Reports

Gulf Stream Ring Coalescence with the Gulf Stream off Cape Hatteras

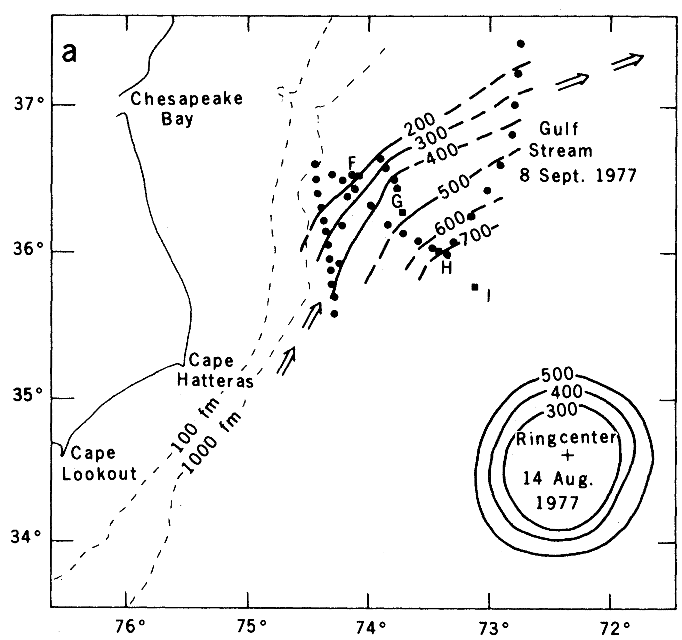
Abstract. *A cyclonic ring, which had separated from the Gulf Stream 7 months earlier and traveled 500 kilometers westward, collided with the stream in September 1977. Within 3 days the ring and stream joined to form a sharp S-shaped meander. Shipboard expendable temperature probes and four bottom-moored inverted echo sounders were used to obtain synoptic descriptions of the rejoining process.*

Gulf Stream rings traveling through the Sargasso Sea have frequently disappeared after approaching the Gulf Stream, apparently rejoining it (*1*). We discovered such a coalescence occurring off Cape Hatteras, North Carolina, during a cruise in September 1977 aboard the research vessel (R.V.) *Endeavor* to study Gulf Stream meanders and to survey a ring known to be approaching the area. This ring (called "Bob") had been tracked by other investigators (*2*) since its formation in February 1977 (*3*) as part of an interdisciplinary ring study. The coalescence occurred very rapidly (~ 3 days), and we were fortunately situated to observe the process in detail.

Gulf Stream cyclonic rings are formed several hundred kilometers east of Cape Hatteras when elongated meanders in the Gulf Stream pinch off, leaving behind a detached vortex. The ring of current has a diameter of 150 to 200 km, a velocity structure similar to that of the parent Gulf Stream, and surrounds a core of colder fresher water from the continental slope region. These energetic mesoscale ocean eddies can persist for 2 years or more (*4*), although many appear to rejoin the Gulf Stream after excursions of shorter duration through the Sargasso Sea (*5*). Sofar floats and satellite-tracked drifters in rings have previously been drawn into the Gulf Stream (*5*); however, until now no detailed observational data have been available to document the rejoining process.

We studied the thermal structure of the region primarily by using expendable bathythermographs (XBT's) to measure temperature as a function of depth. The XBT probes were dropped at 10- to 25-km intervals along the cruise tracks. Because the thermal field was observed to evolve rapidly during the coalescence, the measurements have been separated into 24-hour segments. These quasi-synoptic realizations of the thermal structure of the area (Fig. 1) illustrate the sequence of events.

We also deployed an array of four inverted echo sounders (IES's) at sites (*F*, *G*, *H*, and *I*) across the Gulf Stream, as indicated in Fig. 1. The IES is a bottom-moored instrument that monitors temporal variations in the depth of the main thermocline by precisely measuring the time it takes a sound pulse to travel to



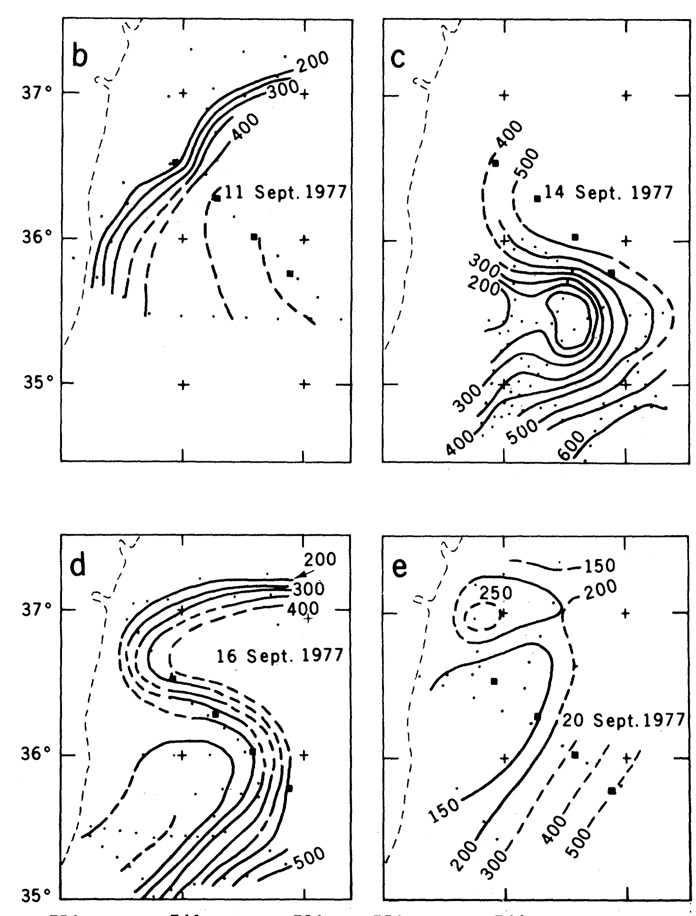


Fig. 1. Contours of the depth (in meters) of the 15°C isotherm. The entire region is shown in (a), including the Virginia–North Carolina coastline, the 100- and 1000-fathom bathymetry (light dashed curves), the XBT measurement sites (dots), and the IES locations *F*, *G*, *H*, and *I* (squares). Subregions are repeated in (b) to (e) for the survey dates indicated. (a) Initial conditions from the ring survey of the preceding cruise and the Gulf Stream at the beginning of our cruise. (b) Last Gulf Stream survey before the coalescence. (c) In coalescing, the stream diverts to flow around the former ring position. The 15°C-200-m contour at the core is still closed. (d) Sharp S-shaped meander with a cold ridge pushing northeastward. (e) Warm feature that may be closed off northwest of the stream.

0036-8075/78/1201-0971$00.50/0 Copyright © 1978 AAAS

the surface and back. In operation, when the main thermocline deepens, there is proportionately more warm water, in which sound travels faster and the acoustic travel time decreases. By this method the thermocline depth (for instance, the 15°C isotherm depth) is continuously monitored with a root-mean-square uncertainty of ±20 m in the Gulf Stream region (*6*). We produced synoptic maps of the isotherm depth contours by combining the data at the IES sites with coinciding segments of the XBT survey.

The ring approached the Gulf Stream from the southeast (Fig. 1). Figure 1a shows the position of the Gulf Stream on 8 September 1977, and the position of the ring on 14 August 1977 from a previous survey. During the surveys of the Gulf Stream before the recombination, the stream shifted progressively to the northwest. This shift is also evident in the deepening of the thermocline recorded at the northernmost IES (*F*) from 9 to 14 September, shown in Fig. 2a. By 11 to 12 September the stream axis, as defined by the 200-m contour of the 15°C isotherm, had been displaced fully 100 km from its mean position and was running along the shelf edge (Fig. 1b). The oncoming ring front reached the southernmost IES (site *I*) on 13 September, as shown by the prominent rise in the main thermocline (Fig. 2d).

Working near site *I* at this time, the ship was set northwest by the current. We commenced a 24-hour XBT survey of the ring as it completed the process of coalescing with the stream (Fig. 1c). By 14 to 15 September the Gulf Stream was flowing around the remnant of the ring core, and no significant baroclinic structure remained close to the continental shelf. The mid-thermocline portion of the ring (12° to 16°C) retained the closed isotherm pattern of Fig. 1c, whereas warmer levels were already open to the Gulf Stream and colder levels had smaller regions of closed contours. Thus the shallowest portions of the ring appear to coalesce with the stream first, while the mid-thermocline core remains intact longest. By 16 September (Fig. 1d) the ring core was no longer discernible, having consolidated with the Gulf Stream to form a meander.

Over the next 4 days this S-shaped meander intensified. A cold ridge accompanied the cyclonic southern portion and pushed northward over the IES sites. The cold front progressed successively (Fig. 2) over site *H* on 15 September, *G* on 16 September, and *F* on 17 September. The frontal zone advanced to the north at 30 km/day as determined by successive positions of the 15°C–200-m contour. The cold ridge increased in size as the cyclonic frontal zone advanced, suggesting an inflow of slope waters from farther north. The northern anticyclonic half of the S meander translated shoreward during this time until the 15°C–200-m contour appeared to shoal on the shelf.

The last frame, Fig. 1e, suggests that the northern portion of the meander was pinching off to form a closed warm feature at 37°N, 74°W. A subsequent transect through the region on 23 September by R.V. *Researcher* confirmed the persistence of this feature. A section through the area by another ring cruise in mid-October showed that no new cyclonic ring formed in the area.

In conclusion, we note the contrast between the rapid decisive developments observed in this ring coalescence (~ 3 days) compared to observations on ring formation (*7*). A multiple ship survey, Operation Cabot, observed the formation of a ring during which a Gulf Stream meander grew into an elongated "sock" and vacillated nearly 2 weeks between a pinched-off and a connected state. The observation that the 12° to 16°C core of the ring is last to rejoin the stream may be an important descriptive feature of the dynamics of coalescence.

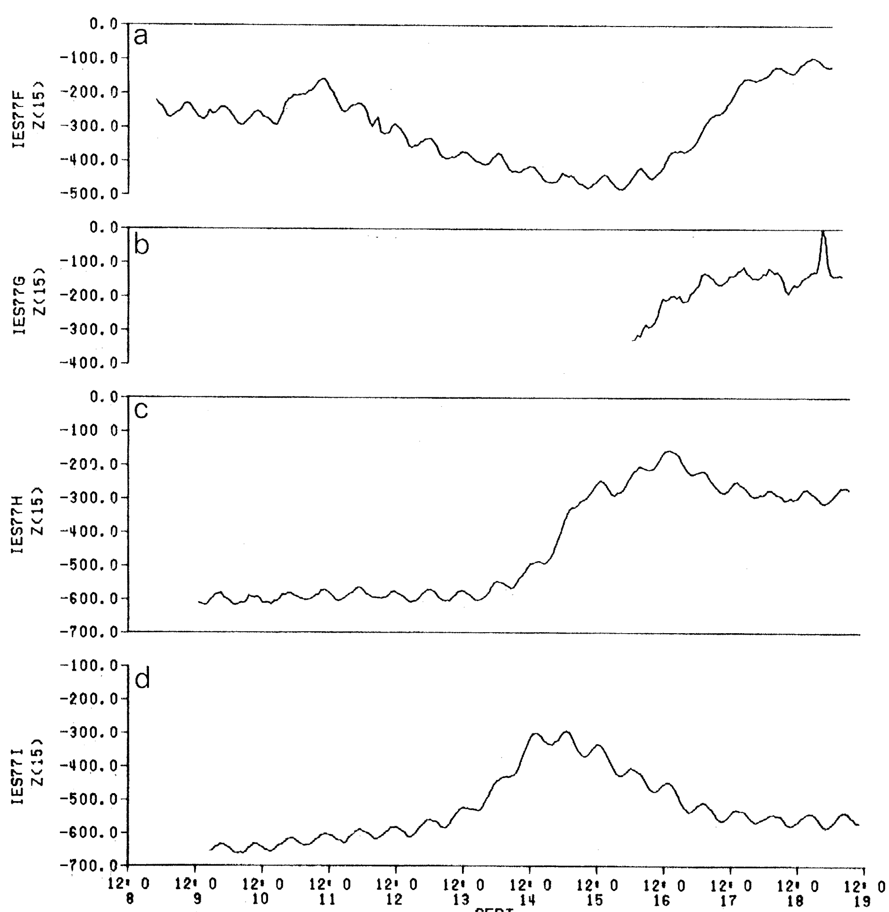


Fig. 2. Records of the 15°C isotherm depth (in meters) determined from IES sites *F*, *G*, *H*, and *I* (a to d). The semidiurnal signal is due to surface and internal tides; the longer-period variations monitor the translations of the ring and the Gulf Stream, as described in the text. Instrument *G* malfunctioned before 16 September.

D. RANDOLPH WATTS
Graduate School of Oceanography, University of Rhode Island, Kingston 02881

DONALD B. OLSON
Department of Physical Oceanography, Texas A&M University, College Station 77843

References and Notes

1. D. Y. Lai and P. L. Richardson, *J. Phys. Oceanogr.* 7, 670 (1977); F. C. Fuglister, in *A Voyage of Discovery*, M. Augat, Ed. (Pergamon, London, 1977), p. 177.
2. R. A. Kerr, *Science* **198**, 387 (1977).
3. R. A. Doblar and R. E. Cheney, *J. Phys. Oceanogr.* 7, 944 (1977).
4. R. E. Cheney and P. L. Richardson, *Deep-Sea Res.* 23, 143 (1976).
5. R. E. Cheney, W. H. Gemmill, M. K. Shank, P. L. Richardson, D. Webb, *J. Phys. Oceanogr.* **6**, 741 (1976); P. L. Richardson, R. C. Cheney, L. A. Mantini, *ibid.* 7, 580 (1977).
6. D. R. Watts and H. T. Rossby, *ibid.*, p. 345.
7. F. C. Fuglister and L. V. Worthington, *Tellus* **3**, 1 (1951).
8. We thank D. Kester for allowing us to show the ring position from the preceding cruise, and G. Maul for sending the R.V. *Researcher* XBT section. Supported by NSF contract OCE 77-08595 and ONR contracts N00014-75-C-0537 and N00014-76-C-0226. This is POLYMODE contribution 104.

1 June 1978; revised 28 August 1978