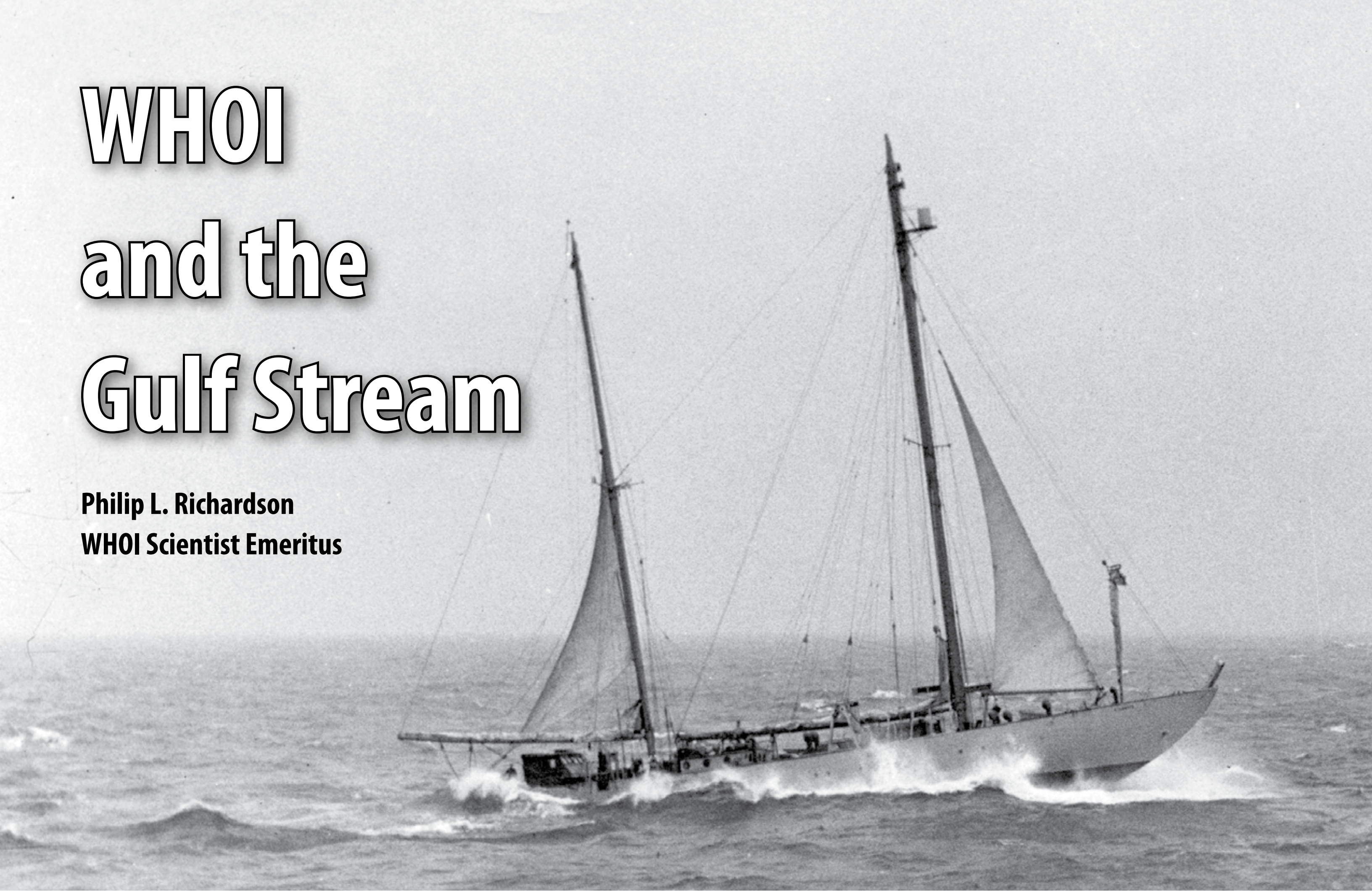
WHOI and the Gulf Stream



Philip L. Richardson
WHOI Scientist Emeritus

▲ *Atlantis* was photographed in rolling seas from the Canadian vessel *New Liskeard* in June 1950 during a six-ship survey of the Gulf Stream called Operation Cabot, the largest survey of the Stream to that date. (Photo from Canadian Naval Research Establishment)

Introduction

Systematic study of the Gulf Stream in the twentieth century began in 1930 with WHOI's acquisition of the 142-foot (43-meter) ketch *Atlantis*, equipped with a deep-sea winch and an array of reversing thermometers and sample bottles. *Atlantis* was small enough for its operation to be limited by bad weather, but at that time a larger all-weather vessel would have been beyond the means of the Institution—the first director, Henry Bigelow, considered $15 a day an outrageously large fuel bill!

Columbus Iselin, the ship's first master and WHOI's designated physical oceanographer at the time, worked up a basic designation of water masses in a physical-geographical study of the circulation of the Western North Atlantic based on data from rather widely spaced *Atlantis* hydrographic stations (Iselin, 1936). His picture was broad brush—it was not in any sense synoptic (that is, not a broad view of the Stream at a point in time), it put no limits on the range of temporal variability, and it did not resolve narrow features like the Gulf Stream frontal structure. Nevertheless, Iselin's study gave the first good idea of the general setting and environment of the Stream and revealed the tightness of the temperature-salinity relation in this part of the ocean.

Iselin's widely reproduced map of the depth of the 10°C isothermal surface clearly illustrated the large-scale average features of the North Atlantic circulatory system (**Fig. 1**). The 10° depth contours coincided with the permanent current system's direction of flow, and their concentration was closely proportional to near-surface current velocities. Iselin's horizontal map of salinity anomalies at mid-depth revealed that relatively fresh "intermediate water" (occurring at about

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Columbus Iselin, center, and shipmates run a hydrostation aboard *Atlantis* in the 1930s. Iselin, a physical oceanographer, was assistant to first director Henry Bigelow and master of *Atlantis* at the Woods Hole Oceanographic Institution's founding. He followed Bigelow as director.

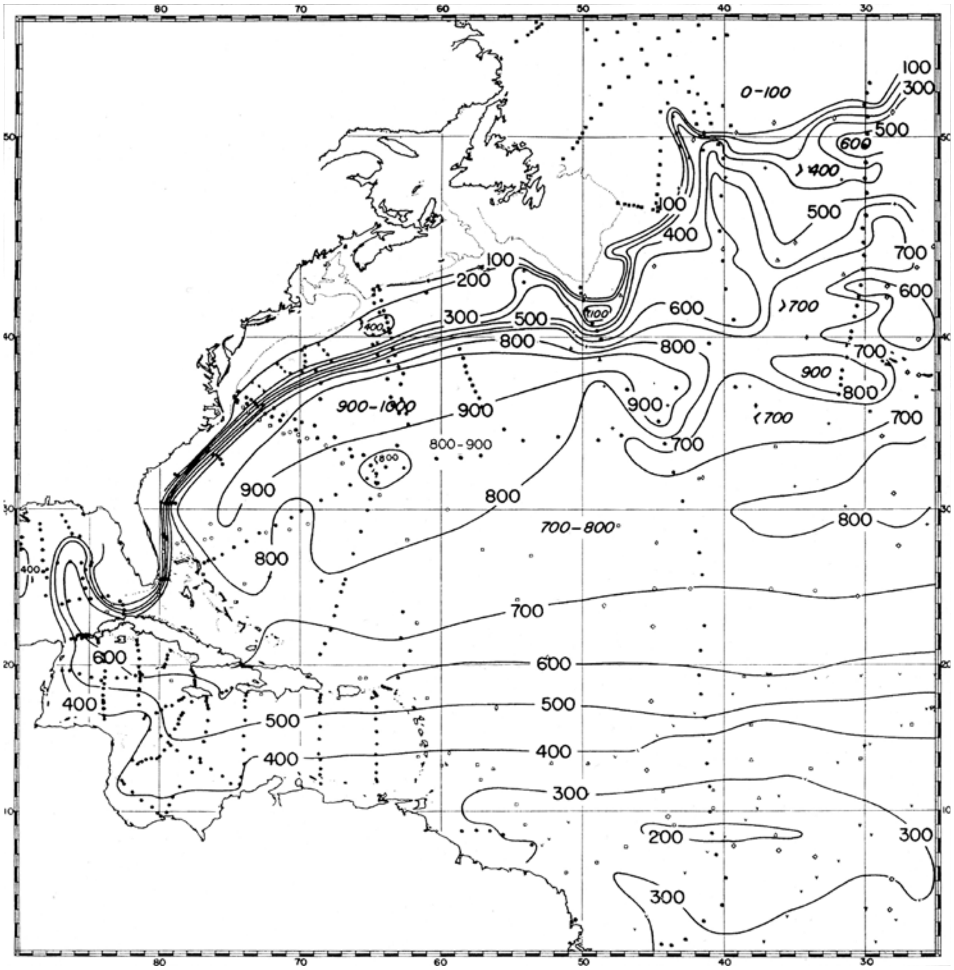


Fig. 1. Chart showing the depth of the 10°C isotherm in the western North Atlantic (after Iselin, 1936). The narrow band of contours extending from Florida to the Grand Banks indicates the location of swift eastward currents in the Gulf Stream.

2,000 feet [600 meters]) originated in the South Atlantic and extended northward along the northern coast of South America, through the Caribbean, into the Gulf Stream, and at least as far as North Carolina. This map emphasized the South Atlantic as a major source of Gulf Stream water.

Iselin's assistants embarked upon a quarterly Montauk-to-Bermuda shuttle with the hope of gaining a good picture of Gulf Stream variability. When successive sections made during these shuttles showed what appeared to be multiple crossings of the Stream, the idea of meanders was not invoked—not knowing their cause, Iselin suggested that what today we recognize as cold core rings were solitary internal waves.

Loran and the BT

Two important technical developments during World War II—the smoked-glass-slide bathythermograph (BT) and loran (long-range navigation)—gave rise to a realistic chance to map the Gulf Stream front and indeed to discover meanders and eddies. The BT was cheap, fast, and usable in fairly bad weather and while underway to measure temperatures in the upper layer. Directly south of Woods Hole, loran (based on radio signals transmitted from shore-based stations) gave positions continuously to about a 0.7 nautical mile (1 kilometer) accuracy. These two tools were used to portray the finer structure of the Stream in all its complexity—the twists and turns of the current, its narrowness and intensity, the puzzle of eddies and meanders—and to determine how these evolved with time (Iselin and Fuglister, 1948). The research vessels used—several even smaller than *Atlantis*—were so slow that the investigators evolved a zig-zag search pattern, moving downstream with the current because the ships could not have made much headway against the Stream.

Frederick "Fritz" Fuglister and Valentine Worthington (1951) showed the positions of the maximum cross-stream temperature gradients at a depth of 330 feet (100 meters) from all BT surveys made during the period from 1946 to 1950 (**Fig. 2**). The lines, which follow the Stream's axis, varied from time to time, but more importantly they indicated that the Stream did not shift position bodily, but rather in wavelike patterns or meanders. The first information on the behavior of these meanders was obtained from the 1950 multiple-ship survey known as Operation Cabot.

In June 1950, Fuglister led a six-ship, Canadian-American effort to map the Gulf Stream for a period of three weeks between Cape Hatteras and Nova Scotia (Fuglister and Worthington, 1951). The ships zig-zagged eastward with the Stream, lowering BTs, taking loran fixes, and using the GEK (geomagnetic electrokinetograph—von Arx, 1950) to measure surface currents. During the second phase of the operation, each of the ships made a hydrographic section across the system of currents. It was hoped that a large meander could be found to study during phase three. To

Val Worthington launches a BT from *Atlantis* during the Mediterranean cruise in 1948.

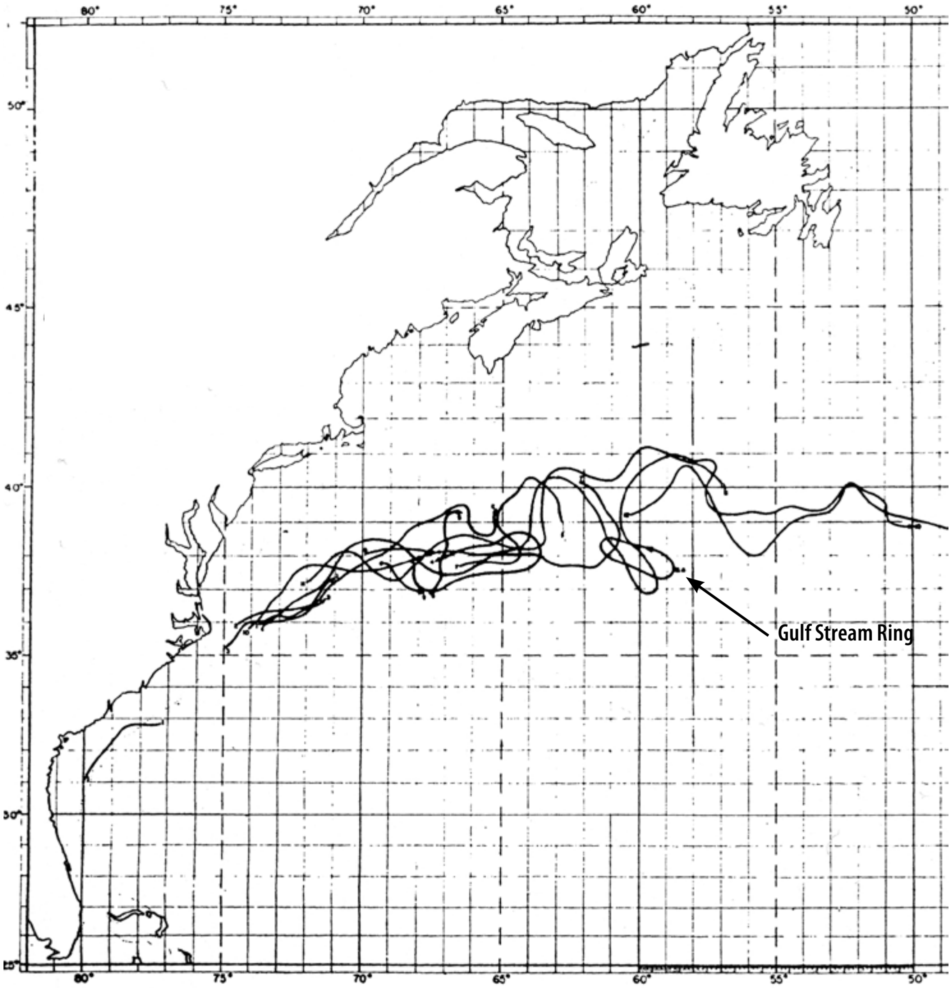


Fig. 2. Positions of the maximum cross-current temperature gradient at a depth of 330 feet (100 meters) from all surveys during 1946–1950 (after Fuglister and Worthington, 1951). These show lateral movements or meanders of the Stream.

the pleasure of all, a suitable meander was located south of Halifax. For the final ten days the ships followed—for the first time—the evolution of a cold core eddy as its originating meander moved southward and pinched off from the Stream (**Fig. 3**). Thus, Gulf Stream rings were discovered, confirming that the large cyclonic eddies frequently found south of the Stream formed in this manner. In addition, these observations yielded synoptic plots of the temperature and surface velocity of the Stream, and of the meander pattern and its changes during the period of observations.

A continuously monitoring temperature and salinity probe was towed near the surface and revealed some of the fine salinity structure of the Stream. On the shoreward side of the meander pattern, William Ford, J. Longard, and R. Banks (1952) found a narrow and presumably shallow ribbon of cool, fresher water entrained into the Stream near Cape Hatteras. This feature was observed during later surveys to extend from the Carolina Bays downstream as far as the Grand Banks. The GEK profiles showed that, instead of having a single core, the Stream was composed of a series of narrow overlapping streaks of swiftly moving water.

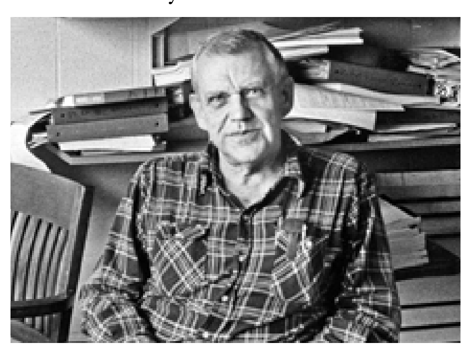
William Von Arx, Dean Bumpus, and William Richardson (1955) successfully exploited the GEK and BT on board *Crawford* in 1958 by repeatedly occupying a section across the Gulf Stream south of Cape Hatteras for a month. From these data they were able to map an asymmetry of meanders, which they called shingles. Ferris Webster (1961) analyzed the surface current field to obtain an estimate of eddy momentum flux and found the surprising result that surface momentum was flowing (eddy-wise) *into* the Stream, not away from it.

Fuglister and Arthur Voorhis (1965) developed a way of using a towed V-fin at 200 meters to follow the axis of the Stream from a moving ship and persuaded the U.S. Coast and Geodetic Survey to undertake a series of voyages using the V-fin for more than a year. These studies, written up by Donald Hansen (1970), showed a downstream progression of meanders.

Henry Stommel's *The Gulf Stream* (1958b)

Early shipboard surveys revealed a narrow and swift Gulf Stream that contrasted significantly with the wide and sluggish eastern part of the North Atlantic gyre (the large-scale clockwise circulation in the subtropics). Stimulated by these new observations and seeking to explain the disparity, Stommel (1948) discovered that the western intensification of wind-driven ocean currents like the Stream is related to the latitudinal variation of the Coriolis parameter due to the spherical shape of the earth.

Stommel's 1948 paper became a classic, one of the most frequently cited papers in modern physical oceanography. In an elegantly simple model—a plane (flat-bottomed), rectangular, homogenous ocean driven by wind stress at the surface



Vicky Cullen, WHOI

Henry Stommel, considered by many the most influential figure in oceanography in the last half of the 20th century, was known for his insatiable curiosity, extraordinary intuition (he was relentless in stripping problems down to their most elemental levels), and ability to visualize physical processes fully in three dimensions.

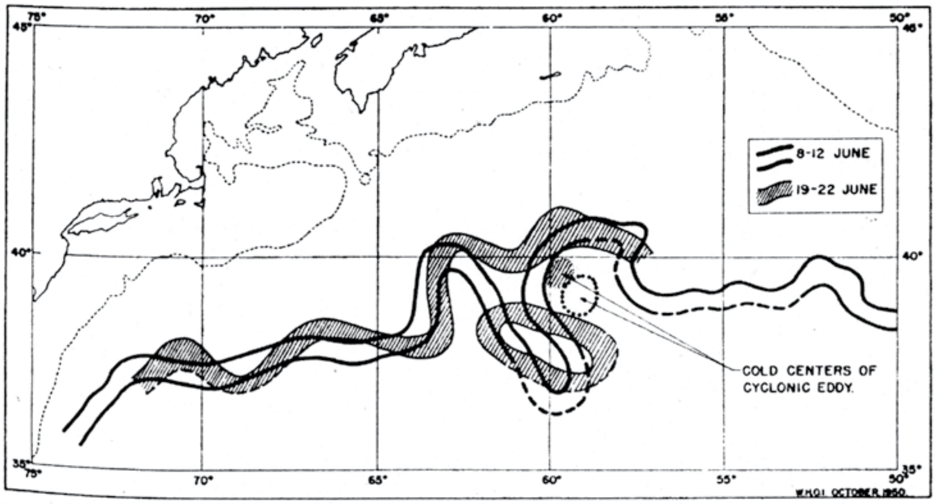


Fig. 3. Positions of the warm core of the Gulf Stream during the first and last periods of Operation Cabot (after Fuglister and Worthington, 1951). A cold core eddy (Gulf Stream ring) was observed as it moved southward and pinched off from the Stream.

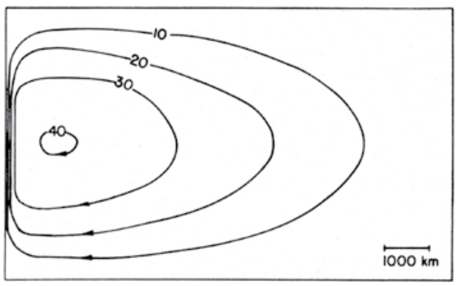


Fig. 4. Streamlines showing western intensification of a rectangular model ocean forced by winds for the case where the Coriolis force increases linearly with latitude (after Stommel, 1948).

and slowed by bottom friction—Stommel showed that the basic dynamical equations predicted a flow with east-west symmetry if the Coriolis term was held constant over the plane, but that a westward intensification, as in the Gulf Stream, emerged if the Coriolis term varied linearly with latitude (the so-called beta-effect) (**Fig. 4**). Until then the significance of the variation of the Coriolis parameter had not been appreciated by either oceanographers or meterologists. Soon, many scientists extended and refined theories of the Gulf Stream, but it was the deep physical insight of Stommel's paper on the western intensification that opened the new field.

Stommel provided a major step forward in our understanding of the Gulf Stream with his widely read book *The Gulf Stream*. The manuscript was finished in 1955, the book was published in 1958, and it was updated and reprinted in 1965. *The Gulf Stream* gave us the first synthesis of the history of the Stream, its characteristics, how it fit into the large-scale circulation, and theories about causes and dynamics. A particularly influential section of the book offered a beautiful schematic and description of the circulation in the upper and lower layers of the Atlantic, showing the combination of wind-driven and meridional overturning (thermohaline) circulations (**Fig. 5**). They reinforced each other in the Gulf Stream, increasing upper-layer flow, and countered each other in the Brazil Current, causing a weak upper-layer current in the South Atlantic.

The Deep Western Boundary Current

Stommel (1957, 1958a) predicted that cold, dense water that forms in the North Atlantic in late winter does not flow southward along the seafloor in the mid-Atlantic as had generally been thought, but instead is constrained to flow southward as a deep western boundary current due to the beta-effect. This was one of the few purely theoretical predictions ever made of a significant oceanic phenomenon, and it had not been anticipated previously. Noting that turbulent processes in the ocean would cause a downward flux of heat, Stommel assumed that an upwelling of cold water kept the temperature constant at a given level. This vertical velocity induced a northward velocity in the interior of the basin, and a southward flowing deep western boundary current was necessary to connect the source in the north and the northward-flowing interior flow farther south. Such a deep western boundary current would have profound implications for the deep Gulf Stream. Thus questions were raised about the interaction of the the two opposing currents and how they could cross each other.

Stommel's predictions motivated Alan Faller to perform illustrative rotating tank experiments on flow patterns in bounded basins, exploring flows arising in the presence and absence of vertical velocities imposed on the basin by a distribution of sources and sinks. Faller's laboratory studies demonstrated that an intense southward western boundary current occurred when a northern source imposed a vertically upward velocity and an associated northward flow in the interior of the entire basin (Stommel, Arnold Arons, and Faller, 1958).

This remarkable result was confirmed in the ocean in 1957 by tracking Swallow floats off the coast south of Cape Hatteras (John Swallow and Worthington, 1961). John Swallow's demonstration of the feasibility of building and tracking neutrally buoyant floats in the deep ocean (1955) brought the first glimmer of hope for determining the direction and strength of the deep flow under the Gulf Stream. Meanwhile, Worthington had made a hydrographic section off Cape Romain, South Carolina, that showed the Gulf Stream up against the continental slope and the deep sloping isotherms displaced seaward. This seemed to be an excellent place to track floats because the ship could operate seaward of the strong surface currents. During a joint float tracking and hydrographic study there in 1957, researchers aboard *Discovery II* (UK) and *Atlantis* found unequivocal

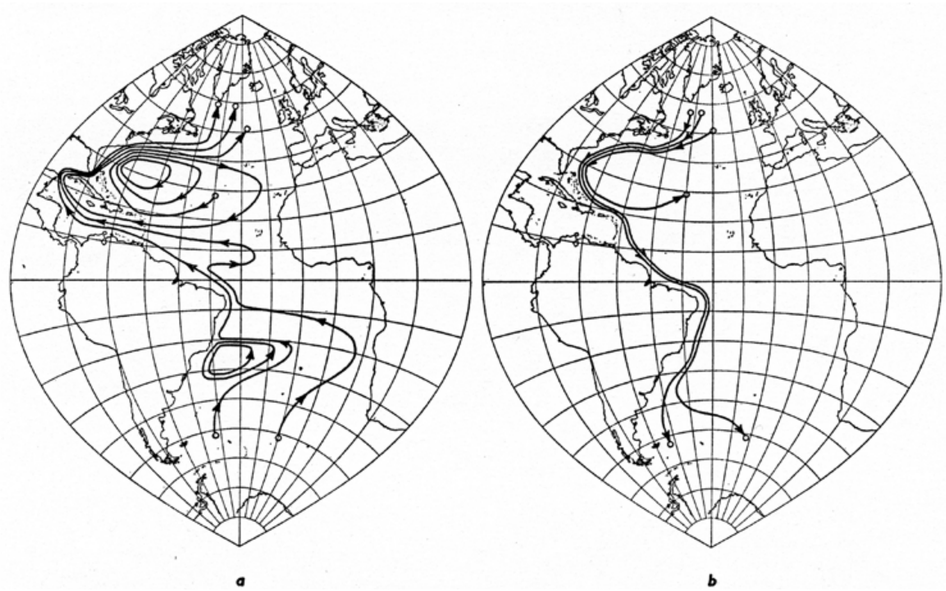


Fig. 5. Schematic map of the total transports in the surface layer (a) and the bottom layer (b) (after Stommel, 1958b). Points of sinking and upwelling across the level surface are indicated by the little circles.

evidence of a deep countercurrent. Further evidence was documented by Joseph Barrett (1965), who tracked floats under the Gulf Stream near Cape Hatteras and observed southward flows of northern origin under the Stream, hugging the continental slope.

A second experiment by Swallow, James Crease, and Stommel in 1959 tracked Swallow floats in the Sargasso Sea west of Bermuda from the 93-foot (28-meter) ketch *Aries*, acquired specifically for this work. Their direct measurements of the predicted northward flow in the ocean interior unexpectedly revealed the presence of energetic mid-ocean eddies whose velocities were around a hundred times greater than the expected mean velocities, indeed so large that it was difficult to imagine that they could be decoupled from the mean fields (Crease, 1962). The implication was that, in the presence of these energetic eddy motions, very long current records were needed to adequately resolve the mean flows in and near the Gulf Stream. This was eventually accomplished using long-term, moored current meters and long-drifting sofar (sound fixing and ranging) floats. Prior to the *Aries* measurements, the deep interior flow had been considered to be so weak that the rotors of current meters would stall and not turn at all. The new float observations stimulated the development of both moored current meters and sofar floats, which were eventually used to map the mean and eddy fields of the Gulf Stream.

The Deep Gulf Stream

The Fuglister strategy of using BTs and loran, supplemented with GEK current measurements, led to the possibility, once the direction of the Stream was known, of steaming on the wire to hold a position in order to make deep reversing-bottle casts in the current. Starting in 1950 with his three classic sections, Worthington (1954) finally made successful casts all the way to the seafloor in 16,500 feet (5,000 meters) of water. These casts revealed a major feature: the slopes of the isotherms and the isohalines extended all the way to the bottom under the Stream in the deep North Atlantic (**Fig. 6**). This was a surprise to those who thought of the Gulf Stream as part of a wind-driven circulation limited to the depth of the thermocline. The implication was that the Gulf Stream velocity also extended to the seafloor, but direct velocity measurements were needed to prove it.

Fuglister organized a second multi-ship survey of the Gulf Stream during spring 1960, called Gulf Stream 60 (Fuglister, 1963). As before, the ships mapped the currents, and another cold core ring was observed to detach from a southward meander. The really new information, however, was provided by Swallow floats tracked 6,600 to 13,000 feet (2,000 to 4,000 meters) under the Stream. They tended to drift in the same direction as the near-surface currents, indicating the Gulf Stream reached to the bottom of the ocean with velocities of around 0.2 knots (10 centimeters per second). When the observed deep velocities were used to reference the velocity profile, the calculated transport of the Stream was 147 Sverdrups (Sv) (1 Sv = 35,000,000 cubic feet [1,000,000 cubic meters] per second), which seemed huge compared

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British oceanographer John Swallow, left, and Gordon Volkmann of WHOI prepare a pinger for a Swallow float aboard *Erika Dan* in 1962. Swallow received WHOI's Bigelow Medal that year. The citation said the Swallow float "has become the principal tool for the study of deep water circulations. The results of these studies have revolutionized our conceptions of the character of the deep water motions. Instead of the sluggish, widespread drift anticipated from continuity considerations, the deep layers seem to be moving briskly and not in accordance with any known process. Here then, is a scientific fact that challenges the imagination."

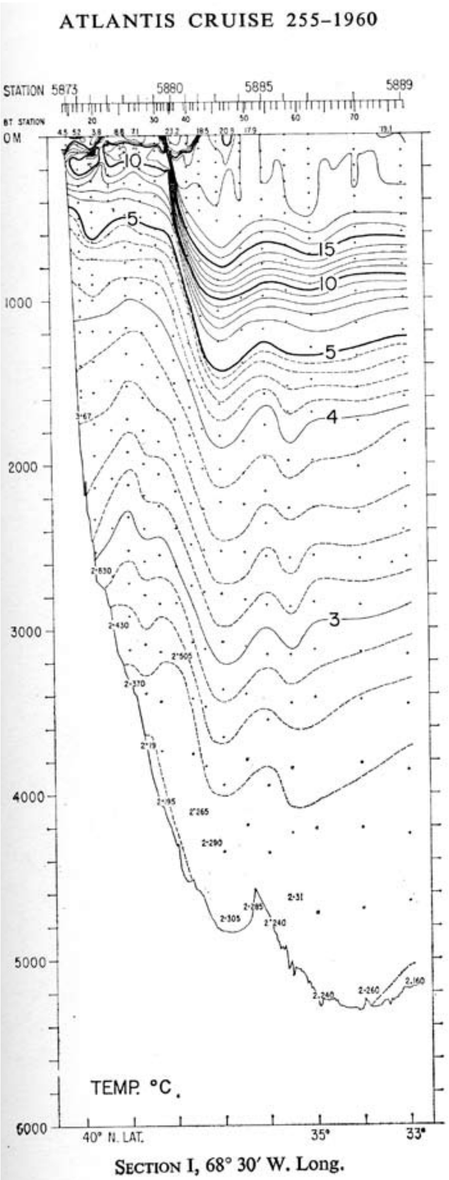

Fig. 6. Vertical temperature section across the Gulf Stream near 68.5°W (after Fuglister, 1963). The Gulf Stream coincides with the region where isotherms plunge steeply down towards the south (right) throughout the water column (centered between 37°–38°N).

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Nick Fofonoff, right, followed Bill Richardson as head of the Buoy Group in 1962, while Ferris Webster, left, set up the data processing part of buoy operations.

to the estimated 30 Sv generated by the winds. This suggested that large unknown movements of water elsewhere provide continuity. Subsequent float tracking in the Stream by Bruce Warren and Gordon Volkmann (1968) also found that the deep floats moved downstream. However, it became obvious that the need for a mother tracking ship was so restrictive and the float trajectories were so short and erratic that a satisfactory program to map deep currents would require another approach.

Gulf Stream Rings

Fuglister conducted the first study to concentrate on cold-core rings in the mid-1960s. (Gulf Stream eddies were called rings because a ring of Gulf Stream water pinched off when they formed, differentiating them from other eddies.) From September 1965 to February 1966 seven cruises followed the evolution of two rings; from March to October 1967 nine cruises measured 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; Charles Parker, 1972; Barrett, 1971).

During 1975 several ship surveys plus satellite infrared images provided a nearly synoptic view of the distribution and number of rings in the western North Atlantic (**Fig. 7**) (Philip Richardson, Robert Cheney, and Worthington, 1976). A chart of the region based on data from a four-month period represents the first attempt to create a quasi-synoptic "weather map" of the Gulf Stream system, including rings.

In 1976 and 1977 several investigators carried out a cooperative, interdisciplinary experiment that followed two cold-core rings over their lifetimes and recorded their physical, chemical, and biological properties and changes in them with time (Ring Group, 1981). Probably the most significant result of the experiment 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, and sometimes coalesce completely with the Stream. In the 1980s a similar program studied warm-core rings north of the Stream (Terrence Joyce, 1984).

Current meter moorings

In the late 1950s William Richardson began to experiment with building moorings and current meters that could be deployed for long periods in the Gulf Stream. It was a slow process, and his group encountered many problems with the choice of sensors, the methods of recording, tactics of sampling and data processing, calibration, mooring and instrument design, and quality control. It took ten to fifteen years of unremitting effort on the part of the WHOI Buoy Group to develop a system that could be used routinely.

Because of the strong currents in the upper levels of the Gulf Stream, the first fairly elaborate moored array experiments were carried out in regions north and south of the Stream, and only at the deeper levels in the vicinity of the Stream itself. The first long-term near-bottom moorings in the vicinity of the Gulf Stream were set in the period from 1973 to 1975 (James Luyten, 1977; William Schmitz, 1976). The next step was to set long-term moorings reaching up to the thermocline near the Gulf Stream between 1975 and 1977 (Schmitz, 1977, 1978, 1980). The earliest near-surface mooring in the Stream itself was in place in 1982 and 1983 (Melinda Hall and Harry Bryden, 1985). As the Gulf Stream meandered past this mooring, its cross-stream location was estimated from the upper-layer temperature field and was then was used with the current measurements to generate the mean synoptic velocity structure of the whole

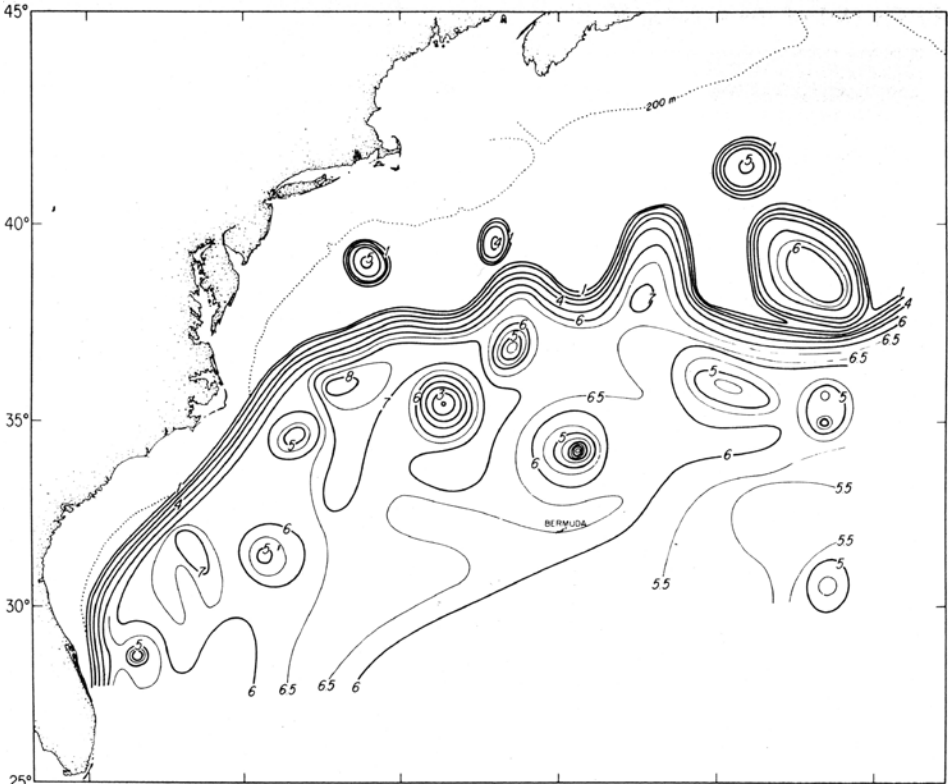

Fig. 7. Chart of the depth (in hundreds of meters) of the 15°C isothermal surface showing the Gulf Stream and nine cold core (cyclonic) and three warm core (anticyclonic) rings (after Richardson, Cheney and Worthington, 1976). The map is based on data from March 16 to July 7, 1975. Near-surface currents tend to flow parallel to the contours—downstream in the Gulf Stream and around rings.

Stream. The Gulf Stream appeared to be narrower and swifter than it was in the rather blurry picture obtained when this technique was not used to remove the effect of the meanders.

The moored current meter data were essential to developing reliable estimates of mean currents in the vicinity of and under the Stream. This body of work is chronicled in a 1979 paper by Schmitz, Allan Robinson, and Fuglister. Schmitz continued the effort (1976, 1978, 1980), estimating long-term mean flow that delineated some features of the cross-stream structure of the deep mean currents and finding evidence for the northern and southern Gulf Stream recirculations. A deep peak of eddy kinetic energy located under the axis of the Stream indicated that eddy energy from the Stream penetrated all the way to the seafloor as "undersea storms." Various statistics revealed aspects of temporal fluctuations, momentum transports, and correlation distances.

Moored current meters had taken their place beside hydrographic stations as one of the main techniques used to describe the Gulf Stream system.

Sofar floats

The interesting but erratic behavior of the early Swallow floats suggested that much longer trajectories were needed. Sofar floats, developed by Thomas Rossby and Douglas Webb (1970), gave the first measure of sub-surface, long-term trajectories of water parcels and their dispersion as they moved. The use of sofar floats in the Stream required a long-lived float, whose acoustic signals could be heard over long distances and through varying water masses, and a moored self-recording listening station to eliminate the need for shore stations, which were located primarily along the Antilles, far from the Gulf Stream. In 1980 the first array of sofar floats in the Gulf Stream was tracked entirely by means of moored listening stations (Schmitz et al., 1981). The resulting trajectories graphically showed the convoluted paths of subsurface water parcels in the Gulf Stream system and their differences with depth. A sufficiently large number of float trajectories was obtained to generate maps of the mean and eddy fields (Richardson, 1985; Brechner Owens, 1991). An increase in eddy kinetic energy was clearly apparent near the Gulf Stream, suggesting that its fluctuations, meanders, and rings were the primary sources of this energy. Some floats launched north of the Stream in the Slope Water region passed southward, some under the Stream to the west, and others through the Stream in complicated trajectories (Amy Bower and Heather Hunt, 2000).

Surface Drifters

In the 1960s, Fuglister employed both ships and airplanes to track drogued surface drifters equipped with radio transmitters (Fuglister, 1963, 1972). The drifters followed surface currents in Gulf Stream rings and were also useful in following their movement and giving surface velocities. Later, Parker

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An electronic current meter goes over the side of *Crawford* in 1965. Development of modern, long-lived current meters was vital to progress in Gulf Stream research.

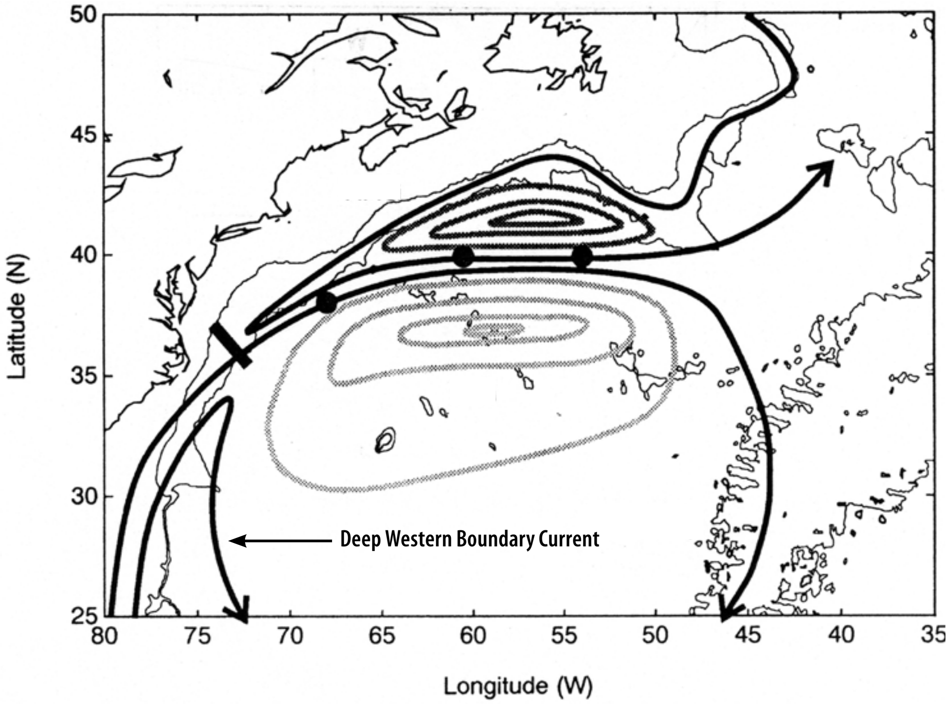

Fig. 8. Schematic chart showing the average surface-to-bottom transport of the Gulf Stream and recirculating gyres (after Hogg, 1992). Each line represents approximately 15 Sverdrups (35,000,000 cubic feet [1,000,000 cubic meters] per second) of transport. The three dots and line in the Stream mark locations where moored current meter arrays provided long-term current measurements.

A surface drifter goes over the side during a 1976 cruise.

(1972) described drifters tracked by ship in the high-velocity part of the Stream and provided some early long trajectories of the Stream. He made concurrent subsurface measurements and concluded that the drifters closely followed the subsurface thermal front for distances greater than 600 miles (1,000 kilometers). Speeds up to 5 knots were recorded and a decrease of speeds toward the east was documented. Remote tracking of drifters over larger areas for longer periods of time became possible in the early 1970s when polar-orbiting satellites were introduced. During the 1970s a sufficient number of drifters was tracked in the Stream to allow qualitative and quantitative estimates of Gulf Stream paths, and to show the influence of seamounts, surface current variability, and movement of rings (Richardson, 1983). Drifter trajectories were combined with satellite infrared images and occasional airborne expendable BT surveys to reveal synoptic scale features of the Gulf Stream. A recent analysis of all available drifter data in the Stream was published by David Fratantoni (2001).

Volume Transport of the Stream

The various drifter, float, and current meter measurement programs documented that the volume transport of the Gulf Stream increases fivefold from around 30 Sv off Miami to about 150 Sv south of Nova Scotia. Roughly 15 Sv of this water comes from the South Atlantic as part of the meridional overturning circulation. To put the transport in perspective, 150 Sv is around 10,000 times the annual average transport of the Mississippi River into the Gulf of Mexico. The measurements have also provided clues about what causes this huge transport and where it goes. Nelson Hogg (1992), summarizing the available information, created an enlightening schematic of average surface-to-bottom transport streamlines; it shows that most of the maximum Gulf Stream transport is recirculated westward in two counter-rotating recirculating gyres centered just north and south of the mean Stream and between 55° and 70°W (**Fig. 8**). Most of the increase in transport downstream of Cape Hatteras is due to barotropic or average top-to-bottom flow in the eastward flowing part of the gyres. The recirculating gyres are thought to be generated by energetic velocity fluctuations of the meandering Stream through eddy momentum fluxes, which feed back into the mean flow and include the deep flow of the Stream and the gyres.

More recent observations

Today, studies of the Gulf Stream use expendable BTs, CTDs (conductivity-temperature-depth profilers), satellite navigation, and acoustic Doppler current profilers, all modern versions of the BT, hyrdrostation, loran, and GEK. New techniques being imaginatively applied to studies of the Gulf Stream include satellite infrared imagery and altimetry. These are starting to provide the extended time series needed to unravel the long-period fluctuations of the Stream and the ocean's effect on climate variability. An effective illustration of the importance of long time series data is a study by Joyce, Clara Deser, and Michael Spall (2000), who merged all available historical subsurface temperature profiles, identified long-term shifts of the Stream, and related them to atmospheric trends. ■

***Acknowledgements*:**

This summary was written to provide examples of explorations and discoveries of the Gulf Stream by WHOI oceanographers and their colleagues. It mentions some of the most important advances in our understanding of the structure of the Stream, concentrating on the earlier years when fundamental advances were made and scientists' conceptual picture of the Stream was changing radically. Unfortunately, many studies and scientists could not be mentioned here in order to keep this manuscript within reasonable limits. The author apologizes to the many WHOI scientists who were not mentioned specifically.

This piece is based heavily on a paper by Fuglister, Richardson, Schmitz, and Stommel (1983). Other important sources of information are provided by Iselin (1936), Fofonoff (1981), Schlee (1978), Schmitz (1996), Sears and Merriman (1980), Stommel (1965), Warren and Wunsch (1981), and Worthington (1976). The author would like to pay special tribute to a few WHOI scientists no longer alive who contributed significantly to our knowledge of the Gulf Stream (and to his own education)—Columbus Iselin, Fritz Fuglister, Val Worthington, Henry Stommel, Gordon Volkmann, and Nick Fofonoff.

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