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Observed decay of a cyclonic Gulf Stream ring

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Abstract—A cyclonic Gulf Stream ring was tracked in the western Sargasso Sea from March 1971 to April 1972. It moved 700 km southwest at 2 km day^{-1} and coalesced with the Gulf Stream off Cape Canaveral. During the first eight months the ring was in relatively deep water and available potential energy relative to 1000 m decayed at an estimated linear rate of 10^{21} ergs day^{-1}. The ring had a life expectancy of approximately 2·5 years. During the final three months it moved into shallower water and the decay rate accelerated more than fourfold. Layers of Sargasso Sea water inside the ring indicated mixing with surrounding water that may be the decay mechanism of the ring.

INTRODUCTION

THE GULF Stream represents a dynamic boundary between cold Slope Water and warm Sargasso Sea Water. Horizontal variations in density result in a large pool of potential energy that could be available for conversion into kinetic energy if the surfaces of constant density became horizontal. One mechanism by which water and energy are transferred across the Gulf Stream is by the formation of rings. Rings are formed from 300- to 400-km diameter Gulf Stream meanders which form closed current loops and separate from the main stream (FUGLISTER, 1971; PARKER, 1971). Rings formed south of the Stream are cyclonic and consist of a cold, less-saline mass of Slope Water surrounded by a ring of Gulf Stream Water. Injection of cyclonic rings into the Sargasso Sea and their subsequent decay may be important in the energy balance of the Sargasso Sea and an important step in the cascade of energy from the large-scale wind driven circulation to smaller scale fluctuations in the ocean.

Approximately five cyclonic rings have been estimated to form annually (NEWTON, 1961; BARRETT, 1971; FUGLISTER, 1971), with estimated lifetimes of approximately four years, based on the rate of decay of available potential energy (BARRETT, 1971). A shorter lifetime is possible if they coalesce with the Gulf Stream, as anti-cyclonic rings north of the Stream have been observed to do (SAUNDERS, 1971; THOMPSON and GOTTHARDT, 1971).

This study is of the decay of a cyclonic Gulf Stream ring first described by RICHARDSON, STRONG and KNAUSS (1973). It represents the longest observation of a cyclonic Gulf Stream ring and the first such series in the western Sargasso Sea. During the observations the ring moved from off Cape Hatteras, N.C., toward Florida with an average southwestward speed of 2 km day^{-1} (Fig. 1). Evidence suggests that it coalesced with the Gulf Stream off Florida and its lifetime was probably two years.

OBSERVATIONS

Observations consist of a variety of data: satellite infra-red, expendable bathythermograph (XBT), salinity–temperature–depth recorder (STD), hydrostation, and ship drift measurements taken aboard numerous ships. Of these observations, five cruises yielded sufficient data to be used in describing the decay process (Table 1). The cruises constitute the last 11 months of the ring's life and although this report discusses only five cruises, all the data

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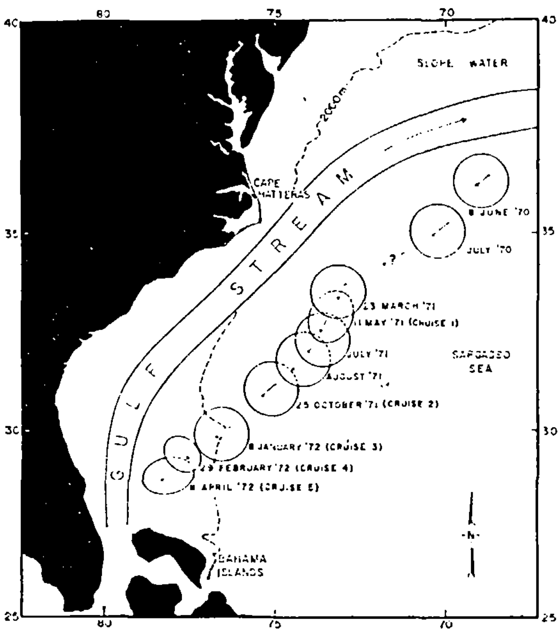

Fig. 1. Movement of the ring as represented by successive positions of the 15°C isotherm at 500 m from XBT data. Outside the ring temperatures of about 17°C were found at this depth while inside the ring temperatures as low as 9°C were measured. Typical diameter was 150 km and average translational speed was 2 km day^{-1}. June and July 1970 positions represent a ring that the Navy (U.S. NAVAL OCEANOGRAPHIC OFFICE, 1970) observed to form. There is no way to prove that this is the same ring except that the size and temperature structure of the two rings are consistent, they are apparently moving in the same direction, and the extrapolated position based on a speed of 2 km day^{-1} is nearly correct. A thorough search for the ring was made east of Florida and north of the Bahamas by XBT at the end of April 1972, but no water colder than 15°C at 500 m was found. We suggest that the ring was absorbed by the Gulf Stream.

strongly confirm that all measurements were made in the same ring (RICHARDSON, STRONG and KNAUSS, 1973).

The first two cruises consist of temperature–salinity sections through the ring and XBT data. The principal data from the last three cruises are temperatures measured with 760-m XBT's. To calculate geostrophic velocities and kinetic and potential energy distributions, the density field must be known. For the last three cruises, salinity values were assigned to the measured temperature profiles using the temperature–salinity relationships of the North American Basin (WRIGHT and WORTHINGTON, 1970), which corresponded closely to the actual *T–S* measurements taken within the ring. Errors in calculating density by assigning salinity are approximately the same size as those caused by the errors in temperature measurement by XBT. For a more complete discussion of the data and the associated measurement errors, see RICHARDSON, STRONG and KNAUSS (1973) and CHENEY and RICHARDSON (1974).

SIZE AND SHAPE

Size and shape of the ring were determined from the temperature data (Fig. 2). Depth contours of the 15°C isothermal surface are depicted because this surface clearly shows the three-dimensional shape of the thermocline within the ring. Temperature sections represent a compilation of all the data in the ring and, when the ring was elliptical, show the average cross-sectional structure. XBT traces could be read to 850 m. Below 850 m, on Cruises 3 and 4, temperature was extrapolated to 1000 m by assuming a linear rate of warming between Cruises 2 and 5 when the deep temperature structure was known.

Three of the cruises (1, 2, and 5) provide reasonably accurate determinations of the ring's shape. Of these, Cruises 1 and 5 clearly show the ring to be elliptical. Cruise 2 indicates the interior region (within 70-km radius) to be approximately circular, although the outer portion seems to be elliptical. Shape determinations were confirmed by near-surface as well as 750-m temperature plots. All XBT sections of each cruise were taken within a two-day period and ring translation can be shown to have a negligible effect on the shape and size when reasonable translation rates are assumed. Although a ring may drift several kilometers during a survey, the error is small compared to the overall dimensions of the ring.

Data from Cruises 3 and 4 were too few to determine accurately the size and shape of the ring. Contours were drawn to be consistent with the data and a gradually decaying ring; they are reasonable when the results of other observations are considered.

The temperature section from the first cruise illustrates the broad, well-defined dome of cooler

Table 1. *Primary observations of the ring.*

Consecutive Cruise Number	Date	Ship	Operating Agency*	Observations**
	1971			
1	May 9-11 17-18	TRIDENT	URI	65 XBT's, 6 hydro-stations, ship drift
2	October 21-24	TRIDENT	URI	45 XBT's, ship drift 6 STD stations
	1972			
3	January 8	WILKES	NAVOCEANO	11 XBT's
4	February 29	MIZAR	NRL	17 XBT's
5	April 8-9	RESEARCHER	NOAA	32 XBT's, 2 CTD stations

*URI—University of Rhode Island. NAVOCEANO—U.S. Naval Oceanographic Office. NRL—Naval Research Laboratory. NOAA—National Oceanic & Atmospheric Administration.

**XBT—Expendable bathythermograph. STD—Salinity-temperature-depth. CTD—Conductivity-temperature-depth.

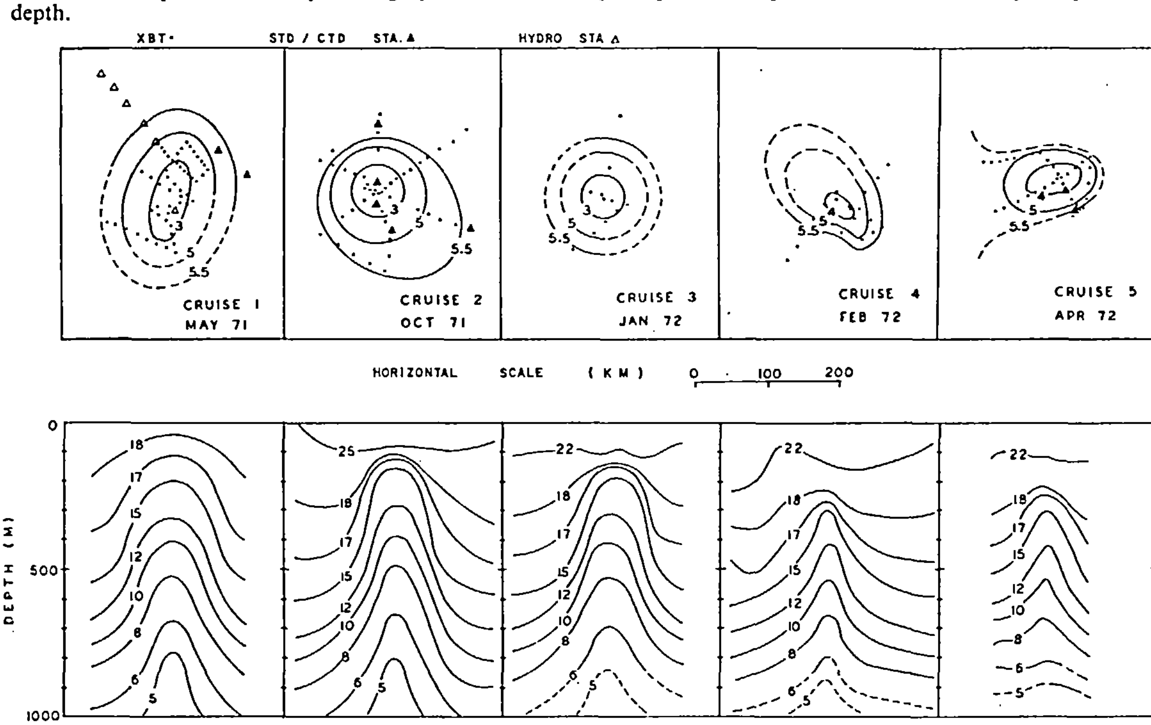

Fig. 2. Temperature structure of the ring at each observation. Upper figures show the depth contours (in hundreds of meters) of the 15°C isothermal surface. Outside the ring the 15° isothermal surface lies at a depth of approximately 650 m while inside the ring it was occasionally above 150 m. Lower figures present vertical temperature sections. The data were plotted to show the mean temperature structure at each cruise.

water at the center of the ring. Minimum surface temperature at the center was 19 compared to 23°C in the surrounding Sargasso Sea. The section from Cruise 2 shows the surface layer to have warmed considerably over the summer while the dome became narrower. In both Cruises 1 and 2 deep hydrographic data at the center of the ring showed the anomalously cold water to extend as deep as 3000 m. The temperature section from Cruise 3 shows little change from that of the previous cruise other than seasonal cooling in the upper 100 m. In less than two months between the third and fourth cruises, however, the thermal dome contracted and sank significantly deeper. The ring is hardly noticeable in the upper 300 m. In the last section, from Cruise 5, further decay of the ring's structure is suggested.

Table 2 is a summary of ring size and shape during the year based on the intersection of the 15°C isothermal surface and 500 m. This criterion does not establish the total extent of the ring but merely provides a convenient standard. The portion of the total energy contained within this arbitrary boundary varied from about 50% during the first cruise to about 90% at the time of the last observation. Depth of the 15°C surface in the center of the ring is also given.

Variation with time of the depth of the thermocline in the core is shown in Fig. 3. These data suggest that spacing between isotherms in the main thermocline (6 to 15°C) at the center of the ring did not change significantly over the 11-month period but subsided as a uniform layer. However, the data also suggest that isotherms rose 40 m between Cruises 1 and 2 and subsided an equal amount between Cruises 2 and 3. This result is confirmed by several XBT observations as well as STD stations. Repeated observations at the ring center suggest that possible errors from aliasing by internal waves were not significant. During this period the size decreased, the average radius shrinking from 79 to 70 km (Table 2).

SURFACE VELOCITIES

Surface velocities were determined from ship drift and fixes taken by satellite navigation (Cruises 1 and 2) and Loran C (Cruise 5). The large scatter of values (Fig. 4) is due to a combination of the errors of the measurements, the time and space averages representative of each measurement, which can be large between satellite fixes, and the elliptical shape of the ring on Cruises 1 and 5.

Surface velocities clearly show a strong cyclonic circulation with speeds in the ring of approximately 100 cm s^{-1}. Surface currents remained strong throughout the life of the ring but as the ring decreased in size the high velocity region moved towards the center from a radius of about 70 km (Cruise 1) to a radius of 35 km (Cruise 5), an average rate of 0·1 km day^{-1}. Qualitative corroboration is the inward radial movement of the location of maximum slope in isotherms (Fig. 2).

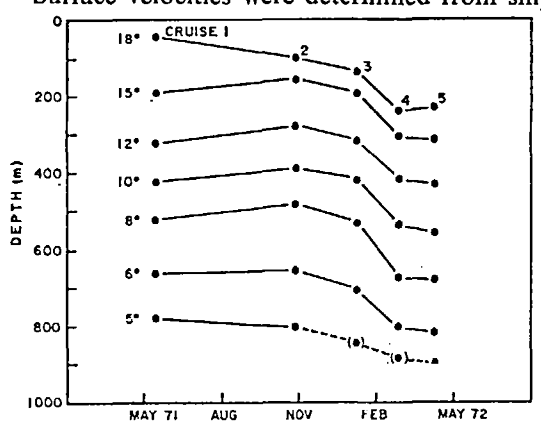

Fig. 3. Variation with time of the depths of selected isotherms measured at the center of the ring.

AVAILABLE POTENTIAL ENERGY

Available potential energy (APE) has been shown to be useful in studying the decay of Gulf Stream rings (Barrett, 1971). The concept, as

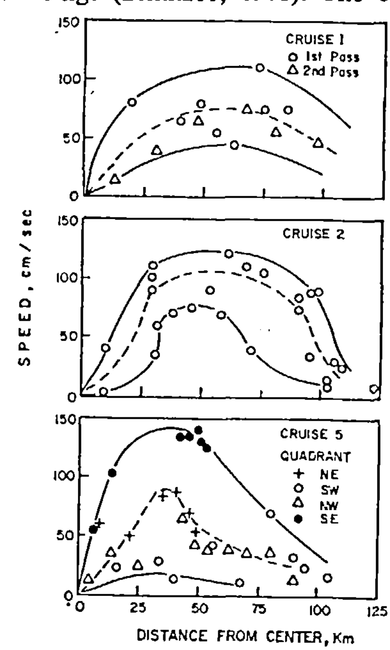

Fig. 4. Surface velocity profiles from Cruises 1, 2, and 5 as measured by ship drift. Magnitudes of velocities are shown plotted as a function of actual distance from the center of the ring.

Table 2. Summary of ring size and shape.

Cruise	Radius (km)*	Shape*	15°C Depth at center (m)
1	79 (± 5)**	elliptical (95 x 65 km)	190 (± 10)**
2	71 (± 4)	circular	150 (± 8)
3	70 (± 9)	circular (?)	190 (± 12)
4	55 (± 16)	elliptical (?)	300 (± 12)
5	55 (± 3)	elliptical (63 x 48 km)	305 (± 8)

*Size and shape of 15°C isothermal surface at 500 m.
**The value in parentheses is an estimate of the error due to temperature and depth measurement errors and error caused by insufficient data.

introduced by LORENZ (1955), can be applied to a fixed mass that has been redistributed in a fixed region. For a cyclonic ring, a mass of Slope Water has been transported across the stream into the Sargasso Sea. Available potential energy of the ring is due to the raised pycnocline at its center. As the ring decays its dome-like structure collapses and APE decays correspondingly. The decay rate gives an estimate of the lifetime of the ring.

APE was determined from hydrographic sections through the center of the ring. The anomaly of potential energy per unit area (FOFONOFF, 1962), defined as:

$$\frac{1}{g}\int_{0}^{p} p\,\delta\,dp$$

where p = pressure, δ = specific anomaly, g = acceleration of gravity,
was computed at each hydrographic station.† This yielded a profile of the potential energy anomaly per unit area across the ring. APE of the ring with respect to the reference value typical for the Sargasso Sea was obtained by integrating the profile over the area of the ring.

The density structure of the Sargasso Sea is not uniform. If no ring decay occurred during the southwest movement the ring's APE would have decreased by almost 15% merely by moving into a slightly denser region of the Sargasso Sea. Because the purpose of the study was to determine the relative rate of APE decay, the reference value of potential energy anomaly, determined from hydrographic stations outside the ring (Cruise 1), was assumed to remain constant throughout the observations. This yielded decay rates dependent only on changes of the structure of the ring and not the environment.

Profiles of the anomaly of potential energy relative to 1000 m are shown in Fig. 5 for each of the five sets of observations. A calculation of similar potential energy profiles relative to selected depths yields potential energy density on a vertical cross-section through the center of the ring (Fig. 6). Potential energy density was calculated at radial intervals of 20 km and at depth intervals of 250 m. Viewed together the figures present a complete picture of the energy decay of the ring as the contours gradually

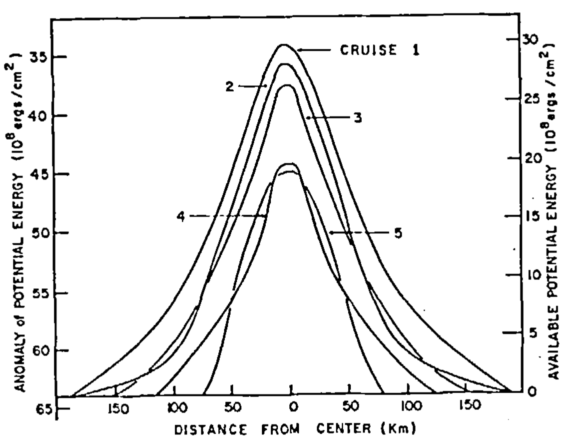

Fig. 5. Profiles of the anomaly of potential energy per unit area relative to 1000 m for the five observations. Right-hand scale is available potential energy with respect to a station in the Sargasso Sea.

†On Cruises 3 to 5 the specific volume anomaly was computed using temperatures from XBT's and salinities from the mean T-S curve as described under 'observations'.

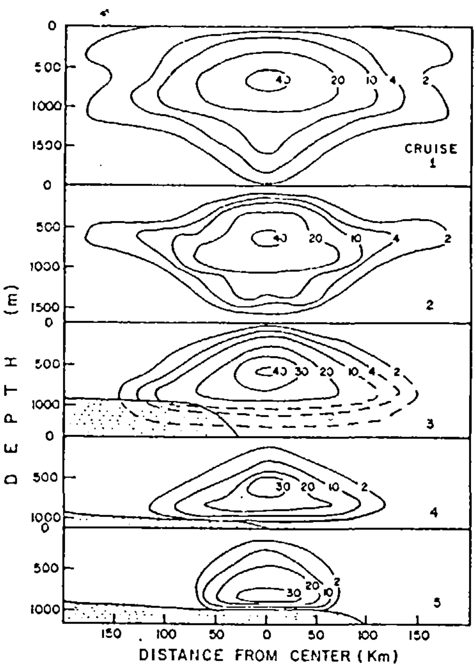

Fig. 6. Decay sequence as depicted by contours of available potential energy density. Contours are in units of 10^3 ergs g^{-1}. Bottom depth is shown for the last three cruises and indicates the passage of the ring on to the Blake Plateau.

shrink towards the center. In each observation a core of high potential energy density was located at the center of the ring near 750 m. In 11 months the effective diameter, as defined by the contour of 2×10^3 ergs g^{-1}, decreased from 360 to 140 km. Thickness of the ring defined the same way decreased from 2000 to 850 m. In the last three distributions bottom contours represent the average depths encountered by the ring as it moved over the Blake Plateau. However, by Cruise 2 much of the energy in the lower layers had been dissipated; approximately 75% of the total APE was above 850 m. Thus there is no major problem in determining what happened to the bottom part of the ring when it reached the Blake Plateau. Furthermore, extrapolation of XBT data from 850 to 1000 m for the last three data sets can introduce only minor errors in the calculation of APE relative to 1000 m.

Total APE was obtained by integrating the energy density (Fig. 6) over the entire volume of the ring. Data are summarized in Table 3, and the decay of energy relative to 1000 m, the deepest common level, is shown in Fig. 7. This figure also shows volume transport (normal to a radial section) and kinetic energy relative to 1000 m, calculated from geostrophic velocity sections.* For Cruises 3 and 4 the estimated error of extrapolating XBT data from 850 to 1000 m is included in the error bars. Potential energy, transport, and kinetic energy decrease together as the dome subsides. All three curves indicate a marked increase of decay rate between Cruises 3

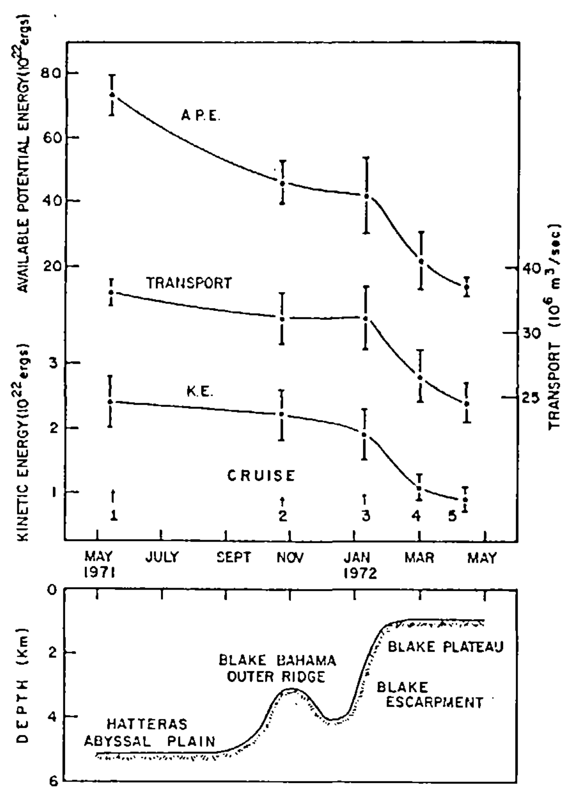

Fig. 7. Decay of available potential energy, transport, and kinetic energy relative to 1000 m. Error bars show estimated certainty to within one standard deviation obtained by combining individual estimated errors of the temperature and salinity data, the size and shape determinations of the ring, the assumed reference level, and the inertial correction to the geostrophic velocity. Variation of depth under the center of the ring is shown below.

*A correction was made according to the gradient wind relationship (VON ARX, 1962) to account for centripetal accelerations. This had the effect of reducing the geostrophic velocities in the high speed region by about one-fourth and the transport values by about 5×10^6 m^3 s^{-1}.

Table 3. Summary of calculations.

	Level of no motion* (reference level)	Available potential energy** (10^{22} ergs)	Volume transport** ($10^6 m^3$ sec)	Kinetic Energy** (10^{22}ergs)	Total APE / Total KE
Cruise 1	1000 m	73 ± 6	36 ± 2	2.4 ± 0.4	
	3500 m	93 ± 8	60 ± 7	5.6 ± 0.8	17 ± 3
Cruise 2	1000 m	46 ± 7	32 ± 4	2.2 ± 0.4	
	1500 m	52 ± 8	40 ± 6	3.5 ± 0.7	15 ± 4
Cruise 3	1000 m	42 ± 12	32 ± 5	1.9 ± 0.4	22 ± 8
Cruise 4	1000 m	22 ± 9	23 ± 4	1.1 ± 0.2	20 ± 9
Cruise 5	1000 m	14 ± 3	19 ± 3	0.9 ± 0.2	16 ± 5

*Quantities given are computed relative to deeper levels when sufficient data were available (Cruises 1 and 2).
**Errors are r.m.s. estimates based on individual errors in temperature, salinity, size and shape of the ring, assumed reference level and inertial correction to the geostrophic velocities.

Table 4. Decay of APE and APE density relative to 1000 m.

Cruise	APE 10^{22} ergs	APE* Density 10^3 ergs/g	Time Interval days	Time Interval 10^5 sec	Linear Decay Rate 10^{21}ergs/day	Linear Decay Rate 10^{-4}ergs/g-sec
1	73 ± 6	19.7 ± 0.6				
			245	211	1.3 ± 0.5	2.1 ± 1.9
3	42 ± 12	15.2 ± 3.9				
			94	81	3.0 ± 1.3	7.7 ± 5.4
5	14 ± 3	9.0 ± 1.9				
			Average Cruise 1-5		1.7 ± 0.2	3.7 ± 0.7

*Energy density was computed within a constant volume (depth ≤ 1000 m, radius ≤ 70 km). Errors are r.m.s. estimates based on individual errors in temperature and salinity.

and 5. This rapid increase coincides with the ring's movement over the Blake Plateau. As indicated in Table 3, the APE/KE ratio remained fairly constant throughout the 11 months; the average ratio for the five cruises is 18 ± 3.

To normalize the rate at which APE was lost from the interior of the ring, the potential energy density of the inner core of the ring and its decay were calculated (Table 4). The core is defined by a cylindrical volume with a radius of 70 km and a depth of 1000 m. This includes the high velocity region and the maximum energy core for all observations. By computing the energy density within a constant volume, the uncertainty in determining the outer boundary of the ring has been eliminated.

Both sets of calculations show an increase in the decay rate as the ring moved on to the Blake Plateau. A linear approximation of the deep water decay (Cruises 1 to 3) yields a rate of $1{\cdot}3 \times 10^{21}$ ergs day^{-1} or $2{\cdot}1 \times 10^{-4}$ ergs g^{-1} s^{-1}. In shallow water (Cruises 3 to 5) the decay progressed more rapidly at an estimated rate of $3{\cdot}0 \times 10^{21}$ ergs day^{-1} or $7{\cdot}7 \times 10^{-4}$ ergs g^{-1} s^{-1}. Based on the decay rate in deep water, the ring's total expected lifetime would be about 2·5 years, assuming the ring to have formed in June 1970. By moving into shallow water its life span was reduced to two years. In both shallow and deep water regimes the decay appeared to slow with time. However, accuracy of the measurements was not sufficient to distinguish which rate—linear or exponential—best models the actual decay. Furthermore, due to the relatively large uncertainty associated with Cruise 3, the APE decay over the entire 11 months could be approximated by a linear rate.

RING DECAY

One particularly interesting result of the study is the accelerated decay in potential energy, kinetic energy, and volume transport as the ring moved into shallow water on the Blake Plateau. Much of the evidence that implies a division of the decay into a deep and a shallow water phase comes from Cruise 3, the least accurate observation in terms of estimating the magnitude of the potential energy ($\pm$ 29%). Despite this weakness in the data, there are other indications of the decay rate that support the conclusion that the decay rate did accelerate when the ring moved into shallow water. A comparison of the temperature sections for Cruises 3 and 4 shows a significant shrinkage of the thermal dome. In less than two months isotherms in the main thermocline sank 110 m ($\pm$ 20 m) at a a rate of over 2 m day^{-1}. The average rate of isotherm subsidence over the 11 months was about 0·4 m day^{-1}. The change of potential energy density within a constant volume (Table 4) also reflects the rapid decay rate between Cruises 3 and 4. Such a calculation tends to eliminate the error from determination of the size of the ring. In addition, the decrease in transport and kinetic energy relative to 1000 m (Fig. 7) is consistent with the separation of the decay into two regimes. Because transport is proportional to the mean change in depth of the isopycnals between the center and the outside edge of the ring, changes of transport with time are not dependent on the relatively inaccurate size and shape determinations of the ring based on Cruises 3 and 4. We conclude that the movement of the ring into shallow water was accompanied by a faster decay rate.

There are several obvious ways by which the decay rate could have been increased over the last three cruises. The first is that the density structure of the ring extended below the depth of the Blake Plateau and that this lower portion was lost when the ring passed over the plateau. On Cruise 2 about 10% of the total available potential energy was below 1000 m and the velocity at 1000 m in the ring was estimated from geostrophic calculations to be about 5 cm s^{-1} relative to 1500 m. Thus one can imagine a dramatic effect on the ring characteristics as the ring passed over the large discontinuity known as the Blake Escarpment and into relatively shallow depths. The deeper portion of the ring ($>$ 1000 m nominal depth) must have been either left behind or destroyed as the shallow part of the ring ($<$ 1000 m) moved over the escarpment. Other ways in which the ring decay could have been increased are by the formation of a bottom frictional layer on the Blake Plateau and by interaction between the Gulf Stream and the ring as it approached Florida. If the ring did coalesce with the stream as we have concluded, then Gulf Stream–ring interaction was important during the final decay of the ring.

What happens to the energy as the ring decays? Much of the available potential energy is converted to kinetic energy which is then converted by friction to heat. Whether this large store of energy also helps drive large-scale motion by means of Reynolds stresses or whether it is radiated away in the form of waves is not known.

Temperature–salinity and oxygen characteristics of the ring have indicated another decay mechanism. When rings are formed they consist of a Slope Water core that has slightly different T–S properties than the ring or Sargasso Water. The anomalous core characteristics were observed to decay gradually during the life of the ring in this study as well as in others (MOLINARI, 1970), implying mixing between ring and adjacent water. During Cruise 2 continuous profiles of salinity, temperature, and oxygen were obtained; those taken near the center of the ring exhibit a pronounced layering in the upper 500 m. Layers approximately 25 m thick, which were characteristic of Sargasso Water, had penetrated to the center of the ring, presumably along isopycnal surfaces. LAMBERT (1974) discussed these results and found them consistent with the theoretical models of MCINTYRE (1970) and MOLINARI (1970).

Small-scale structure observed in the ring is an indication that the ring and the Sargasso Sea were exchanging water. Because this exchange must also include momentum, the layering may indicate the primary decay mechanism. Thus there is evidence that the available potential energy is converted to kinetic energy which is then diffused into the Sargasso Sea. Primary measurements in the ring reflect the shrinkage of the raised thermocline in the dome and are consistent with such a decay.

Decay rate estimates of two previous rings have been made; they suggest ring lifetimes of 1 to 4 years. FUGLISTER (1971) followed a ring for 6 months from its formation in September 1965 and estimated its lifetime to be 12 to 18 months. The first value was estimated from the decreasing diameter of the intersection of 10°C and 800 m, and the second from the sinking rate of the 10° surface in the core. A second ring was studied by Fuglister (personal communication) from March to October 1967. BARRETT (1971) calculated an APE decay rate of the 1967 ring to be $2{\cdot}0 \times 10^{20}$ erg day^{-1} and suggested it might have a lifetime of 3 to 5 years. PARKER (1971) calculated the subsidence of the 17° surface (0·6 m day^{-1}) in the 1967 ring; this implies that the cold core would have vanished 2·0 to 2·5 years after its formation. Both Barrett's decay rate and Parker's 17° subsidence rate are very approximate because they are extrapolations based on short time series (4 and 5 months, respectively).

Our data suggest that approximately similar ring lifetimes are found whether the sinking rate of isotherms, decreasing area* or decreasing APE are used. Our average decay rate of APE is eight times Barrett's, but the initial APE of our ring is more than twice as large as the 1967 ring. The difference in decay rates may arise from differences in initial sizes, ages, measurement errors, or the increased decay rate during the Cruises 3 to 5. The decay rate during Cruises 1 to 3 agrees more closely with that found by BARRETT (1971) and the decay rate during Cruises 3 to 5 agrees closely with that found by FUGLISTER (1971).

*Only on Cruise 2 did the 10° isotherm fall below 800 m, which was FUGLISTER's (1971) criterion of horizontal size. We used the intersection of 15° and 500 m.

MOVEMENT

Movement of the ring was to the southwest with an average speed of about 2 km day^{-1}. Observations of other rings suggest that this southwest movement just offshore of the Gulf Stream may be a common phenomenon with approximately two rings per year following this path (RICHARDSON, STRONG and KNAUSS, 1973; STUMPF, STRONG and PRITCHARD, 1973). Additional evidence for the southwest movement of rings has been given by FUGLISTER (1971), who tracked rings in the region north of Cape Hatteras, and by PARKER (1971), who conducted an historical search for ring anomalies in the Sargasso Sea.

The processes that cause Gulf Stream rings to move southwestward have not been determined. Rings may simply be advected by a large-scale southwestward flow and thus their movement may represent the mean flow in the Sargasso Sea. On the other hand, rings may be self-propelled through the ocean.

Although the current charts of the North Atlantic differ widely in details they generally agree about the main features. Circulation is dominated by the subtropical gyre consisting of a narrow and fast Gulf Stream in the west and north and broad, relatively slow, southwestward flow over much of the remaining part of the ocean (ISELIN, 1936; SVERDRUP, JOHNSON and FLEMING, 1942; WORTHINGTON, in press). As the Gulf Stream flows north and then east its volume transport increases dramatically (KNAUSS, 1969). Most of the transport is thought to be recirculated south and west through the Sargasso Sea, closing the gyre. WORTHINGTON (in press) has prepared detailed current maps using the most recent data; these maps show a flow counter to the Gulf Stream just offshore of it. Although the actual mean velocities in the Sargasso Sea are not well known, speeds of a few km day^{-1} are required in the inflow to the Gulf Stream to account for the transport increase (KNAUSS, 1969). Thus the southwest movement of rings is entirely consistent with what is known about the speed and direction of the mean circulation in the western Sargasso Sea.

There are several ways in which a ring might be self-propelled through its surrounding medium, and WARREN (1967) has discussed some of these. Warren suggested that the westward movement might be caused by the meridional variation of the Coriolis parameter (β-effect). He also suggested that, by analogy, if a ring were to overlie a sloping boundary a displacement could be brought about by the bottom slope. PICKETT (1971) indicated that a possible northwest movement of rings could be produced when inertial effects are added to the westward movement caused by the β-effect. Unevenness in width or velocity profile may also cause movement of a ring. For example, PETTERSSEN (1940) suggested that oblong atmospheric cyclones tend to move along their longest axis.

The ring tracked during this study clearly moved toward the west in agreement with WARREN's (1967) hypothesis, although the westward movement did not decrease rapidly as he suggested it might because of decreasing radius. The ring's apparently steady movement over the Blake Plateau from deep into shallower water suggests that the bottom slope had little effect on the movement. On two of the cruises (1 and 5) the ring displayed considerable ellipticity and the longest axis was approximately aligned with the southwest movement of the ring in agreement with PETTERSSEN's (1940) suggestion. Cruise 2 data, however, showed the ring to be nearly circular except in the outer region, which was slightly oblong with the long axis lying toward the southeast.

None of the theories that attempts to explain ring movement have included the decay of the ring. M. E. Stern (personal communication) suggested that the southward movement of the ring may be related to the sinking of the cold core. As the height of the core decreases the ring may move south to conserve potential vorticity. The equation for the conservation of potential vorticity for a layer of thickness h can be written

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{f+\zeta}{h}\right) = 0 \text{ (STOMMEL, 1965)}, \quad (1)$$

where f is the Coriolis parameter and ζ the relative vorticity. Equation (1) can be expanded to

$$\frac{\mathrm{d}\zeta}{\mathrm{d}t} + V\beta - \frac{f+\zeta}{h}\frac{\mathrm{d}h}{\mathrm{d}t} = 0, \quad (2)$$

where V is the northward velocity and $\beta = \dfrac{\partial f}{\partial y}$, the variation of Coriolis parameter with latitude. Equation (2) gives a relationship between the rate of decay and southward translational speed of the cold core. An order-of-magnitude calculation suggests that the potential vorticity is conserved in the lower region of the ring as it moves south.

On the basis of the data the ring appears to be divided into lower, middle, and upper regions with different characteristics. The lower layer is bounded above by the thermocline (6° isotherm) and below by a deep horizontal isopycnal surface. This layer is assumed to have negligibly small tangential velocities ($\zeta \ll f$) that remain small $\left(\dfrac{\mathrm{d}\zeta}{\mathrm{d}t} = 0\right)$. The major change with time is its decreasing thickness as the cold dome collapses. Equation (2) reduces to

$$V\beta - \frac{f}{h}\frac{\mathrm{d}h}{\mathrm{d}t} = 0. \quad (3)$$

To evaluate (3) we need an estimate of $\dfrac{\Delta h}{h}$ and require a quantity representative of the average shrinkage of the core. The data indicate that the thermocline depth in the ring is nearly proportional to the anomaly of potential energy. Thus the APE integrated over the ring is proportional to the average height of the dome. An estimate of $\dfrac{\Delta h}{h}$ was obtained from the change of APE, within the ring's inner region (radius less than 70 km). The period between Cruises 1 and 5 was chosen and parameters were evaluated at 31°N. The required quantities are

$$\frac{\Delta h}{h} = \frac{9{\cdot}0 - 19{\cdot}7}{19{\cdot}7} = -0{\cdot}54 \text{ (Table 4)}$$
$$\Delta t = 2{\cdot}9 \times 10^7 \text{ s}$$
$$f = 7{\cdot}7 \times 10^{-5} \text{ s}^{-1}$$
$$\beta = 1{\cdot}9 \times 10^{-13} \text{ cm}^{-1} \text{ s}^{-1}$$
$$V = 7 \text{ km day}^{-1}.$$

The predicted southward speed of this layer is 7 km day^{-1}.

Next consider the middle layer that represents the main thermocline and is bounded by 6 and 15°C surfaces. It contains strong velocity shear due to the steeply sloping isopycnals. Although its average thickness remains nearly constant $\left(\frac{dh}{dt} = 0\right)$, as indicated by repeated temperature sections, its average depth increases with time. Friction may be important in this layer but is neglected here. Equation (2) can be simplified to

$$\frac{d\zeta}{dt} + \beta V = 0. \tag{4}$$

The first term can be expressed in cylindrical coordinates

$$\frac{d\zeta}{dt} = \frac{d}{dt}\left[\frac{V_0}{r} - \frac{\partial V_0}{\partial r}\right], \tag{5}$$

where V_0 is the tangential velocity and r is the radius. The measured velocity distribution (Fig. 4) was used to calculate this term; maximum speeds at 500 m were 50 cm s^{-1} from geostrophic velocity profiles.

$$\frac{\Delta\zeta}{\Delta t} = \frac{V_{0\max}}{\Delta r}$$

$$= \frac{50 \text{ cm s}^{-1}}{\underset{\text{(Cruise 1)}}{70 \times 10^5 \text{ cm}} - \underset{\text{(Cruise 5)}}{35 \times 10^5 \text{ cm}}}$$

$$= 1{\cdot}4 \times 10^{-5} \text{ s}^{-1}.$$

Using this value and Equation (4) the predicted southward speed of the middle layer is 2 km day^{-1}.

The upper layer is bounded by 15°C and the sea surface; it contains high tangential velocities (~ 100 cm s^{-1}) and both the velocities and average thickness are changing with time. Friction is probably important in the upper layer and therefore potential vorticity is not conserved. McEwen (1948) and Molinari (1970) have described effetcs of friction on an eddy and these effects are in agreement with our data (Figs. 2 and 4). One effect of friction is to diffuse momentum and vorticity from the ring to the surrounding ocean. A second effect is to retard the nearly geostrophic tangential velocity; this causes the flow to spiral inward toward the low pressure center of the ring (Molinari, 1970). The radial inflow initiated by friction provides a mechanism by which the tangential velocities and local vorticity of the ring are increased (assuming conservation of vorticity). If friction is neglected in the upper layer, and the terms of Equation (2) are evaluated, the variation of the relative potential vorticity term suggests a southward movement (~ 5 km day^{-1}) but the vortex stretching term suggests a northward movement (~ 8 km day^{-1}). The two terms are of different sign and the same order of magnitude.

CONCLUSIONS

(1) A cyclonic Gulf Stream ring was tracked for 14 months as it moved from off Cape Hatteras in March 1971 southwest towards Florida, where it was thought to have coalesced with the Gulf Stream in late April 1972. Average southwest speed was approximately 2 km day^{-1}. The location and description provided by each cruise indicate that the observations were always of the same ring. Supplementary XBT observations over a wide area of the Sargasso Sea provide added evidence that makes it extremely unlikely that observations could have been of two or more different rings.

(2) In 11 months the diameter of the ring (15°C at 500 m) decreased from 158 to 110 km. The dome of cooler, fresher, Slope Water that forms the heart of the ring did not sink or collapse as a unit, but contracted towards the center as the decay progressed.

(3) Surface velocities in the high-speed region remained strong throughout the life of the ring with maximum speeds in excess of 100 cm s^{-1}. The high-speed region was at a radius of approxi-

mately 70 km at the time of the first observation in May 1971. As the decay progressed the radius of maximum speed migrated towards the center at a rate of 0·1 km day^{-1} and in April 1972 was approximately 35 km.

(4) Available potential energy relative to 1000 m decreased from 73 to 14 $\times$ 10^{22} ergs over 11 months. While the ring was in deep water, potential energy was lost at an average rate of 1·3 $\times$ 10^{21} ergs day^{-1} or, per unit mass, 2·1 $\times$ 10^{-4} ergs g^{-1} s^{-1}. Upon moving into shallower water on the Blake Plateau the average dissipation rate increased to 3·0 $\times$ 10^{21} ergs day^{-1} or 7·7 $\times$ 10^{-4} ergs g^{-1} s^{-1}. Assuming the ring to have formed in June 1970, its total lifetime was two years. Based on the estimated linear decay rate from May 1971 to February 1972 (in deep water and away from the Gulf Stream) its total expected lifetime was about 2·5 years.

(5) Decay of kinetic energy and tangential volume transport of the ring followed quite closely the decay curve of available potential energy. The ratio of available potential to kinetic energy was estimated to be about 18 averaged over five cruises.

(6) The data cannot resolve the question of whether the ring was advected by a large-scale flow or was self-propelled. Observed direction and speed of the ring were consistent with inferred currents in the western Sargasso Sea. The southward component of the motion of the ring is also consistent with the hypothesis that the potential vorticity of the dome was conserved as it collapsed during the decay process.

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