Distribution and Movement of Gulf Stream Rings[1]

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(Manuscript received 4 February 1977, in revised form 19 May 1977)

ABSTRACT

The distribution, number and movement of cyclonic Gulf Stream rings were estimated from an analysis of 50 000 temperature records obtained from the National Oceanographic Data Center and Fleet Numerical Weather Central. The data were taken from 1970 through September 1976 in the region bounded by 20–40°N and 50–80°W. Additional ring observations from other sources were also used. Twenty-five ring time series, together with 26 single ring observations were obtained; approximately 11 rings were found to exist at one time. Rings typically moved westward, turned southwest when close to the Gulf Stream and appeared to coalesce with the Stream near Florida. On the average, two rings per year moved down this path with a mean speed of 3 km day^{-1} and an estimated life span of 2–3 years. Although ring observations were concentrated in the northwestern Sargasso Sea, several were documented east of 60°W. In addition to cold core rings several warm eddies were found south of the Stream; they consisted of at least a 150 m deepening of the main thermocline. The movement of anticyclonic rings north of the Stream was also determined; approximately three exist at a single time and they move westward with a mean speed of 5 km day^{-1}.

1. Introduction

Despite considerable effort spent studying Gulf Stream rings, their movement, geographical distribution and number at a given time remain largely unknown. This is due to the difficulty and expense of following rings by ship and aircraft and the lack of adquate remote techniques to track rings in time. In this study we tried to use all data sources—bathythermograms, hydrographic stations and satellite infrared imagery—in an attempt to reveal the general distribution and movement of rings.

We searched through data files in order to find cold anomalies that could be ascribed to cyclonic rings. A newly formed cyclonic ring consists of a cold core with the thermocline raised as much as 500–600 m (Fig. 1). In order to locate anomalies, the mean temperature field of the Sargasso Sea was computed, then ring anomalies equivalent to a minimum of 150 m vertical thermocline displacement were identified. Finally ring trajectories were inferred based on successive observed anomalies and reasonable rates of ring movement. An analysis similar to this was performed by Parker (1971) using all data on file at WHOI from 1932 to 1970. The main difference in this new study was the significantly increased number of ring observations due to the large numbers of recently taken AXBT's and deep XBT's plus high-quality satellite infrared imagery.

It has become increasingly clear that ocean motion is dominated by mesoscale variability or eddies. The most energetic eddies in the ocean are those generated by the strong western boundary currents. An example of these are Gulf Stream rings which form from large meanders in the Stream (Fuglister, 1972). These rings are responsible for a significant part of the recirculation of the Gulf Stream water via their formation, movement and final coalescence with the Stream. They are thought to play an important role in the transfer of energy from the Stream to mid-ocean areas as transient eddies and in redistributing low-frequency mesoscale energy, momentum, chemicals and biota in the ocean. Hence the study of rings is important both to the understanding of the Gulf Stream system and the dynamics of the mid-ocean regions.

2. Data acquisition

The primary sources of data were the National Oceanographic Data Center (NODC) and Fleet Numerical Weather Central (FNWC). Fifty thousand temperature records were obtained from the period 1970–76 in the region bounded by 20–40°N, 50–80°W (Fig. 2). Most of the data, 97%, were from the period

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[1] MODE Contribution No. 88 and Woods Hole Oceanographic Institution Contribution No. 3946.

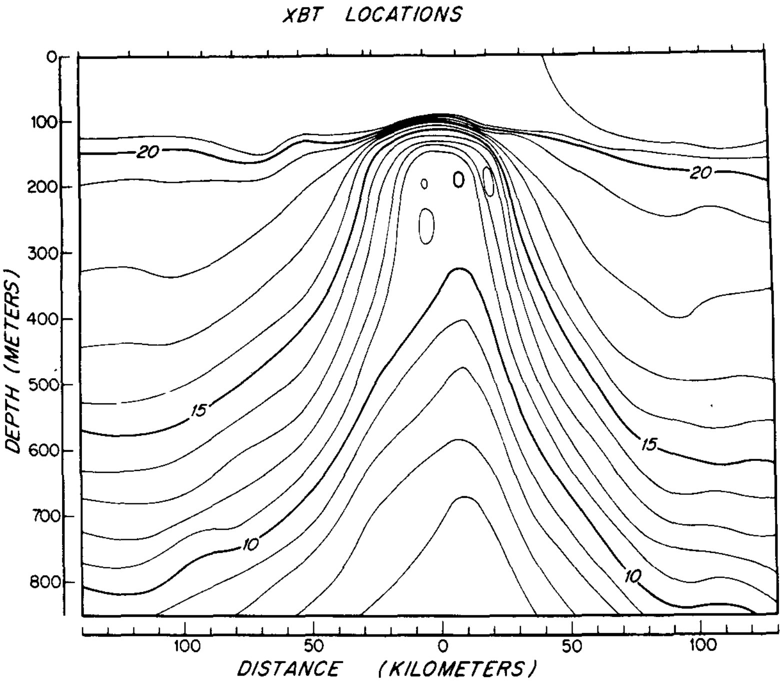

FIG. 1. Temperature section (southwest to northeast) through a cyclonic Gulf Stream ring. The data were taken during December 1975 on R/V *Trident* cruise 175; the ring was centered near 36°N, 58°W. The central core of the ring contained cold, fresh slope water with isotherms rising about 500 m above their mean depth in the Sargasso Sea. The diameter of water colder than 15°C at 500 m is 140 km; the overall size of the ring can be seen to be approximately 200 km. This ring appears to be young and small–medium sized.

1970–73. Lack of more recent data is due to the typical 1–2 year lag between the time the data were taken and the time they are available from NODC.

The records are unevenly distributed and are concentrated heavily in the Gulf Stream and western Sargasso Sea. An abrupt decrease in data density was found in the region east of 65°W, the longitude of Bermuda. There are also some apparent erroneous data which appear on land areas. Data were mostly from 450 and 750 m expendable bathythermographs (XBT's) together with a few salinity-temperature-depth stations (STD's) and hydrographic stations (Fig. 3, Table 1). They were taken from a variety of ships including oceanographic, Navy, merchant and fishing vessels.

Three other sources of data were particularly helpful in this study; they were the U. S. Naval Oceanographic Office (NAVOCEANO), *Polymode News*, and the National Environmental Satellite Service (NESS) of NOAA. A detailed list of published and unpublished references to rings is given in the Appendix.

Although most of the XBT's taken by NAVOCEANO were not available from NODC or FNWC, a summary of their results has been published in the *Gulf Stream Monthly Summary* (U. S. Naval Oceanographic Office, 1970–74) and more recently in *Gulf Stream* (NOAA, National Weather Service, 1975–76). In addition several NAVOCEANO scientists, in particular R. Cheney, G. Gotthardt and R. Perschal, generously provided unpublished cruise and flight reports and analyses of satellite infrared (IR) photos and ship injection temperatures.

During the last three years of this study numerous ring observations were obtained from individual studies in the form of personal communications. Fortunately many of these have been presented in *Polymode News*, formerly *MODE Hot Line News*, which is produced at WHOI.

Satellite IR imagery has recently proved valuable in identifying both newly formed rings and those that are adjacent to the Gulf Stream and which have entrained warm Stream water and advected it cyclonically around themselves. During winter months when the surface thermal contrast across the Gulf Stream and nearby rings is greatest satellite IR photos are particularly useful in identifying rings. We obtained photos from NOAA, NESS and made our own interpretations as well as using those obtained from NAVOCEANO and NESS.

3. Method of analysis

Data analysis consisted of computing the mean temperature field at five different depths. Anomalies from the mean, equivalent to a 150 m upward displacement

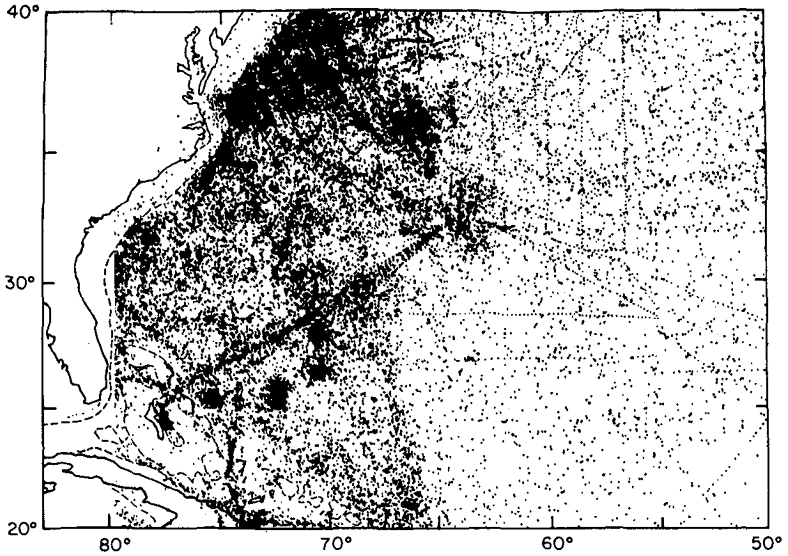

FIG. 2. Geographical distribution of all temperature records reaching a depth of at least 300 m. Data are concentrated heavily in the Gulf Stream and the western Sargasso Sea. There is a substantial decrease in data density in the region east of 65°W. Bermuda can be recognized easily by the numerous ship tracks leading to it. There are a few regions of high data density in the Sargasso Sea, associated with large experiments such as MODE and IWEX. Data points on land are probably due to erroneous positions.

of the isotherms, were identified. A "ring observation" was defined to consist of at least three anomalies taken within a 5-day period and within a 100 km diameter. Since the identification of rings depends strongly on what is considered an anomaly, the mean temperature field and ring criteria are carefully described below.

Temperature anomalies equivalent to a minimum displacement of an isotherm from its mean depth were identified by considering the mean vertical temperature gradient and the difference in mean temperature fields between two depths. Maps of mean horizontal temperature field at various depths were used instead of maps of mean isotherm topography because the latter would have been cold-biased. For example, all XBT's that did not reach deep enough to encounter a hypothetical isothermal surface would have been omitted from the computation and the mean depth of such a surface would have been erroneously shallow.

TABLE 1. Data summary.

Temperature record	Fleet Numerical Weather Central	National Oceanographic Data Center	Total number
XBT's	29 194	20 143	49 337
STD stations	117	1 073*	1 190
Hydrostations	161	0*	161
	29 472	21 216	50 688

* The NODC data file does not distinguish between STD's and hydrostations.

4. Mean temperature field

The region was divided into small bins, 1°×1° or 2°×3° depending on data density, and the mean temperature at depths of 300, 450, 500, 600, 700 m in each bin computed (Fig. 4). Frequently the large number of ring observations in a bin biased the data and gave an unrealistically low mean temperature and large temperature variance. These cold data were removed from the data set in order to obtain a more representative mean temperature field. Those which deviated from a preliminary mean temperature by one standard deviation in bins whose rms temperature was greater than 1°C were removed and the mean temperature was recomputed from the remaining data. The mean temperatures in a few bins which contained extremely few data or a high percentage of ring data were obtained by interpolating between adjacent values.

Temperature contour maps were made by linear interpolation between mean temperature values of adjacent bins (Fig. 5). The mean position of the Gulf Stream coincides with the large horizontal temperature gradient; the axis of the mean Stream coincides with the 13°C isotherm at 300 m, equivalent to the 15°C isotherm at 200 m. At 300 m the field is dominated by subtropical mode (Warren, 1972) or 18°C water (Worthington, 1959) which extends south to nearly 20°N. In the deeper layer, 700 m, the center of the subtropical gyre is located near 34°N and 72°W. South and east of this point the main thermocline rises gradually, indicative of the broad Gulf Stream recirculation zone.

A search was made for seasonal variations in the main thermocline but none was resolvable from the noise level which was approximately ±50 m. The time-averaged temperature field was therefore used to detect rings.

5. Ring criteria

In general practice and as a convenient standard, the size of a ring is estimated from the extent of the 15°C water at a depth of 500 m (Cheney and Richardson, 1976). Since the depth of the 15°C surface lies near 650 m in the northwestern Sargasso Sea, the criterion is equivalent to a 150 m upward displacement of the isotherms from the mean field. A 150 m displacement is about twice the displacement amplitude of eddies in the MODE area (Draft Synoptic Atlas, 1974) and much larger than the 7 m rms amplitude of internal waves (Briscoe, personal communication). Thus a temperature anomaly equivalent to 150 m or more upward displacement of the thermocline was chosen to be indicative of a ring. Furthermore a "ring observation" was chosen to consist of at least three anomalies observed within a 5-day period within a 100 km diameter. The 5-day period and 100 km diameter criteria are based on realistic values of ring size and movement. The criterion of three anomalies was used to reduce the effect of erroneous data. Parker (1971) in his study using older and shallower BT files used the same criteria.

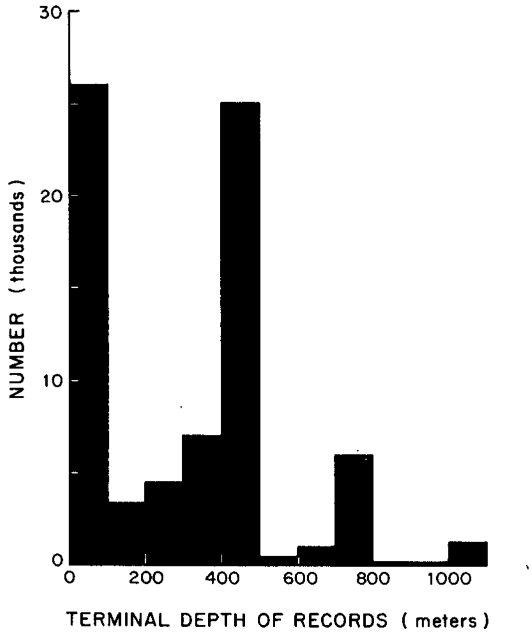

FIG. 3. Frequency distribution of terminal depth of the records. Distribution is trimodal; the peaks represent surface temperature measurements, and 450 m and 750 m XBT's. Since most of the data below the seasonal thermocline were 450 m XBT's, this level was chosen for the main analysis. Large fluctuations in sea surface temperatures due to seasonal and shorter period variability prevented the effective use of surface temperature records in identifying ring anomalies.

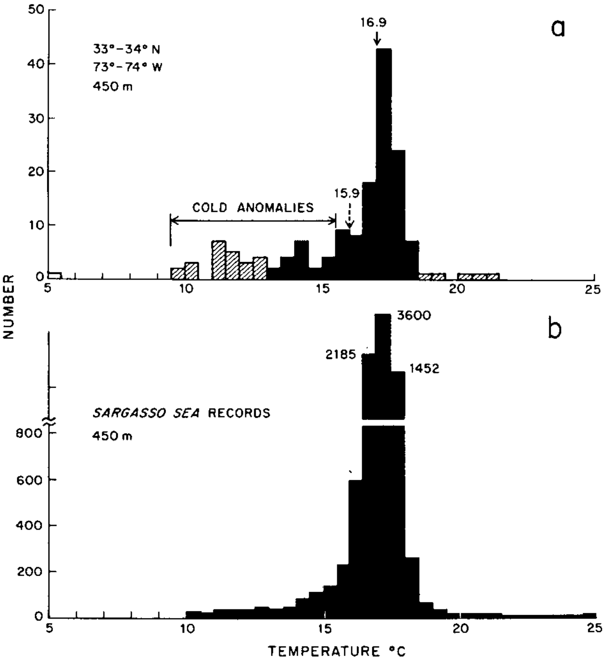

FIG. 4a. Frequency distribution of temperature records at 450 m in the 1° square 33–34°N, 73–74°W. The broken arrow indicates the preliminary mean temperature 15.9°C computed from all the data. The large number of ring observations gave a low preliminary mean temperature. Those temperature records which differed from the mean by at least one standard deviation were removed and the mean temperature 16.9°C was computed from the remaining data (shaded portion) and is indicated by the solid arrow. All temperature records below 15.5°C were identified as anomalies equivalent to at least a 150 m rise in the thermocline. Temperatures above 19°C are considered erroneous.

FIG. 4b. Frequency distribution of all temperature records at 450 m in the warm core of the Sargasso Sea, the region with a mean temperature field higher than 17°C at 450 m. Temperatures above 19°C are probably erroneous.

Ring criteria were varied to see how they changed the results. Although the total number of ring observations changed with variations in time and size criteria (up to two weeks and 200 km, respectively), ring trajectories and the total number of different rings did not vary significantly. Variations in the criteria of height anomaly, however, did show significant differences.

When the height criterion was shifted from 150 to 100 m the number of anomalies increased by a factor of 3 in the southwest region; the increase was smaller in other regions although a large number of the additional anomalies were associated with previously identified rings obtained from 150 m anomalies. Five new "ring observations" were identified. Attempts to infer ring time series from 100 m anomalies proved fruitless; the results depended critically on subjective decisions as to which anomalies to use and which to disregard. When the height criterion was lowered to a 50 m dis-

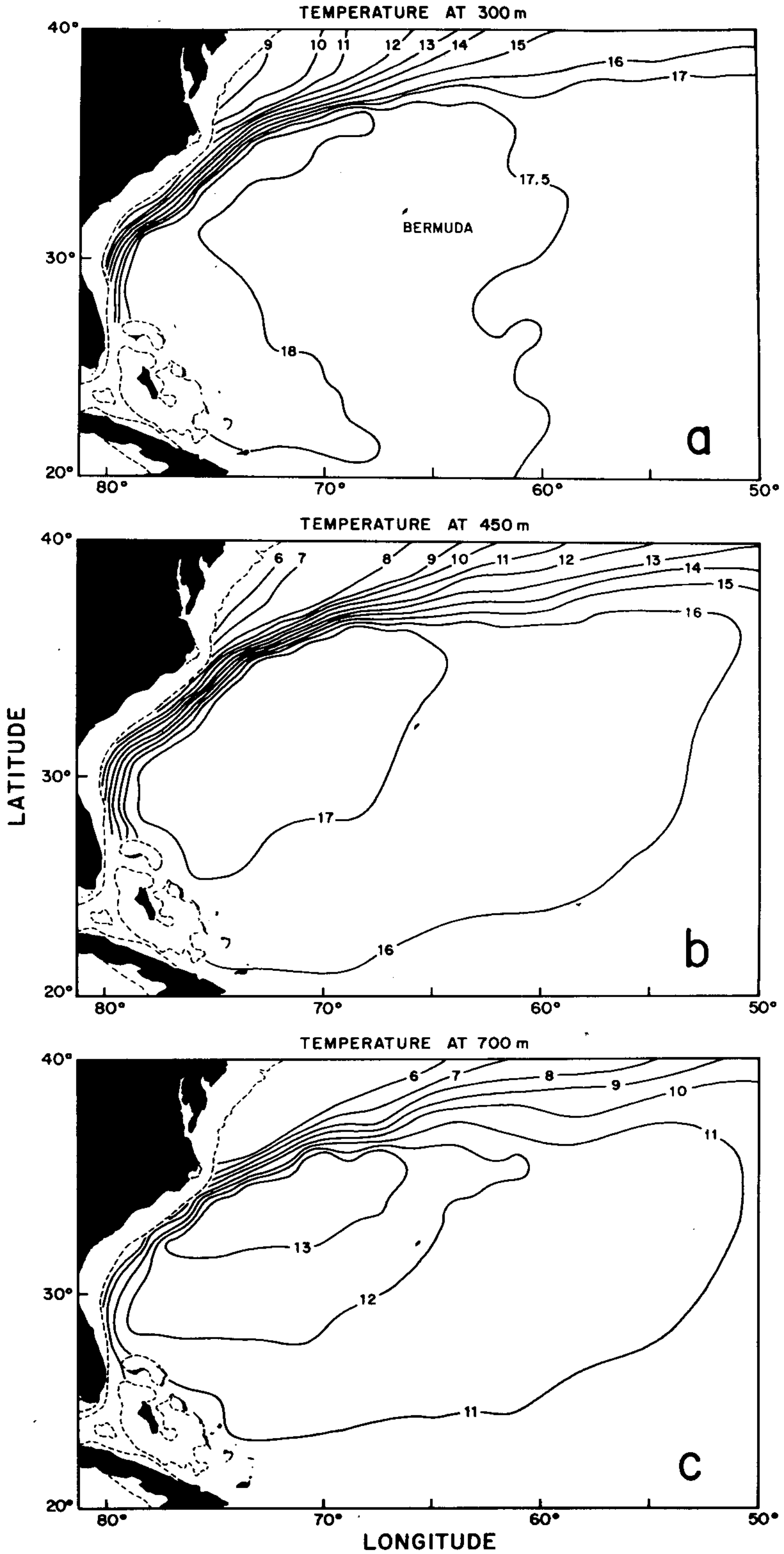

FIG. 5. Contours of mean temperature at depths of 300, 450 and 700 m. Maps were made by linear interpolation of temperature values of adjacent bins. The Gulf Stream is shown clearly as the regions of high horizontal temperature gradient. At 300 m the field is dominated by 18°C water (Worthington, 1959). In the main thermocline, the center of the subtropical gyre is near 34°N, 72°W; the main thermocline rises south and east of this point, indicative of the Gulf Stream recirculation gyre (Worthington, 1977).

placement, even "ring observations" could not be identified without much subjective choosing of anomalies. When the anomaly criterion was increased to 200 m or more most of the measurements taken from ships of opportunity were eliminated since frequently they were not taken near the center of rings; it was impossible to infer movement of rings from the few ring observations identified.

Temperature anomalies were identified in the region bounded by 20°N, 50°W, the Gulf Stream and the Antilles and Bahama Islands and "ring observations" were chosen from those data which satisfied the ring criteria. To avoid the possibility of misidentifying meanders of the Stream as rings we excluded ring observations within 200 km south of the mean Gulf Stream axis (Parker, 1971) unless additional measurements were available that suggested a ring was close but unattached to the Stream. Ring observations, together with those anomalies which did not satisfy the ring criteria, were used to trace the movement of individual rings. The main analysis concentrated on finding anomalies at a depth of 450 m. This depth was chosen because of the large number of data, primarily 450 m XBT's (Fig. 3), and the strong temperature gradient between 450 and 600 m. Temperature anomalies at 400, 500 and 700 m were used but they did not contribute additional ring observations. Records at 300 m were also used to supplement the 450 m analysis but the small temperature gradient between 300 and 450 m made the identification of anomalies difficult.

When cyclonic rings first form they consist of a central mass of slope water surrounded by a ring of Gulf Stream water. Measurements of temperature and salinity inside at least ten of the rings described below revealed an anomalous *T-S* relation (from that of the Sargasso Sea) indicative of slope water. Although the majority of ring observations did not have supporting salinity measurements, those that did gave us confidence that others were also rings.

Six percent of the data set, 1122 temperature records, was identified as cold anomalies at 450 m. The percentage of anomalies in the data is highest in the northwestern region indicating a higher probability of finding rings there (Table 2). A lower probability of finding rings in the southwestern region is suggested by the lower percentage of anomalies there. The small number of data in the eastern region suggested a large uncertainty in computations of the probability of finding rings in this region.

Some data from the same set of instruments and vessels were of questionable quality. In order to reduce the amount of erroneous data, individual temperature profiles were checked for possible errors such as incorrect position, temperature inversions, spikes, etc., and those that looked suspicious were discarded. Ring observations were checked by comparing them to non-anomalous observations; if there was a conflict the ring observation was discarded. Of the total number of cold anomalies, 72% (804) were used to construct ring observations and time series.

Table 2. Summary of 150 m height anomalies at the depth of 450 m. The number in parenthesis is the 90% confidence limits. If P is the proportion of success in a sample of size N drawn from a binomial population in which p is the proportion of success, then the confidence limits for p are given by $P \pm Z_c[p(1-p)/N]^{\frac{1}{2}}$, where Z_c is the confidence coefficient. The computation was done by assuming all temperature records were independent and using the sample proportion P to estimate p.

	Number of data	Number of anomalies	Percentage of anomalies
Northwestern Sargasso Sea (30–40°N, 60–80°W)	10 775	948	8.8(±0.4)
Southwestern Sargasso Sea (20–30°N, 65–80°W)	5 520	71	1.3(±0.3)
Northeastern Sargasso Sea (30–40°N, 50–60°W)	1 603	84	5.2(±0.9)
Southeastern Sargasso Sea (20–30°N, 50–65°W)	627	19	3.0(±1.1)

6. Cyclonic Gulf Stream rings

A total of 163 ring observations were identified using all available sources. Forty-three of these were obtained from NODC and FNWC data files, 38 from other XBT data, 50 from NAVOCEANO XBT's and AXBT's and 32 from satellite photos (Table 3). The movement of individual rings was inferred from the 163 ring observations plus single anomalies which did not satisfy the ring criteria. The single anomalies were helpful in filling in gaps between successive ring positions. Twenty-five ring time series and twenty-six single ring observations were obtained (Figs. 6 and 7). Some of the single rings may be repeated observations of the same rings separated widely in time and space. Thirteen of the time series were long, covering periods from 1–2 years (Fig. 8). An additional six series were established using only one or two anomalies. If the

Table 3. Summary of ring observations.

Years	NODC/ FNWC data file	NOVOCEANO XBT's/ AXBT's	Others XBT's	Satellite photos	Total number
1970–73	42	23	1	4	70
1974–76	1	27	37	28	93
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	43	50	38	32	163

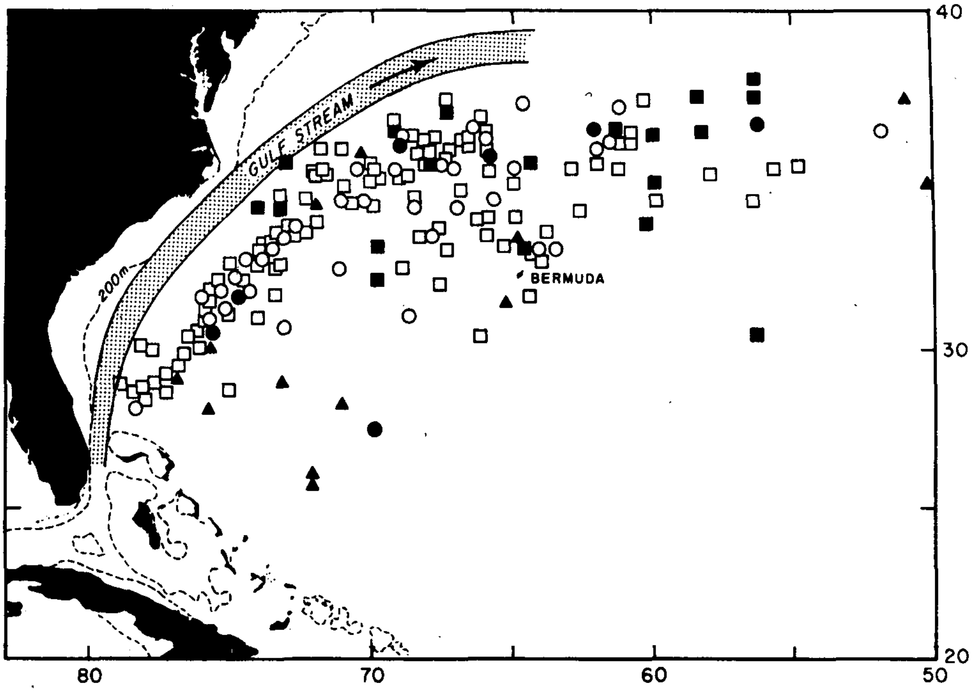

FIG. 6. Geographical distribution of the 163 ring observations. Circles indicate observations from 150 m anomalies based on NODC and FNWC data, squares observations from other sources such as XBT and satellite data (see Table 3), and triangles an additional 13 observations from 100 m anomalies (see text). Solid symbols represent single observations which were not a part of time series. Most of the observations are concentrated in the northwestern Sargasso Sea where the data are densest.

single anomalies and rings seen by satellite imagery are omitted the individual ring trajectories are more numerous and shorter but the general pattern remains the same.

The majority of rings was found in the northwestern Sargasso Sea where the highest data density was found. At least 15 rings appeared to be formed between 60–70°W. Eight rings moved westward until their centers were within 200 km of the Gulf Stream axis. They then turned southwestward and moved along a path parallel to the Stream and appeared to coalesce with the Stream near Florida.[2] Twelve rings moved down this path during the seven years under study, an average of about two per year. Since there may have been undetected rings this estimate should represent a minimum rate. If the rings were assumed to form between 60–70°W and move with an average speed of 3 km day^{-1}, the average life span of rings following this path would be 2–3 years.

Seven rings were found south of 32°N in the western region away from the Gulf Stream. Their motion may consist of a larger southward component into the Sargasso Sea as compared to the westward movement described above. It is possible that many rings moving into this region could have decayed to a point beyond recognition as Gulf Stream rings. This could explain the "cold spots" in the southern Sargasso Sea mentioned in the MODE Draft Synoptic Atlas.

Eleven rings were found in the region east of 60°W which Parker (1971) using shallower mechanical BT's had found to be devoid of rings. A description of several of these rings which appear to be larger than those west of 60°W is given by McCartney *et al.* (1977). The evidence suggests these rings also moved westward and may constitute a significant fraction of those observed to the west of 60°W.[3] An earlier study (Mann, 1967) had suggested that cyclonic rings could break off from the Stream as far east as 41–42°W. No rings were found south of 30°N and east of 65°W. Although there were some temperature anomalies there, the data were too sparse to meet the ring criteria. The question of whether rings are found in this region remains unsolved.

Rings moved with various speeds ranging from 1 to 8 km day^{-1} (Fig. 9). Speeds were estimated from the

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[2] There have been no direct observations of a ring coalescing with the Gulf Stream in this region. Rings appear to move consistently toward Florida where they have been observed on the Blake Plateau and partially attached to the Stream (Cheney and Richardson, 1975; Richardson, 1976). The simplest and most consistent explanation of the available data is that rings coalesce with the Stream off Florida.

[3] One of these rings was tracked using a satellite buoy (Richardson *et al.*, 1976); the ring moved northeastward for 2.5 months and coalesced with the Stream. We think this ring is unrepresentative of the long-term mean ring movement.

positions of the center of adjacent ring observations, sometimes rather subjectively, especially when there were few anomalies in a ring observation. Speed varied not only from ring to ring, but also along the path of the same ring. The mean speed was 3.0 km day^{-1} and 88% of the speed determinations fell between 1 and 5 km day^{-1}. There is no apparent relationship between the speed and the age or position of a ring.

In order to estimate the number of rings co-existing at a single time, the data set was scrutinized for the time of highest data density and greatest number of ring observations. November 1971 was chosen; it was a time during which numerous measurements were being made in the western Sargasso Sea. Ring positions during November 1971 were estimated using the rings' direction of motion and an average speed of 3.0 km day^{-1}. Eleven rings were found; they were concentrated in the western Sargasso Sea (Fig. 10, Table 4). Although the low data density in the eastern and southeastern region suggests the possibility that additional rings could have existed there, a recent near-synoptic ring survey (Cheney and Richardson, 1975) agrees closely with the number estimated here.

Previous estimates of the number of cyclonic rings that form per year range from 5 to 8 (Newton, 1961; Fuglister, 1972). If the average life span is two years, the estimated number of rings is 10–16 which agrees with our findings.

7. Warm Rings

Although our primary focus in this study was on cold rings, we made an attempt to describe the distribution and movement of warm rings. Anticyclonic or warm rings are formed from pinched-off meanders north of the Gulf Stream in the slope water region (Saunders, 1971; Gotthardt, 1973a). They appear to form in a similar manner as cold rings except that in their centers lies warm Sargasso Sea water.

In one way warm rings are simpler to study than cold rings for they are confined to a relatively small triangular region bounded on the south by the Gulf Stream and on the north by the continental slope. In another way they are more complex because the slope water region has frequency intrusions of large Gulf Stream meanders, thus searching for warm anomalies ascribable to warm rings becomes proble-

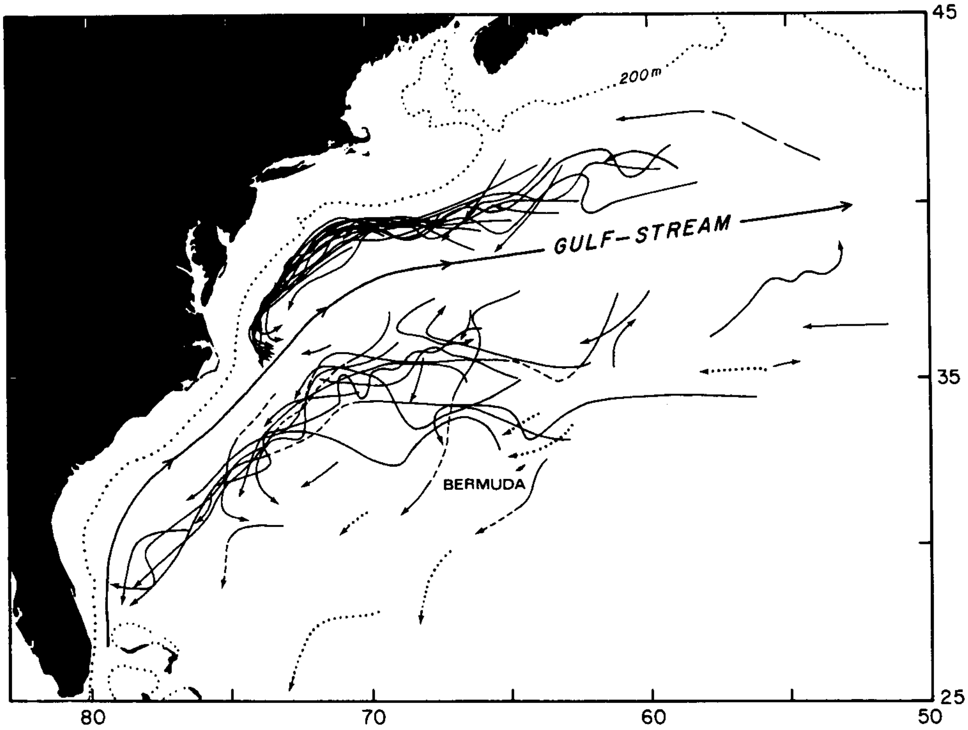

FIG. 7. Ring trajectories.

COLD RINGS SOUTH OF THE STREAM. Unbroken lines represent inferred ring time series, dashed lines indicate a gap of more than three months in a series, and dotted lines are rings that did not meet the ring criteria. It appears that there are two types of cold ring movement. Some rings moved westward until they were close to the Stream, then they turned southwest and appeared to coalesce with the Stream near Florida. Other rings moved in a more southward direction into the Sargasso Sea. Detailed observations of six cold rings are shown in Fig. 8.

WARM RINGS NORTH OF THE STREAM. Movement of warm rings is westward; their mean track is confined between the continental slope and the Gulf Stream. Warm rings routinely coalesce with the Stream near Cape Hatteras, N. C.

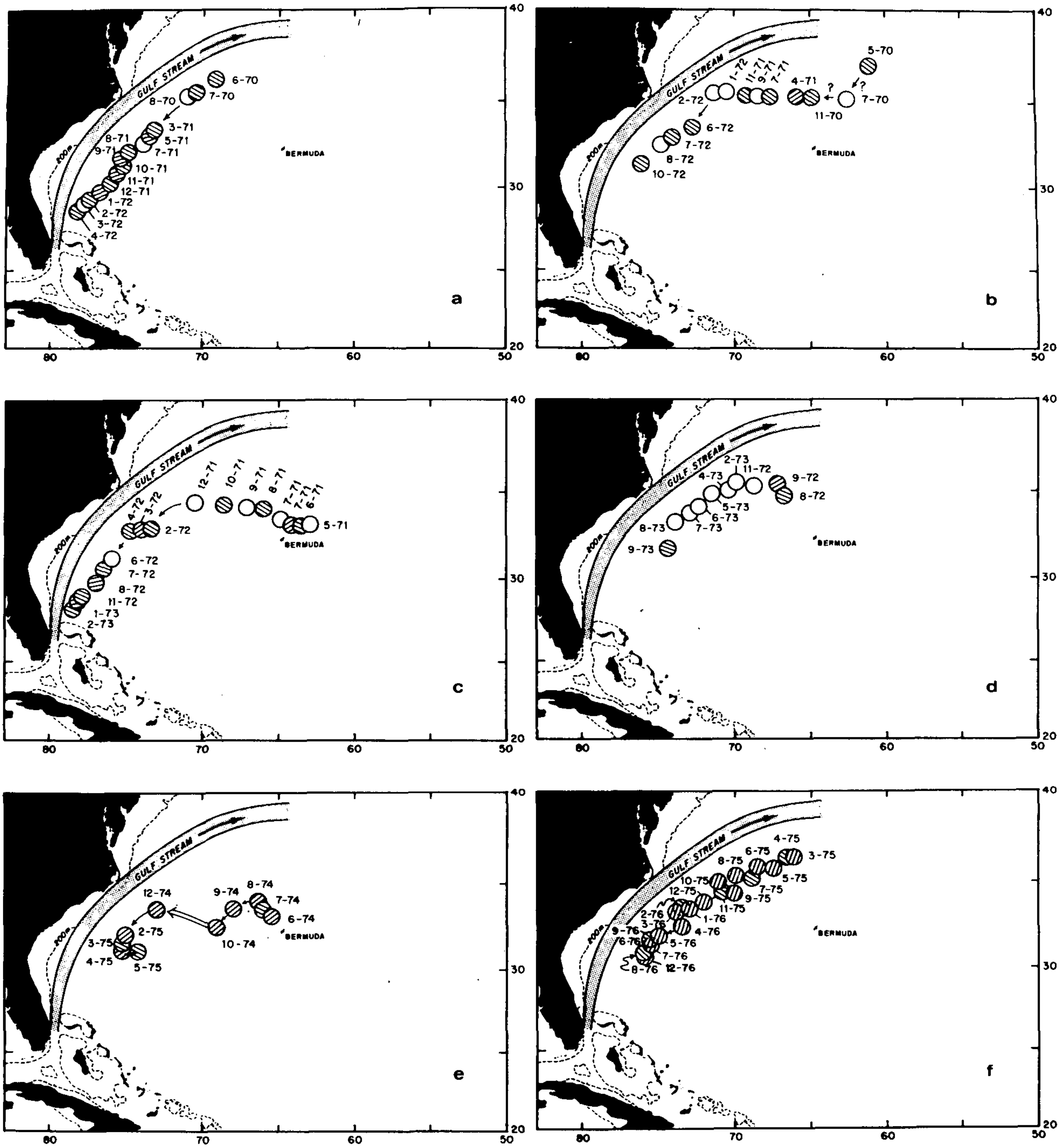

FIG. 8. Observed positions of six of the longest and most complete ring time series. Diameter of circles is 100 km, approximately one-half the typical overall size of rings. Shaded circles indicate ring observations of at least three anomalies. Data gaps of more than three months are indicated by question marks. Details of each observation are given in Lai and Richardson (1977) and are summarized here.

RING a—June 70–April 72, 22-month series (see Richardson *et al.*, 1973; Cheney and Richardson, 1976).

RING b—May 70–October 72, 29-month series. It moved westward extremely slowly (~1 km day^{-1}) and then speeded up on its southwestward path close to the Stream.

RING c—May 71–February 73, 21-month series. The ring shows an example of what appears to be the typical path of cold rings. It moved westward in the Sargasso Sea, turned southwestward near the Gulf Stream and finally coalesced with the Stream near Florida. Rings b and c were very close to one another on portions of their trajectories, especially in November 1971, but there are sufficient data to provide convincing evidence that they were separate rings.

RING d—August 72–September 73, 13-month series.

RING e—June 74–May 75, 11-month series. Part of the series consisted of remote tracking of SOFAR floats (Cheney *et al.*, 1976).

RING f—March 75–December 76, 21-month series. This ring [Ring D in Cheney and Richardson (1975)] has been repeatedly surveyed by XBT and has been tracked for periods by SOFAR float and satellite buoy.

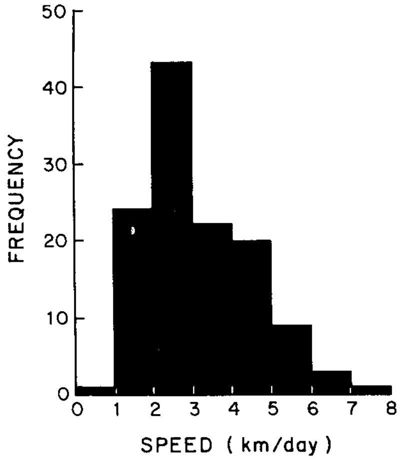

FIG. 9. Frequency distribution of ring speeds. Each speed was estimated from the positions of adjacent ring observations, sometimes rather subjectively, especially when only a single anomaly was available. The mean speed is 3.0 km day^{-1}; 88% of the speeds fall between 1 and 5 km day^{-1}.

matic. Because of this reason we concentrated our search for warm rings primarily on satellite IR photos. The usual large temperature gradients across the slope water region plus the characteristic entrainment of cold shelf water and, occasionally, warm Gulf Stream water by warm rings makes IR imagery particularly useful in identifying them. The few occasions that concurrent ship measurements have been available have generally confirmed our IR interpretations. Additional and important sources of data were *Gulf Stream*, NAVOCEANO's experimental ocean frontal analysis charts, Thompson and Gotthardt (1971), Saunders (1971), Gotthardt (1973a,b), Gotthardt and Potocsky (1974) and Bisagni (1976).

For consistency with the cold ring data we confined our analysis to the period 1970–76, although most of the data comes from the last three years, the period of good satellite coverage. Typically five warm rings per year are formed; their size varies but it appears to be somewhat smaller, ~100 km, than that of cold core rings. Approximately three warm rings exist at a single time. Although they appear to form as far east as the Grant Banks (50°W), they are most frequently observed in the western region. This may be due to better satellite and ship coverage in the western region. The movement of warm rings appears to be westward with mean speeds of 3–7 km day^{-1}. Approximately 20 rings were observed to move westward during the 7-year period (Fig. 7). When the rings reach Cape Hatteras they shrink in size and coalesce with the Gulf Stream (Gotthardt and Potocsky, 1974).

Warm rings exhibit considerable variation from the typical pattern described above. Occasionally a short

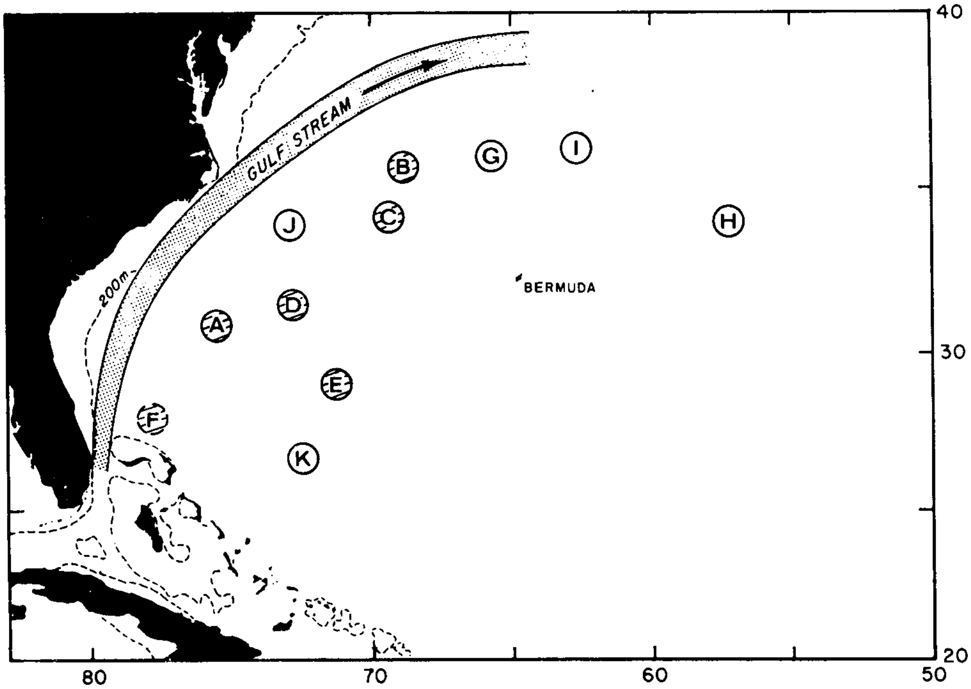

FIG. 10. Estimated positions of 11 rings during November 1971. The date was chosen because it corresponded to a time of high data density and a large number of ring observations. Ring positions were obtained by observations in November (rings A, B, G), by interpolation when successive ring positions were known (ring C), and extrapolation using the ring position closest to November 1971, the apparent ring direction and a speed of 3.0 km day^{-1} (rings D–K except for G). Shaded rings are those associated with time series. A summary of the observations is listed in Table 4. Rings can be seen to constitute nearly 50% of the area of the northwestern Sargasso Sea when realistic overall ring diameters are used.

TABLE 4. Observations of the 11 rings during November 1971.

Rings*	Observation closest to November 1971	Ship	Observations	Assumed ring movement
A	5–9 Nov. 71	*Sumner*, FNWC	3 XBT's	
B	7 Nov. 71	*Lynch*	15 XBT's	
C	20–23 Oct. 71	*Steinaker*	4 XBT's	
D	19 Oct. 71	FNWC	1 XBT	
E	20, 21, 28 June 71	*Daniels*	3 XBT's	Southwestward, 5 months
F	6 Aug. 70	FNWC	1 XBT	Southwestward, 15 months
G	14 Nov. 71	*Lynch*	5 XBT's	
H	2, 3 Mar. 72	*Chain*	5 XBT's	Westward, 4 months
I	30 Sept. 71 2 Oct. 71	FNWC	6 XBT's	
J	17 Sept. 71	*Franconia*	11 XBT's	Southwestward, 2 months
K	14–17 Aug. 71	*Sims*	8 XBT's	Southwestward, 3 months

* Letters identify rings shown in Fig. 10. Rings A–F are associated with time series, rings G–K with a single ring observation.

time after their formation warm rings coalesce with meanders of the Stream and occasionally these meanders appear to reform new rings. Occasionally no rings at all can be identified in the slope water region. We should note that there are times in which a complex temperature structure is present on the IR imagery but we can make no sense of it.

8. Warm eddies

South of the Stream 2% of the total data at 600 m were found to be warm temperature anomalies corresponding to a downward displacement of isotherms of at least 150 m. Three warm "ring observations" satisfying the ring criteria were obtained; these will be termed "warm eddies" since warm rings are only found north of the Gulf Stream. Five additional observations, each with two anomalies, were found (Fig. 11). Of these seven observations three were close to the Gulf Stream and three near the MODE region (28°N, 70°W).

XBT traces in these warm eddies showed a several hundred meter layer with a small temperature gradient, 17–19°C, between 300 and 600 m; sometimes a significant part of the layer was isothermal (Fig. 12).

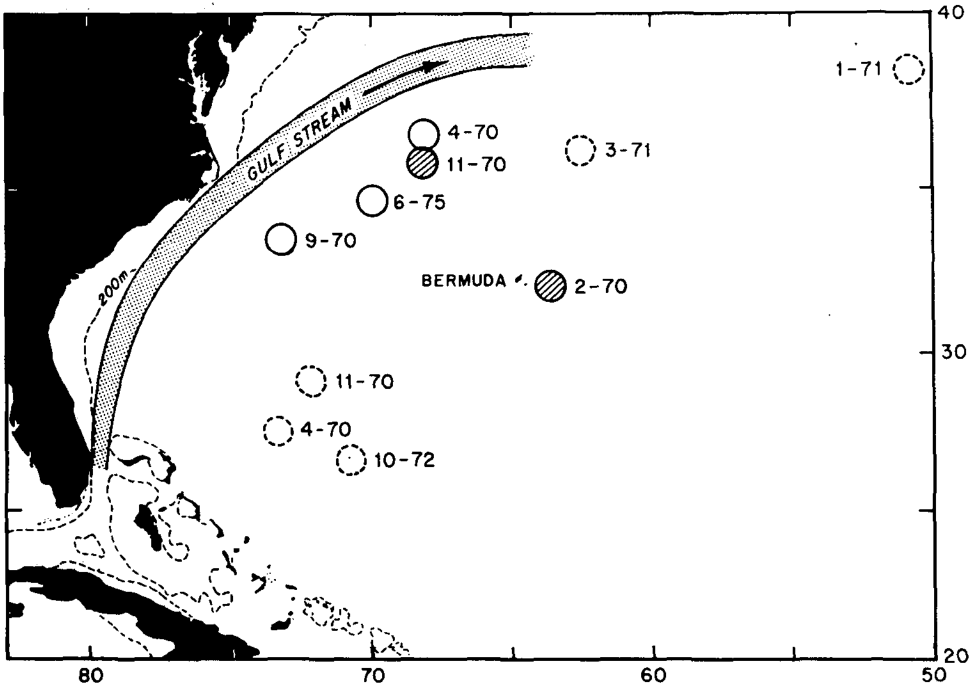

FIG. 11. Geographical distribution of warm eddies. Shaded circles represent warm eddies from 450 m XBT's, full circles are eddies with at least three anomalies, and broken circles with two anomalies (750 m XBT's).

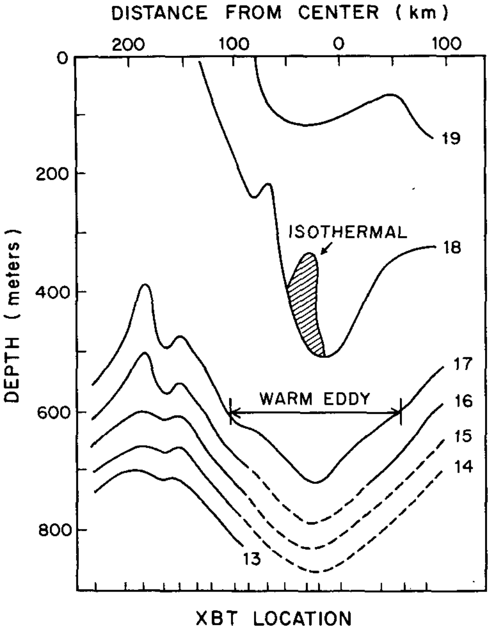

FIG. 12. Temperature section through a warm eddy in the Sargasso Sea, taken from RMS *Franconia* on 17 April 1970. A thick layer of 18°C water extends from 200 to 600 m. There is a corresponding 200 m deepening of the main thermocline at the center of the eddy.

Beneath the thick thermostad layer there was a corresponding deepening of the main thermocline. Two warm eddies near the Gulf Stream showed maximum vertical displacements of more than 200 m (Fig. 12), the others were near 150 m. The extent of the 17°C water at 600 m, which corresponds to a 150 m negative height anomaly, suggests a horizontal scale of about 100 km for warm eddies.

Special care was needed to analyze the 450 m XBT's since a 150 m negative anomaly at this level corresponds to a temperature change of less than 1°C. In two cases there were sufficient data to provide convincing evidence of a warm eddy. On one occasion more than 300 XBT's were taken within a month in a region bounded by 35–38°N and 63–69°W and a warm eddy was located between three cold rings. In the warm eddy 18° water was found down to at least a depth of 450 m. Although a dip in the main thermocline was not detected by the 450 m XBT's the thermocline must have been deeper than usual unless the deep temperature gradient was unusually large. There was a suggestion from the data that the warm eddy moved rapidly westward a distance of 200 km in 10 days.

Warm eddies identified in this study appear to be similar to the Aries eddy, an anticyclonic "rotating lens" of 18°C water observed by Swallow (1971) Under this eddy the thermocline dipped more than 150 m and anticyclonic velocities of 50 cm s^{-1} at 400 m were observed in it. Although no velocity measurements were available in the present study, if geostrophy and a deep layer of zero velocity are assumed, an anticyclonic circulation is also obtained. Other mid-ocean eddies with warm centers described by Swallow (1971), Koshlyakov and Grachev (1973) and Gould *et al.* (1974) were of smaller displacement, about 50 m, and the thick layer of 18°C water was absent in them.

That two of the warm eddies identified in this study were in close proximity to rings suggests a possible relation. Several theoretical studies which have suggested features that could be interpreted as warm eddies have focussed on the interaction between ring-like features and the surrounding fluid. McCartney (1975, 1976) has shown that westward moving vortices generate meandering wakes in a stratified rotating fluid and when the wake becomes large enough warm eddies are generated. Flierl (1977) modeled a ring by a packet of linear Rossby waves and suggested that dispersed waves are left behind by a moving and decaying ring, resulting in a series of high and lows with decreasing amplitude behind the ring; the dominant low could be interpreted as a warm eddy near the ring. Stern (1975) suggested the existence of a closely packed array of coupled cyclonic-anticyclonic systems called "modons," in which the array can be viewed as a series of cold rings intermixed with warm eddies.

9. Discussion

Most mathematical models of rings predict a westward movement due to the meridional variation in Coriolis parameter (Warren, 1967). However, recent long-term current meter measurements both north and south of the Gulf Stream have provided evidence that rings may be advected by the mean ocean flow. Current meter records between 70° and 55°W (Luyten, 1977; Schmitz, 1977) suggest that the swift eastward flowing Gulf Stream is imbedded in a slower westward flow. Between the 4000 m isobath which coincides with the mean surface axis of the Stream along 70°W and the continental slope the mean current throughout the water column appears to be moving westward with a speed of 3.5 cm s^{-1}. This speed is close to the mean 5 cm s^{-1} speed of warm rings inferred in the present study.

Although the current meter data south of the Stream (from 55° to 70°W) are not yet dense enough to reveal the structure of the return flow, they do clearly indicate a sizeable westward flow just south of the Stream and throughout the water column (Schmitz, 1977). The current meter measurements appear to be generally consistent with charts of mean flow in the North Atlantic based on transport variations in the Gulf Stream and oceanwide distributions of water properties (Worthington, 1977). The westward movement of rings south of the Stream is largely in agreement with the mean currents measured by current meter and inferred in Worthington's (1977) model. The main discrepancy of ring motion with the mean current charts is that rings appear to routinely continue to move southwestward and coalesce with the Stream off Florida; the current charts show the offshore inflow to the Stream centered near Cape Hatteras.

The formation of warm and cold core rings represents a transfer into the Sargasso Sea of colder slope water and into the slope water region of warmer Sargasso Sea water. Part of the heat (or heat deficit) in the rings is introduced into the surrounding ocean as they decay. For example, an estimated heat deficit of 10^{25} ergs day^{-1} is introduced into the Sargasso Sea by the decay of the ring followed by Cheney and Richardson (1975). This value is two orders of magnitude larger than the net downward heat flux across the same area of the thermocline as suggested by thermocline models which balance the heat flux with vertical velocity (Veronis, 1969). The presence of 11 rings each $\sim$250 km in diameter constitutes nearly a third of the area of the northwestern Sargasso Sea (Figs. 6 and 10). Thus, the cold ring region appears to be one region in which slow upwelling via the deep western boundary current and abyssal circulation is not required in order to balance the downward heat transport in maintaining the thermocline.

Acknowledgments. We are pleased to acknowledge the support of the Office of Naval Research under Contract N00014-68-A-215-0003 to URI and the International Decade of Ocean Exploration of the National Science Foundation under Grant OCE 08765 to WHOI Numerous ring observations were made on a series of R/V *Trident* cruises (98, 104, 125, 128, 161, 168, 175) funded partly by ONR and partly by NSF. NODC and FNWC provided the primary source of data and NOAA NESS the satellite infrared imagery. Several scientists at NAVOCEANO, in particular R. Cheney, G. Gotthardt and R. Perschal, generously provided unpublished data that significantly added to this study.

APPENDIX

List of Sources of Ring Observations

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