2. Gulf Stream Rings

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2.1 Introduction

Gulf Stream rings are a special type of eddy whose origin has been well documented; they form from cut-off Gulf Stream meanders (Fuglister 1972). Rings are the most energetic eddies in the ocean and their thermocline displacements, swirl speeds and volume transports are nearly equivalent to those of the Gulf Stream.

Recently, field studies of rings have concentrated on obtaining a description of their distribution, structure, biology, movement and life histories. Rings constantly and sometimes rapidly change their size, shape and position. They interact with the Gulf Stream and with other rings. Because of this complexity, accurate measurements of ring dynamics are difficult to obtain.

The descriptive data that we have accumulated are being used to develop and refine models of ocean eddies (see Chap. 18). Recent eddy-resolving general circulation models contain eddies that look and act very much like rings. Although these models are still very idealized, they have been used to identify important mechanisms that contribute to the dynamics of the Gulf Stream system. Model eddies (and by implication, rings) are key sites in which kinetic and potential energy is transformed and transmitted within the system. Eddies generate mean flow; they help drive the deep Gulf Stream, and they enhance the Stream's transport significantly. Eddies are vital in transporting water and its physical, chemical and biological components across the Stream.

The real role of rings in the dynamics of the Gulf Stream is still being assessed with field programs and model studies. The large number of highly energetic rings that coexist near the Gulf Stream, coupled with results of model studies, suggest that rings are a vital component of the Gulf Stream system. In order to understand the Gulf Stream's role in weather and climate we must understand the part played by rings.

2.2 History

Jonathan Williams, grandnephew of Benjamin Franklin, was the first to mention a warm-core ring (Williams 1793). In 1790 he measured surface temperatures, plus some surface velocities by lowering a cooking pot on the end of a long sounding line and concluded:

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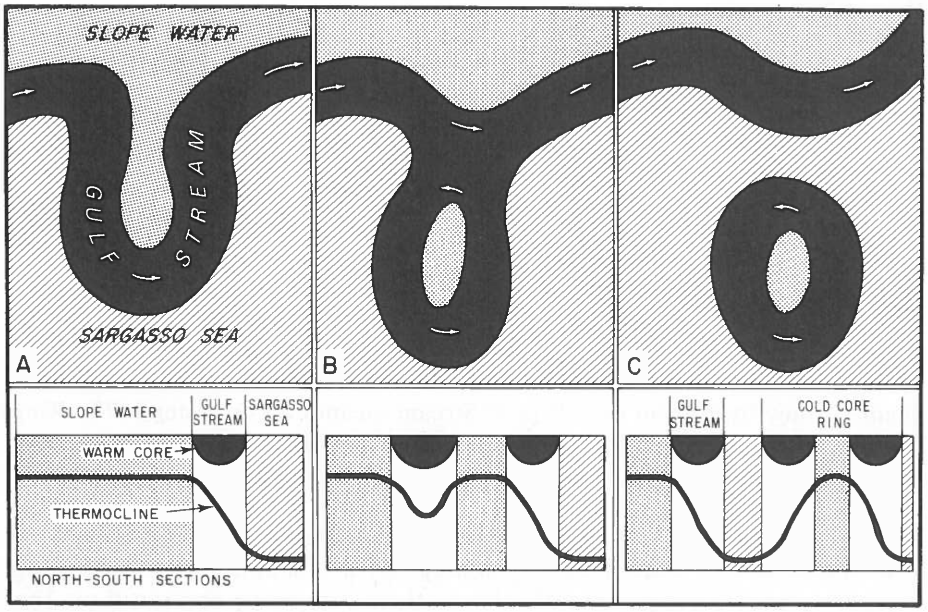

Fig. 1. Schematic diagram showing the formation of a cyclonic, cold-core, Gulf Stream ring. A cold-core ring consists of a closed segment *(ring)* of the Stream circulating around a mass of cold water detached from its former position in the Slope water region north of the Gulf Stream. (Adapted from Fuglister 1972)

"The evidence of this various current in so short a space, the heat of the water not being raised to the heat of the stream, and our situation to the Northward made me conclude that this to be the whirlpools of the eddy of the gulf stream just on the northern edge of it."

The "eddy" of the Gulf Stream refers to the westward flowing countercurrent and thus "whirlpools" is the reference to rings.

More evidence for rings was accumulated in the early 1930's. In the period 1929–1931, Church (1932, 1937) examined ship thermograph records and found warm eddies debouching from the Gulf Stream into the Slope water region. In 1932 on the ATLANTIS, Iselin (1936) began a series of deep temperature-salinity sections across the Gulf Stream which clearly show what today we would interpret as rings. Not knowing their cause, Iselin suggested that a warm-core ring was a "permanent eddy" and a cold-core ring could have been a large amplitude internal wave generated by a severe northeast storm. Iselin's (1940) later sections in 1937 and 1938 contained several additional ring observations, indicating that rings were relatively numerous.

Synoptic oceanography of the Gulf Stream began in 1946–47. LORAN and BT's were first used to circumnavigate a cold-core ring (Fuglister and Worthington 1947, Iselin and Fuglister 1948). These studies led to the discovery that rings are generated from cut-off Gulf Stream meanders. The data also showed that surface speeds in the Gulf Stream reach 200–250 cm/s and in rings

150 cm/s, higher than were commonly thought to occur. In 1950, Fuglister and Worthington (1951) were the first to observe in detail the formation of a cold-core ring from a meander, and they clearly circumnavigated the new ring. Again in 1960, a cold-core ring was observed forming at 60°W near the New England Seamounts (Fuglister 1963).

The first study to concentrate on cold-core rings was carried out in the mid-1960's by F.C. Fuglister. From September 1965 to February 1966 he dedicated seven cruises to following the evolution of two rings, and, from March to October 1967, nine cruises to measuring the life history of another ring. The data from these studies, plus some additional measurements, served as the basis for the first good description of the distribution, movement, and decay of cold-core rings (Fuglister 1972, 1977, Parker 1971, Barrett 1971).

In the 1970's many people became interested in both cold- and warm-core rings and began a series of individual and cooperative experiments.[1] New measurement techniques such as airborne XBT's, satellite infrared images, SOFAR floats, satellite-tracked drifters, and vertical profilers enabled researchers to follow rings and measure their properties in new ways. Scientists from the United States Naval Oceanographic Office also began to study rings more actively during this time and publish data in the *Gulf Stream Monthly Summary*. This publication was replaced by *Gulf Stream* (1975–81) which has since been replaced by *Oceanographic Monthly Summary*. Recent analyses of satellite images and other data that show the Gulf Stream and rings are produced several times a week by NOAA and are called *Oceanographic Analysis*.

During 1976–1977 several investigators carried out a cooperative and interdisciplinary experiment during which two cold-core rings were followed over their lives and their physical, chemical, and biological properties and changes with time measured (Ring Group 1981). Several other rings were measured coincidently. Probably the most significant result of the recent experiments is a description of the complexity of a ring's life history. Rings split into pieces, merge, interact with the Gulf Stream, reform as modified rings, coalesce completely with the Stream. A recent summary of this work has been published by the Ring Group (1981).

2.3 Cold-Core Rings

2.3.1 Formation

Cold-core rings form from Gulf Stream meanders which pinch off to the south of the Stream (Fig. 1). The Gulf Stream loops to the right of its downstream direction and the two sides of the loop with currents flowing in opposite direc-

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[1] My own interest in rings began in 1967 during a chance encounter with an intense one off Cape Hatteras (Richardson and Knauss 1971) and deepened with the results of Fuglister's 1965–67 studies and a second close encounter with a powerful ring near Cape Hatteras (Richardson et al. 1973).

tions approach each other and merge trapping a central core of cold Slope water originally located north of the Stream (Fuglister 1972, Doblar and Cheney 1977). When the closed meander separates from the Stream, a ring is born. It consists of a closed segment of the Stream revolving cyclonically (counterclockwise) around the cold water core (Fig. 2). Some of the five to eight cold-core rings which form each year (Fuglister 1972) are generated quite quickly, in a week, others more slowly, in several weeks. Evidence suggests that the near surface ring pinches off first, followed thereafter by the deeper structure (Fuglister and Worthington 1951, Fuglister 1963).

A new ring is often elliptical, but it usually becomes nearly circular as it moves away from the Stream. Typical overall diameters are 200–300 km and surface speeds 150 cm/s. Newly formed rings can be observed by satellite infrared images due to their initial surface temperature distribution and their sea surface depressions of approximately 0.5–1.0 m (Cheney and Marsh 1981a).

Rings form from 70°W eastward. Most rings have been observed in the region 60°–70°W with a maximum number north of Bermuda near 65°W, suggesting a preferred formation region. Ring generation is apparently common along 60°W near the New England Seamounts (Fuglister and Worthington 1951, Fuglister 1963), where the Stream makes particularly large amplitude meanders. The seamounts seem to be responsible for the large meanders and for a semi-permanent ring-meander located over the seamounts. Periodically rings pinch off from this structure and also coalesce with it. South and east of the Grand Banks the Stream seems to break down into several branches which also shed current rings.

Shedding of cold-core rings, their injection into the Sargasso Sea and subsequent decay there represents a significant transfer of heat across the Gulf Stream (Newton 1961, Cheney and Richardson 1976). The heat transfer includes (1) a ring of warm Gulf Stream water near the surface, and (2) a deep cold-core. The surface water can exchange heat directly with the atmosphere; the deeper layer represents an injection of heat deficit into the internal region of the Sargasso. Mintz (1979) has described the role of rings as interpreted from numerical model studies of ocean circulation. The large-scale Gulf Stream gyre carries heat from its lower latitude source to mid-latitudes where the heat is transferred to rings, both warm and cold, which carry the heat across the mean position of the Gulf Stream front.

2.3.2 Structure and Velocity

Cyclonic rings are characterized by a large raised dome in thermal, salinity and density fields (Figs. 2, 3). Deep hydrographic sections across a few new rings show that the dome structure extends down to the sea floor. The bell-shape has prompted the use of a Gaussian-shaped density field for the initial condition in many models of rings (Flierl 1977b, McWilliams and Flierl 1979, Mied and Lindemann 1979).

Frequently different water properties (temperature-salinity, temperature-oxygen, etc.) can be identified in the upper few hundred meters of a ring (Fuglister 1972, Hagan, Olson, Schmitz and Vastano 1978, Richardson, Maillard and Sanford 1979a, Vastano, Schmitz and Hagan 1982, Ring Group 1981). Initial water properties in cold-core rings vary from ring to ring. This is partly due to seasonal and geographical variations of the ingredient water properties and partly due to the specific details of the formation process for each ring. A ring consists of various amounts of Slope, Shelf, and Gulf Stream water (Fig. 4). Slope water is a mixture of water from northern sources and Shelf and Gulf Stream water. Gulf Stream water is a mixture of southern water plus water entrained along its path northward. West of 60°W the Gulf Stream entrains significant amounts of Shelf, Slope, and Sargasso water plus water from warm- and cold-core rings which have coalesced with the Stream. Some, or all, of these different water masses can be the initial ingredients of a ring.

Continuous profiles of T, S, O_2 show pronounced layering in the upper 500 m of rings (Lambert 1974, Ring Group 1981). Layers 25–100 m thick of Sargasso and Gulf Stream water penetrate into the ring core and core water penetrates into the Gulf Stream remnant. Continuous velocity profiles show strong inertial layers in the ring core as well as in the high velocity region (Richardson et al. 1979a). In the upper 1000 m the layers were 50–100 m thick, had amplitudes of 10 cm s^{-1} and oscillated with a period near the inertial. Given strong gradients of water properties, the inertial layers could provide a mechanism by which property gradients and mixing are enhanced.

Vastano and Hagan (1977) suggest that rings are sites where the Sargasso Sea water is produced by combining, mixing, and subsequent detrainment of Gulf Stream and Slope water. The formation of rings provides a mechanism by which the Gulf Stream front is convoluted and lengthened many times over the straight line mean path of the Stream and enables the different water masses on either side of the Stream an increased area in which to mix.

A young ring has surface swirl velocities of 150 cm s^{-1} (3 knots). Speed increases with distance from the center, reaches a maximum near a radius of 30–60 km and then drops off again towards the outer limits of the ring (Cheney and Richardson 1976, Fuglister 1977, Olson 1980). Figure 3 shows a velocity section through ring Bob at age 6 months (Olson 1980). A pronounced jet surrounds the core which is in nearly solid body rotation. A maximum in relative vorticity occurs just inside the radius of maximum current. The zone inside these maxima is the portion of fluid in the upper layers which translates for long periods of time (months - years) with the ring as it moves through the Sargasso Sea. At any one time the area of fluid translating with the ring extends beyond the radius of maximum swirl speed (Flierl 1976). The strength of the velocity jet is responsible for the maintenance of temperature-salinity and other anomalies in the ring core (Flierl 1976, Olson 1980).

The high speeds and high kinetic energy of rings are partly responsible for the large peak in Eddy Kinetic Energy (E_K) associated with the Gulf Stream region (Wyrtki, Magaard and Hager 1976). Buoys in rings yield an E_K of ~ 6000 $cm^2\,s^{-2}$ in the ring region south of the Stream; buoys in the same area but outside of rings yield values of ~ 1000 $cm^2\,s^{-1}$, and those near 30°N, south of the ring region, ~ 200 $cm^2\,s^{-1}$ (Richardson 1982b). These E_K values near the Gulf Stream are significantly higher (2–10 times) than those given by Wyrtki et al.

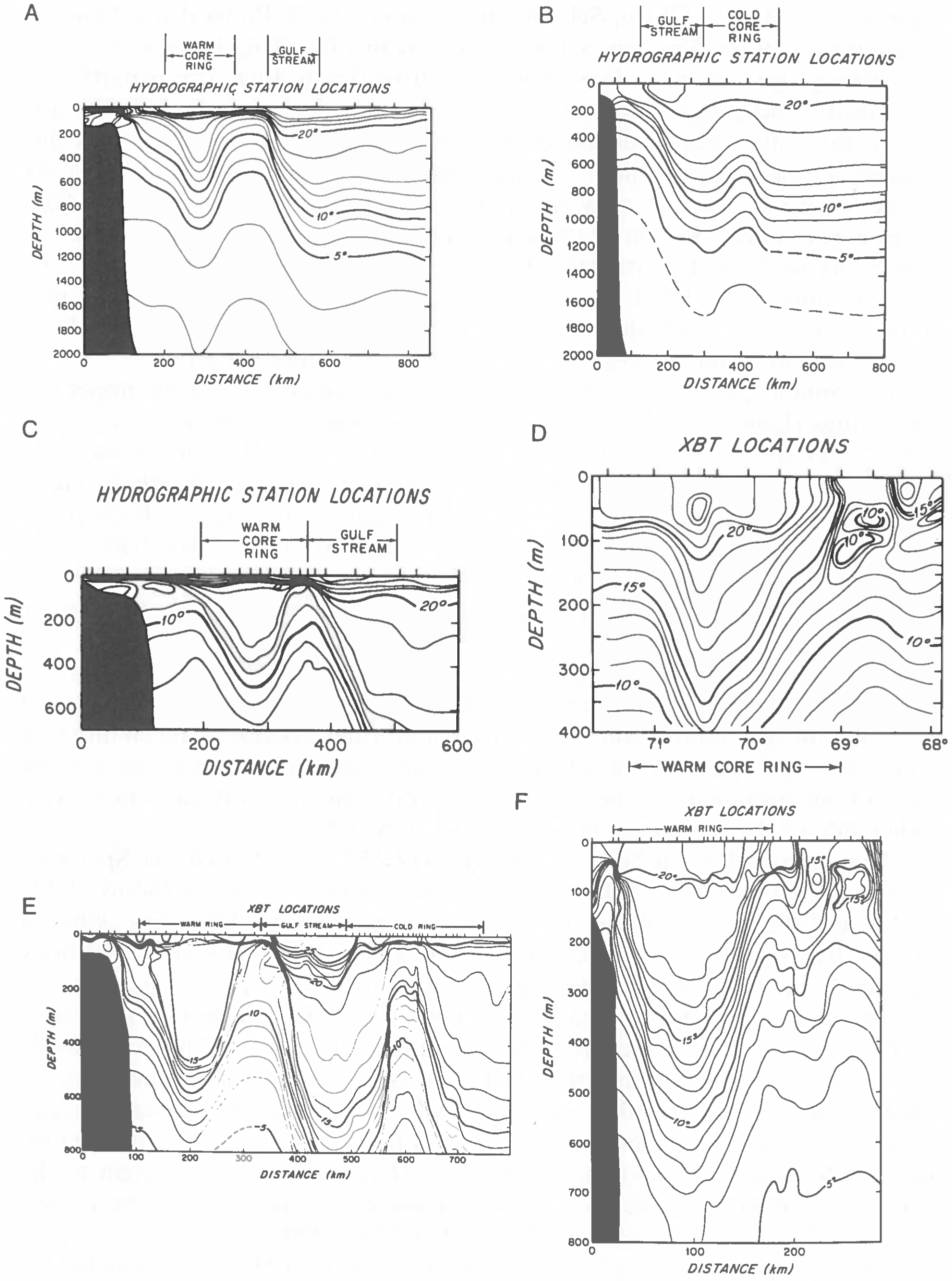

Fig. 2 A–F

Fig. 2. Vertical temperature sections through several rings. **A** After Iselin 1936, Fig. 14. **B** After Iselin 1936, Fig. 10. **C** After Iselin 1940, Fig. 13. **D** After Saunders 1971, Fig. 5. **E** After Richardson, Cheney and Worthington 1978, Fig. 4a. **F** KNORR 71, 1977. **G** After Richardson, Maillard and Sanford 1979a, Fig. 10. **H** After Richardson 1980, Fig. 5. **I** After Lai and

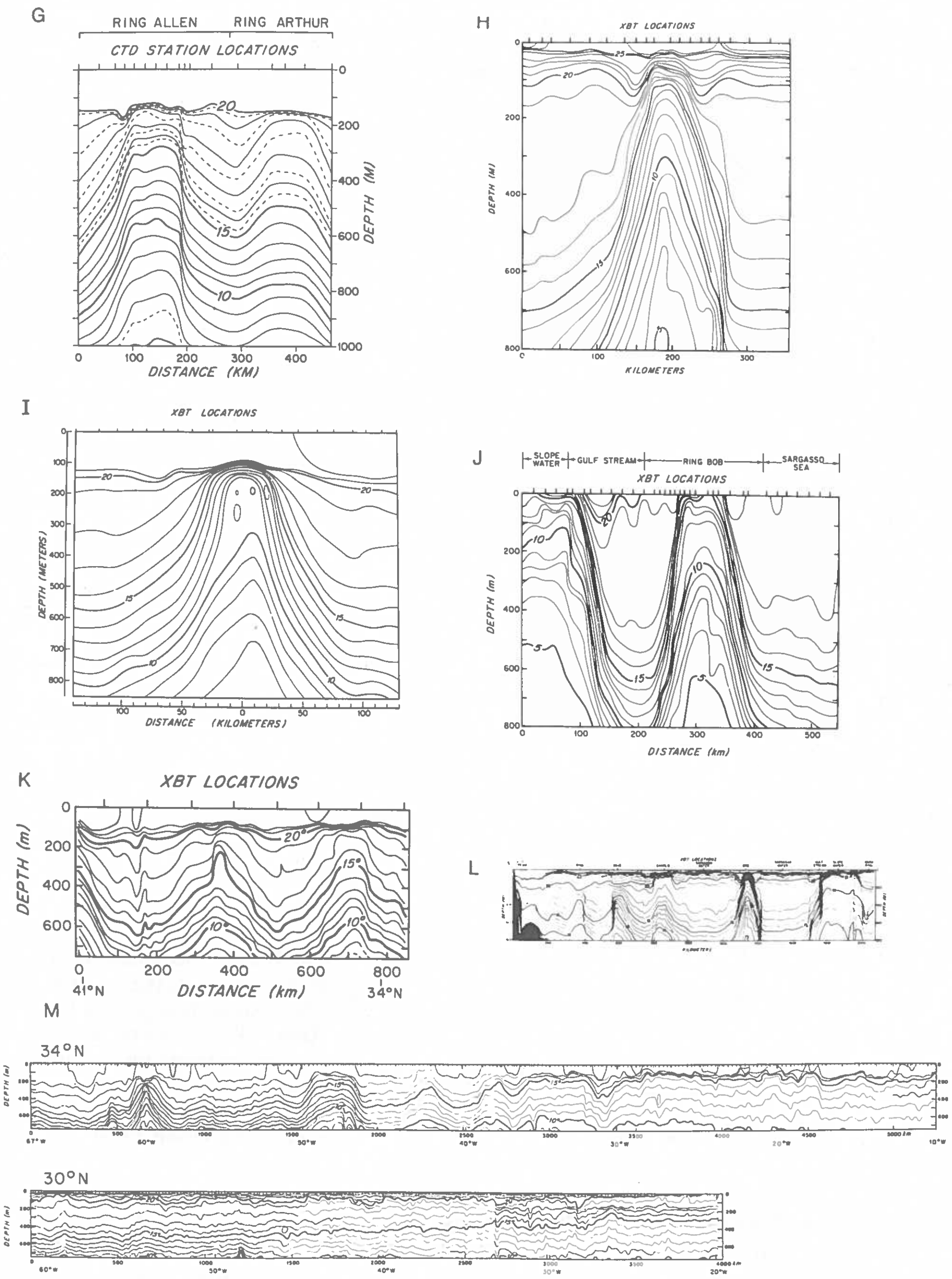

Fig. 2 G–M

Richardson 1977, Fig. 1. **J** After Richardson 1980, Fig. 16. **K** Big Babies along 58 °W after McCartney, Worthington and Schmitz 1978, Fig. 3. **L** Section from Florida to New England through the western Sargasso Sea after Richardson 1980, Fig. 5b. **M** Sections along 34 °N (top) and 30 °N (bottom) after the Mode I Atlas Group, Figs. 3.3 (2) and (3)

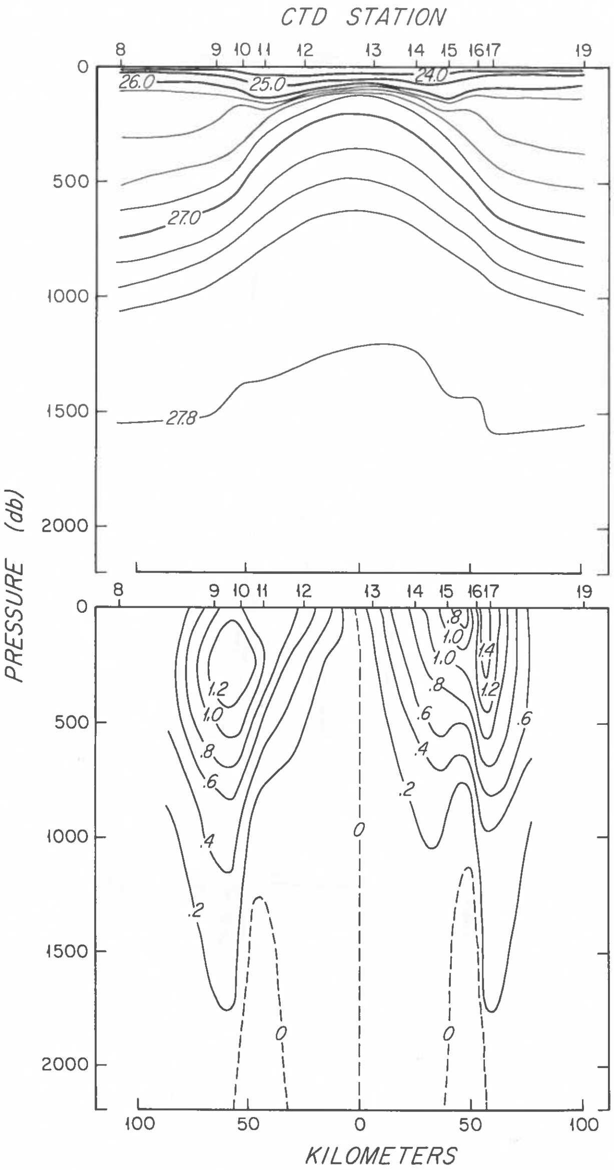

Fig. 3. *Top* Distribution of potential density σ_θ (kg/m^3) for a CTD section through ring Bob. (After Olson 1980). *Bottom* Gradient currents (m/s) corresponding to the CTD section above and a 2500 db reference level. (After Olson 1980)

(1976) derived from ship drift data; the buoy E_K values near 30°N, are significantly lower (one half).

In the central part of rings, near-surface period of rotation ranges from about 2 days for a young ring to 5–10 days for older, less energetic rings (Richardson 1980). Occasionally, periods of rotation down to 1.5 days were measured in rings interacting with the Stream, corresponding to times that the central region of the ring was being spun up (Richardson, Maillard and Sanford 1979a).

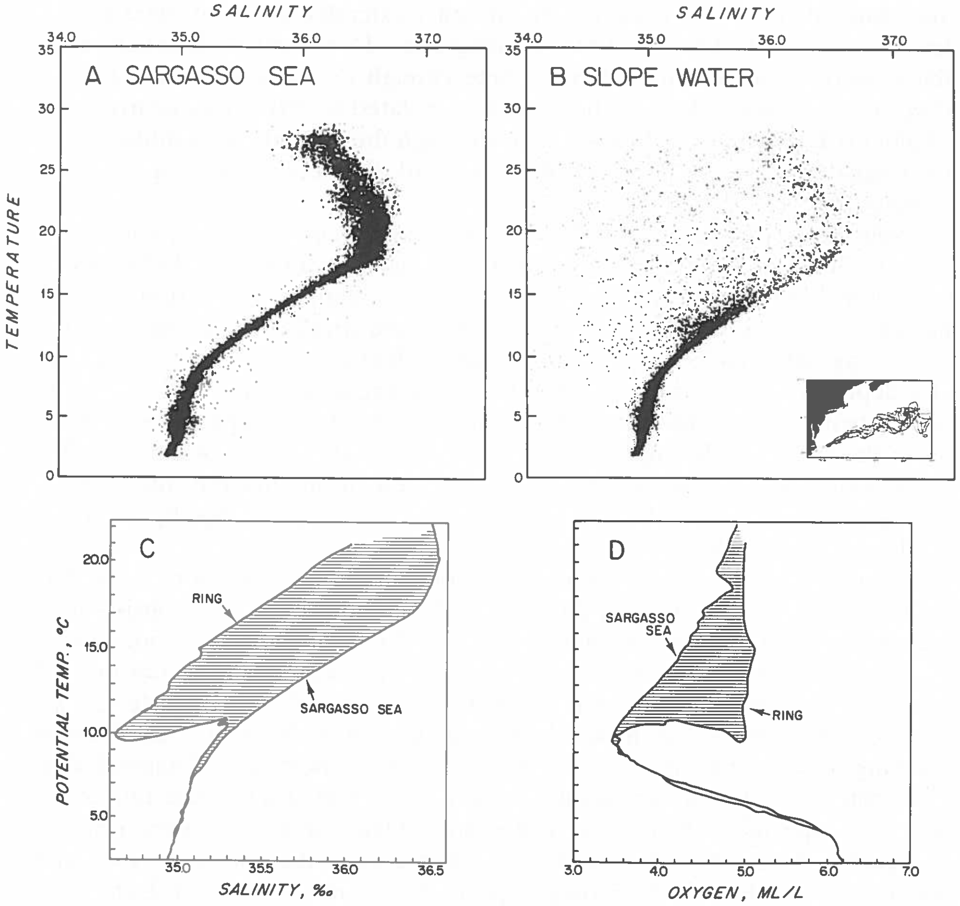

Fig. 4. A, B Temperature and salinity diagrams for the Gulf Stream meander region between 60° and 70 °W showing T-S anomalies across the Stream.
A Plot of Sargasso Sea stations to the south of the Gulf Stream center, stations whose temperature at 400 m was greater than 15 °C.
B Plot of Slope water stations located to the north of the Gulf Stream center, stations whose temperature at 400 m was less than 15 °C.
C, D Temperature-salinity and temperature-oxygen profiles from the center of a ring and the Sargasso Sea, outside of any rings. (Richardson, Cheney and Mantini 1977). The ring station has anomalously low salinity and high oxygen from the surface to at least 10° which is indicative of its Slope water origin

Swirl speeds and the rotation rates decrease with depth (Fig. 3). There is a controversy whether the cyclonic circulation extends coherently to the sea floor under a ring. Vertical shear extends to the bottom under young rings – shear in geostrophic velocity sections as well as shear in absolute current meter profiles. Richardson et al. (1979a) suggest that if the ring translation is subtracted from some current profiles, the cyclonic circulation of a ring then extended to the sea floor. McCartney, Worthington, and Schmitz (1978), however, analyzed current meter measurements from the time that a ring drifted past a mooring and concluded that the cyclonic velocity only extended to about 2000 m; below this depth was a weak counter-rotating eddy. Deep velocity fluctuations in the western boundary undercurrent large enough to occasionally reverse the deep southwestward flow can be visually correlated with the passage overhead of older rings (Mills and Rhines 1979), although the current fluctuations due to the rings do not seem to be a simple downward extension of the ring's surface velocity field.

Neutrally buoyant SOFAR floats have measured currents in rings at depths of 750–1300 m (Cheney, Gemmill, Shank, Richardson and Webb 1976). When three floats were launched in a ring, two were retained for periods of 2–3 months; the loops had a period of 20–40 days and speeds of 3–11 cm s^{-1}. One float came out quickly, in 2–3 weeks. Another float drifting outside of any ring at a depth of 1290 m was overtaken by a ring and made three cyclonic loops before being left behind (Cheney 1977a). During these loops (period of 40 days) the float speeded up from approximately 5 cm s^{-1} to 24 cm s^{-1}. Recently a float at 700 m was entrained in a ring at its formation and stayed in the ring for eleven months (Richardson, Price, Owens, Schmitz, Rossby, Bradley, Valdes and Webb 1981).

Conceptually, there are at least three kinds of volume transport associated with rings. First is a transport due to their formation. Each ring consists of a segment of the Gulf Stream approximately 500 km long, 100 km wide, and 2 km deep. The formation of 5–8 cold rings per year amounts to a transport of Gulf Stream water into the Sargasso Sea of 20×10^6 m^3 s^{-1} (Fuglister 1972). The Gulf Stream itself transports approximately 30×10^6 m^3 s^{-1} off Florida reaching a maximum of 150×10^6 m^3 s^{-1} north of Bermuda (Knauss 1969). Thus, rings constitute a significant part of the Gulf Stream's recirculation or return flow especially when one considers the added transport of warm rings.

Second, there is transport of water circling around the ring core – the swirl transport, estimates of which range up to 73×10^6 m^3 s^{-1} (Richardson et al. 1979a). Because of problems in determining how deep the swirl transport extends and the outer limits and appropriate reference station values, there is a large uncertainty in the calculated values of swirl transport.

Third, there is a transport of water carried by rings as they drift westward; the amount depends on whether they are advected or self-propelled. If rings are carried passively by a large-scale barotropic flow, then their whole volumes are transported with the flow. If, however, rings are self-propelled through an ocean at rest, only their upper part where the swirl speed exceeds the translation speed is trapped and carried along with the ring (Flierl 1976, Olson 1980). The trapped region resembles a cone with its base at the surface and its apex pointed downward. The area is largest near the surface where the surface swirl speed is largest; the area decreases with depth as the swirl speed approaches the translation speed of the ring and its center shifts northward toward the radius of maximum swirl speed. Evidence confirming a trapped region in rings includes surface drifters and anomalous water properties and biota which remain in the upper 500 m of rings for long periods of time (months to years).

2.3.3 Distribution and Number

Approximately ten cold-core rings co-exist at a single time (west of 55°W). This estimate comes from two attempts at making a ring census (Lai and Richardson 1977, Richardson, Cheney, and Worthington 1978; McCartney, Worthington, and Schmitz 1978) plus numerous ring sightings identified on single sections that have tended to confirm the number of rings observed on the censuses. In the spring of 1975 several XBT surveys plus satellite infrared images provided a nearly synoptic view of the number and distribution of rings (Fig. 5). The strongest rings, those with the highest raised dome in their centers, 500–600 m above normal background levels, were found north and northwest of Bermuda. Rings west of Bermuda and those east of 62°W had reduced displacements of the main thermocline. The ring census (Fig. 5) was based on data taken over four months. The effect of a three month gap in time between sur-

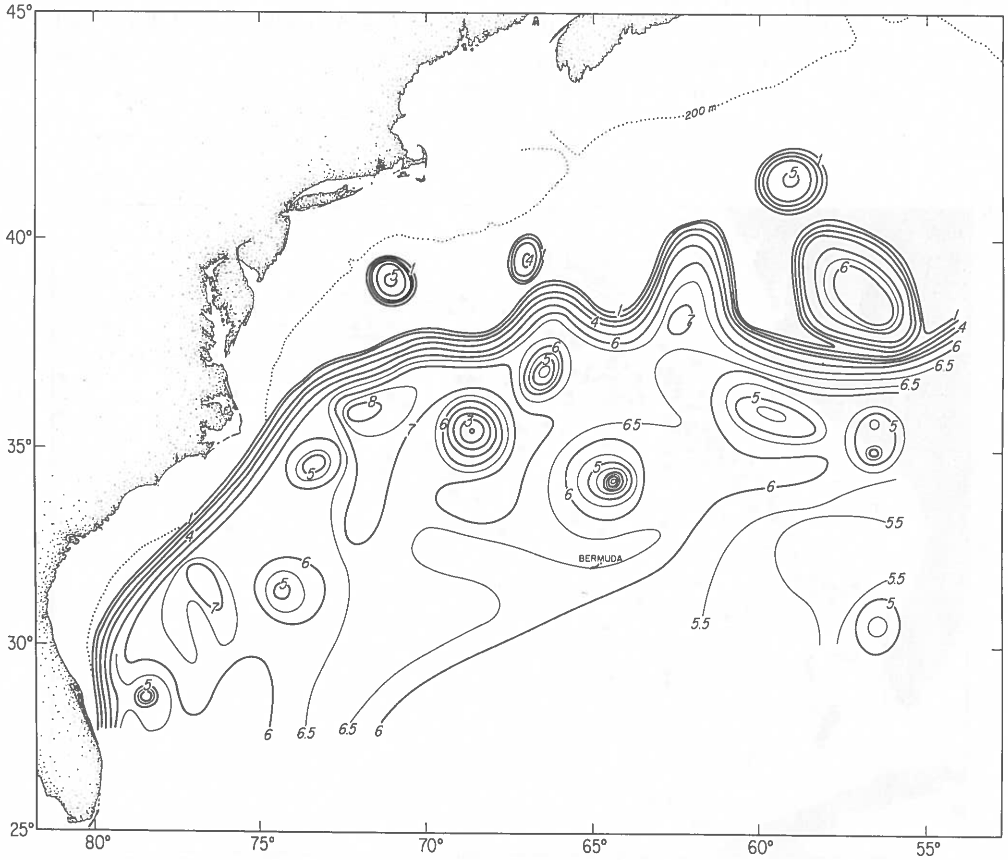

Fig. 5. Chart of the topography (hectometers) of the 15° isothermal surface showing the Gulf Stream, nine cold-core and three warm-core rings. Contours are based on XBT, CTD, hydrographic and satellite infrared data from the period March 16 to July 9, 1975. (Richardson, Cheney and Worthington 1978)

veys was to spread the rings out in an east-west direction near 62°W. It is estimated that if the region had been surveyed simultaneously approximately 10 rings would have been found.

An analysis of hydrographic stations, BT's, XBT's, and satellite infrared images from the period 1932–1976 has resulted in the identification of 225 cold-core ring observations in the area west of 50°W (Parker 1971, Lai and Richardson 1977). Rings were most frequently observed in the northwestern Sargasso Sea (Fig. 6). This reflects the preferred ring formation and migration patterns there plus the higher density of data in that region. The youngest rings, those with the coldest temperature anomalies, are found between 64°–70°W just south of the Stream. Many rings were observed in the western Sargasso, along a path 200 km offshore of the Gulf Stream axis where rings often moved southwestward.

Between 50° and 60°W only 16 rings have been identified, all of them since 1970. This small number is due to the low density of data east of 65°W, and due to the weaker near-surface temperature signal in the rings there that makes identification more difficult especially with shallower mechanical BT's (used by Parker 1971). Rings probably occur much more often east of 60°W than is suggested by the present number of sightings there.

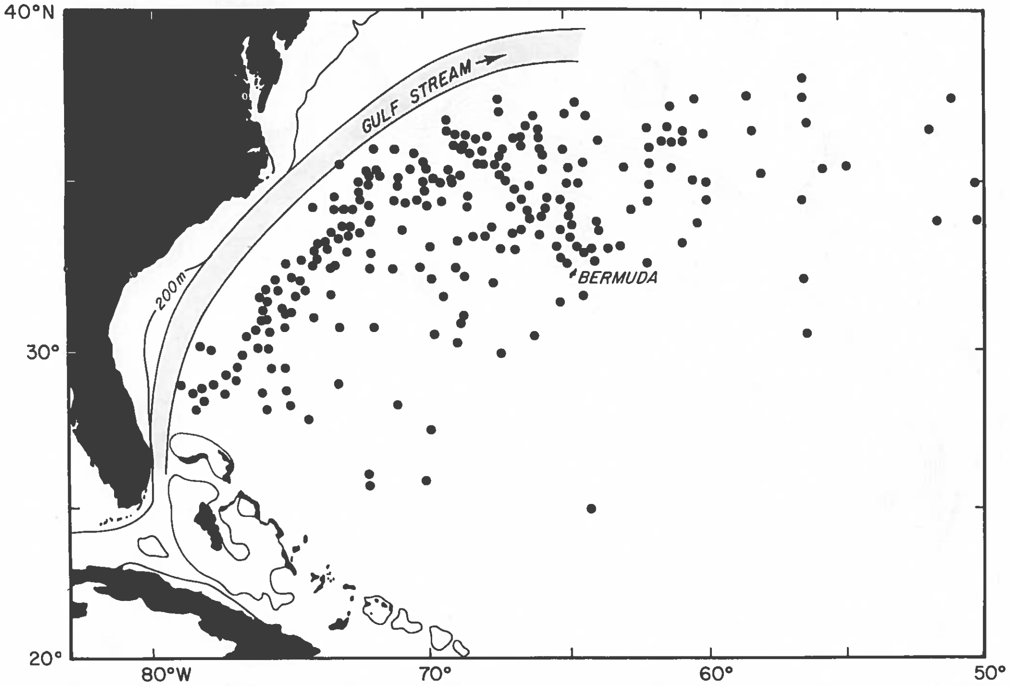

Fig. 6. Geographical distribution of 225 cold-core ring observations from 1932 to the present from Parker (1971) and Lai and Richardson (1977) plus a few recent observations of rings in the eastern area from Bulgakov, Djiganshin and Belous (1977) and Cheney and Marsh (1980)

South of 30°N the eastern area is devoid of ring observations. It is likely that rings do not enter this region or that if they do enter it they have decayed beyond the point of recognition. The few long XBT sections that exist in this region do not show ring-like deviations from large-scale variations in temperature (Fig. 2).

2.3.4 Movement

Rings usually move westward when they are not touching the Gulf Stream and eastward when they are attached to it (Fig. 7, Richardson 1980, Fuglister 1972, 1977). The westward movement, sometimes northwest, sometimes southwest, is characterized by a mean speed of 5 cm s^{-1}, although there are large variations about this, including periods when rings remain nearly stationary. Two hundred miles offshore of the Gulf Stream axis, between 28°-36°N, a ring corridor is located in which rings drift southwestward (Parker 1971; Richardson, Strong and Knauss 1973, Lai and Richardson 1977). At least 12 rings were observed to move down this path during the period 1970-1976. Recent ring trajectories, measured continuously with buoys, are more complicated than earlier

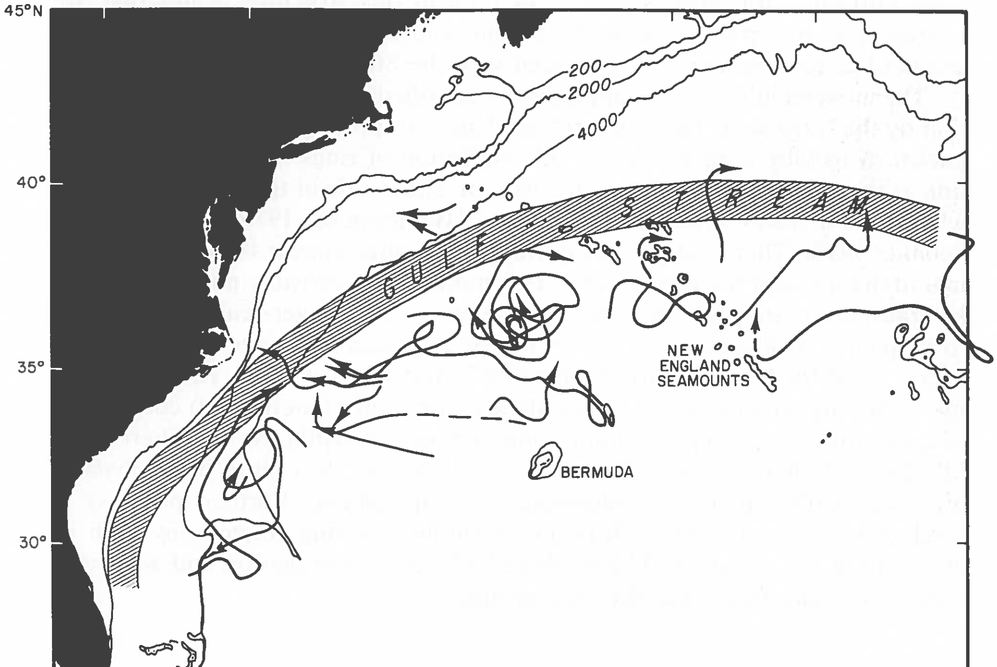

Fig. 7. Ring trajectories. *Dark lines* represent rings continuously tracked with free drifting buoys and SOFAR floats. (Fuglister 1977, Richardson 1980, Cheney and Marsh 1981a, Richardson et al. 1981)

observations based on repeated sightings (Richardson 1980). Although repeated sightings of rings suggest that they can drift into the southern Sargasso Sea, no rings tracked with buoys moved into this region. There is a hint from temperature anomaly observations that rings can penetrate southward near the Bahama Islands to as far south as 25°N, but the anomalies in these rings were quite weak and the observations tentative (Parker 1971). The limited data east of 60°W suggest rings also drift westward there.

Frequently rings become attached to the Gulf Stream and are advected parallel to the Stream in a downstream direction. This eastward movement can be quite fast; maximum daily speeds ranged from 25–75 cm s^{-1} for several rings. Often rings split off from the Stream after an eastward advection and began a westward movement. The result of successive ring attachments to the Gulf Stream is that many rings moved in large clockwise loops with a characteristic period of about 2.5 months and diameter of 175 km. These loops are prevalent north and west of Bermuda (Fuglister 1977, Richardson et al. 1979a, Richardson 1980).

A semi-permanent ring-meander overlies the New England Seamount. It is called a ring-meander because at times a ring seems to be separating from the meander, but often complete separation does not occur and the ring remains trapped near the seamounts. Several buoys moving eastward in the Stream became entrained for various lengths of time in this structure. Rings that appeared to have separated from the Stream and that were tracked with buoys did not last long before they coalesced with the Stream.

The movement of rings is apparently controlled by a combination of advection by the large scale flows and the tendency for propagation to the west as a packet of Rossby modes. The overall translation of rings is in the same direction as the mean flow which is to the west on either side of the Gulf Stream and which has a mean speed of ~ 5 cm s^{-1} (Worthington 1976a, Luyten 1977, Schmitz 1980). There are periods during which rings appear to propagate normal to the inferred large-scale flow. This motion, and possibly part of the regular translation, are probably due to the tendency for longer-scale disturbances to propagate westward on a β-plane. The propagation of a wave-like vortex has been treated by Adem (1956), Warren (1967) and Flierl (1977b). The nonlinearity of the ring circulation can also induce a northward (southward) component of translation to a cyclonic (anticyclonic) ring (McWilliams and Flierl 1979, Mied and Lindemann 1979). The models to date provide a set of basic physical processes with which to understand ring movement. Further progress is needed, however, before a clear understanding of ring trajectories such as those in Fig. 7 is obtained. The combined effects of propagation and advection are of particular interest at the present time.

2.3.5 Interaction and Coalescence with Gulf Stream

The ultimate fate of rings seems to be complete coalescence with the Stream (Cheney et al. 1976, Richardson, Cheney, and Mantini 1977, Watts and Olson 1978, Richardson 1980). Although there is the possibility that rings can move

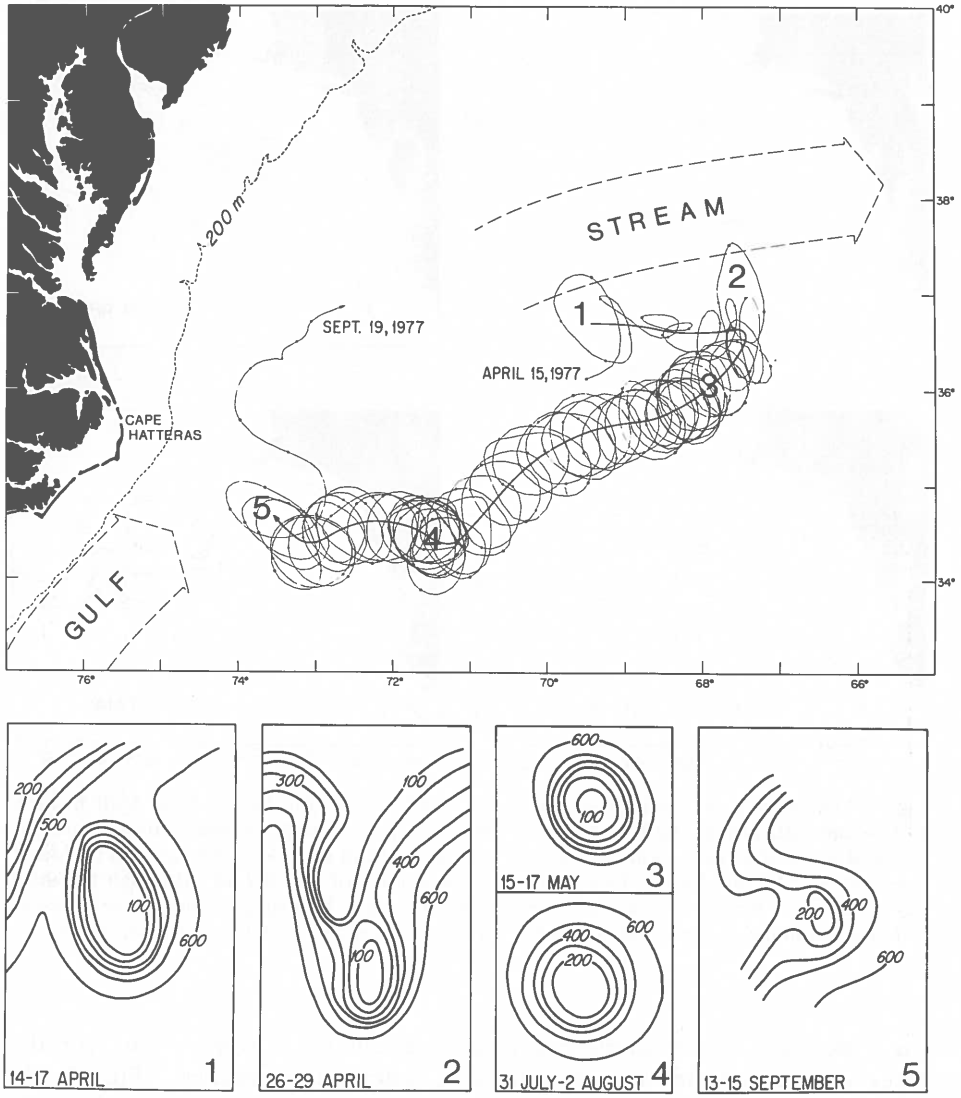

Fig. 8. Trajectory of ring Bob studied by the ring group in 1977. Top panel shows trajectory of free-drifting buoy looping around Bob's core. Bob moved eastward while interacting with the Gulf Stream, split off from the Stream, drifted southwestward through the Sargasso Sea, then coalesced with the Stream near Cape Hatteras after a lifetime of 7 months. Lower panels show the depth of the 15° isotherm in Bob at several times during its life. (After Ring Group 1981)

southward into the southern Sargasso Sea and slowly decay there, separately from the Stream, we have no evidence of this from rings tracked by buoys.

Frequently rings were observed to become attached to the Gulf Stream and interact with it. "Attached" means that ring contours - the topography of the

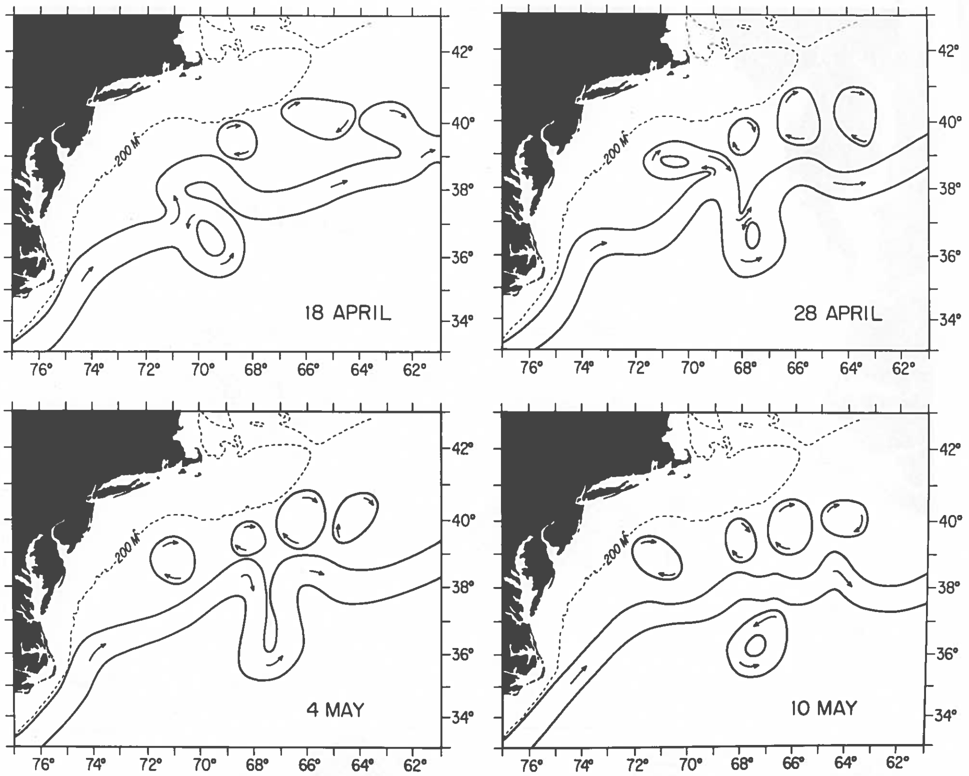

Fig. 9. Schematic representation of the interaction between ring Bob and the Gulf Stream. Bob became attached to the Stream in mid-April, 1977, was advected rapidly downstream, exchanged water and energy with the Stream, and reformed in early May. During this period of time the Gulf Stream formed two warm-core rings north of the Stream. Although the third panel shows an open meander, the evidence from a buoy in Bob suggests that closed circulation was maintained in the central region of the ring-meander. (After Richardson, 1980)

main thermocline, 15° isotherm for example – merge to some extent with the Stream's and that the two are exchanging water and energy, etc. (Figs. 8–10). Although satellite infrared images have shown this interaction since the early 1970's, only recently have we obtained drifting buoy and shipboard data to document it more fully (Watts and Olson 1978, Richardson et al. 1979a, Richardson 1980, Vastano, Schmitz, and Hagan 1980). A recent estimate suggests that on the average approximately six rings (cold- and warm-core) are in proximity to the Stream and that each of these interacts with the Stream every 2 months (Richardson 1980).

At least three modes of interaction have been identified in the available observations; the first two are fatal to the ring and result in its complete coalescence. The first mode occurs when a relatively intense ring becomes attached to the Stream, and the main Gulf Stream current is diverted and flows around the ring. The ring center opens to the north of the Stream which is in the form of

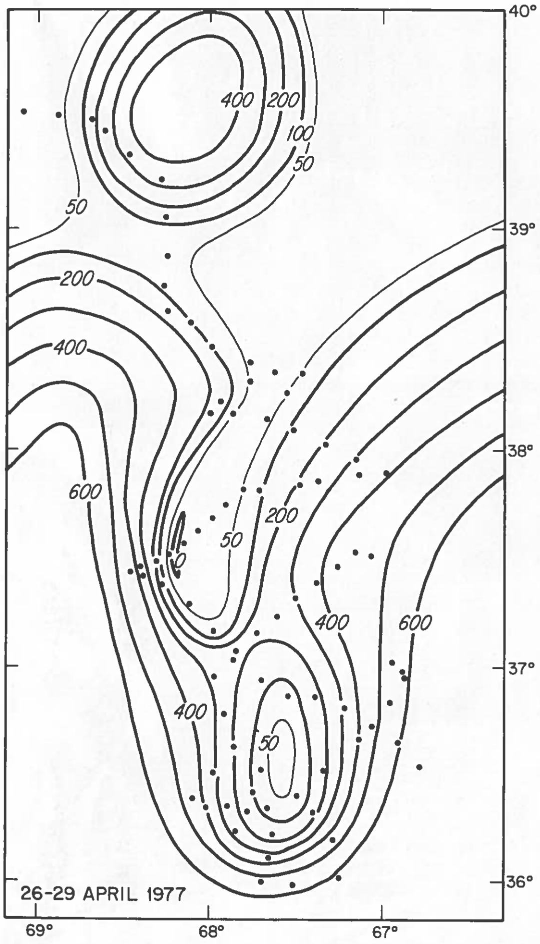

Fig. 10. Topography of the 15° isothermal surface in ring Bob while it was attached and interacting with the Gulf Stream 26–29 April based on an XBT survey, drifting buoys and satellite infrared images. A warm-core ring is located on the northern edge of the Stream. Vertically mixed, 12 °C water from the warm ring was observed to be entrained into the Gulf Stream; this water was possibly incorporated into Bob as it reformed in early May. (After Richardson 1980)

an open meander (Richardson, Cheney and Mantini 1977, Watts and Olson 1978). It is possible for the meander to then dissipate or to pinch off as another ring. The steps in this mode resemble the formation of a ring except that the steps are reversed in time. During the final coalescence, water from the ring center can be transported back across the Stream into the Slope water region.

The second mode occurs when a relatively weak ring becomes attached to the Stream, is advected downstream, and coalesces completely with the Stream (Richardson et al. 1979a, Richardson 1980). Rather than forming a meander as in the previous mode, the Stream seems to absorb the ring and to accelerate it downstream until it can no longer be identified. On two occasions the final coalescence of a ring may have been triggered by another ring which was advected downstream and collided with the ring subsequently lost.

The third and nonfatal mode occurs when a ring becomes attached to the Stream, moves downstream and reforms as a modified ring.

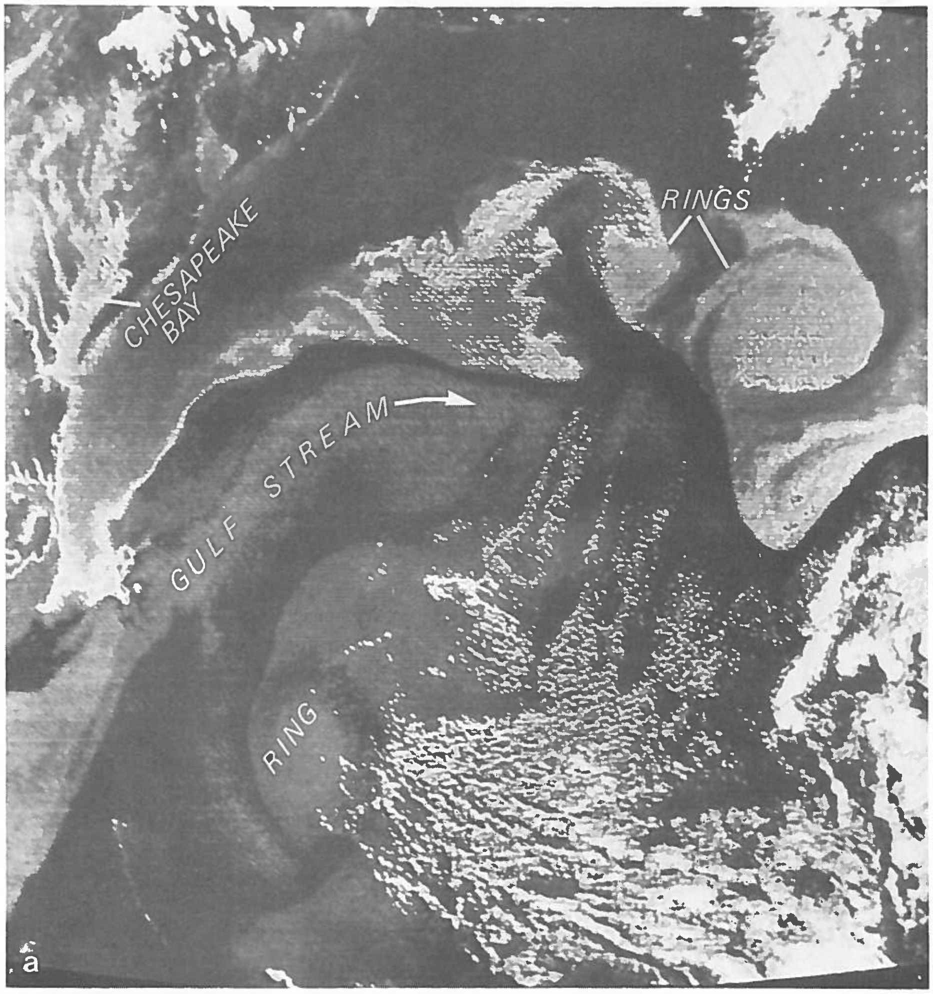

Fig. 11. Satellite infrared images of the Gulf Stream region showing the entrainment of warm Gulf Stream water into cold-core rings. Black and white photographs were made from color-enhanced images to emphasize certain features. **a** 28 April, 1974; **b** 13 April, 1977. (Color photos courtesy R. Legeckis and A. Strong, NOAA, NESS)

During the time the ring is connected to the Stream, significant amounts of energy and water can be exchanged between the two. Although this process can be easily observed in the near surface water with satellite images (Fig. 11) and with before and after XBT sections, it is much more difficult to observe in the deeper water of a ring (Vastano, Schmitz, and Hagan 1980). During an interaction, warm-core Gulf Stream water is entrained into a ring and advected cyclonically around its center. Frequently the warm, near-surface water entrained into rings is then mixed into surrounding areas and sometimes exchanged from ring to ring. Because of the rapid rotation and translation of rings warm Gulf Stream water can be spread throughout wide areas of the

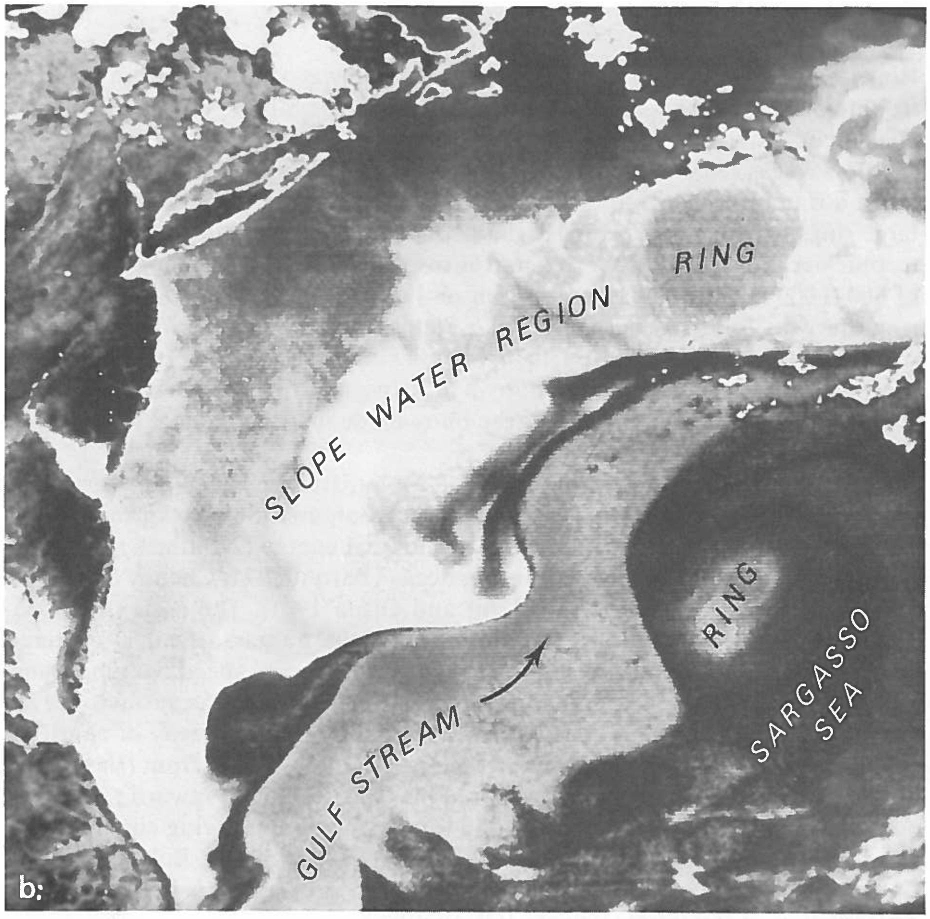

Fig. 11b

Slope water region and Sargasso Sea in periods of weeks. This spreading of warm water may be an important step in maintaining the temperature structure of these areas despite their large wintertime loss of heat. Rings may also limit the size and location of areas in which 18° water forms and the amount of such water that does form.

During several interactions of rings and the Gulf Stream, the rotation rate of the central ring region increased. On two of these occasions the hydrographic properties were measured and the upper part of the ring core was vertically stretched (Richardson et al. 1979a, Vastano et al. 1980, Olson 1980, Olson and Watts 1982). On one of these occasions the 18° isotherm rose 250 m (relative to 10°C), 60% of the thickness before the interaction, and the rotation rate increased from a period of 3.5 days to 1.5 days (Richardson et al. 1979a). Thus, during an interaction, a ring can become spun up; the increase in rotation rate and the stretching of the upper layer are in agreement with the conservation of potential vorticity.

2.3.6 Decay

Rings exhibit both catastrophic decay and a slower spindown decay. Catastrophic decay occurs when a ring coalesces with the Stream and is lost. Rapid coalescence can span periods of time from a few days (Watts and Olson 1978) to a few weeks (Richardson 1980). A second type of catastrophic decay occurs when a ring bifurcates into separate "ringlets" as has been observed with two large rings (Cheney et al. 1976, Richardson et al. 1979a).[2] A third type of catastrophic decay occurs when a ring moves over the Blake Escarpment into depths of 800–1 000 m. Although this last process has not been observed in detail, one ring that was followed onto the Blake Plateau was significantly weaker afterward (Cheney and Richardson 1976, Schmitz and Vastano 1977). Another ring that was tracked with a satellite buoy had its normal ring circulation disrupted as it impinged on the escarpment; the buoy made increasing large loops in the ring and finally left it entirely.

In the slower spindown the dome of cooler, fresher water that forms the heart of the ring slowly subsides towards the Sargasso Sea background. This dome represents a reservoir of available potential energy (2–3 times the kinetic energy) which is slowly released during decay (Barrett 1971, Cheney and Richardson 1976, Olson 1980, Reid, Elliott and Olson 1981). The region of maximum available potential energy (compared to the Sargasso Sea) is centered near the 15° isotherm (Olson 1980). Regions of high swirl speed, volume transport, and kinetic energy, all of which are concentrated near the surface, are related to the cold-core and decay as the core collapses. The decay of ring Bob suggests a slow outward radial shift in the position of the ring front (Vastano et al. 1980, Olson 1980). The outward spread is consistent with inward radial velocity in the surface layers, compensated for by sinking in the ring core and outward radial velocity at depth. Calculations of variations in Bob's core (decreased layer thickness and decreased rotation rate) are consistent with the conservation of potential vorticity (Olson 1980).

Long term rates of subsidence of the core range from about 0.4 m d^{-1} to 1.3 m d^{-1} (Parker 1971, Fuglister 1972, Cheney and Richardson 1976, Richardson et al. 1979a, Vastano et al. 1982); however, the first value is for a moderately old ring which traversed the Blake Escarpment (Cheney and Richardson 1976) and the second is for a young ring that interacted with the Stream and may have bifurcated (Richardson et al. 1979a; Vastano et al. 1982). Considering all the complexities of a ring's life – interactions, infusions of new water, bifurcations, disruption due to topography, variations in background conditions – these values must be viewed as approximate; they imply overall ring lifetimes of 1 to 4 years. The numerous rings encountered in the southwestern Sargasso Sea also show a core subsidence with latitude and an implied life of 1 to 2 years in agreement with the estimated mean southwestward speeds in this region (Parker 1971, Lai and Richardson 1977). Recent evidence suggests that the most frequent finish of a ring is not through long-term decay but through coal-

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[2] Vastano et al. (1982) conclude that one of these rings did not bifurcate but that two separate rings partially merged, interacted, and then split apart.

escence with the Stream; thus the mean age at disappearance is approximately 1 year. One reason the longevity of a ring is difficult to calculate is due to the murky behavior of ring-Gulf Stream interactions. How many "new rings" are really recycled older rings?

Various mechanisms have been suggested as contributing to ring spindown and decay. The earliest of these is simple frictional decay leading to symmetric radial overturning which spins down the ring (Molinari 1970). While such a mechanism is certainly plausible, there are several alternatives which can accomplish the same end without resorting to large eddy viscosities. These include dispersion of the ring as a packet of Rossby waves, and a possible secondary hydrodynamic instability of the ring to the growth of subring scale perturbations. Wave dispersion, postulated as a decay mechanism for rings by Flierl (1977b), could be a fairly effective means for the release of ring energy and property distributions into the Sargasso Sea at the expense of the ring. The nonlinearity of the ring circulation apparently acts to overcome dispersion such that the ring behaves more like a solitary wave (McWilliams and Flierl 1979, Flierl 1979). The other mechanism involving either baroclinic, barotropic, or combined instability in the ring may also be of some importance at least in younger rings (Saunders 1973, Hart 1974, Olson 1976). Observations imply that the necessary conditions for instability are met in rings and that asymmetric disturbances of large enough amplitude to account for ring decay do occur (Olson 1980). Just as in the translation question, it is not certain to what extent each of the three mechanisms mentioned here plays a role in actual rings.

Some recent eddy-resolving general circulation models which develop quite realistic Gulf Stream rings (Holland 1978, Semtner and Mintz 1977, see also Chap. 18) begin to show the complex energy flows within the ocean. One of the dominant pathways of kinetic and potential energy within the system is through rings, where energy is transformed and transmitted both laterally and vertically to other parts of the ocean. Progress in understanding rings will be made as these models are refined, and the life histories of individual model rings are studied and understood.

2.4 Warm-Core Rings

Warm-core, anticyclonic rings form throughout the Slope water, a triangular region bounded on the south by the Gulf Stream and on the north by the continental slope (Saunders 1971, Gotthardt 1973). The largest rings, 200–300 km in diameter, consist of an annular ring of Gulf Stream surrounding a Sargasso Sea core; these are usually seen east of Georges Bank. Smaller rings, 100 km in diameter, form in the west; their formation resembles (on satellite infrared images) an aneurism during which the side of the Stream bulges out to the north and pinches off from the main current. Occasionally two rings pinch off from the same aneurism. This type of formation may explain why most warm-core rings have a smaller amplitude thermocline displacement in their centers (a few hundred meters) than that across the Stream – only part of the Gulf Stream, not its whole width, separates from the main current.

Typically, five warm rings form per year; their size (approximately 100 km) varies, but the average appears to be somewhat smaller in diameter than that of

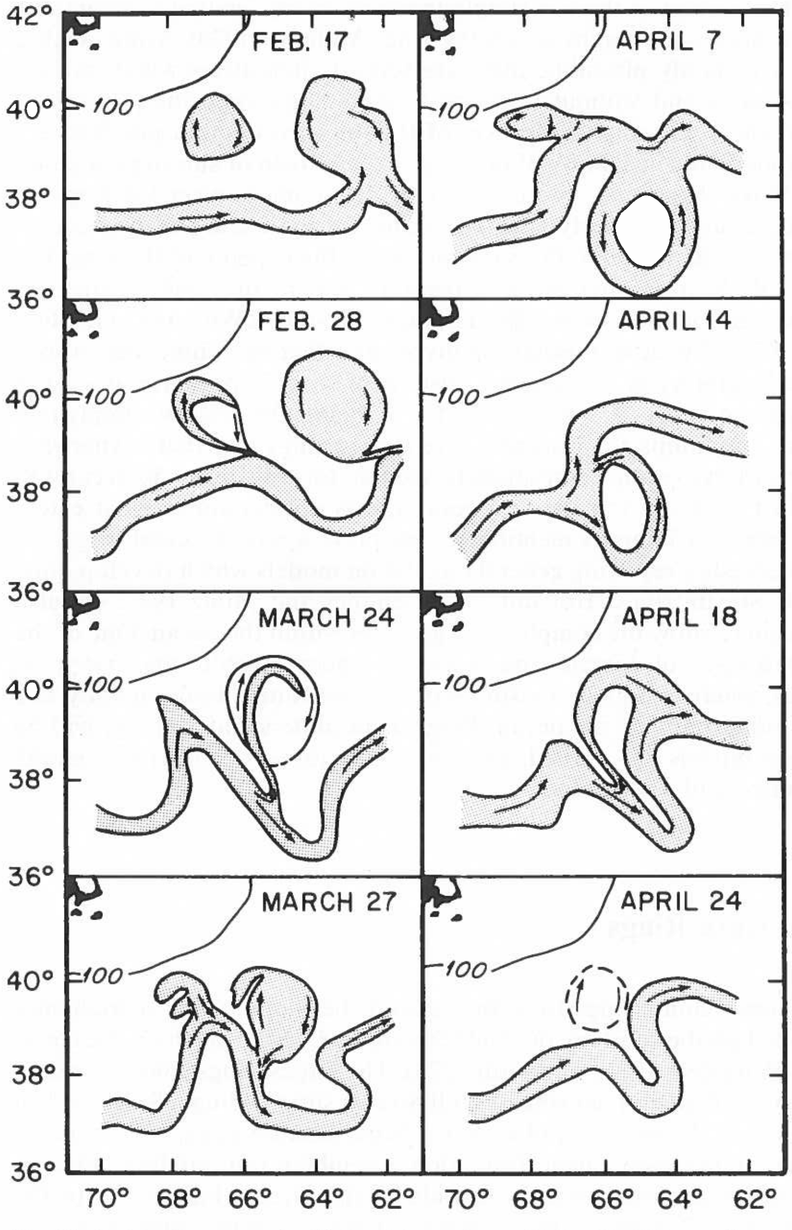

Fig. 12. Series of warm and cold ring interactions with the Gulf Stream from satellite images during 1976. (After Mizenko and Chamberlin, 1979). One hundred meter depth contour is shown in *upper left*

cold rings (Bisagni 1976, Lai and Richardson 1977, Halliwell and Mooers 1979). The proximity of the continental shelf to the mean Gulf Stream position may be a factor in limiting the size of northward meanders. Approximately three rings exist at a single time. Although warm rings form as far east as the Grand Banks (50°W), they are most frequently observed in the western region, due to more frequent satellite and ship coverage in the western region. Warm rings move westward with a mean speed of 5 $\mathrm{cm\,s^{-1}}$, a speed similar to the mean flow in the Slope water region; this implies that these rings might be advected by the mean flow. As warm rings drift westward they gradually shrink in size. When they reach Cape Hatteras, after a lifetime of about 6 months, they coalesce with the Stream (Gotthardt and Potocsky 1974).

Warm rings exhibit considerable variation from the typical pattern described above. Frequently they interact with the Gulf Stream – sometimes separating again, sometimes coalescing completely. Many interactions may be seen with satellite infrared images which show warm Gulf Stream entrainments into rings and ring water entrainments into the Gulf Stream (Fig. 12). Rings also often entrain cold fresh Shelf water and advect it around their eastern sides into the Gulf Stream (Morgan and Bishop 1977). The spilled oil from the ARGO MERCHANT, tracked with a drifter, followed this path into the Stream. At times no warm rings can be identified in the Slope region and at other times the Slope region appears to be nearly filled with rings (May 1980).

During winter the warm-core of these rings is cooled, and deep (down to 500 m) vertically mixed isothermal layers are formed analogous to the 18° subtropical mode water south of the Gulf Stream (Fig. 2). The mixed layer in rings, however, can cool to a temperature of 11°–12°C. During subsequent summer heating, a seasonal thermocline forms over the top of the deeper mixed water. The mixed water is entrained by the Gulf Stream during ring-Gulf Stream interactions and final coalescence. This water can be incorporated into newly formed warm and cold rings.

An interdisciplinary and cooperative study of warm-core rings is presently being carried out. The experiment, scheduled to occur from 1981–1985, should provide significant new information on these rings.

2.5 Gulf of Mexico Rings

Large, anticyclonic, warm-core rings separate from the loop current in the eastern Gulf of Mexico. Elliott (1981) has prepared a summary of these rings and reinterpreted some older data. Early observations were made by Leipper (1970) and Nowlin, Hubertz and Reid (1968). These rings form at an average rate of one to two per year; a maximum of three rings were observed to form in one eight-month period. Their average diameter is 370 km, and they drift westward with a mean speed of 2.4 $\mathrm{cm\,s^{-1}}$. One ring was tracked all the way to the western boundary of the Gulf. The estimated lifespan of these rings, as defined by an e-folding time, is one year.

2.6 Eastern Rings

"Rings" will be used here as a general term for eddies formed by the Gulf Stream system. This is a broader definition than that proposed by Fuglister (1972), who described a ring as being formed from a closed segment of the entire width of the Stream. The eastern rings seem to form much like the western rings with the exception that in the eastern region the Gulf Stream has become broader and less jet-like and often splits into separate filaments or branches. In general, eastern rings do not consist of a closed segment of current which includes the whole width of the Stream. The large, cold-core eastern rings have become popularly known as "Big Babies" (Worthington 1976b).

Ring-like eddies generated by the Gulf Stream system have been observed over a broad area of the North Atlantic. These ring observations coincide closely with a region of large thermocline displacements, high eddy potential energy density (Dantzler 1977) and high eddy kinetic energy (Wyrtki, Magaard and Hager 1976). The region of large thermocline displacements follows the Gulf Stream eastward and is bounded on the south by latitude 32°N and on the east by the mid-Atlantic Ridge; the northern limits are not well known. Two regions of high energy extend eastward across the mid-Atlantic Ridge near latitudes 33°N and 42°N.

Within this region are three sub-areas which contain rings of different characteristics. South of the Stream and extending eastward over the mid-Atlantic Ridge are large, cold-core eastern rings. Overlying the southeast Newfoundland Ridge are cold rings whose cores originate in the Labrador Current. East of the Grand Banks are smaller warm and cold-core North Atlantic Current rings.

Numerous large cold-core rings have been found south of the Gulf Stream and east of 60°W. Some of these rings appear to be larger than western rings and have overall diameters greater than 300 km. Some also have a smaller isotherm slope to their flanks, multiple bumps, a weak near surface temperature signal, and are often not very circular (Fig. 2, McCartney et al. 1978). A large (500 km) triangular-shaped ring was surveyed twice by Soviet scientists (Bulgakov et al. 1977). It was located near 32°N, 50°W, and moved westward with a speed of 4 km/d as did other rings in this area (McCartney et al. 1978). A large eastern ring, 450 km in diameter, was identified near 33°N, 35°W (Gould 1976).

Only twice has the formation of these rings been observed with supporting in situ data. The first was recorded by both satellite images (La Violette, pers. comm.) and a SOFAR float which was trapped in the ring as it pinched off from the Stream near 38°N, 50°W (Richardson et al. 1981). The ring which was approximately 300 km in diameter moved southward, then westward (4 cm s^{-1}) skirting the Corner seamounts and then probably coalesced with the Stream after a lifetime of 11 months, (Fig. 7). A second ring was observed by Gould (pers. comm.) to pinch off from a front lying south of the Azores near 33°N, 33°W. The ring had a diameter of 100–150 km, a thermocline displacement of 150 m, surface speeds of 25 cm s^{-1}, and was propagating westward with a speed of 2.9 cm s^{-1}.

The limited evidence suggests that rings can form from southward meanders of the Stream east of 60°W and also from meanders along the front at the eastern terminus of the subtropical gyre. Some of the observed rings may have formed from the cold water wedge associated with the Gulf Stream recirculation. This wedge or ridge of cold water lies along 35°N and extends from near 40°W to at least 55°W. A good synoptic depiction of this wedge was given by Emery, Ebbesmeyer and Dugan (1980) and a map of the mean temperature field of it at 450 m was shown by Richardson (1981). The front south of the Azores is the eastern extension of the south side of this wedge.

A southeastward projecting ridge of cold water overlies the Southeast Newfoundland Ridge. (An early observation of this cold water and a large iceberg 50 m high, 2 km in diameter was made in a letter from F.D. Mason to J. Williams dated Clifton, England, 20 June 1810; see Furlong 1812). Often the surface manifestation of the cold ridge can be seen on satellite images as an extension of the cold Labrador Current into the warmer Gulf Stream water. Occasionally, water from the cold ridge pinches off to the southeast forming cold-core rings (Mann 1967, Mountain and Shuhy 1980). A study of infrared images shows that within a 5 year period 15 distinct rings formed, and that, at least initially, they drifted southeastward (LaViolette 1981). The location of the cold ridge and subsequent formation of rings from it seem to be dynamically tied to the sea floor ridge underneath. It is not known whether these rings are trapped by the bottom topography or drift away from their source region. Since their cores contain very cold and fresh water from the Labrador Current, it seems clear that they are distinctly different from the large eastern rings described above.

Southeastward of the Grand Banks and Flemish Cap region, North Atlantic Current warm and cold-core rings, approximately 100 km in diameter, are frequently observed both with in situ data (Voorheis, Aagaard, and Coachman 1973, Schmitz 1981a) and with satellite images (La Violette 1981).

Rings are probably formed all along the northeastern extension of the North Atlantic Current. Howe and Tait (1967) observed an elongated cold-core ring 220 × 85 km in size, located near 53°N, 19°W. They suggested its core was formed by an eastward intrusion of water originally located west of a branch of the North Atlantic Current. Krauss and Meinke (1981) recently made an XBT and hydrographic survey of the region north of the Azores between 38° and 46°N; they found four cold and three warm current rings with an average diameter of 150 km.

2.7 Current Rings from Other Currents[3]

Current rings have been seen wherever swift and narrow currents are found; in the South Atlantic (Brazil Current), North Pacific (Kuroshio), South Pacific

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[3] See other chapters for a more complete description of these areas, the currents and the rings there.

(East Australian Current), Indian Ocean (Agulhas Current) and Southern Ocean (Circumpolar Current). The Kuroshio meanders and sheds warm and cold-core rings in much the manner of the Gulf Stream. Recently Kawai (1980) has identified 90 cold-core ring observations made since 1927. He also used a large, areal, synoptic survey of Kuroshio region consisting of 30 ships in the summer of 1939 to chart the coexistence of 13 cold rings and 2 warm rings. These data suggest that cold rings form at three or four specific sites, and that they subsequently drift southwestward through the western Pacific along several preferred paths. Some cold-core rings which formed to the east of the Izu Ogasawara Ridge apparently drifted through gaps in this Ridge south of Japan. A recent synoptic study found three warm rings and three cold rings (Cheney 1977b). One of the cold rings, 250 km in diameter, moved northwestward and coalesced with the Kuroshio after an estimated lifetime of 5 months (Cheney, Richardson, and Nagasaka 1980).

Warm-core Kuroshio rings are generally 150 km in diameter and have lifetimes of 2–10 months (Kitano 1975). One warm ring remained nearly stationary just east of Japan interacting occasionally with the Kuroshio. It finally coalesced with the Kuroshio forming a meander which spawned another warm-core ring (Hata 1969). Another ring moved northeastward with a mean speed of 1 cm s^{-1} over a 20-month period (Hata 1974). During two winters, deep (500 m) layers of isothermal water were formed in the core of this ring - 10° during the first winter, 6° during the second. In summer a seasonal thermocline developed over the isothermal layers. Occasionally two isothermal layers are seen in a single ring. Tomosada (1978), who reviewed warm Kuroshio ring observations, suggests that this occurs when Kuroshio water containing subtropical mode water overrides an older eddy which already contains an isothermal layer.

The Oyashio, a current located north of the Kuroshio, also sheds warm and cold current rings (Cheney 1977b).

Warm-core rings are generated from poleward meanders of the East Australian Current (Hamon 1965, Andrews and Scully-Power 1976, Nilsson and Cresswell 1981). These rings are typically 250 km in diameter and have lifetimes of about one year. Most rings coalesce with East Australian Current meanders, often pinching off again as modified rings. Deep (350 m) isothermal layers form in the core water during winter with temperatures down to 16°C. Recently two warm-core rings, each with an isothermal layer, were observed to coalesce resulting in a ring with two different isothermal layers in it (Cresswell 1981). Observations of cold-core East Australian Current rings have not been reported although there is the possibility they exist.

Infrared images have been used to observe Brazil Current rings (Legeckis and Gordon 1982). Forty-three warm-core ring observations were made in the area bounded by 38°–48°S, 48°–56°W. These include 20 individual warm rings seen during the period September 1975–April 1976. The implication is that at least 20 rings per year can form. However, only three rings were observed during 4 months of 1978, so the formation rate could be much less than 20 on the average. Warm-core rings are usually elliptical with a mean diameter of 150 km. The preferred drift direction was southward. Only four cold-core rings were identified; they were also elliptical and their size ranged from 100–300 km.

South of Cape Town, South Africa, the Agulhas turns abruptly eastward and forms a westward-projecting wedge of warm surface water. At times the tip of the wedge separates from the main current and forms warm-core rings 150–200 km in diameter (Duncan 1968, Gründlingh 1978). The Agulhas return current flows eastward near 40°S in a series of semi-permanent warm and cold meander-rings, some of which probably separate from the main current (Gründlingh 1978, Harris, Legeckis, and van Foreest 1978, Harris and van Foreest 1978). The location of the meander-rings appears to be connected dynamically with sea floor topographic features such as the Agulhas Plateau, which is much like the Gulf Stream where it overlies the New England Seamount Chain and Southeast Newfoundland Ridge.

Cold-core cyclonic rings have been observed to form from the Antarctic Polar Front, a transition zone between Antarctic and Subantarctic water which coincides with a core of high velocity. Two rings were reported in the Drake Passage (Joyce, Patterson and Millard 1981, Peterson, Nowlin and Whitworth 1981); they had diameters of 100 km and they drifted northeastward in the Antarctic Circumpolar Current at speeds of 5–10 cm s^{-1}. The available potential energy of these was on the order of 1/20 of Gulf Stream rings; this is due to smaller vertical displacements and weaker stratification than that which is found in Gulf Stream rings (Joyce et al. 1981). Another cyclonic, cold-core, Polar Front ring was observed south of Australia (Savchenko, Emery, and Vladimirov 1978). This ring was south of and combined with the Subantarctic Front and was moving north northeastward at a speed of 3 cm s^{-1}. The authors suggest it contained a deep anticyclonic eddy beneath the cyclonic ring in the surface layer ($<2\,000$ m).

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