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# GULF STREAM RINGS

by Philip Richardson

The Gulf Stream is the swiftest and most energetic current in the North Atlantic. One of the most interesting features of the Gulf Stream is the horizontal wave motions, or meanders, of its path; frequently these become sufficiently large to pinch off from the main current and form large eddies. The formation process is analogous to the cut-off highs and lows formed by the atmospheric jet stream. Gulf Stream eddies—their formation, movement, and decay—are vital in redistributing water, biological life (see page 69), and momentum and energy in the Gulf Stream system and western North Atlantic.

F. C. Fuglister has suggested the name *Gulf Stream rings* for these eddies because, during their formation, segments of the Gulf Stream form closed rings. Those formed to the south of the Gulf Stream have cyclonic (counterclockwise) circulation and contain cold Slope Water in their centers. Rings formed to the north are anticyclonic and contain warm Sargasso Sea water.

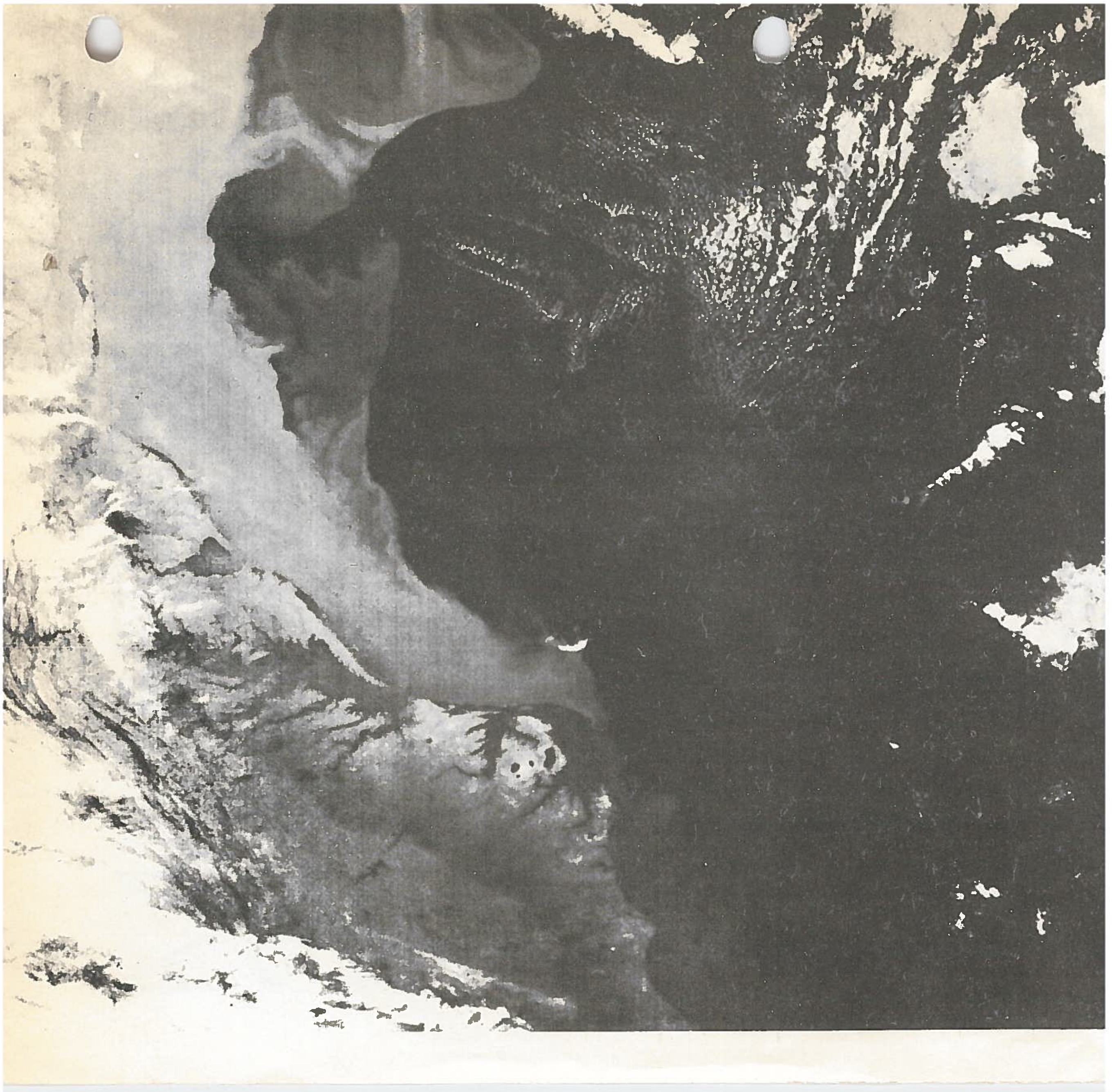
Although we have known about the existence of rings for almost 40 years, it is only during the last several years that we have learned about their distribution, long-term movement, and decay. Recent satellite infrared measurements, as well as ship and aircraft surveys, indicate that rings can be found in greater numbers in the western North Atlantic than we thought.

Advances in satellite measurement techniques have made it possible to view the Gulf Stream system from space over a wide region during a short period of time (less than a day). One of the best satellite infrared photographs is Figure 1, taken just off the U.S. East Coast, showing the Gulf Stream, two anticyclonic rings, and two cyclonic rings. The evidence suggests that the two anticyclonic rings that were first observed in January 1974 north of the Gulf Stream, moved west and south to coalesce with the Gulf Stream during the summer of 1974; the cyclonic rings south of the Gulf Stream both moved southwest, as other rings have been observed to do, and may have coalesced with the Gulf Stream off Florida during mid-1975; the Gulf Stream meander formed a cyclonic ring in June 1974, which was reabsorbed three months later near the place of its formation. Using successive satellite photographs and additional measurements, investigators at several oceanographic laboratories (including the National Oceanographic and Atmospheric Administration, the Naval Oceanographic Office, Research Triangle Institute, Texas A&M University, the University of Rhode Island, and the Woods Hole Oceanographic Institution) are trying to follow the evolution of these and other rings.

**Distribution**

Figure 2 is a synoptic representation of the Gulf Stream and rings at an instant in time. Since there has been no large-scale survey or good satellite coverage of the entire region, the figure is, for the most part, contrived, based on a wide assortment of data including recent satellite, aircraft, and ship surveys of portions of the area. North of the Gulf Stream we frequently see three rings at a time; south of the Gulf Stream and west of 50°W we can find approximately 8-14 rings. Some data suggest that rings can be found east of 50°W, but no thorough investigation has been made in this area. Only limited data exist for the region between 50°W and 60°W. Although rings have been observed to form only between 60°W and 70°W, their location east of 60°W and their westward movement indicate that they must also form east of 60°W.

The early stage of cyclonic ring formation is shown in Figure 2 near 38°N and 58°W where a large meander has trapped Slope Water in its "pocket"; the sides of the meander are closing, and the ring will separate from the Gulf Stream as shown



by the dotted lines. The southern boundary of the ring region is not well known. There is a lack of long-term ring tracking and detailed hydrographic surveys, and the decay of rings makes them more difficult to find when they are old. In any case, no rings have been documented south of about 30°N except for the extreme western region. Just north of the Bahamas several rings were seen very close to the Gulf Stream, apparently coalescing with it.

The initial sizes of rings differ; those north of the Gulf Stream are generally smaller than those to the south. The outer limits of rings are as difficult to determine as those of the Gulf Stream itself. In Figure 2 the Gulf Stream is shown as a band almost 100 kilometers wide, and the rings are from 150 to 300 kilometers in diameter. These limits represent, approximately, the locations where the main thermocline (the transition zone between warm surface water and cold, deep water) becomes horizontal and the current vanishes. The usual shape of rings is nearly circular, although significant variations are often found. There are limited but tempting data suggesting that rings may merge as well as break up into smaller pieces. Neither of these processes has been observed in detail, but they offer the simplest explanations of some observations.

## Movement

Evidence for the movement of rings comes from the real-time tracking of a few rings by several techniques and from inferred trajectories based on an analysis of the National Oceanographic Data Center files of XBT (expendable bathythermographs) and hydrographic data. Rings north of the Gulf Stream move generally toward Cape Hatteras, with average speeds of 3-7 kilometers per day, where they have been observed to coalesce with the Gulf Stream. There is little variation from this mean movement because the rings are confined by the continental slope to the north and the Gulf Stream to the south. Cyclonic rings move south, away from the Gulf Stream, and then in a west and southwest direction. There appears to be a path offshore of the Gulf Stream between Florida and North Carolina along which rings typically travel. Approximately two rings per year follow this path

*Figure 1. NOAA-3 infrared photograph of the Gulf Stream region off the U.S. East Coast from Florida to Massachusetts, April 28, 1974. Warm temperatures appear as dark shades, cold as light shades. The Gulf Stream is depicted as a dark band sweeping across the photograph. Two rings can be seen north of the Gulf Stream and two south of it. One ring to the south is outlined by warm Gulf Stream water that has been entrained by the ring's strong cyclonic flow. The second ring, farther south, is faint, but its existence was verified by ship measurement. Clouds appearing white can be seen in the southeast region. The dramatic effect of rings on at least the near-surface circulation of the ocean is clearly shown by the satellite data. (Courtesy of NOAA/NESS)*

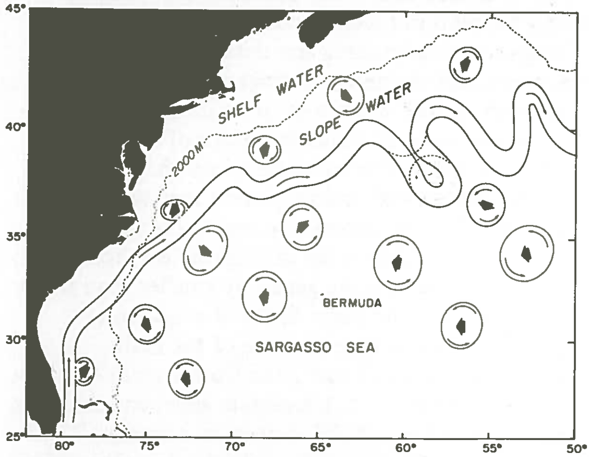



*Figure 2. A schematic representation of the path of the Gulf Stream and the distribution and movement of rings. It is an attempt to summarize a number of studies that were made at different times and that usually focused on a smaller region.*

at an average speed of 2 kilometers per day. The motion described here is long-term or mean motion; rings exhibit considerable variation from the mean over periods up to several months, and some coalesce with the Gulf Stream only a few months after formation. Rings sometimes move in complicated trajectories—for example, a looping clockwise motion with a speed of 10 kilometers per day, period of 60 days, and amplitude of 75 kilometers, as observed by Fuglister (personal communication).

The processes causing rings to move southwest have not been determined. Most mathematical models of rings predict a westward movement due to the Coriolis effect (see page 28). Rings may also be carried passively along with the mean ocean flow; their movement is consistent with what is known about the speed and direction of the return flow from the Gulf Stream. As the Gulf Stream flows north and then east, its volume transport increases dramatically, from about $30 \times 10^6$ cubic meters per second off Miami to approximately $150 \times 10^6$ cubic meters per second north of Bermuda. The Gulf Stream's transport then decreases as it flows toward the Grand Banks. Although there is at present a debate on just how the water is recirculated in order to account for the transport variation of the Gulf Stream, rings are clearly an integral part of this circulation. Each ring consists of a sizable portion of the Gulf Stream, approximately 500 kilometers in length and roughly 20 percent of the mean path from Cape Hatteras to the Grand Banks. Thus the formation, movement, and subsequent entrainment of rings by the Gulf Stream represents an important part of the return transport of Gulf Stream water, especially when one considers the large number of rings forming each year, estimated to be about 5-8 per year on each side of the Gulf Stream. For example, the volume transport associated with the formation and movement of 13 rings per year, each one consisting of a 500-by-100-by-2-kilometer section of the Gulf Stream is $41 \times 10^6$ cubic meters per second.

## Decay

When rings were first seen, they were thought to have short lives of only a few months. Several recent time-series measurements continuing for more than a year indicate that some rings may last as long as 2 years. This long life is possible since most (95 percent) of the energy is in the form of potential energy; only a small portion is in the form of kinetic energy, which can be dissipated by friction. A young cyclonic ring has the main thermocline raised 500-600 meters in its cold core. This potential energy, on the order of $10^{24}$ ergs, is "available" to be released as the thermocline slowly subsides in the decay process to the mean Sargasso Sea background level. During decay, the peak tangential velocities in the high-velocity core remain strong, at approximately 100 centimeters per second, but move radially inward as the core subsides. The initial distinctive Slope Water characteristics of the core gradually disappear, indicating that the ring mixes with surrounding Sargasso Sea water.

## Conclusions

Rings are interesting and worthy of study in their own right, but their important, though poorly understood, role in general ocean circulation makes it imperative that we learn more about them. A number of investigators are planning a large-scale study of rings, including surveys of distribution, tracking of trajectories, and detailed measurements of decay. We hope to combine theoretical modeling and field experimentation from a variety of disciplines into a unified study of rings.

*Philip Richardson is an assistant scientist in the Department of Physical Oceanography, Woods Hole Oceanographic Institution.*

### Suggested Readings

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