Tracking a Gulf Stream Ring with SOFAR Floats

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ABSTRACT

An experiment to test the feasibility of tracking Gulf Stream rings with neutrally buoyant SOFAR floats was begun in September 1974. Three floats were launched at depths of 750, 1050 and 1080 m in a ring west of Bermuda. One float left the ring after 3 weeks. The other two floats remained in the ring for 2–3 months, while it moved 375 km westward at a rate of 6 cm s^{-1}; they were subsequently entrained by the Gulf Stream off Cape Hatteras. A second ring seeded with floats coalesced with the Gulf Stream and five of its six floats were carried eastward in the Stream. The sixth float drifted south out of the ring and into the Sargasso Sea. One float was launched in the Sargasso between the two rings; its net drift over a 6-month period was to the west at 1.1 cm s^{-1}. These results indicate that there is considerable exchange of water between a ring and surrounding water at depths of 750 to 1100 m and that rings can be tracked for periods of only a few months with SOFAR floats at these depths. Paths of the three floats tracked in the northwestern Sargasso Sea outside of rings and the Stream indicate a net westward drift approximately equal to the observed westward movement of rings in this region.

1. Introduction

Gulf Stream rings are the most energetic of ocean eddies in the North Atlantic, and are thought to play an important role in the general ocean circulation, especially in the vicinity of the Gulf Stream. In order to learn more about their movement and physical structure a method of following rings for long periods, one to two years, is required. This report describes an attempt to follow a ring and to examine its kinematical properties by using SOFAR floats.

Cyclonic rings are formed from large Gulf Stream meanders and consist of a core of cold Slope Water surrounded by a ring of swiftly flowing Gulf Stream Water (Fuglister, 1972). Approximately 5–8 rings form per year and their life span is about 2 years (Fuglister, 1972; Parker, 1971; Barrett, 1971; Richardson *et al.*, 1973; Cheney and Richardson, 1976). Previous ring studies have primarily relied on repeated ship and aircraft observations but the large amounts of time and high cost of these techniques makes them unreasonable for long-term tracking. The movement of a few rings has been followed by using satellite infrared imagery plus limited ship observations (Richardson *et al.*, 1973; Stumpf *et al.*, 1973). Although the initial surface temperature signature of a ring is detectable by infrared measurements, later, as the surface layer is subjected to cooling and heating by atmosphere and sun, the temperature gradients disappear. In addition the Gulf Stream region is frequently cloud covered and this restricts the usefulness of infrared observations. Thus satellite measurements have occasionally provided supplemental ring observations but they cannot be used for long-term ring tracking.

The cold core of a ring extends to at least 3000 m and the currents flowing around the core probably also extend this deep. The density structure of a ring plus its slow change with time suggest that neutrally buoyant floats placed in the upper region of a ring would move in closed circles about the ring center and be carried along as the ring moved. The development of the SOFAR float (Rossby and Webb, 1970; Rossby *et al.*, 1975) provided an instrument with which to attempt the long-term tracking of neutrally buoyant floats in a ring and to investigate its velocity structure.

2. Methods

The SOFAR floats were built at WHOI and tracked acoustically by NAVOCEANO. Their designed life was two years. Float depth at launch was determined acoustically by steering the ship directly over the float; depth error is ±5 m. Float positions were determined once daily with an estimated accuracy of 5 km. Position errors were due primarily to variations of sound speed between float and receiver and from drift of the floats'

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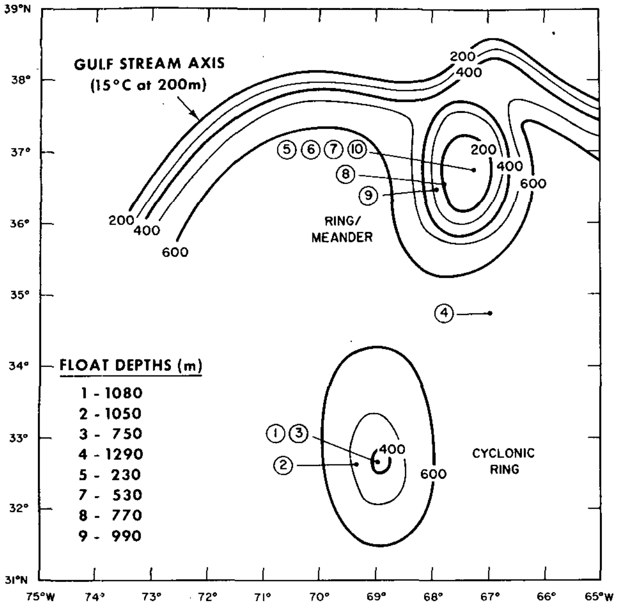


FIG. 1. Initial float positions relative to the cyclonic ring and ring/meander (attached to the Gulf Stream). Contours are 15°C depths (m). Floats 6 and 10 were not tracked.

internal clocks. A correction factor to compensate for the clock drift was calculated from hyperbolic fixes using the time of the received signals at three stations. A different average sound velocity was used for each station; these values were calculated from initial known float positions and travel times and were assumed to remain constant throughout the tracking period.

Although the overall accuracy of a fix is 5 km, the precision or relative error between fixes over short periods (several weeks) is significantly smaller. Movement of the floats is large enough that position errors result in small float velocity errors. For example, an error of 5 km over 400 km gives rise to a velocity error of only 1%.

3. The experiment

During the period 17 September–14 October, 1974, nine SOFAR floats were launched in two Gulf Stream rings and a tenth float was placed in the Sargasso Sea between the rings (Fig. 1, Table 1). Several of the floats were placed near the sound velocity minimum to obtain long-range signal transmission; the depth of the deep sound channel axis varies from about 1300 m in the

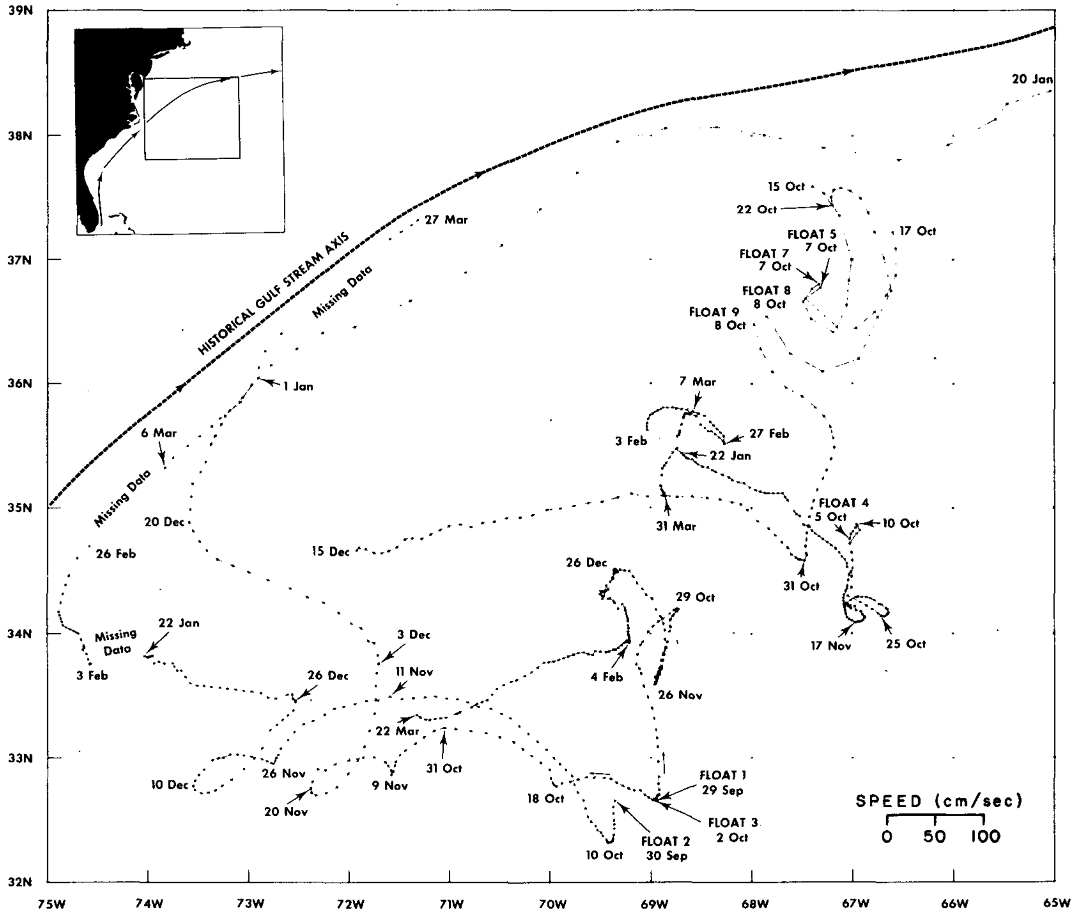


FIG. 2. SOFAR float trajectories during 1974–75. Dots are spaced at 1-day intervals; scale at lower right is proportional to distance moved per day. Floats 5, 7 and 8 were tracked for only 1–2 weeks before being carried eastward in the Gulf Stream.

Sargasso Sea to about 600 m in a new ring. Several additional floats were placed at shallower depths to see if they would stay in the rings longer. Subsequent movement of the floats is shown in Fig. 2. The float trajectories taken together clearly show the northwestern part of the subtropical gyre. The Gulf Stream flows swiftly to the northeast; south of it is located a slower return flow to the west.

a. The southern ring

The first three floats (1–3) were launched in the cyclonic ring centered at 32°40′N, 68°55′W during the period 29 September–2 October. The ring was elliptical with an average diameter (15°C isotherm at 500 m) of 115 km. Size and amplitude of the 15°C surface in the ring at the time of the September survey (Fig. 3) suggest it is about one year old. A salinity anomaly from the mean $T-S$ relation of the Sargasso Sea of 0.1‰ was measured in the ring core above 15°C and is indicative of its Slope Water origin.

During the first two months float 1 (1080 m) drifted north out of the ring, oscillated in a north-south direction and then moved westward. Floats 2 and 3 (1050 and 750 m) moved westward in a pattern resembling the summation of cyclonic rotation and westward translation, thus suggesting that these floats had remained in the ring.

A ship XBT survey in December relocated the ring and confirmed that floats 2 and 3 were in the outer region of the ring, 2.5 months after their initial launch (Fig. 3). From September to December the ring moved 375 km toward the west at an average rate of 6 cm s^{-1}. The December survey revealed that the ring had become bi-modal with two separate centers and that the weaker southern part may have been separating from the dominant northern part. Float 2 was moving along a curved path between the two centers. Float 3, originally placed in the center, had nearly left the ring and was moving westward along its northern edge.

By assuming a uniform rate of movement for the southern ring between its October and December positions, it was possible to subtract the ring's translatory movement from the float trajectories and obtain float motions relative to the ring. The result, for the average ring movement of 6 cm s^{-1} toward 285°T, is shown in Fig. 4. Float 1, placed in the center, drifted away from the center during the first week after launch. During the next 2 weeks this float appeared to be influenced by the ring's counterclockwise circulation but maintained a radial velocity component of 8 cm s^{-1} and left the ring by the end of October. Float 3, also launched near the center, completed a small, cyclonic loop about the center during the first 3 weeks with an average speed of about 3 cm s^{-1}. It then spiraled outward around the ring with speeds of about 11 cm s^{-1} until it was expelled during mid-December, possibly because of the ring's interaction with the Gulf Stream.

TABLE 1. Initial float locations.

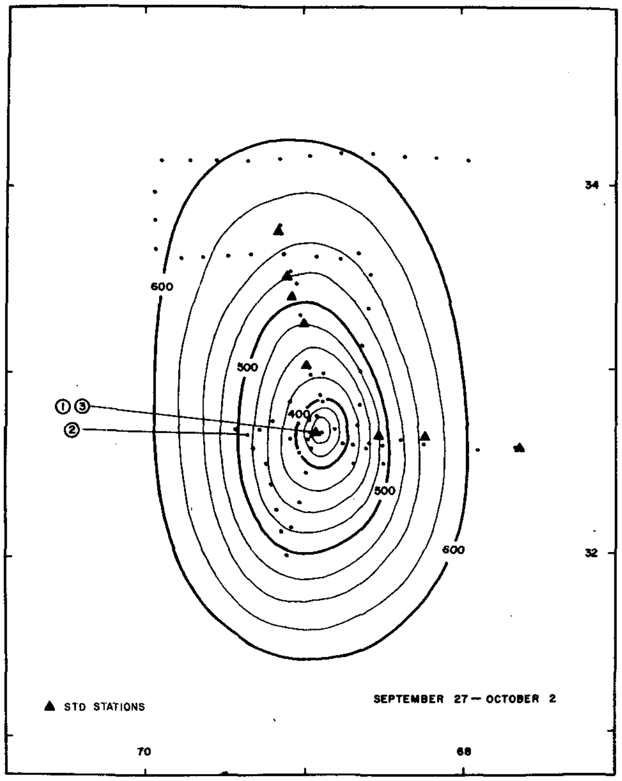
Float no.	Date (1974)	Latitude (N)	Longitude (W)	Depth* (m)
1	29 Sept	32°40′	68°58′	1080
2	30 Sept	32°38′	69°22′	1050
3	2 Oct	32°40′	68°58′	750
4	5 Oct	34°45′	66°59′	1290
5	7 Oct	36°46′	67°19′	230
6	7 Oct	36°48′	67°20′	1130
7	7 Oct	36°48′	67°20′	530
8	8 Oct	36°32′	67°51′	770
9	8 Oct	36°28′	67°58′	990
10	11 Oct	36°50′	67°02′	2100

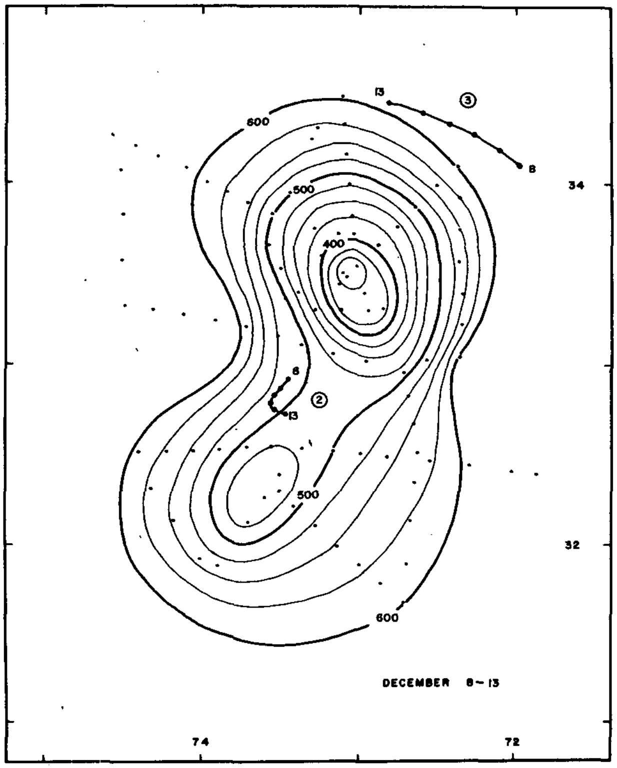
* The depth of floats changed after launch (see text).

Float 2, placed 37 km west of the center, followed a nearly circular path around the ring during the first 2 months and maintained an average speed of 7 cm s^{-1}. It then moved gradually outward and by 11 December was 90 km from the ring center. Both floats 2 and 3 were eventually entrained by the Gulf Stream and moved rapidly to the northeast (Fig. 2). Departures of float trajectories from smooth paths may be caused by real float movement relative to the ring center, by variations of the size and shape of the ring, and by fluctuations of the ring movement about the assumed average velocity. The limited observations make it impossible to reveal which of these is the dominant effect.

Geostrophic currents based on a reference depth of 3500 m were computed along two perpendicular, radial STD sections in the ring. Both surface currents and currents near a depth of 1000 m reached maximum speeds $\sim$80 km from the center. It is difficult to make a detailed comparison between geostrophic currents and float speeds since the floats were constantly changing their distance from the ring center and because their velocities contain both radial and tangential components. General agreement is good, however. Geostrophic speed at a depth of 750 m averaged between the ring center and a radius of 100 km was 12 cm s^{-1}. This may be compared to the average speed of float 3 (750 m) within a 100 km radius, which was about 9 cm s^{-1} with the effects of ring translation removed. At 1050 m the average geostrophic speed was 3 cm s^{-1}, while the corresponding speed for float 2 was 7 cm s^{-1}. A similar comparison for the 1080 m float is probably not valid since its velocity was almost completely radial.

The response of a neutrally buoyant float to vertical and horizontal water motions has been described by Voorhis (1971). For horizontal currents the time for the float to catch up to the current is less than a minute for currents of 1–10 cm s^{-1}. A float responds to vertical water oscillations like a harmonic oscillator with frequency-dependent mass and damping. For slow vertical motions a float moves so as to equilibrate its density with the moving water. Since the thermocline was raised about 300 m in the southern ring, the floats launched at the center experienced a vertical thermocline drop of 300 m as they moved out of the ring. The estimated response of the floats was to move down about 100 m, a descent rate of 1 m day^{-1} for float 3 and 7 m day^{-1} for float 1. Relative to the thermocline, however, the floats rose about 200 m. In addition to changing depth due to water movements, the floats experienced a long-term descent rate estimated to be 0.5 m day^{-1} due to compressional creep. Thus, due to compressional effects and vertical water movement, the floats continuously sampled different water layers.





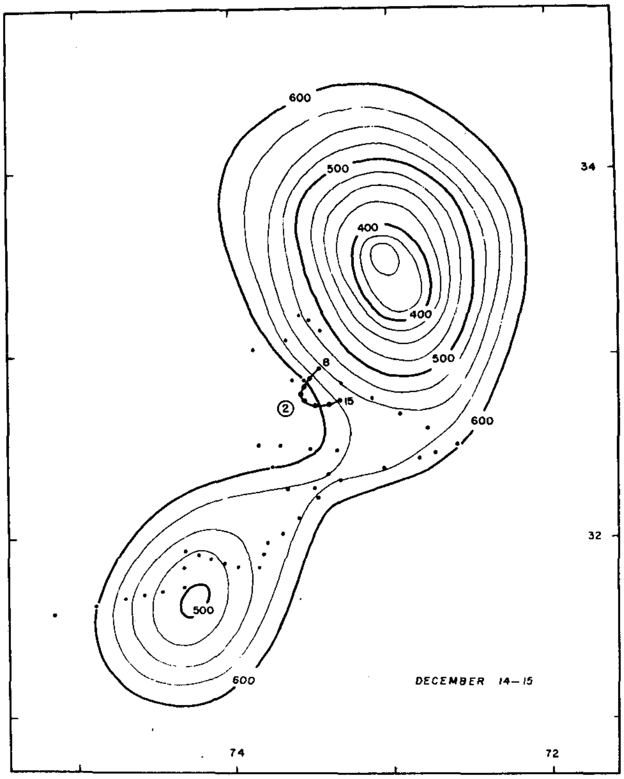


FIG. 3. Sequence showing structure of the southern ring in September and December 1974. Depth (m) of the 15°C isothermal surface is based on ship surveys with 760 m XBT's (represented by dots). Contours are drawn to represent best estimates of size and shape of the ring even in portions where the data are limited or absent. Trajectories of floats 2 and 3 during the December survey are shown; note rapid changes in the ring over a few days.

Movement of the ring over 11 months is shown in Fig. 5. The ring was observed weekly from June to August 1974 from M/S *Sea Venture*, transiting between New York and Bermuda (U. S. Naval Oceanographic Office, 1974). From September to December it was tracked continuously by SOFAR floats. From December to June 1975 it was observed repeatedly by satellite infrared photos and from several ships. The movement agrees with the inferred trajectories of other rings in this area (Lai and Richardson, 1975); it moved west until it encountered the Gulf Stream and then moved southwest.

The results of this experiment show that floats placed at depths of 750–1080 m in a ring come out of it within several months. The radial speeds (1–8 cm s^{-1}) are in the same direction, although much larger, than those

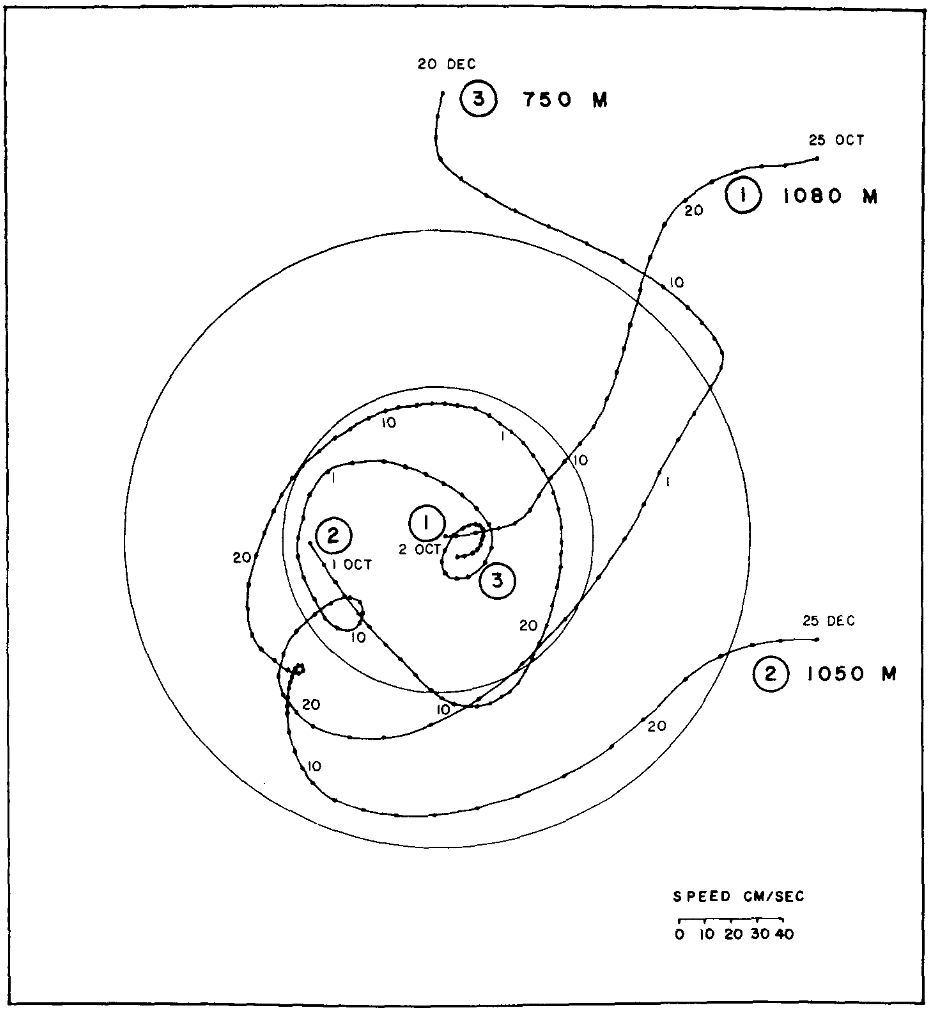


FIG. 4. Trajectories of floats 1, 2 and 3 with the mean translational velocity of the ring (from September to December) subtracted from them. Concentric circles represent radii of 50 and 100 km. Scale at lower right is proportional to distance moved per day.

calculated by Schmitz and Vastano (1975) based on the decay of a ring. In their model radial inflow exists above 600 m and outflow below with speeds of 10^{-2} cm s^{-1}. Lambert (1974) suggested the presence of alternating layers of flow into and out of a ring based on continuous temperature, salinity and oxygen profiles. The layering appeared to be confined to the upper 500 m but the exchange of water may also have occurred below 500 m, where Core Water was indistinguishable from Sargasso Sea Water. The presence of layers moving in different directions could explain the different trajectories of floats 1 and 2 which were launched at nearly the same depth (1080 and 1050 m) and same temperature (5.1 and 5.4°C). Float 1 had a large radial component (8 cm s^{-1}) while float 2 had a smaller one (1–2 cm s^{-1}). Flierl (1975) has modeled a ring which moves, due to the variation of Coriolis parameter with latitude, through an ocean at rest. He predicts that a region is advected with the ring for all depths at which the swirl or tangential speed (V_θ) of water around the ring is greater than the translational speed (U) of the ring. As V_θ approaches U with increasing depth the advected area becomes smaller and its center moves northward toward the radius of maximum V_θ. At depths of 750–1080 m V_θ calculated from the floats and by geostrophy is nearly equal to U of the ring (6 cm s^{-1}). Although the float trajectories differ from Flierl's calculated trajectories there is some similarity of pattern and basic agreement with his conclusion about the advected region. In summary, the float trajectories cannot be explained by any one existing model although there is qualitative agreement with several of them.

There is evidence that floats placed at shallower depths (400–700 m) and near the ring center would remain in the ring longer. Evidence comes from the

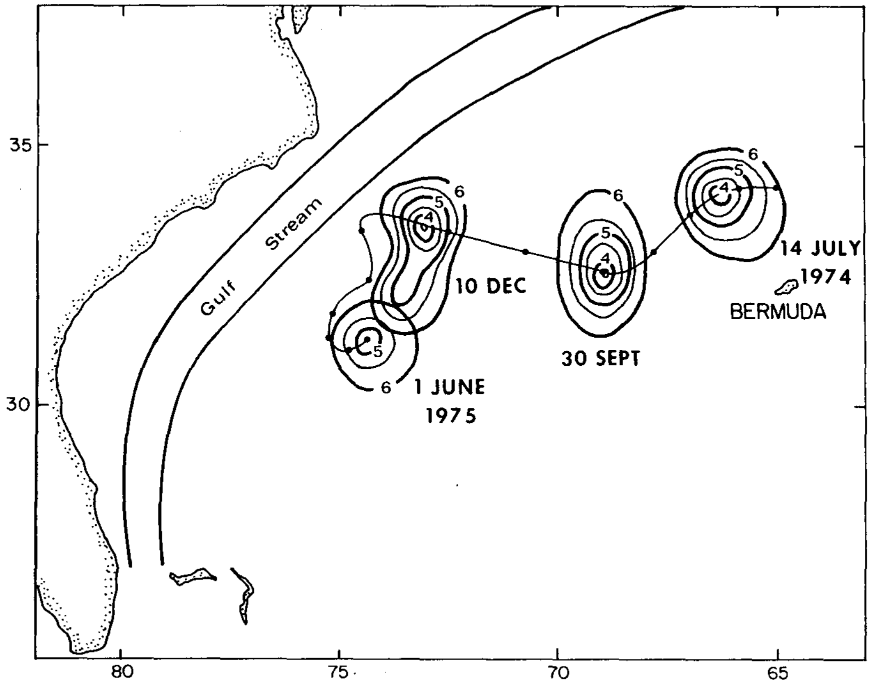


FIG. 5. Movement of the southern ring during 1974–75. Contours represent 15°C depth (in 100 m units) based on XBT surveys. (July, M/V *Sea Venture*; September, USNS *Lynch*; December and June, R/V *Trident*). Dots represent the ring position at the beginning of each month from June 1974 to June 1975 as inferred from satellite data, XBT's from ships of opportunity, and the SOFAR floats. Average velocity over the period shown is 3 cm s^{-1} toward the southwest.

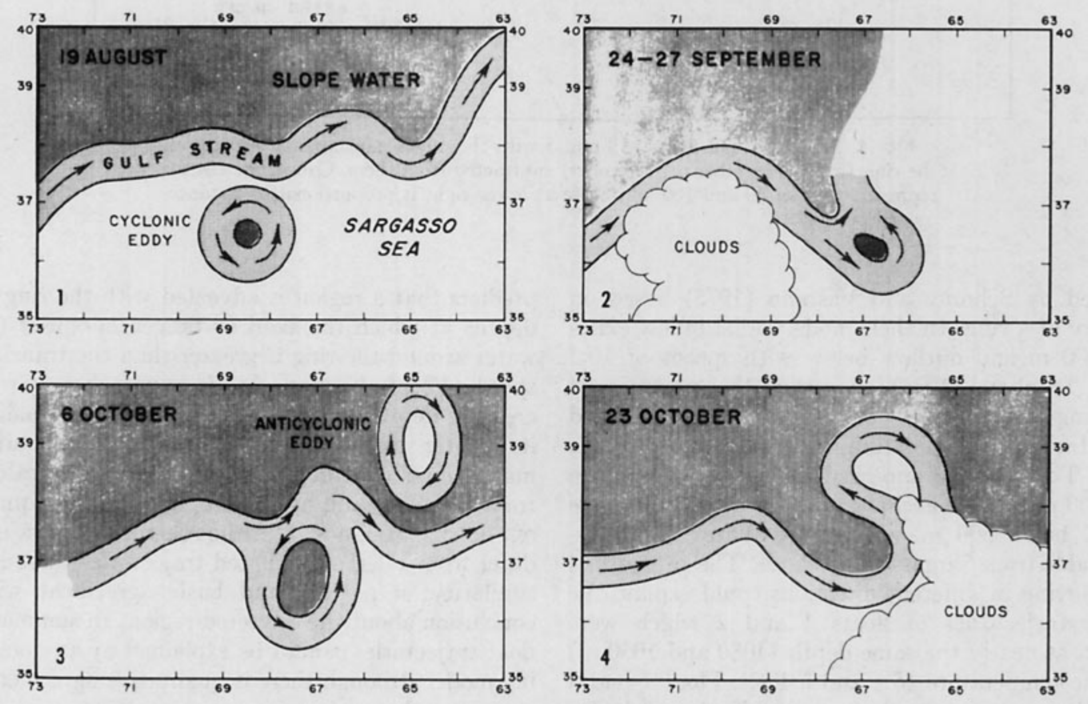


FIG. 6. Life cycle of a ring formed in June 1974. It was surveyed with shipboard XBT's in August and again in September, when it was found to have coalesced with the Gulf Stream. During a subsequent ship survey on 6 October a new ring appeared to be forming but coalesced completely with the Stream by the end of the month. An anticyclonic ring which had been moving to the west may have also coalesced during the same period. Shipboard data were supplemented by satellite infrared imagery.

anomalous $T-S$ relation in rings and models of ring velocity. The upper region of a newly-formed ring, warmer than 10°C, retains $T-S$ characteristics which are indicative of Slope Water. The salinity anomaly of a ring (anomaly from the mean $T-S$ relation in the Sargasso Sea) slowly diminishes throughout the life of the ring. The anomaly of older rings is located above the 10°C surface which is at depths of 300–500 m. The long persistence of the $T-S$ anomaly suggests that it is advected along with the ring. Second, the calculated radial velocity in a ring (Schmitz and Vastano, 1975) is inward above 600 m and implies that shallow floats tend to be retained. Third, the model of Flierl (1975) predicts that a float will have a better chance of being carried along with a ring when placed in the upper several hundred meters, where the high tangential velocity is located.

b. The northern ring

The northern ring was first observed at 37°25′N, 67°15′W on 14 June 1974, probably within a few days of its formation. This ring was created after an older cyclonic ring coalesced with the Gulf Stream in May; the resulting meander separated from the Stream to spawn a new, rejuvenated ring. Observations of this event consist of aircraft XBT surveys in April and June (Gotthardt and Doblar, 1974) and daily satellite infrared imagery. Several XBT sections through the new ring were obtained from M/S *Sea Venture* during June and July (U. S. Naval Oceanographic Office, 1974) and in August 1974 a complete XBT survey was made by Peter Wiebe aboard R/V *Atlantis II*. By 19 August the ring had moved 150 km southwest to 36°30′N, 68°30′W. However, in late September a thorough XBT survey from USNS *Lynch* revealed that the ring had become reattached to the Stream, forming a partially closed "ring/meander" at 67°W (Fig. 6). When ship and aircraft XBT surveys in early October suggested that the ring/meander was pinching off to form a new ring, similar to the process observed the previous May, six floats were launched in it. Subsequent satellite measurements and a shipboard XBT survey by P. Wiebe on 20 October indicated that the ring never completely separated from the Stream. By the end of October the ring had completely merged with the Stream and had formed a large open meander.

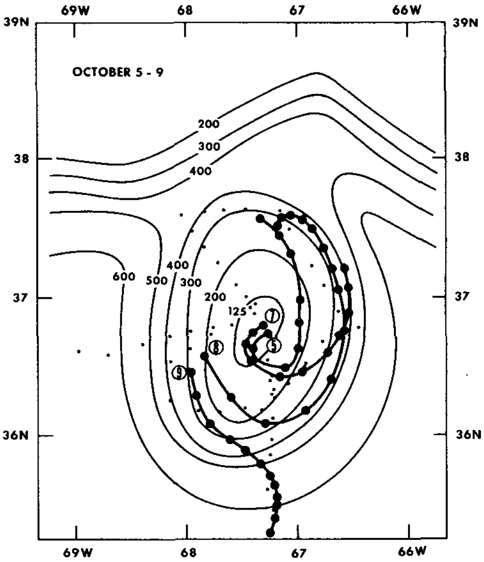


FIG. 7. SOFAR float trajectories in the northern ring. Contours are depths (m) of the 15°C surface. 760 m XBT observations are indicated by dots. Float tracks begin on 7 and 8 October; each large dot represents 1 day. Floats 5, 7 and 8 subsequently moved east with the Gulf Stream and could not be tracked. Contours of the Gulf Stream are based on satellite infrared imagery on 5 October.

Float trajectories and a detailed picture of the ring/meander are shown in Fig. 7. During the first few days the floats followed the cyclonic flow and moved at speeds of 20–40 cm s^{-1}. Three of the floats (5, 7, 8) moved around the ring/meander and then apparently were swept eastward in the Gulf Stream. Although signals from floats 5, 7 and 8 became steadily weaker in October and positions could not be determined, the data clearly showed them to be moving rapidly eastward by the end of the month. One float (9) at 990 m moved south out of the ring/meander and then west at 11 cm s^{-1}; it ceased transmitting in mid-December.

TABLE 2. Float velocity summary.

Float	Depth (m)	Dates*	Average speed** Standard deviation*** (cm s^{-1})	Average velocity** Speed (cm s^{-1})	Direction (°T)
a) Ring floats					
2	1050	30 Sept–22 Jan	8.3 (3.7)	4.6	287
3	750	2 Oct–15 Dec	10.6 (5.4)	6.9	299
b) Sargasso Sea floats					
1	1080	1 Nov–22 Mar	4.7 (2.7)	2.1	248
4	1290	5 Oct–31 Mar	4.7 (2.3)	1.1	283
9	990	1 Nov–15 Dec	11.2 (4.0)	10.6	271

* Dates used to calculate averages.

** Values for ring floats include ring translation.

*** Given in parentheses.

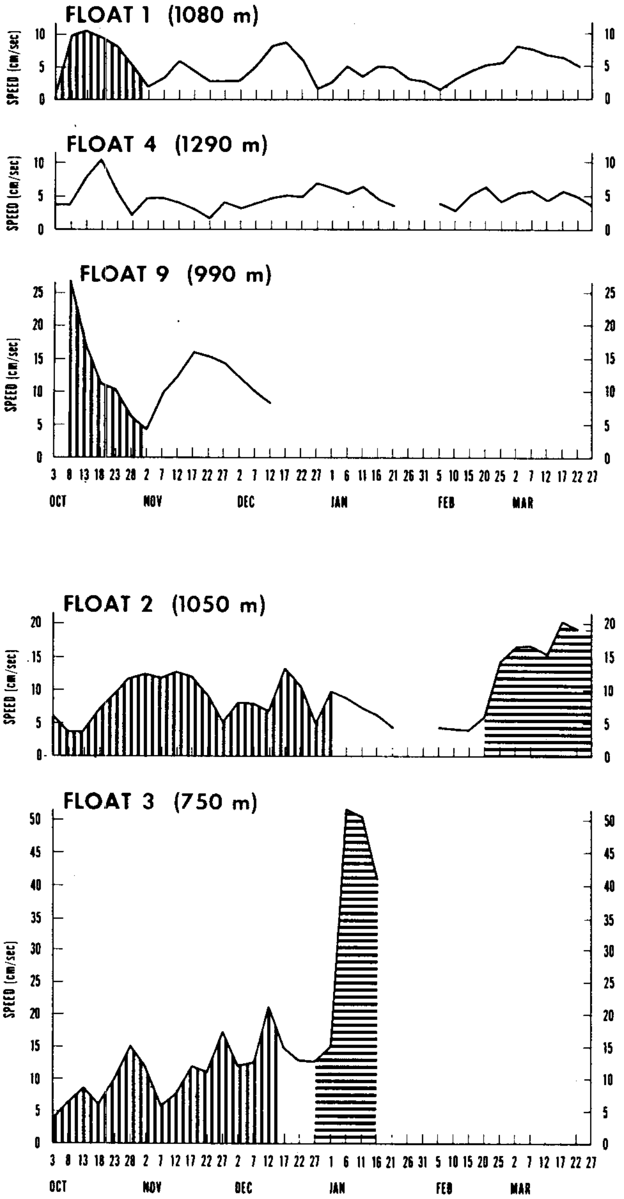


FIG. 8. Mean speeds (5-day averages) of floats in the Sargasso Sea (1, 4 and 9) and two floats which remained in the southern ring for 2.5 months (2 and 3). Vertical shading indicates periods when floats were in rings, horizontal shading represents Gulf Stream, unshaded portions are in the Sargasso Sea.

Two floats (6, 10) ceased transmitting shortly after launch and were not tracked.

c. *Sargasso Sea floats*

In order to obtain some information about the movement of floats outside of the rings one float was launched on 5 October between rings in the deep sound channel at a depth of 1290 m. By November two additional floats had moved out of rings into the Sargasso Sea. Float 1 (1080 m) had moved north out of the southern ring and float 9 (990 m) had left the ring/meander and moved south. By November these three were within 175 km of each other and separated vertically by less than 300 m.

Although the trajectories of the three floats show little visual coherence they all display an average westward velocity (Fig. 2, Table 2). The magnitudes of the average velocity of floats 1 and 4 were 2.1 and 1.1 cm s^{-1}. Float 9, the shallowest of the three, moved significantly faster (10.6 cm s^{-1}) than the other two and almost due west; it was approaching the Stream when it failed. Its average velocity was calculated over a 1.5-month period which included a large burst of speed (Fig. 8) and thus it may overestimate a longer term mean. If, however, we assume that float 9 gives a valid representation of the velocity field at its depth, there appears to be an abrupt decrease of velocity with depth both inside and outside of rings (Fig. 9). The decrease coincides with the bottom of the main thermocline (6°C).

The observed variations of the float trajectories result in large uncertainties associated with the calculated means (Table 2). Longer trajectories and larger number of floats would be required to make a more accurate estimate of the long-term mean velocity field. All three trajectories do have a net westward component which suggests that a westward flow is characteristic of this location and time. There is a similarity of the movement of rings in this region and the movement of floats outside of rings at depths of 1000–1300 m. The existence of the westward velocity agrees with the circulation diagrams of Worthington (1976). However, the floats also exhibit large meridional excursions, suggesting perturbations superimposed on the mean flow.

The fluctuations of speed of the floats is shown in Fig. 8. There is a slight decrease of speed as floats moved out of the ring (floats 1 and 2) and a large increase as they moved into the Gulf Stream (floats 2

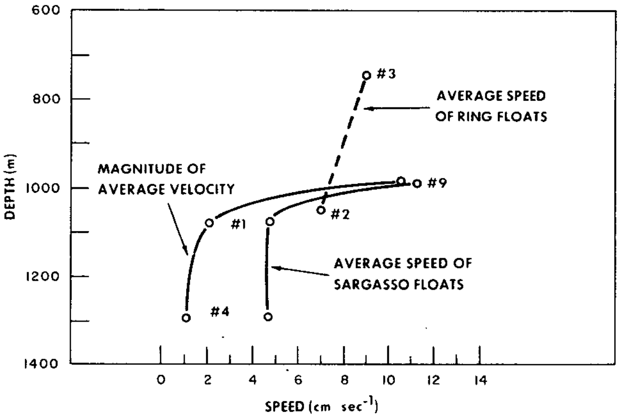


FIG. 9. Magnitude of the average velocity and average speed plotted versus depth for three Sargasso floats and two ring floats. Data are taken from the period 1 November–22 March for float 1, 5 October–31 March for float 4, and 1 November–15 December for float 9. Values for the ring floats are within 100 km of center with ring translation subtracted.

and 3). The two floats which were outside of rings and the Gulf Stream the longest (floats 1 and 4) moved with nearly the same average speed; there appears to be little long-term trend to the curves, suggesting stable statistics.

4. Conclusion

The overall pattern revealed by these float trajectories is dramatic in that it clearly shows the subtropical gyre in the northwestern Sargasso Sea. In the north is the swift, narrow Gulf Stream, while the southern region consists of a relatively broad and slow westward flow. Evidence for the westward movement comes from the movement of floats in the southern ring and also the three floats outside of the rings.

The northern ring/meander was involved in a complex succession of events. First, an older cyclonic ring coalesced with the Gulf Stream in May 1974, formed a large meander, and spawned a new ring in June. This ring was observed repeatedly during summer as it moved 150 km southwest. However, in September the ring again coalesced with the Gulf Stream and in early October appeared to reform another new ring. It finally merged completely with the Gulf Stream and formed a large, open meander at the end of October.

Since the floats in the northern ring were swept eastward by the Gulf Stream and could only be tracked for two weeks, our major findings were in the southern ring. One float, launched at 1080 m, drifted out of the ring after only three weeks while maintaining an average radial speed of 8 cm s^{-1}. The other two floats at 750 and 1050 m remained in the southern ring for 2.5 and 3 months before being entrained by the Gulf Stream. These two floats thus provided a continuous record of the ring's movement and ensured that the rings surveyed in October and December 1974 were one and the same. This experiment has demonstrated that SOFAR floats can be used to track Gulf Stream rings remotely for periods of a few months. Observations of the float trajectories within the translating ring provide evidence of considerable transfer or mixing of water through a ring at these depths and indicate that it may be necessary to periodically replace floats in rings if these features are to be tracked throughout their lifetimes by this method.

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