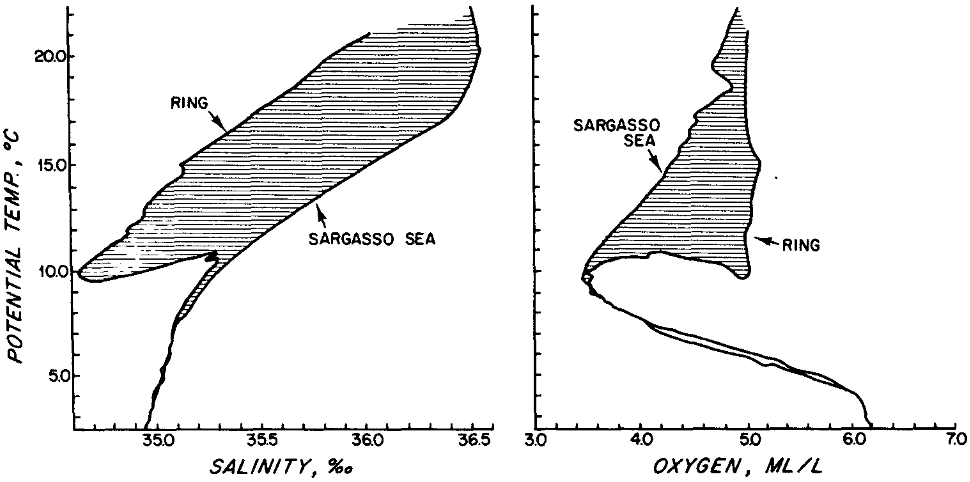

FIG. 3. Salinity and oxygen profiles as a function of potential temperature from a CTD station near the ring center compared to a CTD station outside the ring and in the Sargasso Sea taken on 7 December 1975 and located at 33°23'N, 64°13'W. The ring station has anomalously low salinity (minimum, 0.90‰) and high oxygen (maximum, 1.5 ml l⁻¹) from the surface to at least 10°C and possibly to 7.5°C (salinity) which is indicative of its Slope Water origin.

During late January and early February the character of the buoy trajectory changed radically. At first the loops became smaller (radius 11 km) and they occurred every 4 days. They have the appearance of being advected by a larger scale looping motion. From 9–24 February the buoy made one large loop (radius

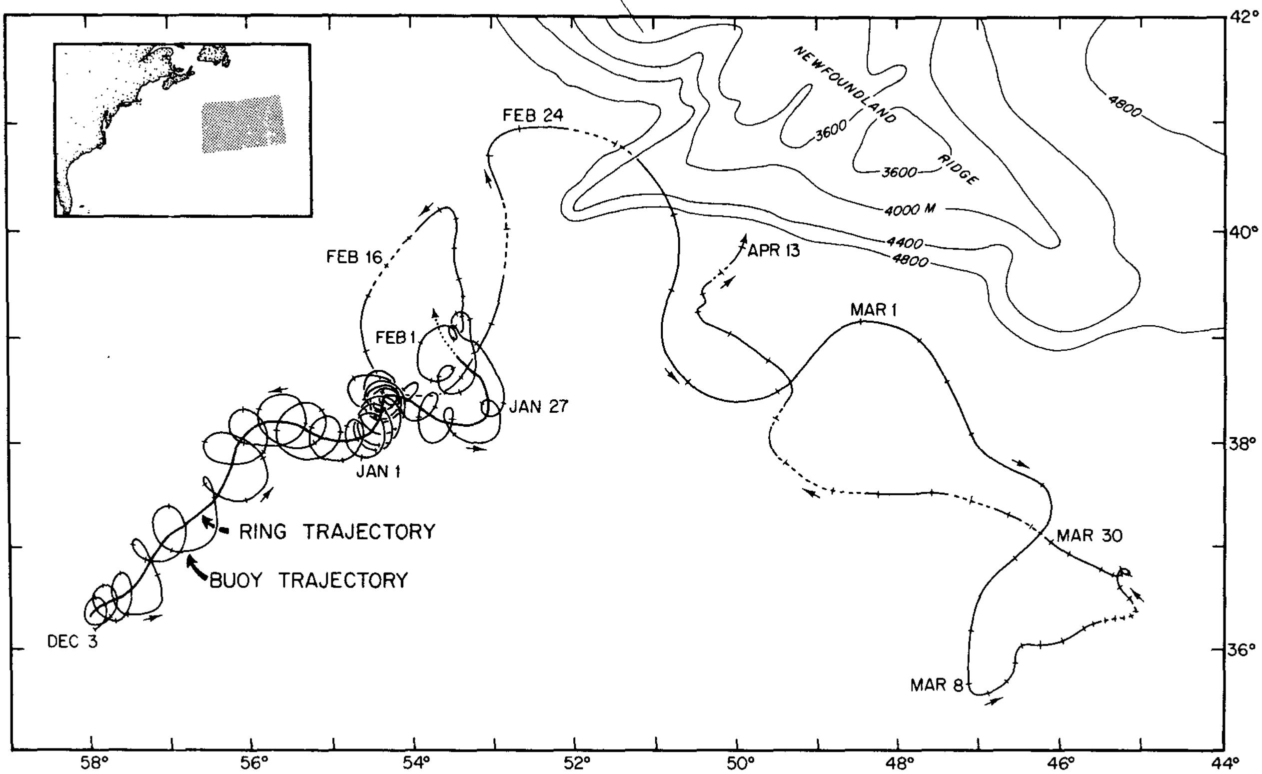

FIG. 4. Trajectory of the buoy and ring. Tick marks indicate daily positions and dashed line indicates periods when daily fixes were not obtained. Dark curve is interpreted trajectory of Gulf Stream ring. From 3 December 1975 to mid-February the buoy was clearly following the ring. During February the ring coalesced with the Stream and the buoy moved east in it. Although the drogue came off on 29 January, there is little apparent wind effect on its trajectory until 9 March, at which time the buoy velocity is correlated to the wind velocity.

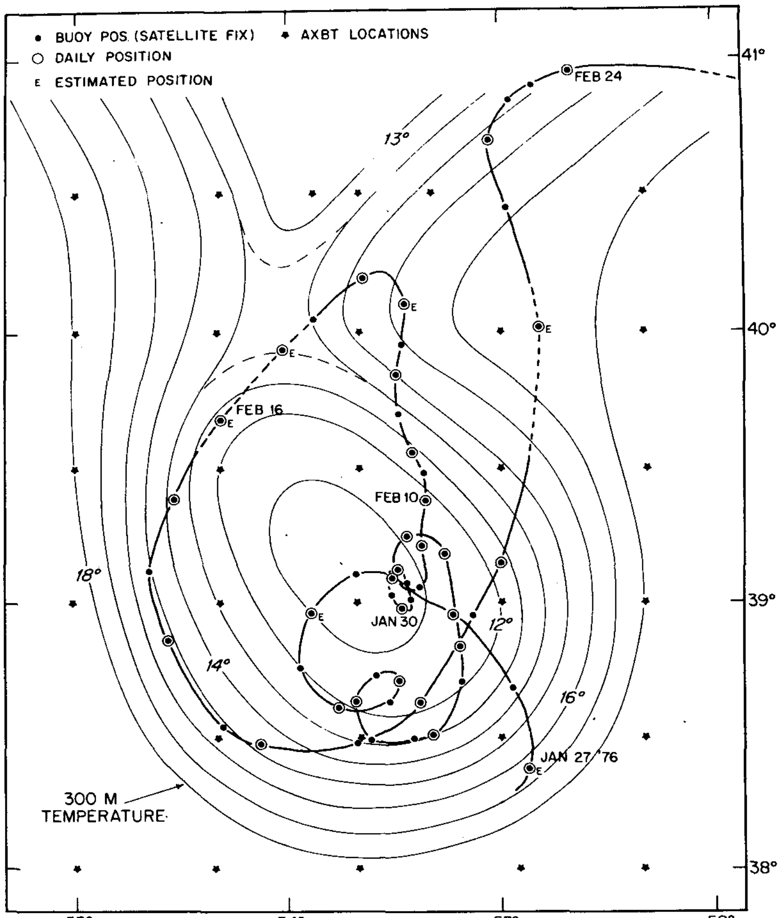

FIG. 5. Ring coalescing with the Gulf Stream. Contours are isotherms at 300 m measured by AXBT survey on 16 February 1976. Dark line is buoy trajectory from 27 January to 24 February.

80 km) and was then carried southeastward in the Gulf Stream. During February there is good evidence to show that the ring coalesced with the Gulf Stream and that as it did so it increased in size and was transformed into a Gulf Stream meander. The evidence consists of an AXBT (Airborne XBT) survey of the ring on 16 February and subsequent satellite infrared radiometry photos obtained from the National Environmental Satellite Service, NOAA (Figs. 5 and 6). The last loop of the buoy was made just as the ring center opened to the north and became a meander. By 16 February the ring had almost completely merged with the Gulf Stream and the diameter of the 15°C water at 300 m had increased from 35 km in December to 90 km. During the AXBT survey, the sea surface temperature difference between the core and the outer portion of the ring was approximately 4°C. Satellite photos on 20 and 28 February and 22 March show this contrast and provide what we believe is convincing evidence that the ring completely merged with the Stream and deepened into an open meander (Fig. 6).

Other interesting features can be seen in the satellite photos. One is the possible formation of a warm eddy north of the Stream between 20–28 February northwest of the ring/meander. A second is the occurrence of two cyclonic rings along 60°W which appear close together near the Stream. A third is the small meander in the Stream along 50°W; the influence of this meander is clearly reflected in the trajectory of the buoy. There is some evidence from the 22 March satellite photo that the meander eventually formed a cold ring. There is also a hint in this photo that the Stream may have split into two filaments, one moving to the east, then north, and one to the southeast. Clouds in February prevented additional observations of the southern filament.

From 24 February to 9 March the buoy moved rapidly to the southeast possibly in the southern filament of the Gulf Stream. Between 9 and 28 March the buoy's velocity is quite small and appears well correlated with the wind. During this latter period the buoy was northeast of the temperature gradient associated with the southern filament in agreement with the conclusion that the buoy was longer in the Gulf Stream (Fig. 6).

It is tempting to make interpretations such as these from infrared satellite imagery especially when supporting measurements such as the AXBT survey confirm what we see. However, when complementary measurements are not available, for example to confirm the splitting of the Stream, we remain doubtful of our interpretations. Velocity and temperature measurements of the buoy, however, are consistent with the conclusion, based on satellite measurements, that there was a southern filament.

5. Buoy speed

The speed of the buoy, calculated between daily fixes, reflects variations in the trajectory (Fig. 7). While the buoy was in the ring its motion was a result of its cyclonic rotation around the ring and the ring translation. A typical speed around the ring was 75 cm s^{-1} and the magnitude of the average ring translational velocity was 9 cm s^{-1}. There is a large scatter in speed because daily values were averaged over too long a period to adequately resolve each loop, and because the cyclonic velocity and ring translation velocity sometimes add and sometimes subtract.

The peak speed along the buoy's path was 116 cm s^{-1}; it occurred while the buoy was moving southeastward in the Gulf Stream. After the buoy came out of the Stream on 9 March the speeds remained low for about a month and then increased to about 60 cm s^{-1}. After 9 March the buoy velocity is correlated with wind velocity; the trajectory and speeds should not be interpreted as being caused only by currents.

6. Sea surface temperature

Sea surface temperature decreased from 3 December (T=21°C) to 21 February (T=16°C) partially as

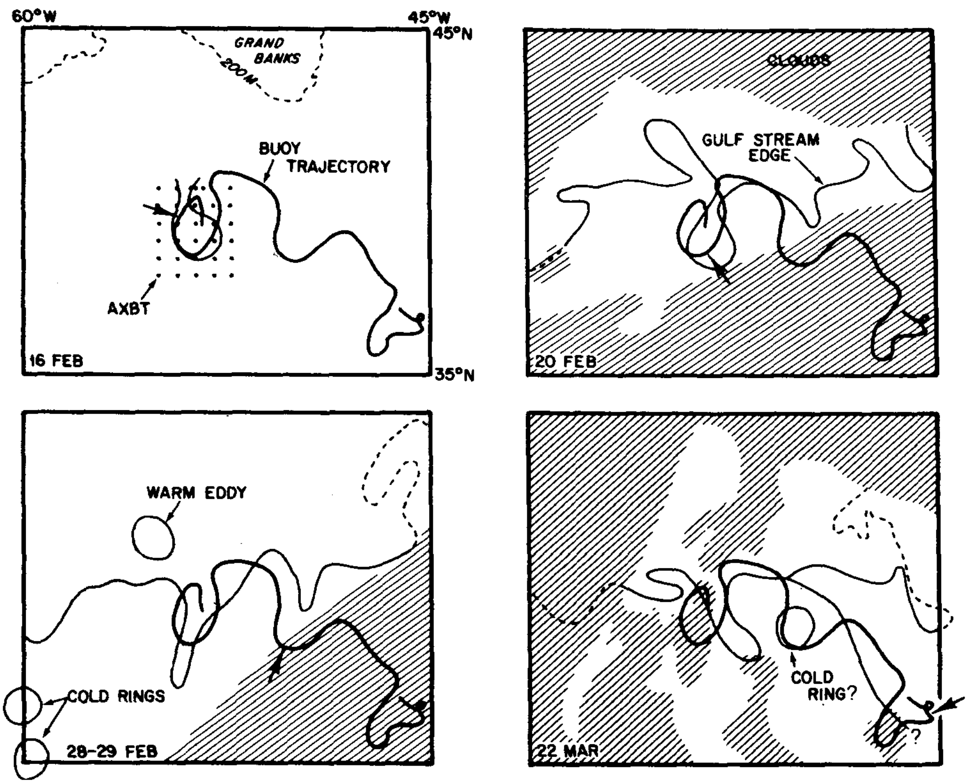

FIG. 6. Ring coalescing with Gulf Stream as observed by AXBT and satellite infrared radiometry. Buoy trajectory is shown by a dark line; the light line represents the location of maximum temperature gradient (4°C in the first panel) and is associated with the northern edge of the Gulf Stream. In past experiments the surface temperature front associated with the Stream was usually located 15 km north of the high velocity core (Hansen and Maul, 1970). A dark arrow indicates location of buoy during each observation.

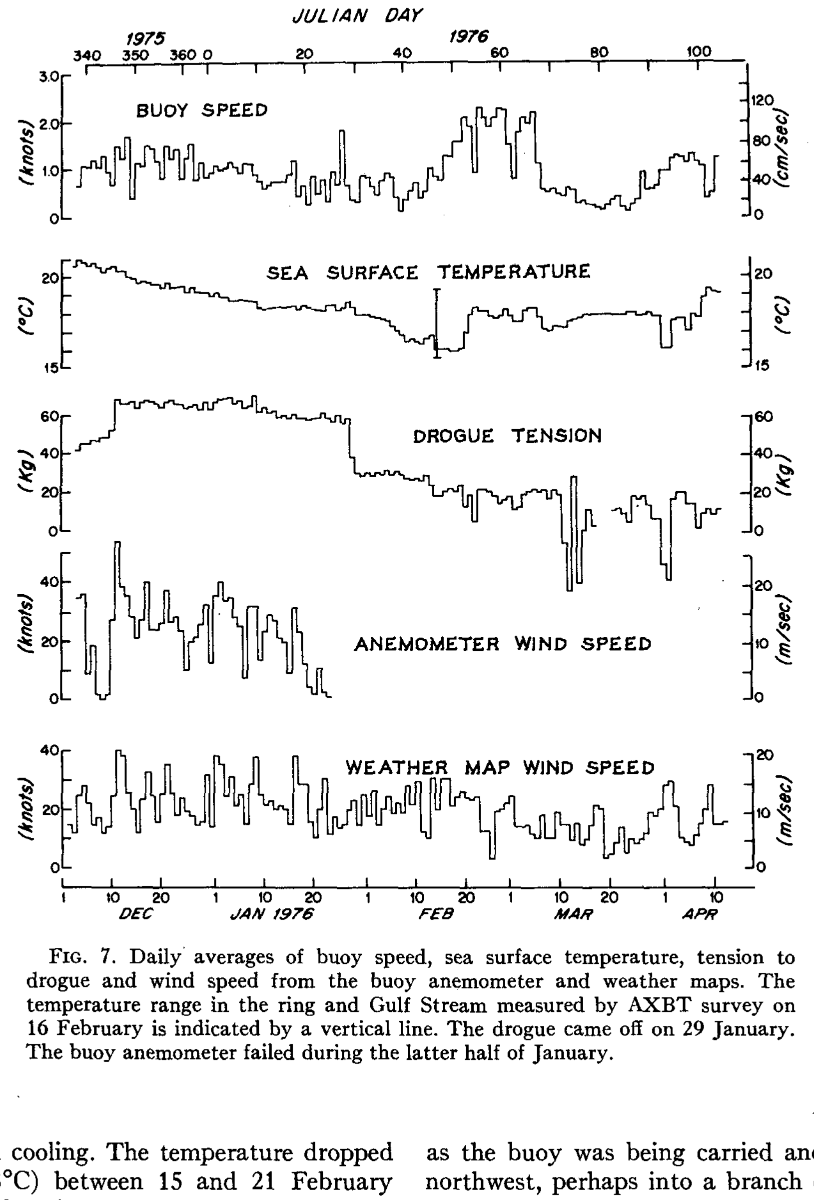

FIG. 7. Daily averages of buoy speed, sea surface temperature, tension to drogue and wind speed from the buoy anemometer and weather maps. The temperature range in the ring and Gulf Stream measured by AXBT survey on 16 February is indicated by a vertical line. The drogue came off on 29 January. The buoy anemometer failed during the latter half of January.

a result of seasonal cooling. The temperature dropped to its lowest (15.8°C) between 15 and 21 February during the time the ring was coalescing with the Stream. Surface temperature recorded by AXBT on the 16th was 15.4°C inside the ring and 19–19.5° in the Gulf Stream. Temperatures recorded by the buoy support the satellite and AXBT data which show the ring was opening to the north and that the area of cold water in its core was increasing. Between 21–23 February the temperature measured by the buoy jumped to 18°C and this coincided with the beginning of the buoy's movement east in the Gulf Stream. The small decrease in temperature (1°C) on 8 March may reflect the buoy's movement out of the Gulf Stream and across the surface front seen by satellite (Fig. 6). The decrease in temperature from 1–3 April and subsequent increase remain unexplained but may be a measure of the different water types encountered as the buoy was being carried and windblown to the northwest, perhaps into a branch of the Gulf Stream.

7. Drogue tension

The tension of the line to the drogue was measured with a tension sensor on the buoy. Since the sensor was uncalibrated the value of 40 kg at launch on 3 December was based on the weight of the drogue in water. During the first eight days the tension slowly increased and on 12 December it jumped to a plateau of 65 kg. The rapid increase in tension coincided with the highest winds encountered over the 4.5-month period—a 24 h average of 54 kt (28 m s^{-1}). There is the possibility that the high winds could have blown the buoy radially outward into a region of stronger vertical shear (of horizontal current) which added to the tension. Evidence from the trajectory is marginal but suggests that the radius increased from 23 to 28 km during this period.

On 29 January the tension dropped suddenly to 30 kg and afterward decreased slowly with occasional large fluctuations. We think that the large drop in tension on 29 January represents the bulk of the drogue coming off. It is not obvious whether the whole drogue or just the bottom bar (weight 35 kg in water) came off. The residual tension might be hysteresis of the load sensor as suggested by laboratory studies (J. Harris, personal communication). Certainly after 9 March there is little evidence to suggest that any part of the drogue remained. An investigation of the effect of wind on the buoy is given under wind observations.

The premature loss of drogue is a serious problem if long-term trajectories are required. In the present case the severe weather could have hastened the disintegration of the drogue; it might have lasted longer in milder conditions. There is also the possibility that a fish could have bitten through the nylon tether line. Nylon line was used to reduce the expected shock loading caused by heavy seas. In the future we plan to try the addition of a 5 m section of 1.0 cm chain between buoy and tether line and to increase the thickness of line from 1.9 m to 3.8 cm.

8. Wind observations

Two time series of wind data were obtained, one from the buoy anemometer (speed only), and the second from daily weather maps obtained from the National Weather Service. Four weather maps are prepared each day showing pressure patterns, fronts and ship reported wind velocities. Wind velocity, estimated to the nearest 5 kt and nearest octant, was taken from these maps at 6 h intervals along the buoy trajectory and average daily mean velocities and speeds were computed.

A comparison of the anemometer and weather map speeds indicates a significant correlation between the two, $r=0.76$ (Figs. 7 and 8). Maximum and minimum speeds observed by the buoy were missed on the weather maps but the means of the two series are very close; the anemometer mean was 24.4 kt (12.6 m s^{-1}) and the map mean was 23.8 kt (12.2 m s^{-1}). The discrepancy *in extrema* is due partially to the different kinds of data they represent, and partially to problems in trying to infer a velocity from a weather map. Ship reports are spot values four times per day usually from an anemometer on the ship's mast. The buoy speed represents an integration of speed over each day measured only 1.5 m above the ocean surface. Although the precision of the anemometer measurement is estimated to be less than 0.1 kt for daily values, the accuracy of the method is in question due to the large possible effect of the waves in shielding the anemometer from the wind.

The good agreement between anemometer and weather map winds gave us encouragement to use the latter to examine the effect of the wind on the buoy's drift (Fig. 8). The results suggest the following:

1) When the buoy was in the ring and the drogue was attached to the buoy there was no discernible wind effect except possibly during the highest winds when the buoy's loops became slightly larger (the radius increased from 23 to 28 km) and the tension increased. The highest winds were measured on 12–13 December; the daily average was 54 kt and over a 1.7 h period the wind speed was 66 kt.

2) When the buoy was in the ring/meander and then the Gulf Stream and the drogue was off, the buoy velocity had no visual (nor statistical) correlation to the wind velocity and the wind effect was considered to be small compared to the swift currents. The integrated effect of the wind during this period, however, which was east-northeastward at an average 10 kt could have blown the buoy northeastward as much as 100 km and may have caused the buoy to have come out of the Stream.

3) When the buoy was out of the Stream after 9 March with the drogue off, the buoy's velocity appeared to be significantly determined by the wind. During this latter stage the buoy velocity was well correlated with wind velocity ($r=0.55$) and the wind progressive vector plot is very similar to the shape of the buoy trajectory (Fig. 8). The buoy drifted with a rate of 3.0% (±0.5%, the 95% confidence limits) of the wind speed. Based on this rate and the average winds (10 kt) the buoy drift was 0.3 kt. This value is large except when compared to the high velocity core of the Gulf Stream or a ring which can reach speeds of 4–5 kt. A calculation assuming steady wind and a velocity squared drag law suggests a 3% drift speed for this buoy undrogued and a 0.3% drift speed for it as launched fully drogued.

9. Discussion

The measurements quite clearly reveal that over a 2.5-month period a young and intense ring moved northeastward and coalesced with the Gulf Stream. This result appears surprising in the context of what we think we know about the behavior of rings. The few attempts to track rings, the analysis of historical data to infer the movement of rings, and theoretical models all suggest that rings move on the average southwestward. Although this discussion is an attempt to reconcile the difference, we really do not know why the ring moved to the northeast.

The first point is that several rings have appeared to coalesce with the Gulf Stream. Although the present case is the most convincing other studies have made the same conclusion off Florida (Richardson *et al.*, 1973) and north of Bermuda (Cheney *et al.*, 1976). Details of the process are unknown but one can imagine a similar process as the formation of a ring with time running in reverse.

The second point is that a ring can move in a complicated trajectory. Fuglister (1977) observed a ring to move in large loops (radius 75 km) with a period of 60 days, while slowly translating to the west. Although the mean motion of rings may be to the southwest considerable variation from this mean has been seen. It is not clear what causes the erratic movement; possibilities are the variation of size, shape and velocity field of the ring itself, and response or interaction of the ring to the Gulf Stream and other rings. There is the possibility that the observed movement of the present ring was an example of the movement observed by Fuglister but that on its northern excursion the ring coalesced with a Gulf Stream meander before finishing a loop. Fuglister's ring also disappeared and may have also coalesced with the Gulf Stream (Parker, 1971).

There is also a possibility that the ring never fully separated from the Gulf Stream. The evidence for closed contours comes from the XBT survey which suggests the ring had separated at least out to a radius of 85 km and from the buoy trajectory which showed that the ring continued its cyclonic circulation for at least 2.5 months. Outside the area of the XBT survey, or perhaps, in a deeper layer the ring may have been dynamically attached to the Gulf Stream; thus the ring movement could have been directly tied to the Gulf Stream's which, unfortunately, we did not study concurrently.

10. Conclusions

The satellite buoy provided a good method to track the ring. During the 2.5 months before the ring coalesced with the Stream there was no observable tendency of the buoy to move out of the ring. During this period the movement of the ring which was to the northeast could be inferred from the buoy trajectory. To take advantage of this tracking technique for rings we need to improve the life of the tether-drogue system and the buoy radio transmitter. Recent developments (Livingston, 1976) have shown that the technical problems are being solved.

This study presents the most convincing evidence so far that a ring can coalesce with the Gulf Stream. When this result is combined with a few other studies which have come to the same conclusion, there is a suggestion that rings may coalesce with the Gulf Stream more frequently than previously believed.

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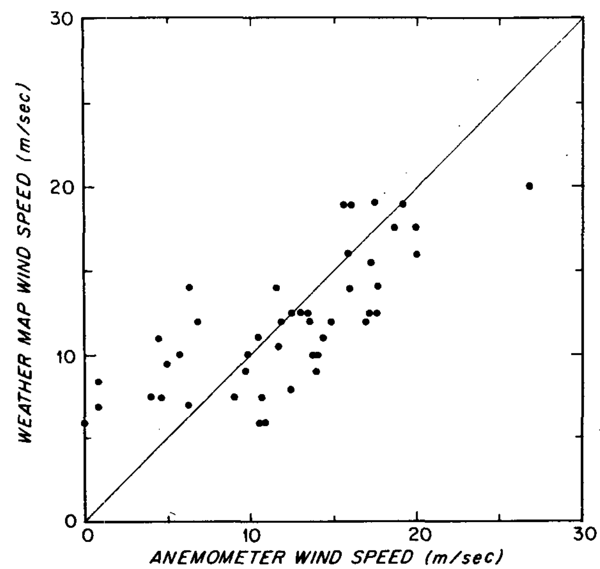

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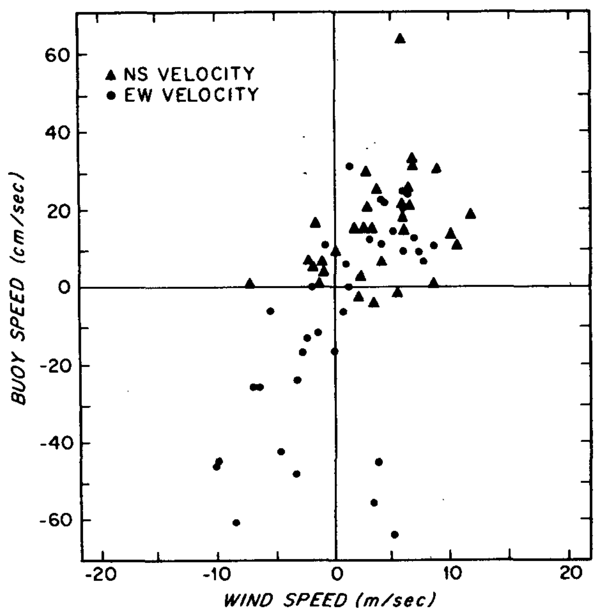

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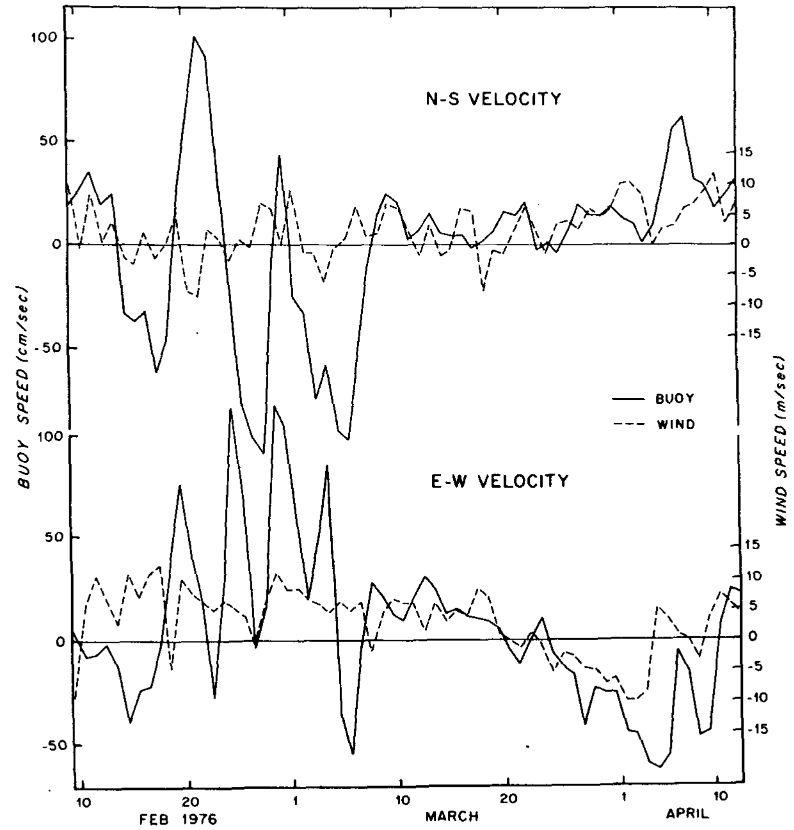

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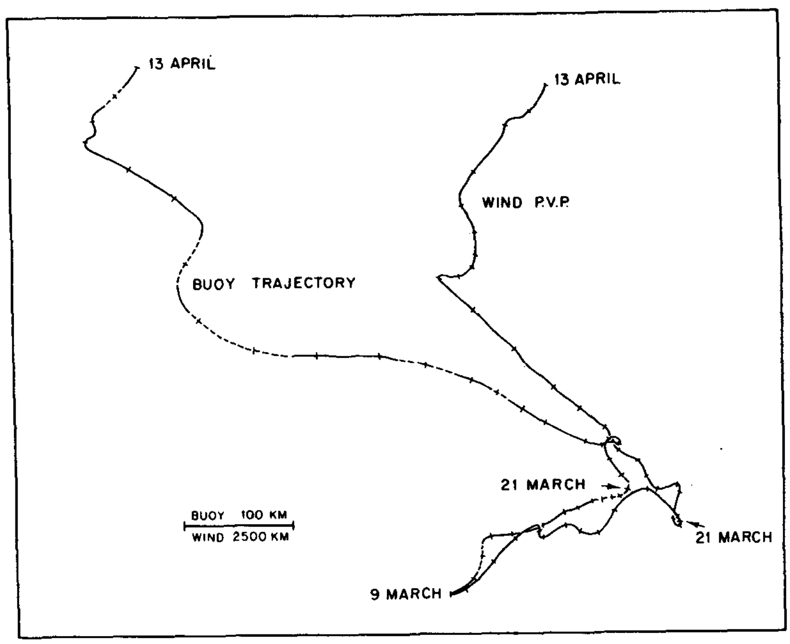

(d)

FIG. 8. Comparison of buoy velocity and wind velocity: (a) anemometer and weather map wind speeds from 6 December to 5 January (each dot represents a daily average); (b) time series of N–S, E–W buoy and wind velocity components, 9 February to 13 April; (c) scatter plot of buoy and wind velocity components, 9 March to 13 April, and (d) buoy trajectory and wind progressive vector plot, 9 March to 13 April. After 8 March the buoy velocity is significantly correlated ($r=0.55$) with the wind; the drift factor is about 3% of the wind.

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