A Census of Gulf Stream Rings, Spring 1975

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During 1975 several shipboard expendable bathythermograph surveys plus satellite infrared imagery provided a nearly synoptic view of the distribution and number of Gulf Stream rings in the western North Atlantic. Twelve rings were identified; nine were cyclonic (cold core) rings and three were anticyclonic (warm core) rings. This is the largest number of rings ever observed during a short period of time (4 months). Evidence suggests that the mean movement of these rings was southwestward.

INTRODUCTION

Gulf Stream rings formed from large, 200- to 300-km diameter, meanders are an important part of the Gulf Stream system [*Fuglister*, 1972, 1977; *Parker*, 1971; *Barrett*, 1971; *Saunders*, 1971]. The formation of rings provides the dominant mechanism by which mass, momentum, vorticity, energy, and chemical and biological material are transported northward across the Gulf Stream into the slope water and southward into the Sargasso Sea. The intensity and the relatively long life (up to 2 years) of cold core rings [*Fuglister*, 1972, 1977; *Cheney and Richardson*, 1976; *Lai and Richardson*, 1977] suggest that they probably have a significant effect on the region where they are found.

During 1975 we were fortunate to have three ships measuring the thermal structure of a large part of the western North Atlantic during a 4-month period. When the results of these cruises are combined with data obtained from the National Oceanographic Data Center (NODC) and satellite infrared (IR) images, we are able, for the first time, to determine the distribution and number of rings in the western North Atlantic and to map the temperature structure of this region in considerable detail. Repeated observations of many of these rings have provided a measurement of their long-term, westward trajectories.

DATA

The primary data source was four large-scale expendable bathythermograph (XBT) surveys in the western North Atlantic during 1975. They were the following: *Knorr* 48, March 7 to April 16; *Knorr* 49, April 21 to May 19; *Trident* 168, May 24 to June 11; and *Lynch* 708-75, June 22 to July 9. Deep (760 m) XBT's and some conductivity, temperature, depth (CTD) and hydrographic stations were made along the track lines of each of these cruises. Although the purpose of the first two cruises was not a search for rings, several large rings were found in the eastern region [*McCartney et al.*, 1978]. Results of these two cruises were particularly interesting as the rings were discovered in an area previously thought to be devoid of them [*Parker*, 1971]. The purpose of the two subsequent cruises was to find as many rings as possible in the western region and to measure their size and shape.

Data from these cruises plus all additional XBT's and hydrographic data on file at NODC for the period March–August 1975 were plotted on maps covering successive 2-week periods. The location of the Gulf Stream and rings near it that were visible on NOAA satellite infrared imagery were added to the maps and used to fill in areas lacking ship observations. There was a significant amount of overlap between surveys, and some major features (meanders, rings) were observed on several of them. A final composite map (Figure 1) was prepared from the biweekly maps; it covers a 4-month period from March 10 to July 9, 1975.

Topography of the 15°C isotherm was chosen in order to describe the Gulf Stream and rings. This isotherm extends from the sea surface in the north to a depth of about 800 m just south of the Gulf Stream, and this range is well covered by 760-m XBT's. In the North Atlantic the average depth of the 15°C surface lies about 250 m shallower than the 10°C surface which was contoured by *Iselin* [1936] and *Fuglister* [1963]. The 15°C surface lies within the main thermocline, and because of the linear TS relation and nearly constant vertical temperature gradient in the main thermocline, contours representing topography of the 15° surface have a pattern similar to that of dynamic height contours. However, the reader must be cautioned that a depression of the 15° surface is dynamically 'high' and an elevation of the 15° surface is dynamically 'low.'

Another chart portraying the 'mean' 15° isothermal topography was prepared (Figure 2) to show the mean shape of the Gulf Stream and subtropical gyre. The chart was based on the mean temperature maps of *Lai* [1977] and *Lai and Richardson* [1977] in which ring observations were excluded. The effect of including rings in such a map is shown by *Dantzler* [1977] and shifts the center of the gyre (or the location where the 15° isotherm reaches its greatest depth) to the south.

Observations of each ring are given in Table 1. Topography of the 15° surface in each ring and vertical temperature sections through each of the major features are shown in Figures 3 and 4.

An attempt was made to determine the trajectories of each ring, and the results are shown in Figure 5. The method described by *Lai and Richardson* [1977] was used. The movement of warm core rings was determined chiefly from analyses of satellite IR images [*NAVOCEANO*, 1975; *NOAA/NESS*, 1975; *NOAA/NWS*, 1975]. The movement of cold core rings was obtained from many different methods including XBT and AXBT surveys, Sofar floats, satellite drifters, and satellite IR images. A list of positions of the cold core rings is given in Table 2.

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Paper number 8C0789.
0148-0227/78/128C-0789$01.00

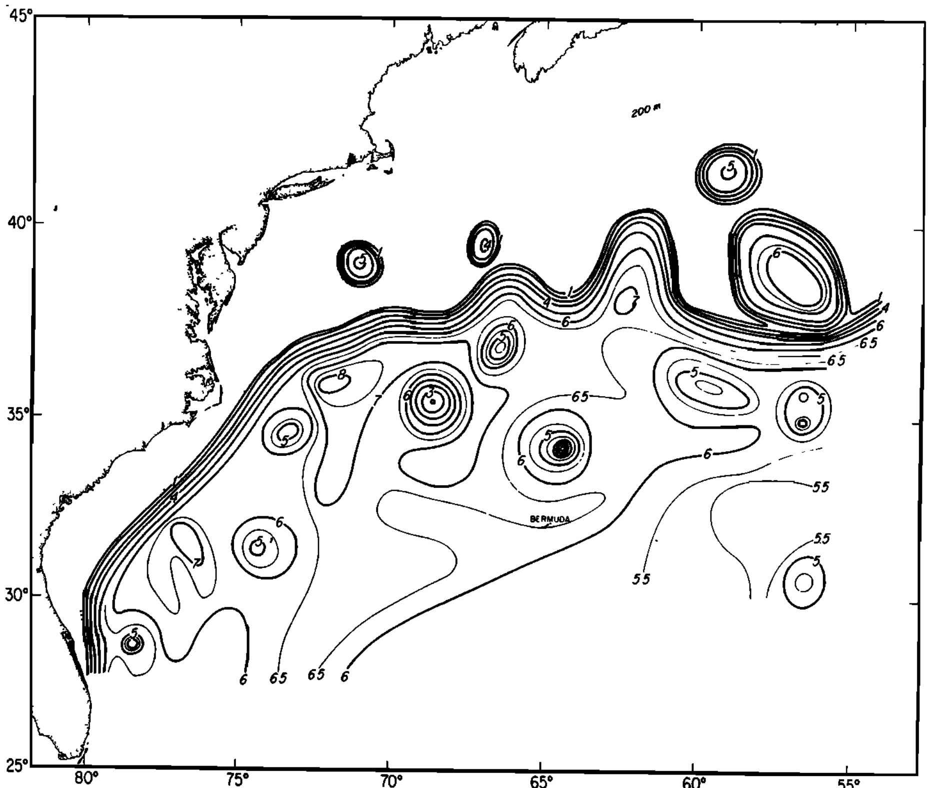

Fig. 1*a*. Chart of the topography of the 15° isothermal surface showing the Gulf Stream and nine cyclonic and three anticyclonic rings. Contours are based on XBT, CTD, and hydrographic data over the period March 16 to July 9, 1975. Contours in two anticyclonic rings north of the Gulf Stream and in portions of the Gulf Stream are based on satellite infrared imagery.

RESULTS

The Gulf Stream is characterized by an abrupt north-south deepening of the 15° isotherm from 100 m in the slope water region to 700 m in the Sargasso Sea (Figure 1*a*). Thus the Gulf Stream can be seen as a meandering zone about 100 km wide extending from the Florida Straits to 55°W. Southeastward of the Gulf Stream the thermocline gradually rises again as part of the Gulf Stream recirculation [*Worthington,* 1977]. The

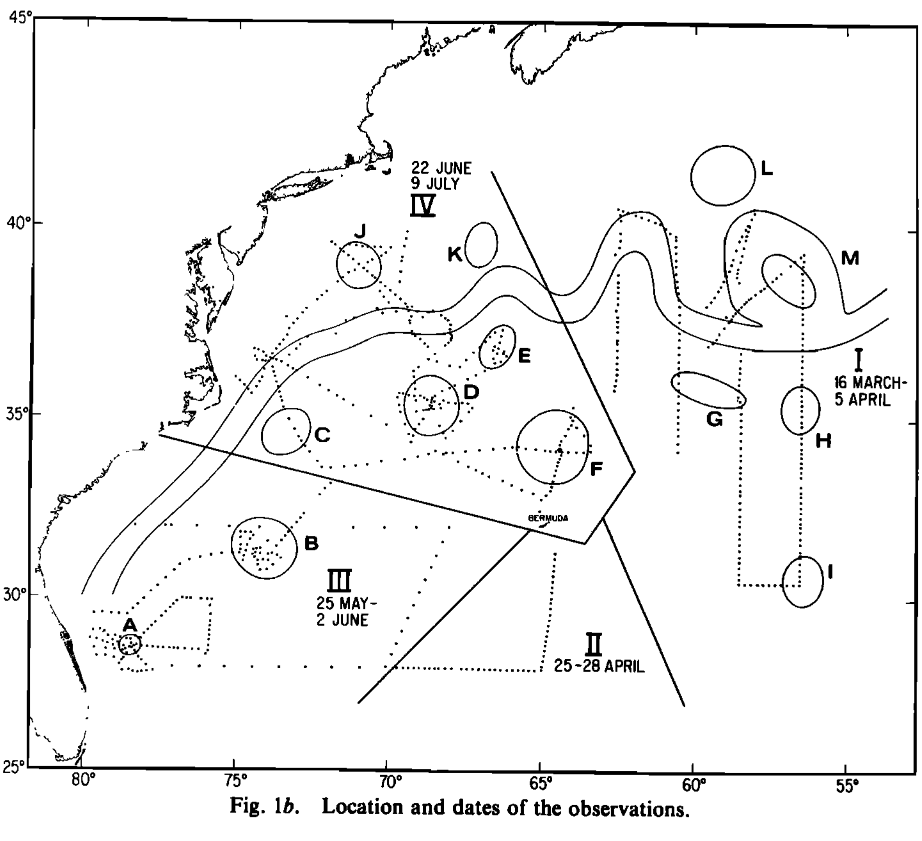

Fig. 1*b*. Location and dates of the observations.

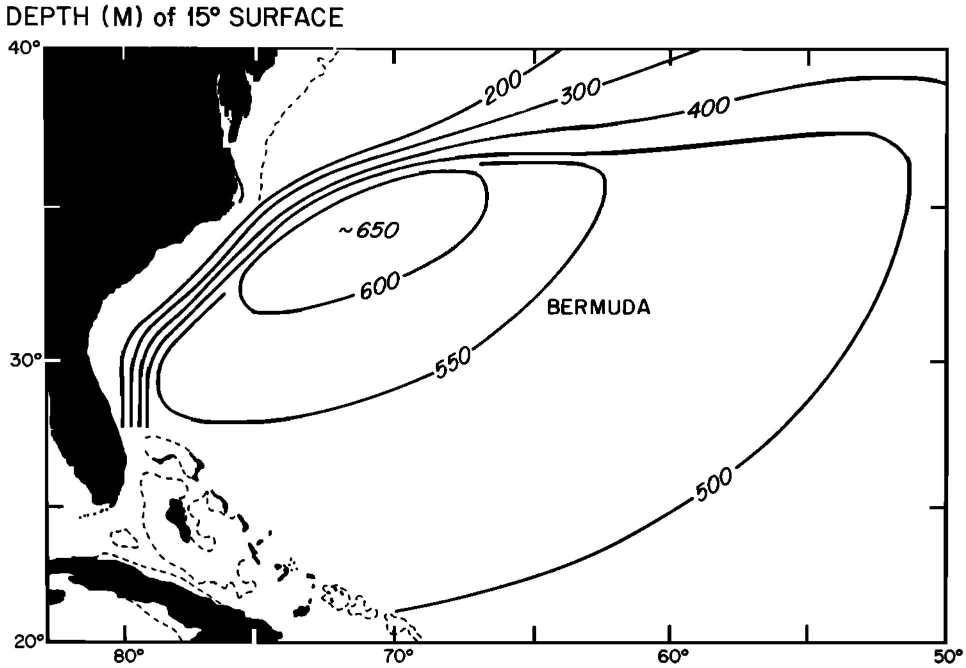

Fig. 2. Mean topography of the 15° isothermal surface exclusive of ring observations. This figure is based on temperature maps prepared by *Lai* [1977] and *Lai and Richardson* [1977] with data from 1970–1974. The center of the gyre (deepest spot) is located near 36°N, 72°W.

areas north and south of the Gulf Stream are populated by intense rings manifested as elevations and depressions. Three anticyclonic warm core rings (manifested by depression of the 15° isotherm) are found north of the Gulf Stream, and nine cyclonic cold core rings (manifested by elevation at the 15° isotherm) are found south of it. Because of limited data in some regions (Figure 1*b*) it is possible that there are a few additional rings that were not observed. Immediately south of the Gulf Stream and between rings, there are a number of deep depressions in the thermocline, indicating anticyclonic circulation.

Gulf Stream

The Gulf Stream forms a meander along 62°W and a meander/ring along 57°W. A careful examination of satellite IR and XBT data suggests the following sequence of events. The 62°W meander formed when an earlier warm core ring coalesced with the Gulf Stream in early March. This meander formed another warm core ring by mid-April which moved westward and is shown as ring K in late June. Although the Gulf Stream configuration along 57°W suggests that a warm ring is forming, subsequent IR data indicate that this ring did

TABLE 1. Observations of the 12 Rings

Ring	Depth at Center of 15° Isotherm, m	Size of 15° Isotherm at 500 m, km	Approximate Overall Size, km	Location °N	Location °W	Date, 1975	Data Source
A	330	70	180	28.6	78.4	May 26	*Trident* 168
B	458	50	200	31.3	74.2	June 1	*Trident* 168
C	480	50	180	34.6	73.3	July 2	*Lynch* 708-75
D	204	120	220	35.4	68.6	June 25	*Lynch* 708-75[a]
E	408	60	150	36.7	66.5	June 28	*Lynch* 708-75
F	203	105	250	34.1	64.4	July 5	*Lynch* 708-75
G	465	80 × 220?	250	35.8	59.5	March 24	*Knorr* 48[b]
H	385	130	200	35.3	56.5	March 25	*Knorr*[c]
I	407	85 × 135?	160	30.5	56.5	April 3	*Knorr*
J	518	45	120	39.0	71.0	June 29	*Lynch* 708-75[d]
K			110	39.5	67.4	June 29	NOAA IR[e]
L			160	41.1	59.0	March 19	NOAA IR[f]

For rings G, H, and I, sufficient data were not available to verify that the center had been crossed; the size and shape are thus in question. Approximate overall size was estimated from the diameter at which the isotherms began to become level (Figures 3 and 4) or from satellite imagery for rings K and L.

[a]Ring A of *McCartney et al.* [1978].

[b]Ring B of *McCartney et al.* [1978].

[c]Ring C of *McCartney et al.* [1978].

[d]Ring 6 of *Bisagni* [1976]; see also Gulf Stream, December 1975.

[e]Ring 8 of *Bisagni* [1976].

[f]Ring 10 of *Bisagni* [1976].

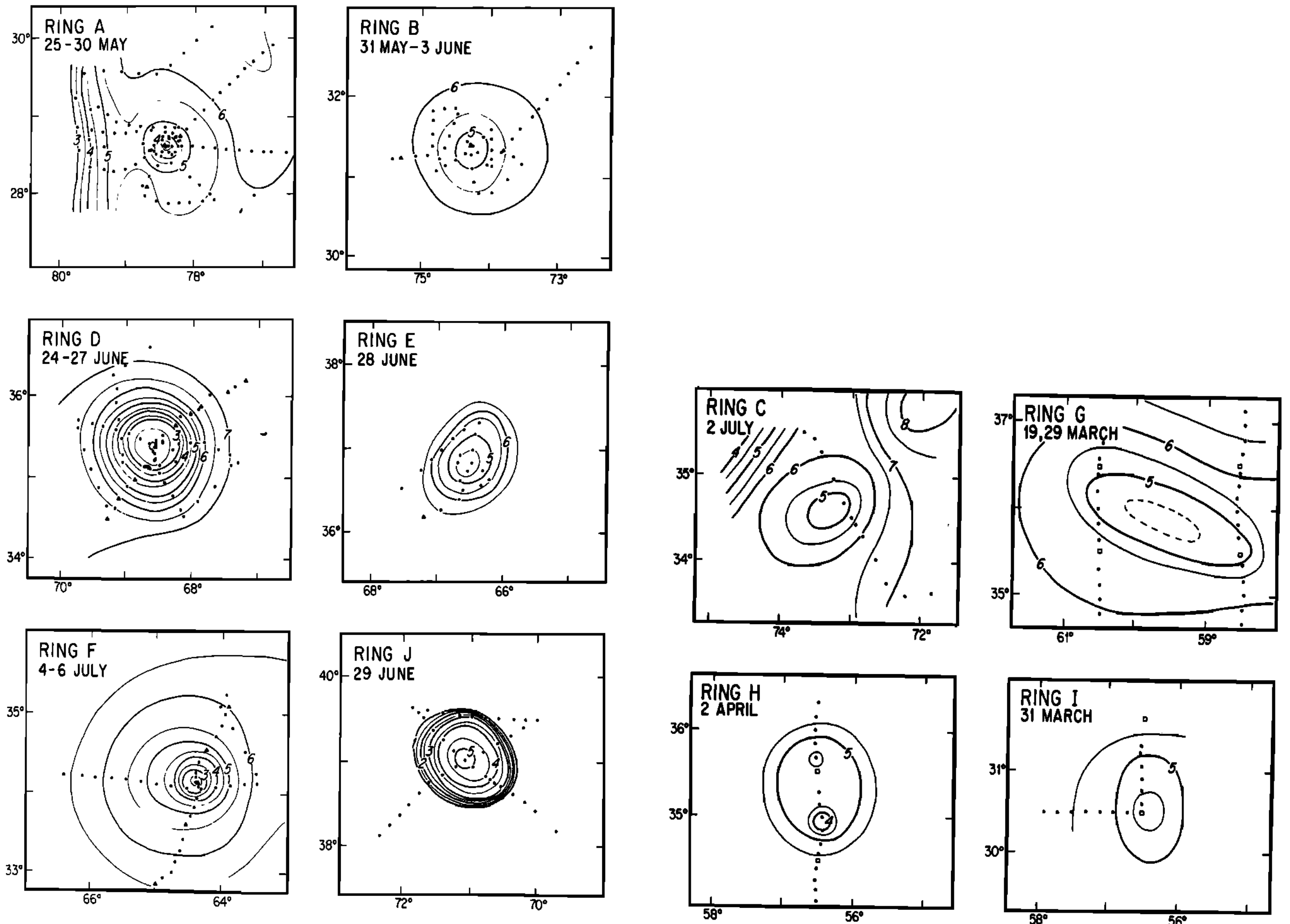

Fig. 3. Detailed maps of each ring showing the topography of the 15° surface in hectometers. Dots represent XBT's, triangles represent CTD or STD stations, and squares represent hydrographic casts. Rings A, B, D, E, F, and J are well surveyed rings, and rings C, G, H, and I are poorly surveyed rings.

not completely separate and that there continued to be a large meander in this region at least until July 1975. It is possible that a ring did detach in this region but that it remained undetected.

Frequently, with closely spaced XBT sections, one can see what resembles a depressed trough, a maximum in the depths of isotherms, on the offshore side of the Gulf Stream (Figure 4*a*). This trough marks the location where currents reverse direction from the eastward flow of the Gulf Stream to the westward flow of the recirculation. Occasionally, there are deep depressions in the thermocline significantly deeper than the usual trough. An example of one is located near 36°N and 72°W where the 15°C depth reaches 810 m (Figure 4*a*, section 3). Occasionally, cold core rings, especially young ones, also appear to have a small depressed trough in the thermocline near their outer edges (Figure 4*a*, rings D and H). A possible explanation is that when cold core rings form from a meander, this trough detaches with the ring. The deep depressions may reflect the coincidence of troughs associated with the Gulf Stream and rings. Apparently, it is above those deep depressions that much of the renewal of the 18°C water [*Worthington*, 1959] takes place. On *Knorr* cruise 65 in April 1977 we found a deep depression with 15°C at 845 m located near 34.4°N, 71.3°W. Above this spot was a vertically homogeneous water mass with a temperature of 18.4°C extending from the surface to 500 m. It had apparently just formed during the winter of 1976–1977 [*Leetmaa*, 1977; *Worthington*, 1977]. This deep spot was centered between three cyclonic rings. Later, in December 1977, an especially deep spot was measured from the *Endeavor* by XBT (W. G. Metcalf, personal communication, 1977). Eighteen-degree water was observed to extend to 825 m near 34.0°N, 68.5°W. Although the 15° isotherm was not reached, its depth was estimated to be 1000 m from the vertical temperature gradient between 15° and 18° near this location and time.

Rings

Nine cold core rings, three warm core rings, and one ring/meander were found in this study. Of the cold core rings, A, B, D, E, and F were adequately sampled to determine reasonable estimates of their size and shape (Table 2, Figure 3). The others, C, G. H, and I, were not sampled well, and the contouring is largely conjectural. Although C, G, H, and I all clearly appear to be rings, we suspect that the XBT sections did not pass through their centers and thus their intensity could be underestimated. Of the warm core rings, only J was well surveyed by XBT. The others K and L, were repeatedly observed with satellite IR images, although there were no XBT's to document the temperature structure. Contours (Figure 1) were drawn consistent with the IR data and sections through other warm core rings. Occasionally, the water in a warm core ring can be cooled below 15°C during the winter, and if this should occur, the ring would not appear on a contoured 15° surface. The evidence suggests that ring M never completely separated from the Gulf Stream and remained part of a meander at least until July 1975.

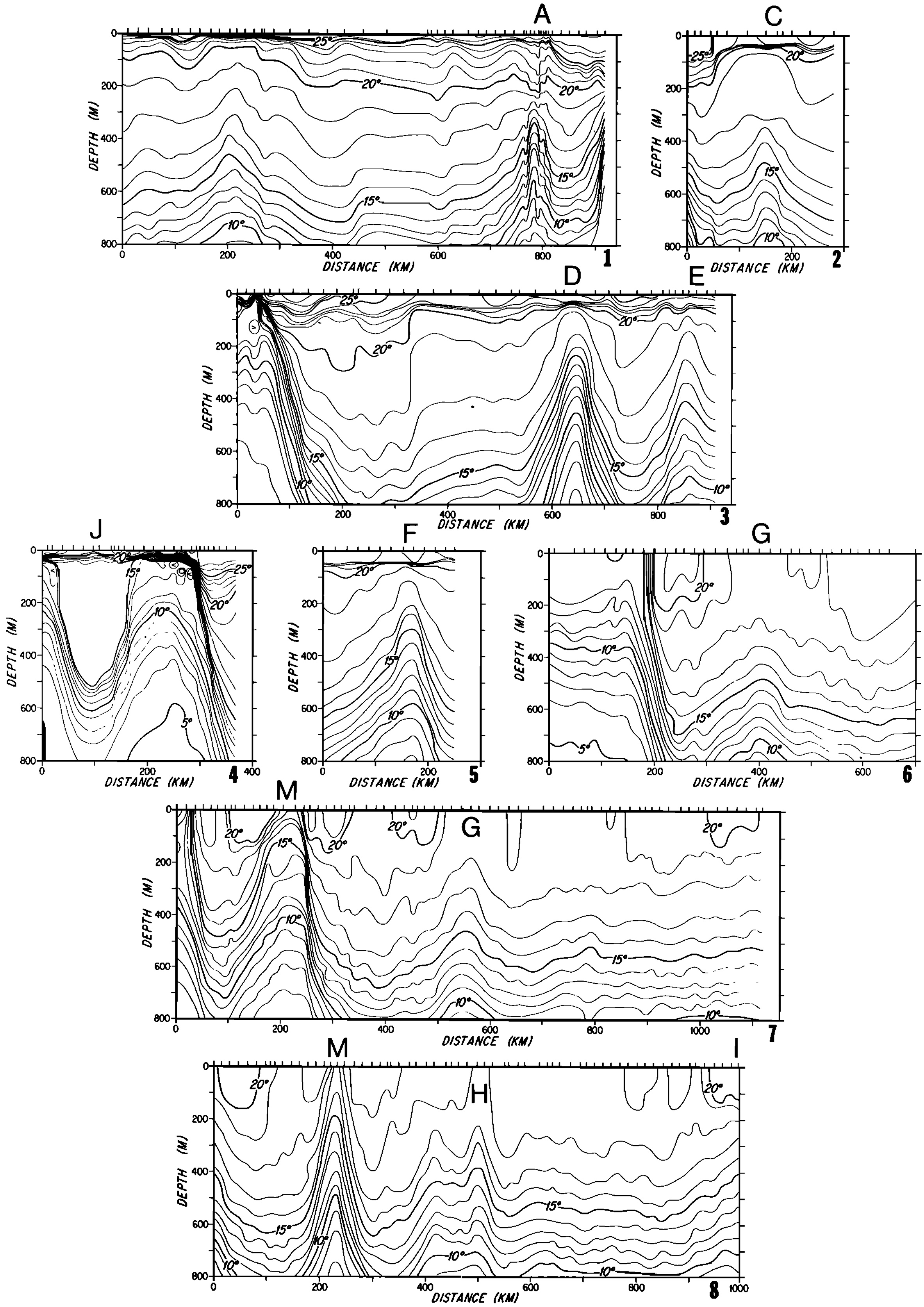

Fig. 4*a*. Vertical temperature sections through the Gulf Stream and rings based on XBT data. Letters A–I refer to individual rings.

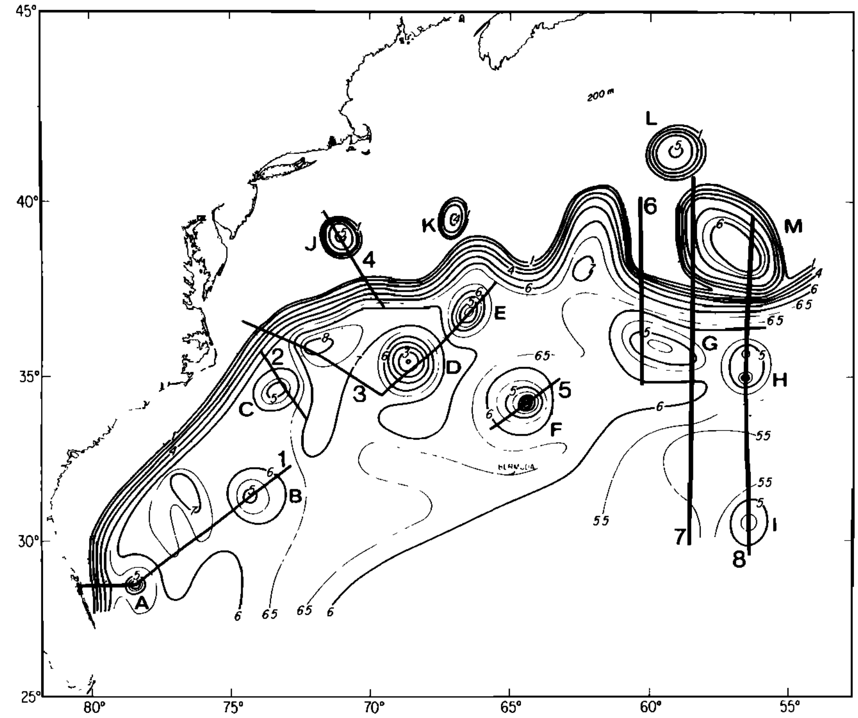

Fig. 4*b*. Location of XBT sections.

The character of the cold core rings east of about 60°W appears to be different from that of the rings to the west (Figures 3 and 4). The western rings appear nearly round; they have steep sides and a single peak. Eastern rings appear lumpier, have less slope to their flanks, and may not be very round (see the work of *McCartney et al.* [1978] for additional sections through the eastern rings). A possible explanation is that as the Gulf Stream passes over the New England Seamount Chain, it is split into filaments and made broader [*Fuglister,* 1963; *Vastano and Warren,* 1976]. Rings which form east of the seamount chain may reflect the Gulf Stream's character at the time of formation and therefore look different from the rings formed west of the seamount chain. *McCartney et al.* [1978] concluded that the eastern rings could have formed at the eastern extremity of the gyre, near 40°W, and moved westward.

Movement of the rings, inferred from repeated sightings and sometimes continuous tracking, is shown in Figure 5 (Table 2). For some of the rings the data are very good (B, D, J, K, and L), but for others it is spaced widely in time (A, E, F, and G) or nonexistent (C, H, and I), and therefore the trajectories of some rings are not very reliable. The general movement of the rings is to the southwest with typical mean speeds of 3–4 km/d This is in agreement with the results of *Lai and Richardson* [1977] based on a larger sample of rings. Apparently, few rings penetrate below 30°W except in the extreme western region, where they are found extending south to the Bahama Islands. Ring A was found attached to the Gulf Stream and presumably coalescing with it. The following is a brief description of each ring.

Ring A. Ring A was well surveyed by XBT in May 1975. It appears to be attached to the Gulf Stream and may be coalescing with it as another ring is believed to have done [*Richardson et al.,* 1973]. Two possible earlier sightings (Table 2) indicate a possible southwestward movement.

Ring B. Ring B was tracked from June 1974 to June 1975 by successive XBT surveys and satellite IR images and from October to January, 1974, by Sofar floats [*Cheney et al.,* 1976].

Ring C. Ring C was observed with only one XBT section across it, and thus its size and shape remain in question.

Ring D. Ring D is one of the best studied rings to date. It was first observed in March 1975 and was tracked until February 1977 with repeated ship and aircraft surveys, satellite IR images, and a free drifting buoy. There is good evidence for a mean southwestward movement at 3 cm s^{-1}, at least until ring D reaches the vicinity of the Blake Bahama Outer Ridge and Blake Escarpment, where the movement became erratic and difficult to follow.

Ring E. Ring E is a small ring, possibly one first observed on *Knorr* 48 in April 1975. There are several possible sightings which suggest that ring E also had a mean southwestward movement.

Ring F. Ring F is a large ring which moved westward after its initial observation in November 1974. *McCartney et al.* [1978] have described in detail the movement, velocity, and density structure of this ring.

Ring G. Ring G was observed with only two north-south XBT lines in March which were made 10 days apart. The data were interpreted as indicating a single ring whose center lies between the XBT lines. The size and shape of ring G remain in doubt. Evidence for the movement of this ring is slight and consists of three possible sightings over 7 months.

Ring H. Ring H was observed with only one north-south XBT line, and it was contoured with the assumption that it was symmetrical. Ring H was observed to have two peaks like other rings in the eastern region [*McCartney et al.,* 1978].

Ring I. Ring I was observed by an XBT crossing in its northwest quadrant. Its size and shape are largely extrapolated. The amplitude of ring I is not great, 100–150 m, but the XBT lines could have missed its center, and therefore this ring could be considerably more intense than is shown.

Ring J. Ring J was first seen on December 31, 1974, near

TABLE 2. Repeated Observations of the Rings

Date	Position °N	Position °W	Source or Platform	Data
		Ring A		
Feb. 15, 1975	30.5	76.5	NOAA/NESS	satellite IR
March 23, 1975	30.5	78.5	NOAA/NESS	satellite IR
May 26, 1975*	28.6	78.4	*Trident* 168	XBT
		Ring B		
June 17, 1974	34.2	65.0	*Sea Venture*	XBT
July 15, 1974	33.5	66.0	*Sea Venture*	XBT
July 29, 1974	34.0	66.3	*Sea Venture*	XBT
Aug. 12, 1974	34.2	66.8	*Sea Venture*	XBT
Sept. 29, 1974	32.5	69.0	*Lynch* 708–75	XBT, STD
Sept. 29, 1974 to Dec. 15, 1974†	32.5 to 33.5	69.0 to 73.0		
Jan. 22, 1974	33.5	74.7	NAVOCEANO	satellite IR
Jan. 27, 1975	32.5	74.3	NOAA/NESS	satellite IR
Feb. 12, 1975	32.0	75.0	NOAA/NESS	satellite IR
March 23, 1975	31.0	75.6	NOAA/NESS	satellite IR
April 9, 1975	31.2	75.2	*Duane, Lynch, Advance II*	STD, XBT
April 26, 1975	30.5	76.0	NOAA/NESS	satellite IR
June 1, 1975*	31.3	74.2	*Trident* 168	XBT
		Ring C		
July 2, 1975	34.5	73.3	*Lynch* 708–75	XBT
		Ring D		
March 24, 1975	36.5	66.2	NOAA/NESS	satellite IR
April 10, 1975	36.5	66.7	NAVOCEANO	AXBT
April 24, 1975	36.0	66.8	NOAA/NESS	satellite IR
May 12, 1975	35.7	67.2	NOAA/NESS	satellite IR
May 21, 1975	35.7	67.7	NAVOCEANO	AXBT
June 7, 1975	35.9	68.3	*Trident* 168	XBT, CTD
June 17, 1975	35.5	68.5	NAVOCEANO	AXBT
June 25, 1975*	35.4	68.6	*Lynch* 708–75	XBT, STD
July 8, 1975	35.7	69.5	NAVOCEANO	XBT
Aug. 8, 1975	34.6	69.9	*Chain* 125	XBT
Sept. 3, 1975	35.2	70.0	NAVOCEANO	Sofar float
Sept. 10, 1975	35.3	70.7	*Chain* 127	XBT
Sept. 26, 1975	34.5	70.7	NAVOCEANO	Sofar float
Oct. 14, 1975	34.8	70.8	NAVOCEANO	AXBT
Oct. 14, 1975	35.0	71.0	*Eastward*	XBT
Nov. 20, 1975	33.9	71.9	*Knorr* 53	XBT
Jan. 6, 1976	33.8	73.0	NAVOCEANO	satellite IR
Jan. 13, 1976	33.6	73.2	NAVOCEANO	satellite IR
Feb. 5, 1976	33.5	73.6	NAVOCEANO	satellite IR
Feb. 11, 1976	33.5	73.7	NAVOCEANO	satellite IR
Feb. 14, 1976	33.8	73.8	NAVOCEANO	AXBT
Feb. 25, 1976	33.7	73.4	NAVOCEANO	satellite IR
Feb. 29, 1976	33.7	73.3	NAVOCEANO	satellite IR
March 1, 1976	33.6	73.6	NAVOCEANO	satellite IR
March 7, 1976	33.0	73.5	NAVOCEANO	satellite IR
April 24, 1976	32.5	74.0	NAVOCEANO	satellite IR
May 20, 1976	32.2	75.0	NAVOCEANO	satellite IR
June 7, 1976	31.8	75.5	*Oceanus* 7	XBT
June 7, 1976 to Sept. 10, 1976‡	31.8 to 31.9	75.5 to 75.1		
Sept. 20, 1976	32.3	75.1	*Wilkes*	XBT, STD
Oct. 5, 1976	32.3	74.2	NAVOCEANO	satellite IR
Dec. 17, 1976	31.0	75.3	NAVOCEANO	satellite IR
Feb. 23, 1977	30.0	75.3	NAVOCEANO	satellite IR
		Ring E		
April 11, 1975	35.9	64.5	*Knorr* 48	XBT
April 24, 1975	36.0	64.5	NOAA/NESS	satellite IR
June 28, 1975*	37.0	66.5	*Lynch* 708–75	XBT
July 4, 1975	36.5	66.4	NAVOCEANO	satellite IR
Aug. 4, 1975	36.0	67.0	NOAA/NESS	satellite IR
Sept. 2, 1975	35.2	67.0	Gulf Stream	
Sept. 30, 1975	35.0	67.7	Gulf Stream	
Oct. 16, 1975	34.2	66.6	NAVOCEANO	AXBT's
		Ring F		
Nov. 15, 1974	34.8	56.5	*Knorr* 43	XBT
Jan. 24, 1975	34.6	59.8	*Chain* 118	XBT
March 25, 1975	34.2	62.7	*Knorr* 48	XBT
April 30, 1975	33.6	64.0	*Knorr* 49	XBT
May 1, 1975	33.0	64.3	current meter	velocity
June 17, 1975	34.0	65.0	NAVOCEANO	AXBT
July 5, 1975*	34.1	64.3	*Lynch* 708–75	XBT
Sept. 15, 1975	33.8	68.0	*Chain* 127	XBT
Oct. 16, 1975	33.0	67.5	NAVOCEANO	AXBT
Oct. 16, 1975	33.3	67.0	*Eastward*	XBT
		Ring G		
Oct. 15, 1974	37.8	56.5	*Knorr* 48	XBT
March 24, 1975	35.8	59.5	*Knorr* 48	XBT
May 17, 1975*	35.2	61.5	*Knorr* 49	XBT
		Ring H		
March 25, 1975*	35.5	56.4	*Knorr* 48	XBT
		Ring I		
April 3, 1975*	30.5	56.5	*Knorr* 48	XBT
		Ring J		
Dec. 31, 1974	41.3	62.0	NOAA/NWS (vol. 1, no. 12)	satellite IR (first formed)
June 29, 1975*	39.0	71.0	*Lynch*	XBT
Nov. 5, 1975	36.0	74.0	NAVOCEANO	satellite IR (coalesced)
		Ring K		
April 15, 1975	40.2	63.5	NAVOCEANO	satellite IR (first observed)
June 22, 1975*	39.5	67.1	NAVOCEANO	satellite IR
July 6, 1975*	39.5	67.7	NAVOCEANO	satellite IR
Dec. 20, 1975	35.5	74.5	NAVOCEANO	satellite IR (coalesced)
		Ring L		
March 19, 1975*	41.1	59.0	NOAA/NESS	satellite IR (first formed)
March 24, 1976	36.5	73.0	NAVOCEANO	satellite IR (coalesced)

Warm rings can be followed throughout their lifetimes with satellite IR imagery; trajectories in Figure 5 were determined primarily from *NAVOCEANO* [1975]. Additional position information has been found in Gulf Stream (December, 1975) and in *Bisagni*'s [1976] report.
*Observations used in Figure 1.
†Tracked by Sofar floats [*Cheney et al.*, 1976].
‡Tracked by free drifting satellite buoy.

41.3°N, 62.0°W and last seen on November 5, 1975, coalescing with the Gulf Stream off Cape Hatteras near 36.0°N, 74.0°W. An isothermal, 15.5°C layer formed by winter cooling extended from 70 to 430 m at its center when it was observed in June 1975.

Ring K. Ring K formed from the meander shown in Figure 1 along 62°W in mid-April 1975 near 40.2°N, 63.5°W. It moved southwestward and coalesced with the Gulf Stream by the end of December 1975 near 35.5°N, 74.5°W. Ring K was observed solely with satellite IR images.

Ring L. Ring L formed in mid-March 1975 near 41.1°N, 59.0°W. It moved southwestward, possibly coalescing with the Gulf Stream and reforming again in May 1975. By March 24, 1976, it had coalesced with the Gulf Stream near 36.5°N, 73.0°W. Ring L was observed solely with satelite IR images.

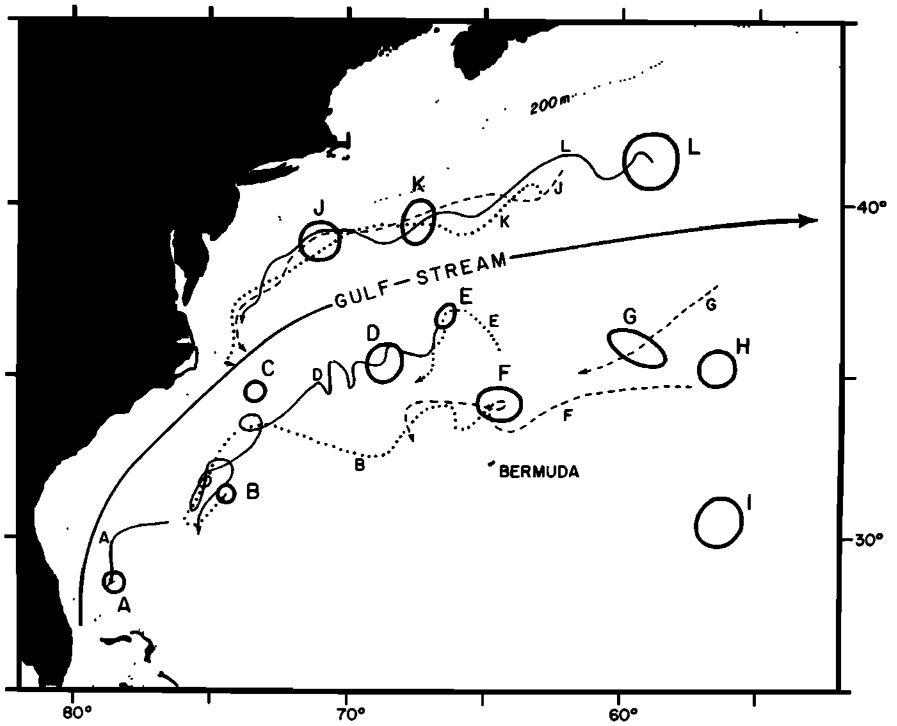

Fig. 5. Inferred trajectories of the rings. Trajectories are based on successive observations and reasonable velocities (see text).

DISCUSSION

For the first time a 'weather map' has been prepared for a 4-month period of the western North Atlantic Ocean. The map shows the location of the Gulf Stream and the distribution of warm and cold core rings. Two important questions about this map need to be answered. The first is how much distortion occurs in the map due to movement of the features during the 4-month period over which the data were obtained. The second is whether it represents typical or anomalous conditions.

The map can be divided into four regions in which the data can be considered synoptic, e.g., the movement of the major features (rings) was relatively small compared to the size of the features. A potential problem occurs where the edges of these regions meet. The worst difficulty is between regions I and IV where there is a gap in time of 11 weeks. The Gulf Stream did not appear to make large shifts across this boundary except for the formation of ring K. There was apparently a westward movement of the rings, but no ring moved so far as to be shown twice. The effect of the time jump between regions I and IV is to spread out the rings in an east-west direction. If the western region had been surveyed first, the rings would have appeared more crowded. One can imagine that if region I had been surveyed 4 months later, the whole pattern could have moved west, and an additional ring could have moved into the region.

We have compared Figure 1 with other, more limited XBT surveys and satellite IR data for other periods of time and conclude that it represents a rather typical picture of the Gulf Stream system. The region to the north of the Gulf Stream frequently has three rings in it as seen on satellite infrared images. However, at times, no rings can be seen there, and at other times, as many as six rings can be identified. The few occasions for which simultaneous satellite IR and XBT measurements exist, for example, during June 1975, have confirmed our identification of rings with infrared images.

Rings to the south of the Gulf Stream are not easily detectable on satellite IR images, and we need to depend on deep XBT's, CTD's, or hydrographic stations. Recent data in the 1970's tend to confirm that the distribution of cold core rings shown in Figure 1 is typical, or at least is not anomalous [*Lai and Richardson*, 1977; *McCartney et al.*, 1978].

Acknowledgments. We are pleased to acknowledge the support of the International Decade of Ocean Exploration of the National Science Foundation under grant OCE75-08765 and the Office of Naval Research under contract N00014-74-C-02621 NR 083-004. George Heimerdinger helped obtain data from NODC. NOAA/NESS provided the satellite infrared imagery. Claes Rooth provided data taken from the R/V *Gillis* which were not available at NODC. This paper is contribution number 4126 of the Woods Hole Oceanographic Institution and number 102 of the Mid-Ocean Dynamics Experiment.

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(Received March 29, 1978;
revised July 26, 1978;
accepted July 26, 1978.)