The Physical Structure and Life History of Cyclonic Gulf Stream Ring Allen

P. L. RICHARDSON[1]

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543

C. MAILLARD

Centre Océanologique de Bretagne, Département de Physique, 29 Plouzané, France

T. B. STANFORD

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543

A cyclonic Gulf Stream ring, Allen, was followed over its life from September 1976 to April 1977 in the region north of Bermuda. Conductivity, temperature, and depth; expendable bathythermograph; and velocity profile measurements were made in Allen, and over the last 5 months of its life, satellite buoys were used to track continuously its movement. The measurements indicate that in December 1976 Allen split into two rings, a large one, Allen, and a small one, Arthur. Arthur moved rapidly eastward and coalesced with the Gulf Stream near the New England seamounts. Allen moved in a large clockwise loop; at the end of February 1977 it became attached to the Gulf Stream and reformed into a modified ring, smaller in size and faster in rotation. At the end of April 1977 the modified ring coalesced with the Gulf Stream and disappeared as it was advected downstream in the stream. The principal results of this study are that (1) the New England Seamount chain was a major influence in the genesis of Allen and on the trajectories of nearby rings; (2) while a free eddy, months after its formation, Allen evolved into a bi modal or peanut-shaped structure; (3) the bimodal structure ultimately bifurcated, spawning a new isolated eddy, denoted as Arthur, and a modified remnant, Allen; (4) the velocity field of Allen involved the whole water column, with bottom velocities of 10–15 cm s^{-1}; (5) the barotropic velocity at the center of Allen (6 cm s^{-1} to NNW) was about equal to its translation velocity (4 cm s^{-1} to NW); (6) especially energetic inertial motions were seen at the center of Allen, and these may play a role in enhancing the stirring of water properties; (7) Allen survived several close encounters or entrainments with the Gulf Stream, proving that such encounters can be nonfatal to a ring; (8) the encounters appear to result in injections (exchanges) of water (momentum, heat, etc.) into the rings at an estimate rate of 10^6 m^3 s^{-1} per ring; and (9) the behavior of Allen and Arthur was in contrast to the results of some other studies which have shown that rings generally drift slowly and passively southwestward.

INTRODUCTION

In December 1976 the Ring Group, an interdisciplinary group of scientists from several institutions, began a study of cyclonic Gulf Stream rings. The plan was to find a newly formed cyclonic ring, to follow it over its life, and to make measurements of its physical, chemical, and biological characteristics and their changes with time. The motivation for the experiment was (1) to obtain basic descriptive data of rings in an attempt to understand their behavior and decay and how they fit into the general ocean circulation, (2) to obtain data with which to develop and test models of rings, and (3) to study a traceable water mass and to attempt to understand how physics, chemistry, and biology interact within it.

Cyclonic rings are formed from large meanders of the Gulf Stream and consist of a central core of slope water surrounded by a ring of Gulf Stream water [*Fuglister*, 1972]. A ring is an energetic phenomenon and one in which a strong contrast in water properties exists. Although rings have been frequently observed [*Parker*, 1971; *Lai and Richardson*, 1977] and attempts have been made to follow them, there has been only one study [*Fuglister*, 1977] in which a ring was positively followed. Fuglister followed the ring by tracking drifting buoys with a ship, and over a 5-month period, he repeatedly measured the ring's physical structure. The results of Fuglister's study (which suggested a buoy would stay in a ring for long periods of time) plus the development of satellite-tracked surface buoys, provided a relatively inexpensive system to remotely track a ring [*Richardson et al.*, 1977]. In the present study we used these buoys to track rings and a series of interdisciplinary cruises spaced at intervals of about 3 months to make detailed measurements of the ring's characteristics. Additional cruises on a ship-of-opportunity basis were used to obtain complementary physical data.

From September 1976 to September 1977 two rings were followed. This paper describes the physical measurements of the first ring, named Allen, which formed in September 1976. It coalesced with the Gulf Stream in April 1977 and was lost. The main observations of the ring were listed in Table 1 and are described in detail in subsequent sections.

Four cruises visited ring Allen from October 1976 to April 1977. The first was *Knorr* 60 in October, the second was *Knorr* 62 in December, the third was *Knorr* 63 in January, and the fourth was *Knorr* 65 in April. The most complete data set was taken on *Knorr* 62. For this cruise the physical oceanography program consisted of two expendable bathythermograph (XBT) surveys of the ring; a conductivity, temperature, and depth (CTD) section; velocity and microstructure profiles; and free drifting buoy trajectories. The following three data reports describe the measurements in detail: *Dunlap et al.* [1978], *Richardson et al.* [1979], and *Schmitz et al.* [1977]. A series of chemical samples and biological net tows and trawls were also made but will not be discussed here.

[1] Presently visiting Laboratoire d'Océanographie Physique, Muséum National d'Histoire Naturelle, 43 rue Cuvier, Paris, France.

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TABLE 1. Observations of Ring Allen

Observation	Date	Comments
Satellite IR	Sept. 4–21, 1976	Formation of large Gulf Stream meander
Satellite IR	Sept. 26, 1976	Meander pinched off to form ring Allen
Knorr 60	Oct. 1, 1976	XBT section across newly formed ring
AXBT survey	Dec. 1–3, 1976	Located double ring structure
Knorr 62	Dec. 1–23, 1976	First interdisciplinary cruise to ring, XBT surveys, CTD sections, four buoys launched
Satellite buoys	Dec. 4, 1976 to May 1, 1979	Followed movement of ring
Knorr 63	Jan. 5, 1977	XBT section across ring
Knorr 65	April 24–25, 1977	Second interdisciplinary cruise, short XBT survey

EARLY HISTORY

The evidence for the formation and early history of the ring comes mainly from NOAA's satellite infrared (IR) data. Because we do not have positive information about the movement of the ring until December 1976 when we launched the buoys, the following must be viewed as our best estimate of what occurred. During September 1976 a large Gulf Stream meander deepened by moving southeastward. On September 21 it had reached a position along 37.5°N from 63° to 66°W (Figure 1). This meander seemed unusually long and narrow as compared to others that we have seen; its position parallel and just west of the New England Seamount chain suggested the seamounts may have had an effect on the path of the stream at that time. By September 26 the meander had apparently formed a ring. Although the ring could not be detected by IR data, the Gulf Stream could be seen northwest of the earlier meander. It seems unlikely that such a large meander could have disappeared within a 5-day period without its having formed a ring. October through January were very cloudy in this region, and little of the ocean surface could be seen with the IR data. On October 1, however, an XBT section (*Knorr* 60) traversed the area, and a ring was observed near 37°N 64°W. Two other XBT sections were made in October, one north of the ring and one south of it along 35°W (Vernadsky); neither detected the characteristically raised thermocline structure of a ring in the region between 60° and 70°W.

On December 1–3 the U.S. Naval Oceanographic Office made an AXBT survey over the region to assist us in locating a suitable ring to study. The survey extended from 33°–37°N and 58°–70°W (Figure 2). A large double ring was observed just south of the location where the large meander was seen 2 months earlier. The evidence suggests that this ring is probably the same one which formed during the last part of September. The AXBT survey also showed that no other intense rings were in the vicinity which implied we had not been confused by an adjacent ring. The one additional ring, Valentine, which was observed near 38°N, 59°W, was first observed near 37.7°N, 58.5°W on October 25 (*Knorr* 60) and subsequently by a second AXBT survey on January 15–16, 1977 [*Potocsky and Kerling*, 1977]. Throughout the period from October 25, 1976, to January 15, 1977, the position of ring Valentine was measured by satellite buoy, and this ring did not move far.

THE MOVEMENT OF THE RINGS

In December on *Knorr* 62 we made a detailed XBT survey of the ring (Figure 3). The ring, which was peanut-shaped, consisted of a relatively intense western ring, which we named

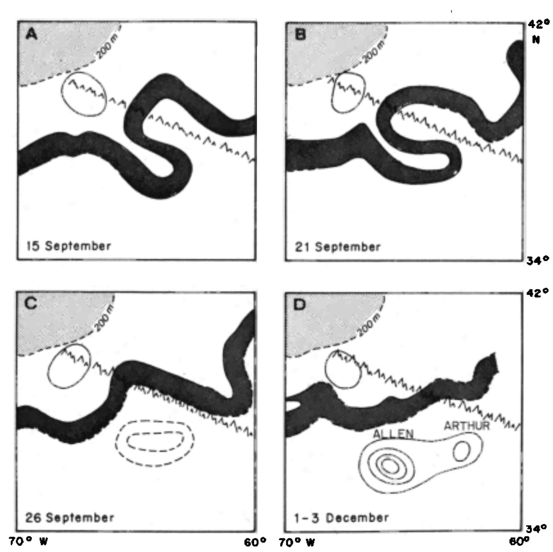

Fig. 1. Formation of ring Allen as observed by satellite infrared imagery and XBT data during 1976. Solid lines in panels (*a*–*c*) are surface fronts observed on NOAA satellite images. Dashed curves are inferred from continuity. The contours in rings Allen and Arthur in December are drawn from XBT data. The approximate location of the New England Seamount chain has been added.

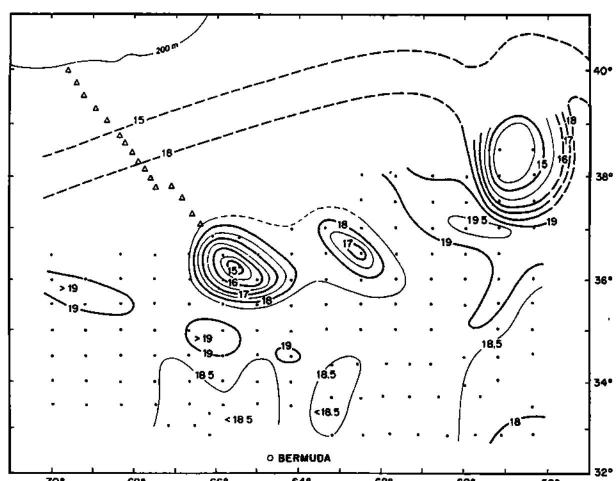

Fig. 2. Temperature at 300 m as measured by an AXBT survey conducted by the U.S. Naval Oceanographic Office, December 1–3, 1976. A line of XBTs taken on *Knorr* 62 during the same period is shown in the upper left (open triangles). The path of the Gulf Stream was inferred from satellite infrared imagery. Two large Gulf Stream rings can be seen. The first is a double ring (Allen and Arthur) located near 36.5°N and extending from 62°–67°W; minimum temperature is 14.8°C. The second ring (Valentine) is attached to the Gulf Stream near 38.5°N 59.0°W and has a minimum temperatue of 14.3°C. A warm band of water, 19°C, lies adjacent to both rings.

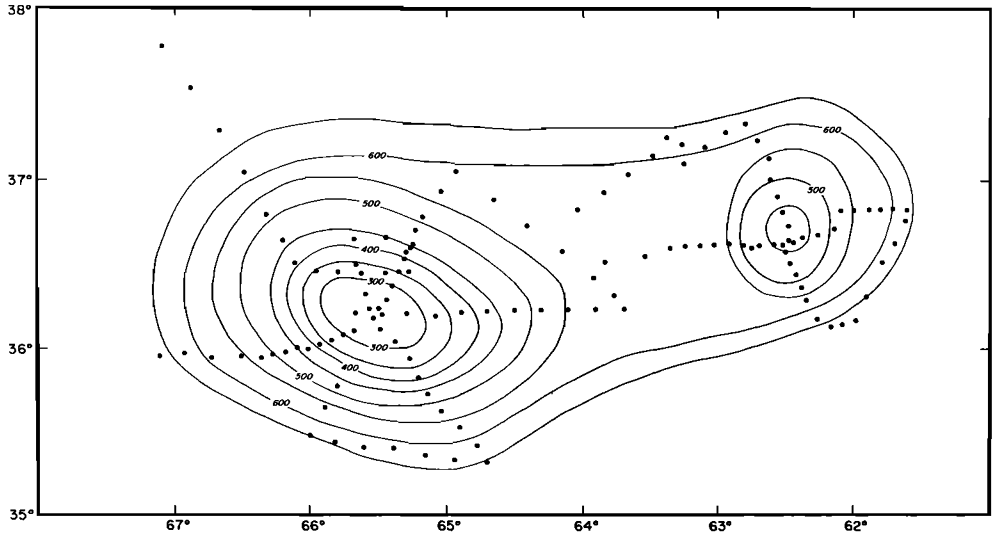

Fig. 3. Depths of the 15°C surface from the *Knorr* 62 XBT survey, December 2–16, 1976. The ring is peanut shaped with a dominant western part, Allen, and a weaker eastern part, Arthur. The XBT survey was made as the two parts were separating.

Allen, and a weaker eastern part, Arthur. The names were given to assist us in differentiating the several rings we have studied.

The size of the double ring was large. Along the major axis the overall distance across the rings, defined by the intersection of 15°C isotherm and 650-m depth, was 500 km. The respective diameters of the individual rings Allen and Arthur were 165 km and 65 km on the basis of the intersection of the 15°C isotherm and 500-m depth (Table 2).

The data clearly indicate that in December the two rings were connected. By connected we mean that the depth of the main thermocline was shallower between rings than it was on the outside edge of the rings. The implication was that the geostrophic velocity field had a significant part which circulated around the entire double ring structure.

During December and January the two rings, which were tracked by satellite drifters, completely separated. Our conclusion is that rings Allen and Arthur were formed from the same ring which was splitting into two pieces during December. The evidence consists of (1) the large oblong meander formed in September 1976 which lay in an east-west direction near the location of the double ring which was also oriented in an east-west direction in December; (2) the overall sizes of the large meander and double ring are approximately equal; (3) the rate of separation in December suggests the two rings could have begun to form 3–4 weeks before the December survey; (4) the CTD section data indicate that temperature perturbations extended to the sea floor under both rings, suggesting both rings were young; and (5) the TS relation in the center of Arthur matches that of the high velocity part of Allen.

BUOY TRAJECTORIES

Four satellite-tracked free-drifting buoys were launched in the rings, three in Allen (0125, 0215, and 0264) and one in Arthur (0162). The mean movement of the rings (Figure 4) was inferred from the characteristic looping motion of each buoy about the ring center. The buoys were tracked by NASA by means of a Doppler-shifted radio signal received by the Nimbus F satellite. Typically, two good positions were obtained

TABLE 2. Ring Summary

Ring/Cruise	Minimum 15° Depth, m	Diameter, km 15° at 500 m	Diameter, km 15° at 650 m	Comments
Knorr 60				
(Oct. 1, 1976)				
Allen/Arthur	180	145	290	Location of ring center and shape not known
Knorr 62				
(Dec. 2–3, 1976)				
Allen/Arthur	275		500	Along the major axis
Allen	275	165		
Arthur	440	65		
Knorr 63				
(Jan. 5, 1979)				
Allen	310	120	210	
Knorr 65				
(April 23, 1977)				
Allen	275	50		Allen was moving rapidly and coalescing with the Gulf Stream

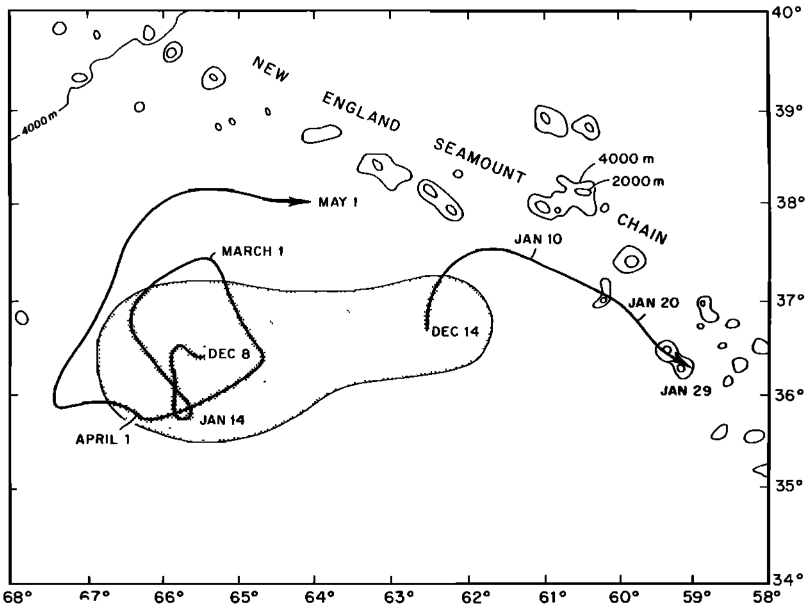

Fig. 4*a*. Trajectories of rings Allen and Arthur inferred from free drifting buoys. The shaded area indicates temperatures colder than 15°C at a depth of 600 m during the XBT survey December 2-16, 1976.

each day, 12 hours apart, and the accuracy of a position is estimated to be 1-2 km.

Ring Arthur

Arthur moved rapidly (10 cm s^{-1}) eastward and over the New England Seamount chain. In January 1977, as Arthur passed over a seamount whose minimum depth was 2125 m, buoy 162 made one last loop and moved eastward in the Gulf Stream (Figure 5). As Arthur moved eastward, buoy 162 looped for 46 days with a mean period of 3.8 days and a radius of 20 km (range 10-30 km). During the second week in January as Arthur was translating at its fastest rate (20 cm s^{-1}), the loops became smaller (10-km radius), and the period decreased to 2.8 days. As Arthur passed over the seamount the loops increased in radius (to 30 km), and the period increased to 3.7 days. Buoy 162 left the ring and moved eastward after January 30, 1977.

By early January 1977, ring Arthur had come in contact with the Gulf Stream and was advected rapidly eastward in it. The evidence consists of two buoys that were moving eastward in the Gulf Stream at this time; one became entrained into the remains of ring Arthur just as buoy 162 was detrained from the ring. The second buoy passed just to the north of Arthur and continued eastward in the stream. By the end of January, Arthur had partially merged with the stream forming a ring/meander in the vicinity of the seamounts. Evidence from three additional buoys suggests that the Gulf Stream formed a semipermanent ring/meander along the seamounts from January to at least August 1977. Frequently, as one buoy was detrained from the ring and swept away in the stream, another buoy was entrained into the ring and began the looping motion characteristic of a ring.

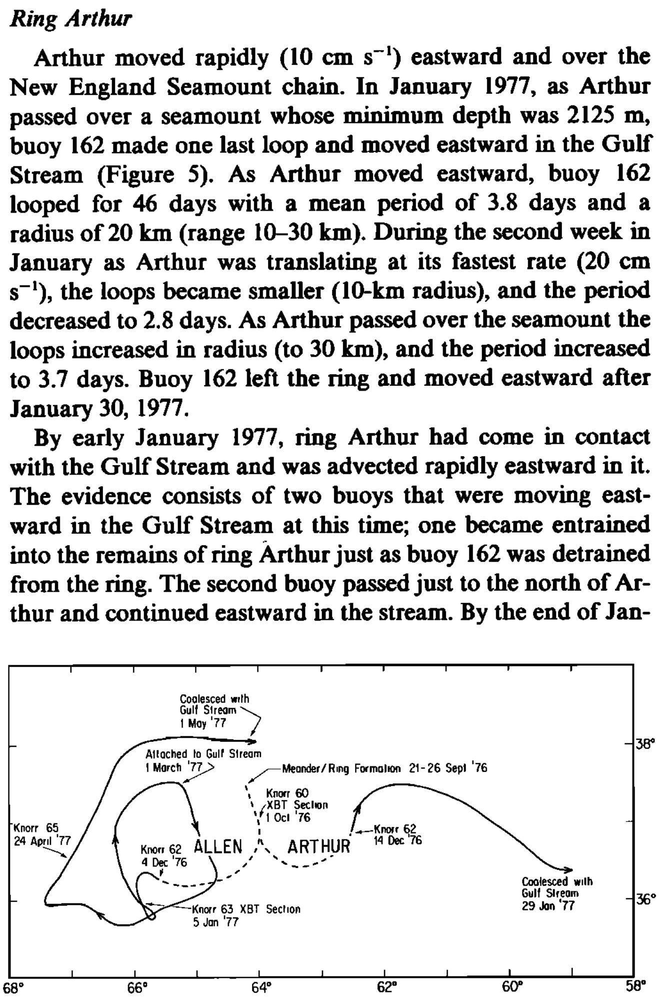

Fig. 4*b*. Schematic diagram showing the life history of rings Allen and Arthur.

Ring Allen

Ring Allen moved first in a small counterclockwise loop and then a large clockwise loop; it never translated far from its early December position (Figure 6). During the clockwise loop, as Allen reached its northerly limit at the end of February, it became attached to the Gulf Stream and reformed as a modified ring, smaller in size but with a faster rotation rate (Figure 7). After reforming, Allen moved southward, then westward, and collided with a ring/meander (Bob) which was moving eastward (Figure 8). By May 2, Allen had become attached to this meander, accelerated northeastward in the stream, and disappeared. Buoy 215 which had been in Allen moved eastward in the stream and was entrained into ring/meander Arthur as described above.

Buoy 215 was launched in Allen in December 1976. During the first 2 weeks it moved radially outward (radial speed 2 cm s^{-1}) until it reached a radius of 35 km (period 5 days, swirl speed 51 cm s^{-1}) which it and the other two buoys seemed to prefer. This radius is located within a strong salinity anomaly in the upper 200 m and within the radius of the maximum swirl speed (60 km) of Allen.

At the end of February, Allen became attached to the Gulf Stream. At this time satellite IR data showed the northern edge of the stream and a newly formed ring, Bob [*Doblar and Cheney*, 1977], located 400 km to the westward of Allen. Although Allen cannot be seen with the IR data a small meander can be seen extending toward the center of Allen on that date (Figure 7). Since the width of the stream is approximately 100 km in regions away from rings, the stream must have encompassed Allen at that time. On February 21, buoy

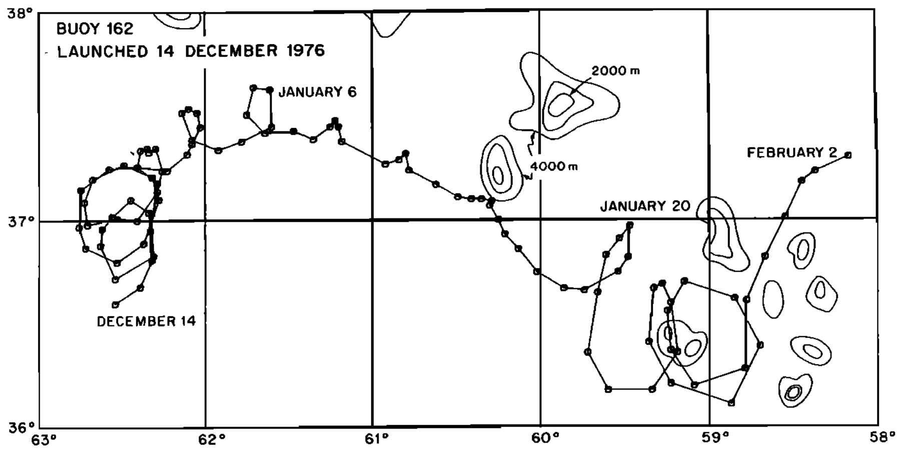

Fig. 5. Trajectory of buoy 162 launched in ring Arthur on December 14, 1976. Two positions per day are shown. Arthur became attached to the Gulf Stream and moved eastward over the New England seamounts. Observations from six buoys suggest that Arthur remained near the seamounts as a ring/meander until at least August 1977.

264 ceased looping around Allen and moved eastward near the offshore side of the stream. Buoy 215 remained in Allen, looping and translating eastward presumably under the effect of the stream, and on March 4 buoy 215 moved away from the stream. By March 4 the trajectory of buoy 215 had changed; the period of rotation decreased from 5.0 to 2.0 days, and the radius changed from 35 to 20 km. From March 4 to April 19, as Allen moved southward then westward, buoy 215 gradually moved radially outward from 20 to 30 km, and its period increased from 2.0 to 3.5 days.

In April 1977, as Allen was coalescing for the final time, we made a short XBT survey of it (Figure 9). Allen was considerably smaller than it had been during the December and January visits. In April the minimum 15° depth was 275 m, and the diameter of the 15°C intersection with 500 m was estimated to be 50 km. Because Allen was so small and moving rapidly, we probably would not have been able to find it without the positions of buoy 215 which were sent to us at sea. More small rings like Allen may exist, but because of their small size they remain undetected.

As Allen coalesced with the stream and was advected downstream, buoy 215 decreased its period of rotation from 3.5 to 1.5 days and decreased its radius from 30 to 15 km. Because of the rapid translation rate, 75 cm s^{-1}, the last two loops only appear as loops when the translation is subtracted

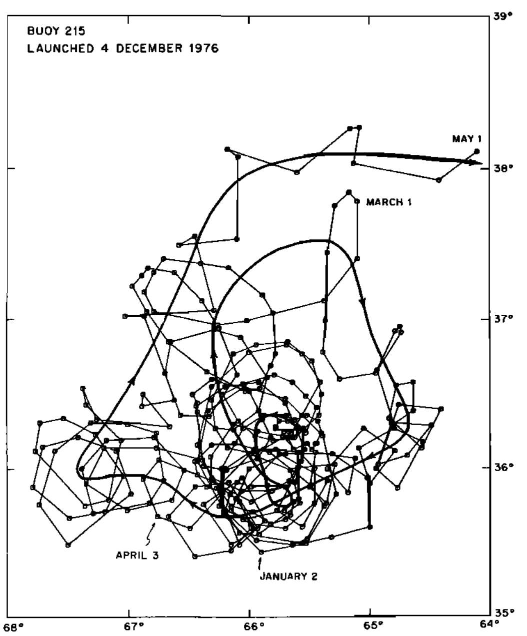

Fig. 6*a*. Trajectory of buoy 215 launched in ring Allen on December 4, 1976. Two positions per day are given. The movement of Allen is shown by the heavy curve; the dominant movement is a large clockwise loop.

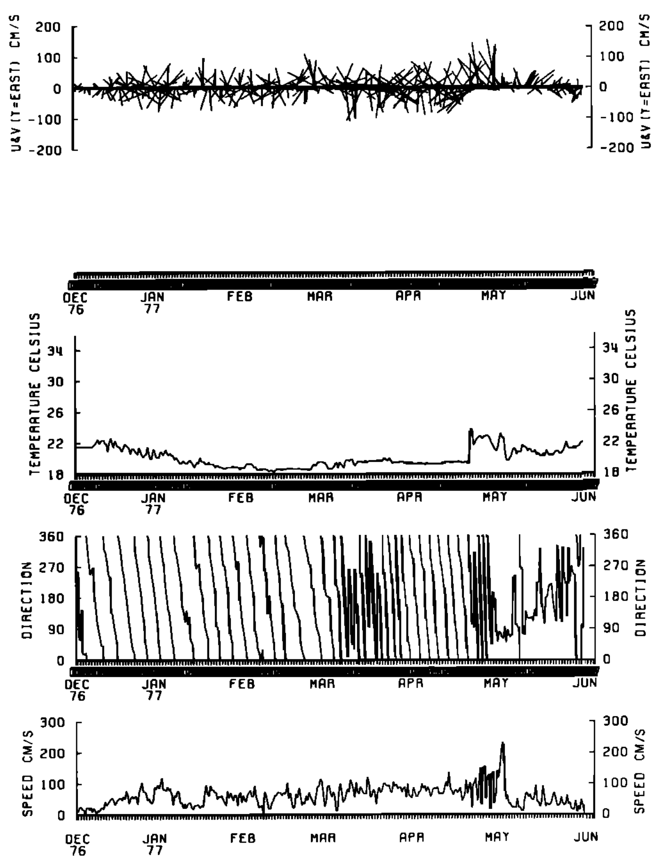

Fig. 6*b*. Velocity, temperature, speed, and direction along the trajectory of buoy 215. The rotation rate can be seen in the direction series; the rate changed when Allen interacted with the Gulf Stream at the end of February and again at the end of April when Allen coalesced with the stream.

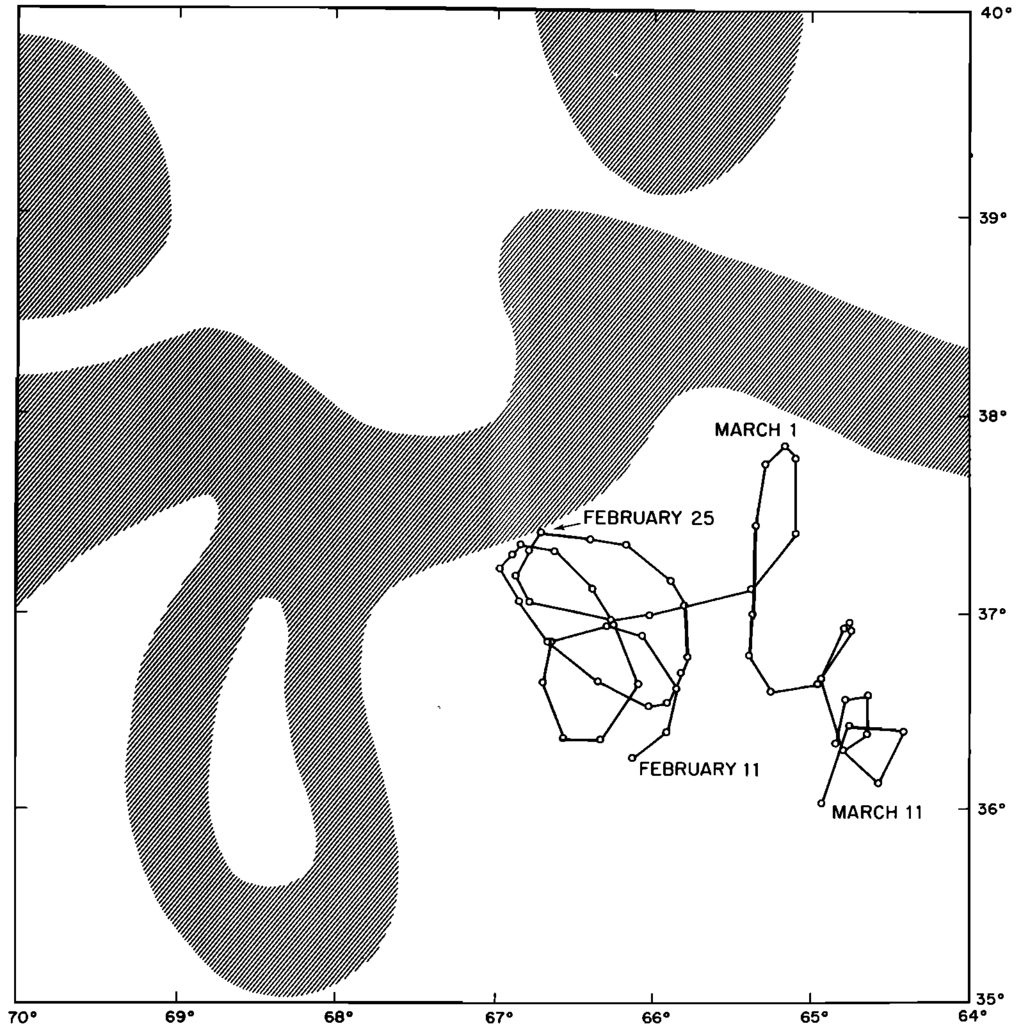

Fig. 7. Trajectory of buoy 215 in ring Allen and a nearly instantaneous picture of the Gulf Stream and rings as seen on satellite infrared images. February 26–27, 1976. Two warm rings are located north of the stream. A cyclonic ring, Bob, is in the process of splitting off from the Gulf Stream [see *Doblar and Cheney*, 1977]. Ring Allen moved northward, became attached to the Gulf Stream, and reformed with a smaller diameter and faster rotation rate.

from the trajectory. The looping motion continued at least until May 2.

The sum of the information suggests that the rings moved eastward when they were attached to the Gulf Stream and westward when unattached, presumably in the Gulf Stream recirculation. As Allen first became attached to the stream and reformed again, its trajectory was in the form of a large clockwise loop similar to the motion measured by *Fuglister* [1977]. The trajectory of a later ring, Franklin, measured with a buoy in this region, also showed a large clockwise motion. An important conclusion derived from this study is that rings in the area north of Bermuda can interact strongly with the Gulf Stream and in the process become modified.

Temperature Structure From XBT's and Buoys

The four cruises which visited ring Allen (Table 1) provided XBT sections that give a view of the evolving temperature field (Figures 10 and 11). Although the first section on October 1 looks as though it may have passed near the center of newly formed ring Allen, we have no additional measurements of its location, size, and shape at that time with which to verify this inference. Each of the other three sections, however, passed near the center of Allen, as measured by the drifting buoys. We also searched satellite IR images for temperature information about Allen, but, because of cloudy conditions and small thermal gradients, the images were not very helpful.

In October 1976 (Figure 10*a*), Allen had the appearance of being newly formed. The 15°C isotherm was raised to a depth of 180 m in the center, and in the upper layers the water had the same temperature as the Gulf Stream nearby. A small surface temperature difference of about 1.5°C was found between the core and the water over the flanks of the ring. It was probably this small temperature change which was seen on the September 21, 1976, satellite infrared image (Figure 1).

The December 1976 section was made along the axis running through the centers of Allen and Arthur. The 15°C isotherm had dropped to 275 m in Allen and was located at 440 m in Arthur. The surface water had cooled from 26°C in October to 20°C in December, and no horizontal temperature gradient was observed in the upper 100 m despite the swift currents and salinity anomaly which were located there. Thus Allen and Arthur would have remained undetectable by satellite infrared measurements even if the sky had been free of clouds at the time.

In January 1977 the 15°C isotherm had dropped to 310 m

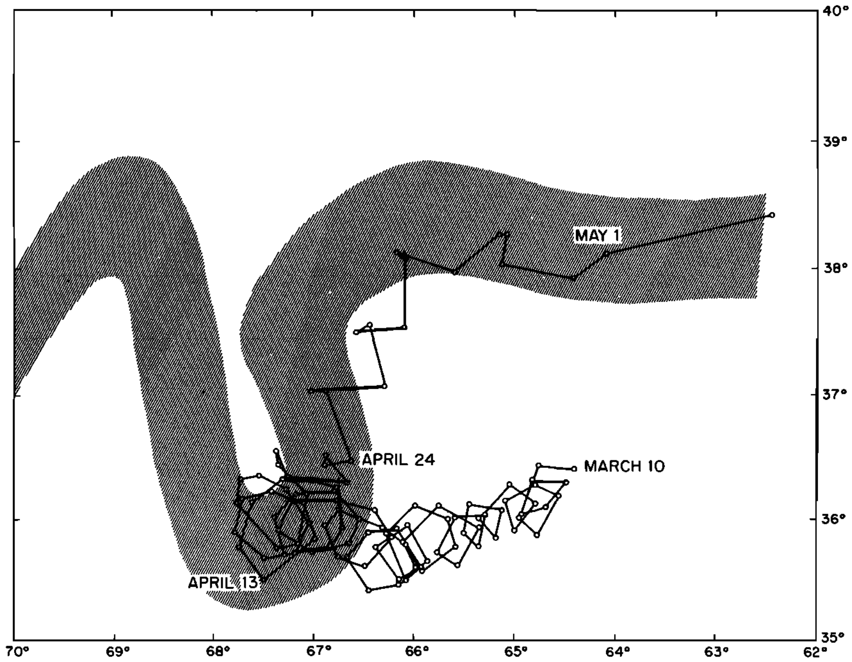

Fig. 8. Trajectory of buoy 215 in ring Allen as it coalesced with ring/meander Bob. In mid-April ring Bob had become attached to the Gulf Stream and moved rapidly eastward running into ring Allen which was moving westward. There is evidence from one buoy that the ring/meander Bob never fully opened to the north, as implied in this overly simplified schematic diagram based on satellite infrared imagery, April 26, 1976. On April 22 the sea surface temperature measured by buoy 215 jumped from 19°C to 24°C as the buoy encountered the warm Gulf Stream water.

in the center of Allen. Although the surface water over the center of Allen had cooled to 18.5°C, the water over the flanks on the southeastern side was 21°C, warmer than it had been in December and implying an intrusion of Gulf Stream water.

The April 1977 section was made as Allen had partially coalesced with the Gulf Stream, had reformed again, and was in the process of coalescing with the stream a final time. The section from left to right is in the same direction that the ring was moving, northeastward. The presence of Gulf Stream water in the ring can be seen on the southwestern side; this water was probably advected around the ring as we have observed occurring with other rings. There are two interesting features observed in the temperature field of this section; they may be a result of the coalescence process. The first is that the upper part of Allen was vertically stretched. Although the deeper isotherms (colder than 10°C) have dropped since January, the upper isotherms (warmer than 15°C) have risen; relative to the 10°C isotherm, the 18°C isotherm rose 250 m, a distance equal to 60% of the thickness of the 10°–18°C layer in January 1977. The stretching was accompanied by a decrease in the period of Allen's rotation. Just before the April section was made, Allen's period had decreased from 3.5 to 1.5 days and during Allen's February interaction with the Gulf Stream, the period of rotation decreased from 5.0 to 2.0 days. Arthur's period of rotation also decreased from 4.2 to 2.8 days as Arthur became attached to the stream and was advected eastward in it. Thus during a ring's interaction with the Gulf Stream, the upper part of the ring can be 'spun-up.'

The second interesting aspect of the April XBT section is

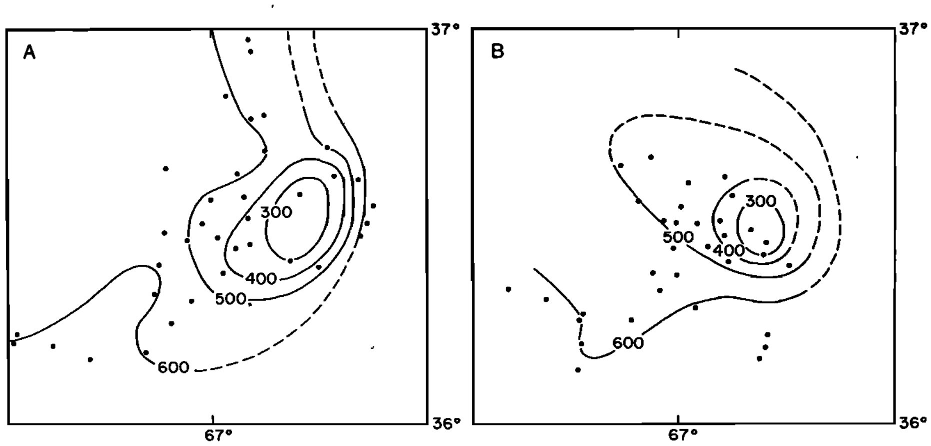

Fig. 9. Depth contours of the 15°C surface in ring Allen from the *Knorr* 65 XBT survey, April 24–25, 1977. Ring Allen was moving rapidly northeastward with an estimated speed of 30 cm s^{-1} based on the buoy trajectory. Ring/meander Bob is located to the northwest of Allen. (*a*) The XBT positions are in the usual geographical frame of reference; (*b*) the XBT positions have been adjusted to remove the effect of the movement of Allen.

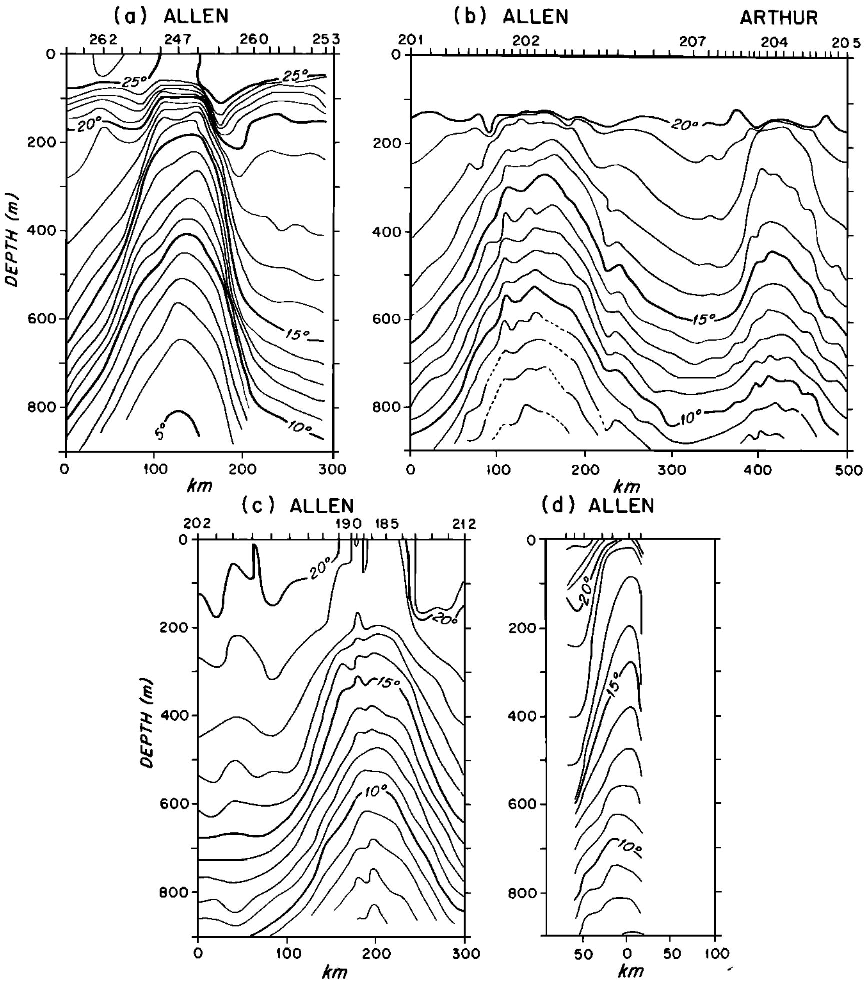

Fig. 10. XBY sections through ring Allen, (*a*) October 1, 1976, *Knorr* 60; (*b*) December 7-13, 1976, *Knorr* 62; (*c*) January 5, 1977, *Knorr* 63; (*d*) April 24, 1977, *Knorr* 65.

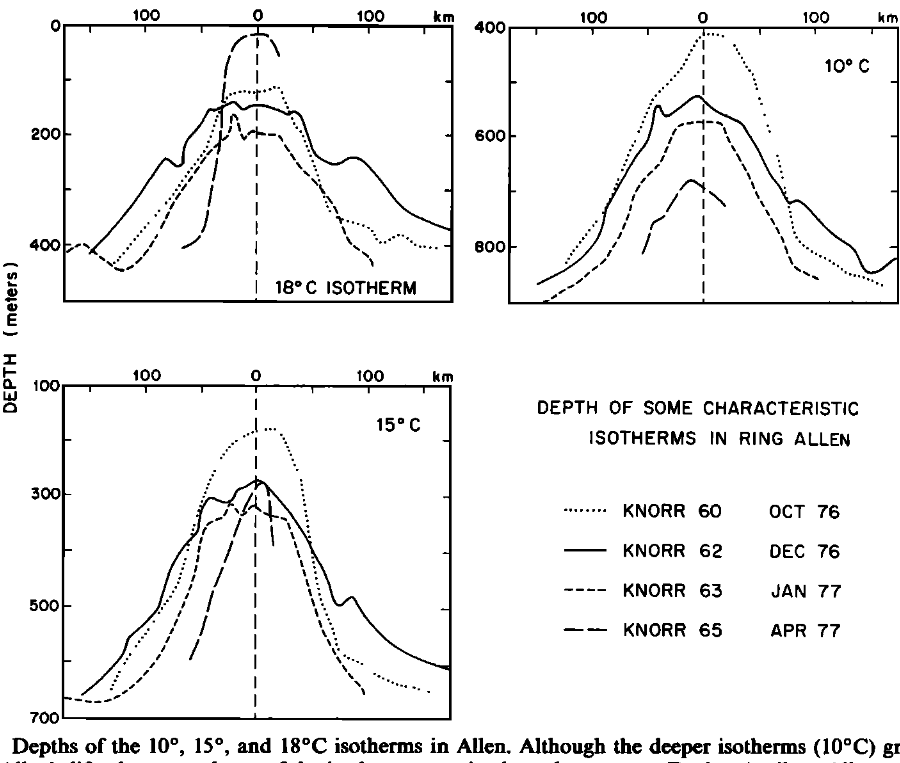

Fig. 11. Depths of the 10°, 15°, and 18°C isotherms in Allen. Although the deeper isotherms (10°C) gradually subsided over Allen's life, the mean slopes of the isotherms remained nearly constant. During April, as Allen coalesced with the Gulf Stream, the upper isotherms rose, and Allen's rotation rate increased.

TABLE 3. Satellite Buoys

Buoy Number	Ring	Date	Latitude	Longitude	15°C Depth, m	Drogue type*	Buoy Life, days	Comments
0125†	Allen	Dec. 5, 1976	36°34′N	65°17′W	406	WS, 1.6-cm line	40	Stopped transmitting on Jan. 13, 1977
0162‡	Arthur	Dec. 14, 1976	36°37′N	62°33′W	465	3.8-cm line	420	Came out of ring on Jan. 30, 1977
0215‡	Allen	Dec. 4, 1976	36°14′N	65°34′W	290	3.8-cm line	377	Ring coalesced with Gulf Stream on May 2, 1977
0264‡	Allen	Dec. 17, 1976	36°10′N	66°07′W	360	WS, 3.8-cm line	324	Came out of ring on Feb. 21, 1977

*Buoys 0125 and 0264 had a 200 m tether line attached to a 1.8 × 13.7 m window shade drogue. Buoys 0162 and 0215 had 200 m of 3.8 cm diameter polypropylene tether line attached to a 40 kg weight. All four buoys had safety shackles and 5 m of 0.95 cm galvanized chain between the hull and tether.

†Buoy Hull made by Nova University; radio transmitter made by American Electronics Laboratory.

‡Buoy made by Polar Research Laboratory.

that the near-surface isotherms (15°C–17°C) appear to be offset ahead of the deeper isotherms (8°–10°C). This offset may indicate that the ring is experiencing the strong vertical shear in the horizontal currents typical of the Gulf Stream.

Two buoys provided a time series of the near-surface temperature in Allen, buoy 215 (Figure 6*b*) and 264. The temperatures of buoy 215 show a gradual decrease from 21.5°C in December to 18.5°C in mid-February. At the end of February, when Allen became attached to the stream, the temperature rose to 19.5°C. It stayed near this temperature until April 22, when Allen was coalescing with the stream. At that time the temperature jumped suddenly to 24.1°C.

Buoy 264, which only remained in Allen until mid-February, shows a different picture. The temperatures remained between 21°–22°C from December through February with the exception of three warm periods during which temperatures increased to 23°C (January 1, 12, and 20).

An explanation of the different temperature series could be that Allen came in contact with the Gulf Stream during January and entrained the warmer stream water into the ring's cyclonic circulatoin, trapping it there. Buoy 264 was probably located at a slightly greater radius than that of buoy 215 and thus measured the presence of the warmer water while buoy 215 measured the cooler central water. (Note that buoys 215 and 264 had different drogues (Table 3).) This interpretation is in agreement with the January XBT section which shows a cool, 18.5°C, center surrounded by a warm ring with temperatures up to 21.2°C on the southeastern side. We suggest that the reason the surface water over the flanks of ring Allen remained warm throughout the winter despite unusually cold conditions [*Worthington*, 1977] was through an entrainment process whereby warm Gulf Stream water periodically replaced the ring water.

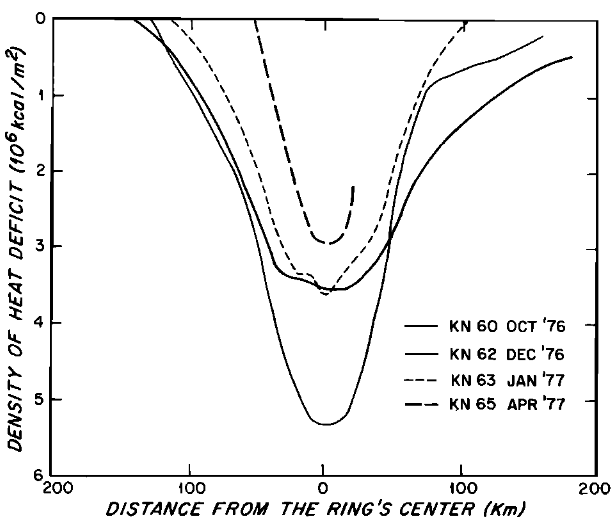

Fig. 12. Heat deficit in ring Allen in the upper 800 m. The curves were calculated from the XBT data. On each cruise an XBT outside of the ring was used as a reference value.

The inferred interaction between Allen and the Gulf Stream during January did not have as dramatic results as those interactions measured during February and April because no change in overall size or rotation rate was detected. However, it was during January that Allen made a jog to the east, presumably another sign of Allen's interaction with the stream. It is possible that earlier interactions between Allen and the stream occurred during October and November but that they remained unobserved.

An order of magnitude calculation suggests that the rate with which a ring could exchange water with the Gulf Stream is about 0.7×10^6 m^3 s^{-1}. For this calculation it was assumed that an interaction occurs every 2 months and that the volume replaced during each interaction is made up of an annular region extending from 50 to 100 km in radius and from the sea surface to a depth of 150 m, the region of warm water in Figure 10*c*. It is possible that additional deeper water is also exchanged, thus the above estimate is conservative. Since approximately 10 cyclonic rings and 3 anticyclonic rings coexist at any one time [*Lai and Richardson*, 1977; Richardson *et al.*, 1978] as many as 5 or 6 may be in a position adjacent to the stream and able to interact with it. These rings could exchange, on the average, as much as 4×10^6 m^3 s^{-1} with the stream and could be important in the redistribution of water, heat, and energy within the Gulf Stream system.

Despite the intrusions of warm Gulf Stream water into Allen and the stretching of its upper thermocline seen in April, the ring continued to decay over its life. To show the overall changes in Allen the vertically integrated heat deficit was computed from the XBT sections relative to an XBT on the outside of the ring on each cruise. The results show the dominating effect of the subsiding cold core relative to the warm Sargasso Sea (Figure 12). The decay rate suggests that if Allen had not coalesced with the stream and been lost at the end of April 1977 its life expectancy would have been another 6 months.

The mean decay rate of Allen from October to April is considerably larger than that of the two other rings which were observed for long periods of time. On the basis of the sub-

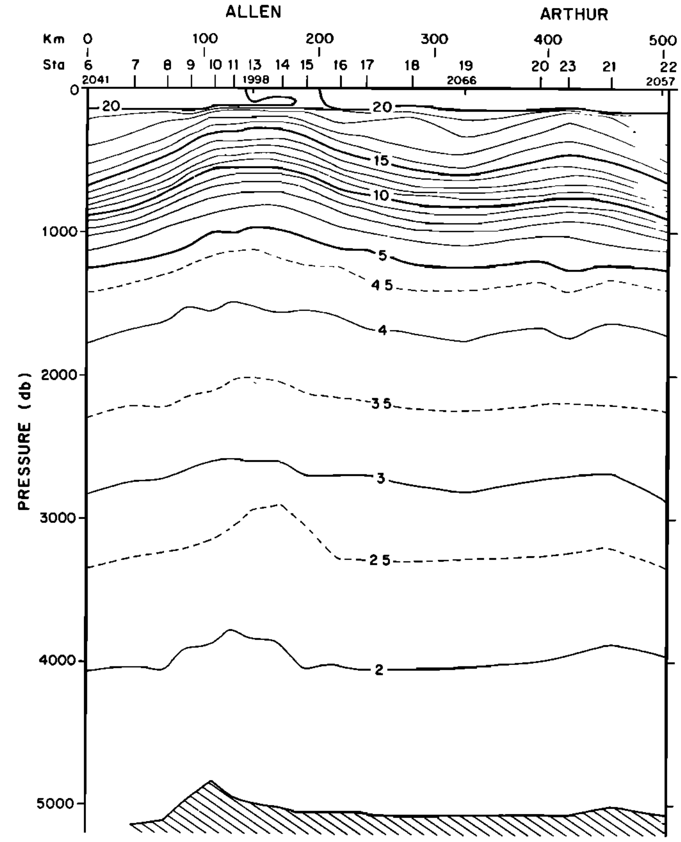

Fig. 13*a*. Potential temperature section through rings Allen and Arthur measured by CTD on *Knorr* 62, December 7-12, 1976.

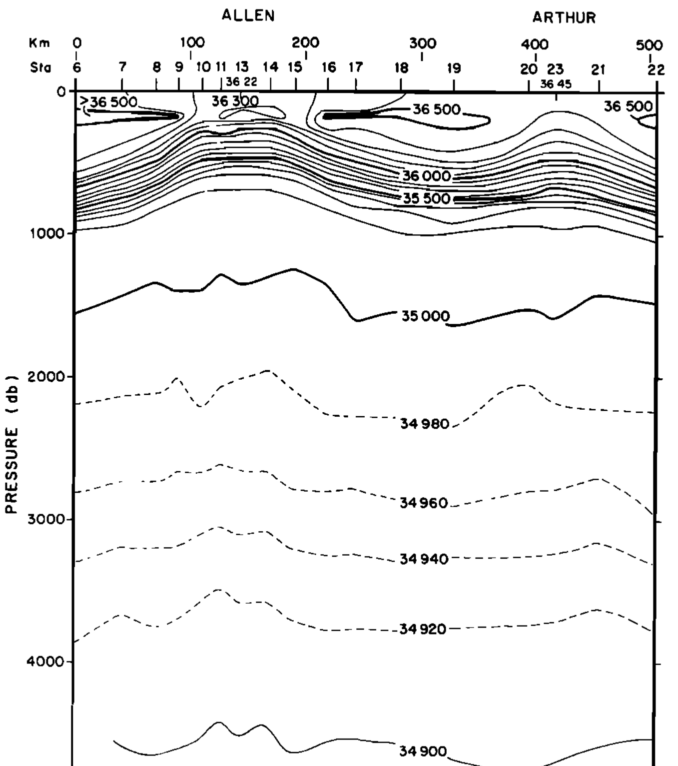

Fig. 13*b*. Salinity section through rings Allen and Arthur measured by CTD on *Knorr* 62, December 7-12, 1976.

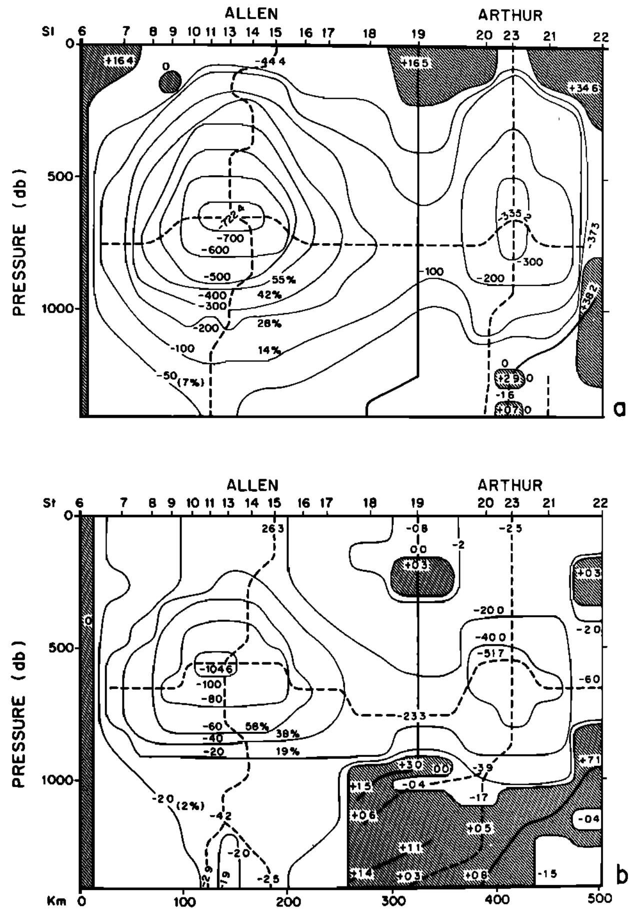

Fig. 14. (*a*) Section through rings Allen and Arthur showing the anomalies in temperature (0.01°C) by using CTD station 6 on the left as a reference profile in temperature. (*b*) Section through rings Allen and Arthur showing the anomalies in salinity (0.01‰) by using CTD station 6 on the left as a reference profile in salinity.

sidence of the 10°C isotherm at the center of the rings, we find a value of 1.3 m d^{-1} for Allen; *Cheney and Richardson* [1976] found a value of 0.4 m d^{-1} and *Fuglister* [1977] found 0.7 m d^{-1}. The high decay rate probably reflects Allen's fission into two rings and the energetic interactions with the stream.

TEMPERATURE AND SALINITY STRUCTURE FROM CTD PROFILES

In December 1976, on Knorr 62, a line of CTD stations was made along the axis of rings Allen and Arthur (Figure 13). The ring structure, indicated by the doming of the isopleths near the center of each ring, is found to extend all the way to 4500 dB, near the ocean floor. Although there is little temperature structure in the upper 100 m, as is also seen on the XBT sections (Figure 10), there is considerable salinity structure in this region. The salinity structure reflects two things: the raised thermocline and the variation of θS properties indicative of the slope water origin of the water in the central region of the rings.

The presence of the rings in the Sargasso Sea represents anomalies of heat, salt, and energy. The anomalies of the rings were calculated from a reference station (CTD 6) on the ring periphery; the anomalies of temperature and salt are shown in Figure 14. The maximum anomaly is located near a depth of 600 m and amounts to 7.2°C and 1.05‰. It is near 700 m that the strongest connection between Allen and Arthur can be seen to exist.

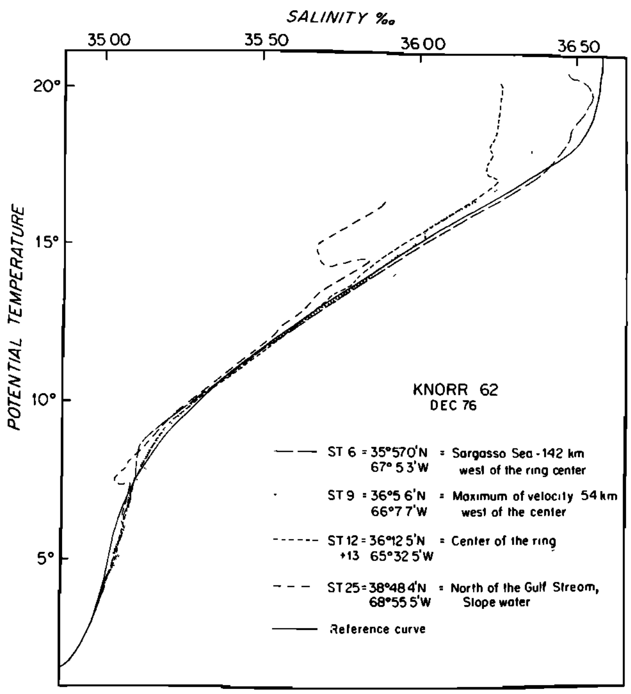

Fig. 15. Potential temperature-salinity profiles from ring Allen, the Sargasso Sea, and the slope water region (*Knorr* 62, December 1976). The mean θS relation of the western North Atlantic is also shown. The upper portion of the ring has a lower salinity than the surrounding Sargasso Sea water.

To identify the extent of the slope water remnant, θS diagrams were constructed (Figure 15), and the mean θS of the western North Atlantic [*Iselin*, 1936; *Worthington and Metcalf*, 1961] was subtracted from these (Figure 16). The central surface water in Allen is the freshest observed (−0.35‰ anomaly); the θS characteristics are located between the mean θS of the western North Atlantic and the slope water station. The anomalously fresh near-surface water grades into the background values near depths of 400–500 m and near the edges of the rings. Thus, although the ring structure extended to the ocean floor, the anomalous water in the core was only found in the upper 10% of the water column.

The maximum horizontal gradient in salinity anomaly occurs between stations 8–10 and 15–16 near the region of the swiftest currents. Ring Arthur has a smaller anomaly than that found in the center of Allen; however, the θS profiles in Arthur's core resembled those obtained near the flanks of Allen. Thus it is concluded that Arthur was formed from a piece of the flank region of Allen.

Layers of θS anomaly were found in the vertical profiles, and an attempt was made to trace these through the rings (Figure 16). The shallowest layer that we could follow through the rings was located near a temperature of 12°C and varied in depth from 800 m outside the rings to 400 m in the center of Allen. Above this layer was located the fresh central core water. Below 12°C and in the ring core we could not identify any water masses that were clearly different from those near the edges and outside of the ring.

The potential energy anomaly (*Hagan et al.* [1978] refer to this quantity as the transport potential energy) associated with rings Allen and Arthur was computed by using the equation given by *Fofonoff* [1962] and CTD station 6 as a reference station. The total potential energy anomaly of both rings due to the internal density variations amounts to 172×10^{15} J of which 134×10^{15} was in ring Allen. The kinetic energy of both rings, computed from the geostrophic velocity profiles, was 3.6×10^{15} J. Approximately 50% of the potential energy anomaly and 95% of the kinetic energy were located in the upper 1000 m.

A comparison of Allen with other rings (Table 4) suggests that Allen contained θS anomalies between the extreme anomalies measured in some new rings [*Fuglister*, 1977; *Richardson et al.*, 1977] and the barely perceptible anomalies of older rings [*Barrett*, 1971; *Cheney and Richardson*, 1976]. Allen was found to have a larger potential energy anomaly than that in other rings. This is because a significant part of the anomaly of potential energy was located in the lower layer of

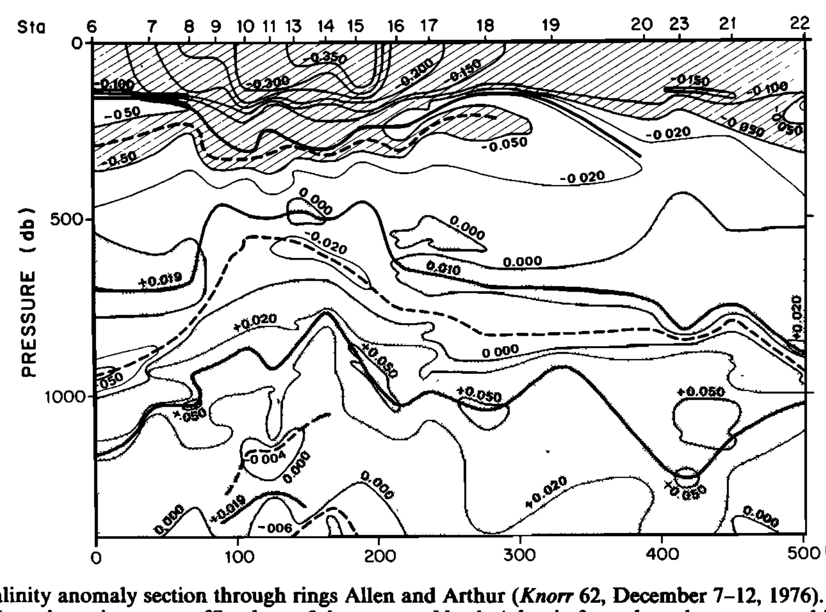

Fig. 16. Salinity anomaly section through rings Allen and Arthur (*Knorr* 62, December 7-12, 1976). Salinity anomaly was obtained by subtracting means θS values of the western North Atlantic from the values measured by CTD. Stippled area represents positive (more saline) anomalies, values fresher by 0.50‰ than the mean. Layers of minima in salinity anomaly are shown by a dashed curved line and crosshatched area represents negative anomalies, and maxima are shown by a heavy solid curved line.

TABLE 4. A Comparison of Several Rings

Ring	Date	Location (°N)	Location (°W)	Ship	Diameter 15°C at 500 m, km	Minimum 15°C Depth, m	Volume Transport, 10^6 m³/s	Anomaly Potential Energy, 10^{15} J	Kinetic Energy, 10^{15} J
Sock [*Barrett*, 1971; *Fuglister*, 1963]	May 1960	36	65	*Atlantis* 225	150	175	45 (2000)	74	
Joe [*Barrett*, 1971]	Oct. 1963	28	74	*Crawford*	90	300	25 (2000)	22	
Fritz [*Barrett*, 1971; *Fuglister*, 1977]	June 1967	36	66	*Crawford* 156	115	0	40 (3000)	32	
Gordon [*Barrett*, 1977]	April 1970	31	70	*Atlantis* II	65	355	15 (1000)	15	
John [*Cheney and Richardson*, 1976]	Oct. 1971	32	73	*Trident* 102	160	190	60 (3500)	93	6
	May 1972	28	78	*Researcher*	110	305	19 (1000)	14	1
Big Baby [*McCartney et al.*, 1978]	March 1975	34	63	*Knorr* 48	260	215	45 (2000)		
Dave (Ring D)	June 1975	36	68	*Trident* 168	120	150	73 (3000)		
George [*Richardson et al.*, 1977]	Dec. 1975	36	58	*Trident* 175	140	120	70 (3000)		
Mike	Dec. 1975	35	65	*Trident* 175	160	170	46 (3000)		
Allen	Dec. 1976	36	66	*Knorr* 62	165	275	61 (4700)	134	3
Arthur	Dec. 1976	37	62	*Knorr* 62	65	440	29 (5000)	38	0.6

Note: Names were given to rings to aid us in differentiating them. Volume transport values are relative to a depth of zero velocity which is given in parenthesis. Anomaly of potential energy was calculated by using the equation given by *Fofonoff* [1962]. Barrett's values are from the upper 1000 m of the rings. Kinetic energy was estimated from geostrophic velocity profiles.

Allen. This deep contribution is due partly to the doming of the isopleths which extended near to the sea floor and partly to the pressure term which magnifies the contribution of the anomaly of potential energy at great depths. The kinetic energy of Allen is less than that given by *Cheny and Richardson* [1976] probably due to the slower near-surface speeds in Allen.

VELOCITY PROFILES

Velocity profiles were obtained directly with a current-meter profiler and also indirectly from the CTD stations using the geostrophic relation.

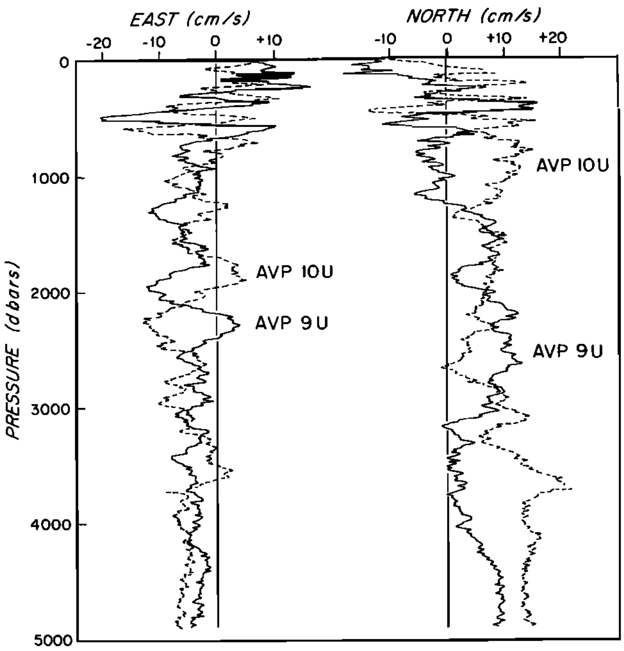

Fig. 17*a*. A pair of absolute velocity profiles taken 11 hours apart (approximately one-half inertial period) in the center of ring Allen. Profiles AVP 9 and 10 were made on December 5, 1976, at 36°14′N, 65°35′W.

Absolute Velocity Profiles

Vertical profiles of absolute velocity in ring Allen were made with a recently developed absolute velocity profiler (AVP) [*Sanford et al.*, 1978*a*]. The AVP measures a profile of horizontal velocity from the sea surface to the sea floor by means of the principle of motional induction [*Sanford*, 1975; *Sanford et al.*, 1978*b*]. An acoustic Doppler system was used to determine the absolute motion of the instrument within several hundred meters of the bottom. Performance estimates of the instrument suggest uncertainties in velocity of about 1 cm s^{-1} rms [*Dunlap et al.*, 1978].

A pair of absolute velocity profiles, a half-inertial period apart, was obtained in the center of ring Allen (AVPs 9 and 10) and a single profile (AVP 11) was obtained near the high velocity region of Allen, southwest of the ring center (Figure 17). The profiles from the center of Allen show the familiar mirror imagery due to inertial currents [*Sanford*, 1975]. However, the amplitudes of the deep water inertial fluctuations in the ring are about twice as large as is seen in other profiles obtained in the western north Atlantic. In the upper 1000 m the layers were approximately 50–100 m thick, and below 1000 m they were about 300-m thick; typical amplitudes were 10 cm s^{-1}. Given the strong horizontal and vertical gradients of TS structure, for example, the inertial current layers could provide a mechanism by which layers of different properties could be brought in proximity to one another enhancing property gradients and mixing.

The depth-averaged flow at the center of Allen was calculated from AVPs 9 and 10 to be 6 cm s^{-1} toward the north-northwest. The movement of Allen during this period as measured with drifting buoys, was toward the northwest with a mean speed of 4 cm s^{-1}. The mean velocity of Allen over a 2-week period from December 4 to December 17 as measured by two XBT surveys was 3 cm s^{-1} toward the northwest. The evidence suggests that Allen gradually slowed as it moved northwestward and that during the last week in December Allen turned and began to move southward (Figure 6*a*). Thus the depth-averaged AVP velocity coincided quite closely with the ring translation, but the mean translation rate was about half the depth-averaged flow.

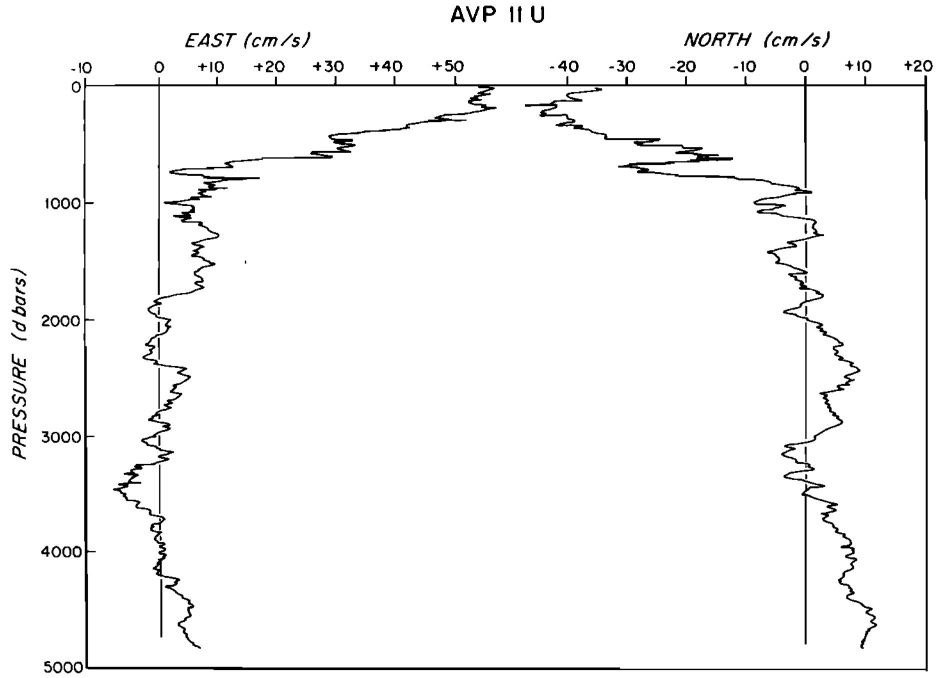

Fig. 17*b*. Absolute velocity profile, AVP 11, taken on the southwest side of Allen in the high speed region (December 6, 1976; 36°00′N, 65°50′W).

AVP 11, made in the swift current region of Allen, revealed strong baroclinic and barotropic velocities (Figure 17); both velocities were directed nearly parallel to the isotherms mapped by XBT (Figure 3). Unfortunately, the second profile in the high speed region, a half-inertial period after AVP 11, did not yield adequate data to calculate a mean velocity profile. However, one can imagine by smoothing the curve by eye what the mean profile might look like. The swiftest current (70 cm s^{-1}) was located near a depth of 200 m. Below this depth the profile showed a strong mean shear to a depth of 1000 m and then a more gradual shear extending, possibly, to the bottom. Taken alone, AVP 11 suggests that the cyclonic circulation in Allen extends to a depth of about 2000 m, where one can imagine that a smooth curve through the inertial velocity components would intersect the zero velocity line. This depth, 2000 m, is in agreement with the results of *McCartney et al.* [1978], who computed the velocity field in a ring that passed over a current-meter mooring.

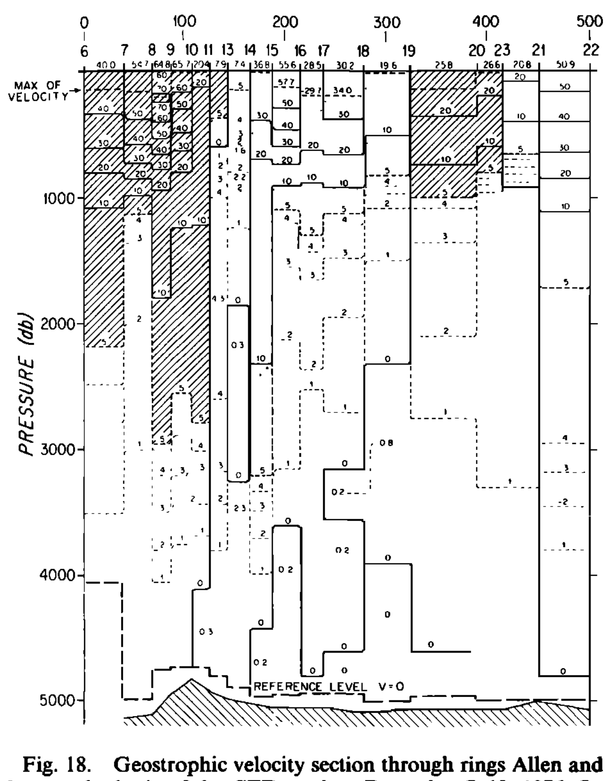

Fig. 18. Geostrophic velocity section through rings Allen and Arthur on the basis of the CTD section, December 7-12, 1976. Speeds (cm s^{-1}) were calculated relative to a deep, near bottom zero, velocity level.

It is possible, however, that a portion of the absolute velocity observed on the AVPs may be due to the translation of the ring. If we assume that Allen was advected toward the north-northwest by a large scale barotropic flow, then, to obtain the velocity profile relative to a coordinate system moving with the ring, we need to subtract the movement of the ring from the absolute velocity profiles. In doing this the mean depth-averaged velocity of the ring, which was obtained from AVPs 9 and 10 [*Dunlap et al.*, 1978, Table 4], should be subtracted from AVP 11. The effect of this subtraction would be to shift the zero velocity lines of the east component to the left by 3.3 cm s^{-1} and of the north component to the right by 5.0 cm s^{-1} (Figure 17*b*). The results suggest that the cyclonic flow of ring Allen may indeed extend all the way to the sea floor. Although the assumption that Allen was imbedded in a large scale barotropic flow may be reasonable for the period of time that the profiles were made, it would probably not be reasonable to make this assumption for the time during which Allen was attached to the Gulf Stream and was advected rapidly eastward.

Geostrophic Velocity

Velocity profiles between CTD stations were calculated from the geostrophic relation. A correction was made to include the centripetal acceleration, a term which is important in the upper high speed layers. A deep, near bottom, zero ve-

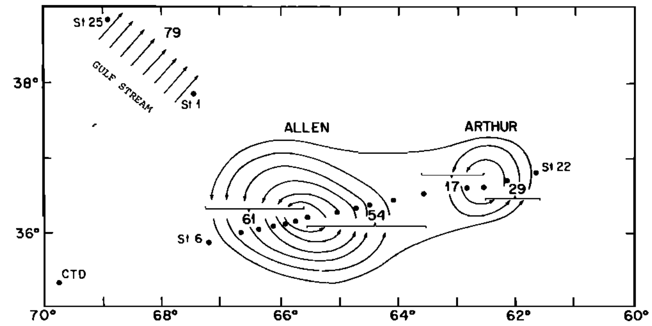

Fig. 19. Volume transport (10^6 m^3 s^{-1}) of the Gulf Stream and rings Allen and Arthur. Each line indicates, approximately, a transport of 10×10^6 m^3 s^{-1}. The transport of the Gulf Stream is relative to a zero velocity level at 2800 dB, the depth reached by CTD 25. Transport in the rings is relative to a deep, near bottom level (see Figure 18). Approximately 3×10^6 m^3 s^{-1} were flowing eastward between the ring (CTD 6) and the Gulf Stream (CTD 1).

locity level was chosen since there were insufficient velocity profiles to establish a reference level across the section.

Four bands of current are seen (Figure 18) composing the cyclonic circulation around rings Allen and Arthur. The high current region is located near a radius of 60 km from the center of Allen, which was near station 13. Maximum speeds of 70 cm s^{-1} are located near a depth of 200 m and between stations 8 and 9 on the west side of Allen; this subsurface peak is also seen on AVP 11 which was made near this region and time. AVP 11 has the addition of inertial currents not seen in the geostrophic velocity profiles. The vertical shear in the horizontal currents can be seen to extend downward to at least 4000 m beneath Allen, as also inferred from AVP 11. The total volume transport in Allen was 61×10^6 m^3 s^{-1} (Figure 19) and in Arthur 29×10^6 m^3 s^{-1}. Part of the transport in Allen and Arthur, estimated to be $7–12 \times 10^6$ m^3 s^{-1} circulated around both rings. The total transport in Allen amounted to 77% of the Gulf Stream transport, 79×10^6 m^3 s^{-1}, which was also measured in December 1976 but only relative to 2800 m.

The volume transport of several rings is summarized in Table 4 where values range from 15×10^6 m^3 s^{-1} to 73×10^6 m^3 s^{-1}. Thus Allen is a ring with large transport, and Arthur is one with small transport. Because of the assumptions and approximations which go into transport estimates, these values should be viewed as approximate. The problem of determining the transport of a ring is much like that of determining the transport of the Gulf Stream [*Warren and Volkman*, 1968]. One must select an appropriate zero velocity level and an appropriate reference station outside of the ring. Because of the highly variable depth of the thermocline in the Saragasso Sea, one can imagine that one could significantly 'vary' the calculated transport of a ring or the Gulf Stream by selecting the reference station in a location where the thermocline is particularly deep or shallow. In the present study we chose a reference station on the edge of ring Allen, near where the thermocline began to become level. We thought it appropriate to compute the transport and also anomalies with a reference station made near the ring, near the same time and with the same techniques as the stations in the ring. (*Hagen et al.* [1978] chose to use a single hydrographic station (*Chain* Cruise 7, station 35; April 22, 1959; 35°16′N 68°22′W) as being representative of the mean Sargasso Sea conditions; by using this station they compared the properties and anomalies of properties of several rings including Allen.)

SUMMARY

A cyclonic Gulf Stream ring was followed over a 7-month period from the time of its formation in September 1976 to its final coalescence with the Gulf Stream in April 1977. During this period the ring split into two pieces; the larger was named Allen and the smaller was named Arthur. Arthur became attached to the Gulf Stream and moved rapidly eastward to the vicinity of the New England seamounts, where it remained attached to the stream in the form of a ring/meander for approximately 7 months.

During its life, Allen interacted with the Gulf Stream several times; the interaction consisted of periods when Allen became attached to the Gulf Stream, exchanged water and energy with the stream, and moved eastward under the influence of the stream. One of these periods ceased when Allen broke away from the stream and moved southward, then westward, and then northward again. The overall movement of Allen consisted of a large clockwise loop much like the movement that *Fuglister* [1977] charted in his 1967 study.

During December 1976 absolute velocity profiles and CTD measurements suggested that Allen extended all the way to the sea floor. A region of anomalous θS properties was identified in the upper 400 m of Allen. Unusually energetic inertial currents measured by the current profiler provide a mechanism by which the ring (water, velocity, energy, and other chemical and biological components) could be stirred with its surroundings.

The picture of rings seen in this study is very different from that described by *Cheney and Richardson* [1976], in which it was concluded that a ring moved rather steadily to the southwestward slowly decaying in the Sargasso Sea. In the case of Allen the dominant decay appeared to occur in a series of strong interactions with the Gulf Stream. During the last interaction, Allen coalesced completely with the stream and disappeared.

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