Tracking Ocean Eddies

Drifting below the surface, floats reveal energetic masses of swirling water that transport salt and energy

Philip L. Richardson

In 1768, while serving in London as Deputy Postmaster General for the American colonies, Benjamin Franklin was asked to look into why British mail packets were taking two weeks longer than merchant ships to sail from London to New York. When Franklin consulted his cousin, Timothy Folger, about the matter in October of that year, the Nantucket ship captain told him that British mariners were ignorant of a powerful current. To explain, he sketched the first good depiction of the Gulf Stream.

Franklin had Folger's sketch engraved and distributed copies to packet captains to help them navigate around the Stream, but his efforts were largely in vain. Perhaps because the British did not appreciate the implication that American fishermen knew more about ocean currents than they did, the Franklin-Folger chart was largely ignored. By the early 1770s, with relations between Britain and the colonies deteriorating, Franklin himself may have begun suppressing distribution of the chart to keep it from the British Navy. In any event, over the next two centuries, copies of the original Franklin-Folger chart became very rare. Despite considerable effort, none was found until September 1978, when I located two copies in the Bibliothèque Nationale in Paris.

The Franklin-Folger chart is remarkable for several reasons, but as I studied it in the Paris library, two characteristics stood out. First, the chart is very accurate. The mean path, width and speed of the Stream at the surface as we know them today are much as Franklin and Folger plotted them. Second, the Stream appears to flow between well-defined boundaries, like a wide river running from the Straits of Florida out toward the Azore Islands. Although the Nantucket captains may well have known better, the first good chart of the Gulf Stream shows it as a broad, steady flow along the surface of the ocean, a superficial understanding that persists in the public mind to this day.

Since 1945, measurements of surface flows have revealed a much more variable Stream than the one depicted by Franklin and Folger. If it is a river, the Gulf Stream is a narrow, somewhat unpredictable one that meanders widely and sheds many energetic eddies. In addition, it has become clear that surface measurements do not necessarily represent flow fields at depth. Not only does the Gulf Stream extend to the ocean floor, but other important and complex currents are found below the surface.

To better understand subsurface currents, the overall movement of ocean water, and how currents, meanders and eddies distribute kinetic energy in the ocean, scientists have been recording for the past 20 years the paths of neutrally buoyant, freely drifting floats. Dropped from research vessels and ballasted to wander at depths of a few hundred to a few thousand meters, these floats have provided a new view of the ocean that would be difficult or impossible to obtain with surface-based technologies or measurements at fixed locations. As a float drifts at depth, its position is recorded at intervals. From these points, a trajectory emerges. In effect, we can observe the motion of a parcel of water within the ocean.

Taken together, the 240 float-years of data collected to date by U.S. scientists have been used to calculate velocity fields and plot maps of the mean velocity and kinetic energy of much of the water in the Atlantic Ocean. Such maps do much to enhance our understanding of subsurface flow. In merging the trajectories, however, some information is lost as other information is gained. Most float paths are so convoluted that superposing many trajectories obscures the individual original patterns. Details of the flow field are lost in the tangled mass of trajectories, and I have discovered while exploring individual float trajectories that those details can reveal striking patterns. Currents may meander; they may probe surrounding water in swirling tongues; they may even separate entirely into eddies.

Using the existing float data set, I concentrated recently on studying the distribution and number of subsurface discrete eddies (eddies that have nearly circular flow around their centers and that survive for many rotations) and their sizes, paths and speeds. Owing to the great difficulty in following discrete eddies, especially subsurface ones, their trajectories and life histories remain largely unknown. Although satellite images show clearly the newly formed rings of water that separate from meandering portions of the Gulf Stream

Philip L. Richardson is a senior scientist in the Department of Physical Oceanography at Woods Hole Oceanographic Institution. He obtained his M.S. and Ph.D. in oceanography from the University of Rhode Island. Among his scientific interests are observations of the general ocean circulation, its large-scale, low-frequency variability and the role of ocean eddies. These interests have led to studies of the Gulf Stream and its rings, the Mediterranean saltwater tongue and its eddies, deep western boundary currents and their cross-equatorial flow, equatorial currents and the history of ocean-current measurements. He uses surface drifters and subsurface floats to learn where ocean water goes. Address: Woods Hole Oceanographic Institution, Woods Hole, MA 02543.

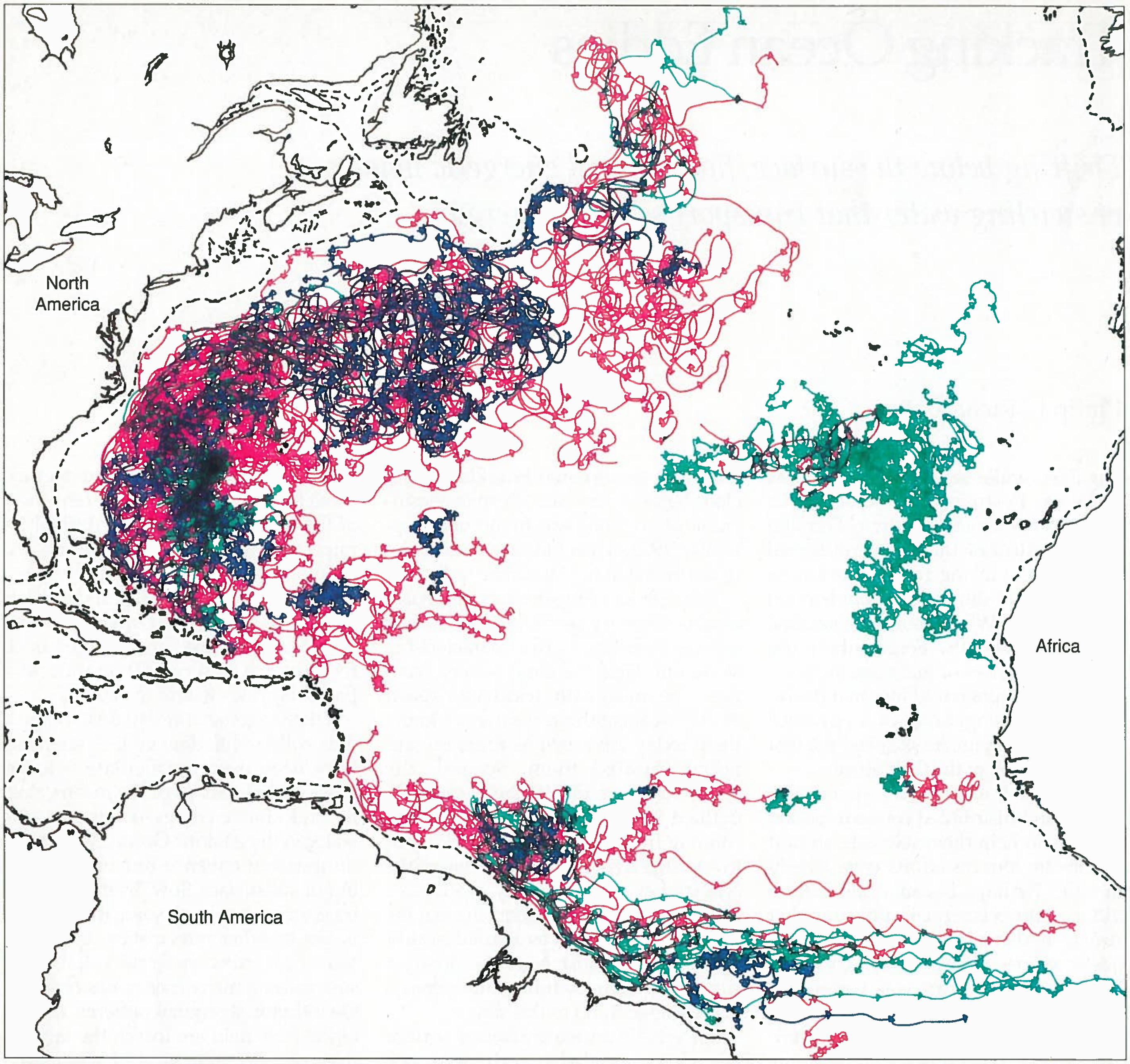

Figure 1. Tangle of lines showing the trajectories of floats drifting in the North Atlantic at depths from 500 to 3,500 meters reveals the great energy and complexity of currents and eddies in the ocean. Red lines show the paths of floats drifting at depths between 500 and 1,000 meters, green lines are those at 1,000 to 1,700 meters, and blue lines indicate floats drifting 1,700 to 3,500 meters below the surface. The trajectories are concentrated in the region around the Gulf Stream off the North American coast, showing the multitude of meanders and eddies (which appear as loops in the float paths) that spread the Stream's energy and mass through the ocean. To the south are cross-equatorial currents and eddies that move northwestward along the coast of South America. The middle-depth trajectories off the northwestern coast of Africa were made by floats tracking eddies created from water flowing out from the Mediterranean Sea. Arrowheads mark float positions every 30 days. (Image courtesy of Woods Hole Oceanographic Institution.)

(in much the same way as oxbows form in rivers), older rings and several other forms of eddies are difficult or impossible to see on the surface.

Floats are uniquely suited to the study of subsurface eddies. When a float becomes trapped in the rotating swirl around an eddy's center, the path of the eddy can be inferred from the float's trajectory. Looking into the data, I found that about 15 percent of all the float data are in discrete eddies consisting of at least two consecutive loops. A single looping trajectory or "looper" is a powerful tool, because it traces the progress of the huge mass of water advected by the eddy. Each eddy has particular water characteristics that distinguish it from background water. An eddy may, for example, have a higher or lower salt content and temperature than nearby water, and it may move through that background water at speeds and directions inconsistent with background flows.

Eddies are water-mass anomalies, and their trajectories give clues to the fluxes of salt and temperature in the ocean. With the existing float data, we have been able to piece together patterns of eddies over a large part of the North Atlantic at different depths. New float data obtained in the equatorial Atlantic suggest that eddies may play an important role in exchanging water between the South and North Atlantic.

SOFAR Floats

The floats used since the 1970s to monitor eddy trajectories were developed 25 years ago by Douglas C. Webb, then at Woods Hole Oceanographic Institution in Massachusetts, and H. Thomas Rossby, then at the Massachusetts Institute of Technology. A zone of minimum sound velocity that traps and carries sound long distances, located at ocean depths around 1,000 meters, is known as the Sound Fixing and Ranging (SOFAR) layer. The floats were designed to take advantage of this layer—hence their name, SOFAR floats. Webb led the development of neutrally buoyant floats capable of transmitting large amounts of acoustic energy for extended periods, whereas Rossby planned tracking from military listening stations.

A SOFAR float consists of either an aluminum tube or, for the deepest floats, several glass spheres, ballasted to drift at a particular water density. The float emits a low-frequency (250-hertz) signal that sounds like a boat whistle. Because of the SOFAR zone's characteristics, the signal can reach listening stations at ranges of a few thousand kilometers. Differences in arrival times at different stations are used to calculate distances and to triangulate float position.

Modern SOFAR floats benefit from microprocessors, better clocks, louder signals and automatic ballasting control, but the biggest improvement in SOFAR technology since the early 1970s has been the autonomous listening station (ALS). In 1977, Albert M. Bradley and James R. Valdes, also at Woods Hole, developed a tracking station that can be moored anywhere in the ocean, freeing SOFAR tracking from the limitations of land-based military stations, some of which were unable to hear floats in the Gulf Stream and other areas far offshore (Some of the stations that could hear the floats were at the time virtually inaccessible to scientists.)

The lifetimes of SOFAR floats and the listening stations have increased significantly with technological improvements; nine years and four years, respectively, are almost routine. Most of the original autonomous listening stations are still operational and typically are deployed for two-year missions. The reliability of SOFAR floats and listening stations has made floats a great resource with which to study ocean circulation, and the original designs are now being replaced by an improved system, called RAFOS. As the name implies, RAFOS floats work backward from SOFAR floats. They receive sound signals from moored transmitters,

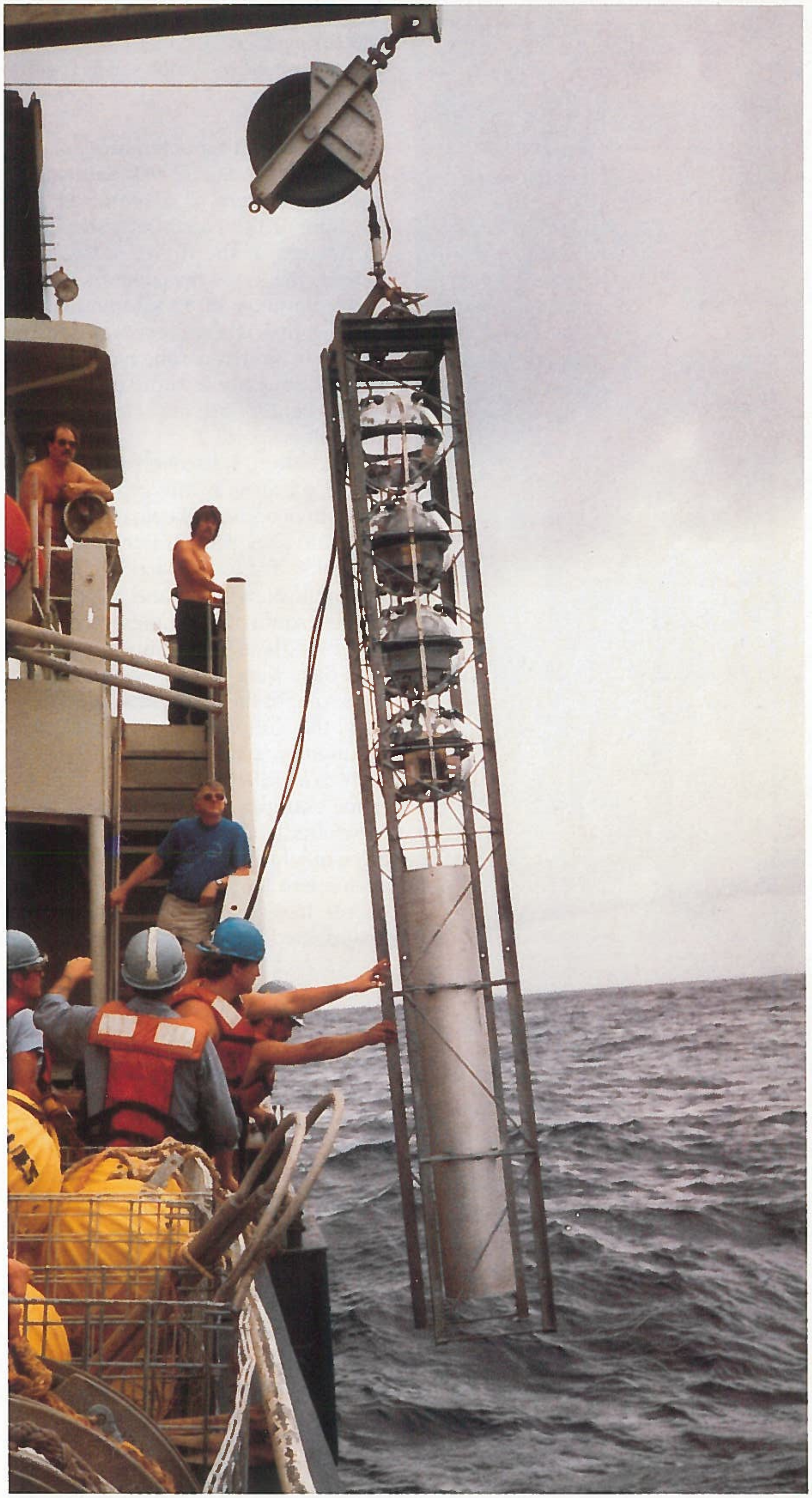

Figure 2. Instrumented float that will drift at a depth of 3,300 meters is launched as the research vessel *Oceanus* crosses the equator in the Atlantic Ocean in January 1989. Unlike shallower floats, this float has glass spheres to house electronics and batteries to resist the enormous pressures of the deep ocean. The aluminum tube is an acoustical resonator that produces a signal once a day. Forty-eight floats, some all-aluminum, some glass and aluminum, were launched in the tropical Atlantic to measure cross-equatorial currents. An array of six moored listening stations recorded data from these floats over a four-year period. (Photograph courtesy of the author.)

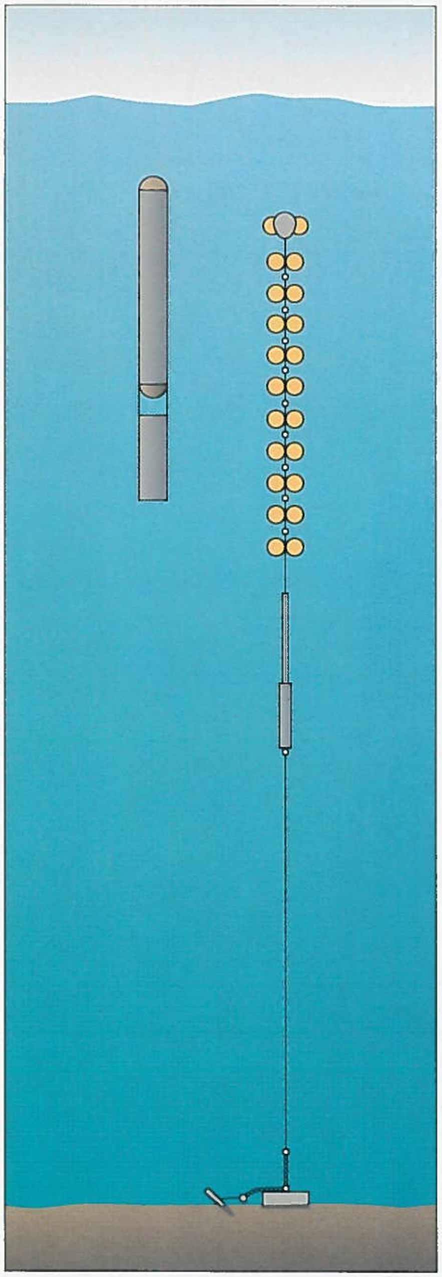

Figure 3. SOFAR (Sound Fixing and Ranging) floats are tracked by their acoustic signals, which are detected by autonomous listening stations moored to the ocean bottom. A typical float equipped for drifting at depths of 500 to 2,000 meters consists of an aluminum pressure hull 30 centimeters in diameter and 5 meters long. Inside are electronics and batteries. Attached to the bottom is an acoustic resonator that transmits a 250-hertz signal as often as every eight hours. The listening station detects signals within several thousand kilometers and stores data for later retrieval. It is housed in an aluminum tube also 5 meters long and suspended at the Sound Fixing and Ranging depth—generally near 1,000 meters. A hydrophone array is attached to the station. The yellow spheres supply flotation. An alternative technique, called RAFOS and designed to retrieve data more economically, reverses the process: A small glass float drifts and listens for signals from moored transmitters.

record the times of arrival of the signals and surface periodically to transmit the data to a satellite, which sends them to our laboratory.

General Eddy Characteristics

As I sifted through SOFAR data searching for loopers, I discovered that throughout the North Atlantic, about 15 percent of the floats' trajectories looped; the loops revealed an average eddy diameter of 80 kilometers. Assuming this is a representative sampling, the North Atlantic has a population of roughly a thousand eddies whose centers are an average of 200 kilometers apart.

In addition, I discovered distinct regional patterns in the type, size and strength of eddies. The floats most likely to have looping trajectories were those that drifted at a depth of 700 meters in the Newfoundland Basin and in and just south of the Gulf Stream. In the Newfoundland Basin, almost half of all float-days were spent in loopers; about 20 percent of the float-days in the vicinity of the Gulf Stream were in loopers. Frequently, a float jumped from one eddy to another in short order. In an extreme example, one float drifted in the Newfoundland Basin for a total of 1,032 days, of which 560 days appear to have been spent looping in seven different eddies. In the Gulf Stream vicinity, one float drifted a total of 306 days in five eddies, and another may have looped in four different eddies for 656 days.

South of the Gulf Stream there were fewer looping trajectories, except along the western boundary of the North Atlantic. The percentage of float days spent in loopers decreased with increasing depth and with increasing distance from the Gulf Stream. Overall, 21 percent of the 700-meter float days were in loopers, compared to only 6 percent at 2,000 meters.

There are at least two possible explanations for the decrease in loopers below 700 meters in the western Atlantic. First, there simply may be more eddies at 700 meters than below this depth. Second, the swirl velocity may be much lower at depth, so that fewer deep floats are caught long enough to make closed loops. Both explanations are probably partially correct, but the limited available data suggest the latter in the vicinity of the Gulf Stream, where most of the 2,000-meter floats were located. Between the latitude of 35 degrees north and the Gulf Stream at 40 degrees north, swirl velocity at 700 meters averaged 32 centimeters per second, whereas the average swirl velocity at 2,000 meters dropped off to 12 centimeters per second.

Overall, the rotations of about half (48 percent) of the loops were counterclockwise, or cyclonic, and about half (52 percent) were clockwise, or anticyclonic. However, great geographical differences in distribution were observed, reflecting different eddy-formation mechanisms. In the Canary Basin, almost all (96 percent) of the loopers at 1,000 meters rotated clockwise. In the west the situation was reversed. Counterclockwise-rotating eddies predominated by a ratio of 2 to 1 in the Gulf Stream region and in the Newfoundland Basin.

Gulf Stream Rings

Gulf Stream rings are the most thoroughly studied form of eddy. Their origins and life histories have been well documented from satellite infrared images (which detect the surface-temperature variations that distinguish warm Gulf Stream water from the surrounding cooler waters), shipboard measurements, surface drifters and subsurface floats. Counterclockwise rings form when Gulf Stream meanders pinch off to the south of the Stream. At the surface, a newly formed ring consists of a closed segment of warm water revolving around a cold core (*Figure 4*). The rings are most energetic at the surface, where the highest average speeds reach 150 centimeters per second. At 700 meters, the highest average swirl speeds recorded by floats ranged from 42 to 45 centimeters per second. In two cases, 700-meter and 2,000-meter SOFAR floats looped simultaneously in the same ring, revealing that 2,000-meter speeds were 20 to 60 percent of those at 700 meters.

Counterclockwise rings tend to translate eastward while still attached to the Gulf Stream, southward as they separate from the Stream, westward when they are free from the Stream, and northward when they encounter the Stream again. Interactions at that point can be intense. Some can be fatal, when a ring completely coalesces with the Stream. In other cases, a ring separates from the main current again, often significantly modified.

The rates at which the rings move through the ocean can be quite fast; a ring attached to the Gulf Stream was once clocked moving at 75 centimeters per second as it carried a looping sur-

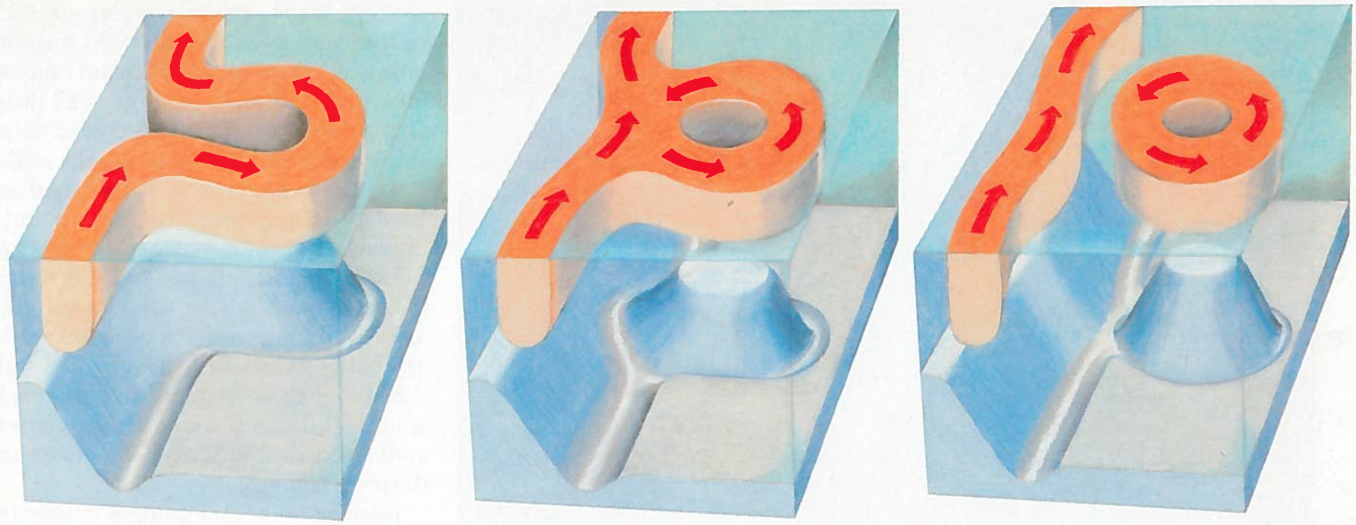

Figure 4. Gulf Stream rings form when a meander *(left)* pinches off from the main current. Near-surface Gulf Stream water is significantly warmer than water to the north; thus, the core of a counterclockwise-rotating Gulf Stream ring *(right)* is cold, made up of the colder water trapped in the meander. The thermocline *(lower surface)*, the boundary between warmer surface water and cooler deep water, rises from south to north beneath the Gulf Stream and in the center of a cold-core ring. Rings that form on the landward side of the Stream are different, with somewhat warmer cores and a thermocline depression below. Rings may survive for many months, or even years, but ultimately coalesce with the Stream.

face drifter. Because of their rotation, eddies may induce their own motion based on the earth's rotation. Thus, they may move through surrounding water, although the movement of rings is much slower after they separate from the Gulf Stream. In addition to self-advection, however, eddies may be propelled by background currents, which vary in space and time and with depth, and by other eddies nearby. Because of the complex motion of eddies and of their surroundings, it is impossible to know how large the self-induced motion is.

Just as counterclockwise rings form south of the Gulf Stream, clockwise rings may form north of it. Only two clockwise loopers were found north of the Stream, but the data there are quite sparse.

Gulf Stream Anticyclones

Were Gulf Stream rings the only discrete eddies that formed in the western North Atlantic, no anticyclones would be observed south of the Stream. But SOFAR float trajectories have revealed another type of eddy to the south that has not been readily apparent from the surface. I shall call these eddies Gulf Stream anticyclones.

Unlike the rings, Gulf Stream anticyclones have lower speeds at the surface than at depth, making them difficult to document with near-surface measurements. Recent float data show that roughly one-third of the loopers in the northern Sargasso Sea had the clockwise rotation of an anticyclone. Their highest

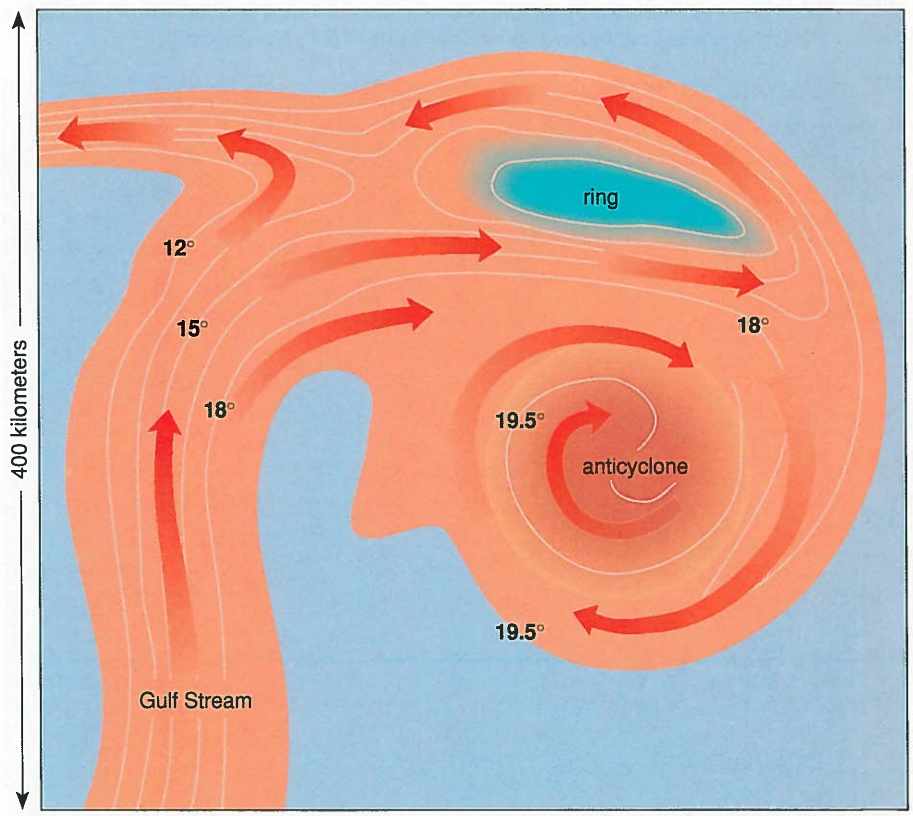

Figure 5. Gulf Stream anticyclones are warm-core eddies that spin below the surface of the Sargasso Sea. They may form when parcels of water at 18 degrees Celsius separate from the thick layer of warm, homogenous surface water near the Stream and move southward into a region where the 18-degree layer is thinner. Shown here are the results of a numerical model of one possible mechanism of anticyclone formation in the Gulf Stream; in this scenario a warm parcel of water below the surface pinches off a meander, rotating clockwise, as the meander forms a cold-core ring via the scenario shown in Figure 4. The thick parcel would be expected to take on a lens shape as it moved through the ocean; the clockwise rotation of its core would be sustained by a balance between the outward pressure gradient resulting from the lens shape and the inward acceleration, or Coriolis force, created by the earth's rotation. Contours show temperature in degrees Celsius. (Adapted from Spall and Robinson 1990.)

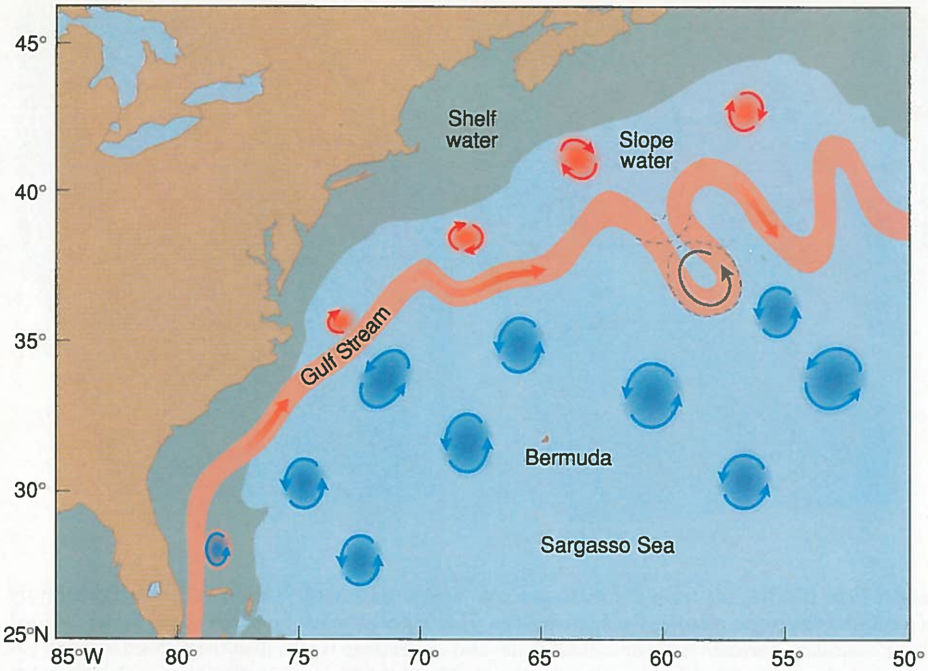

Figure 6. If the Gulf Stream rings that formed from meanders were the only type of medium-sized eddies in the western North Atlantic, existing data suggest that the distribution of eddies would look something like this at a particular point in time. Counterclockwise-rotating cold-core eddies *(blue)* lie south and east of the Stream, whereas clockwise-rotating warm-core eddies *(red)* are less frequent and on the north or landward side of the great current.

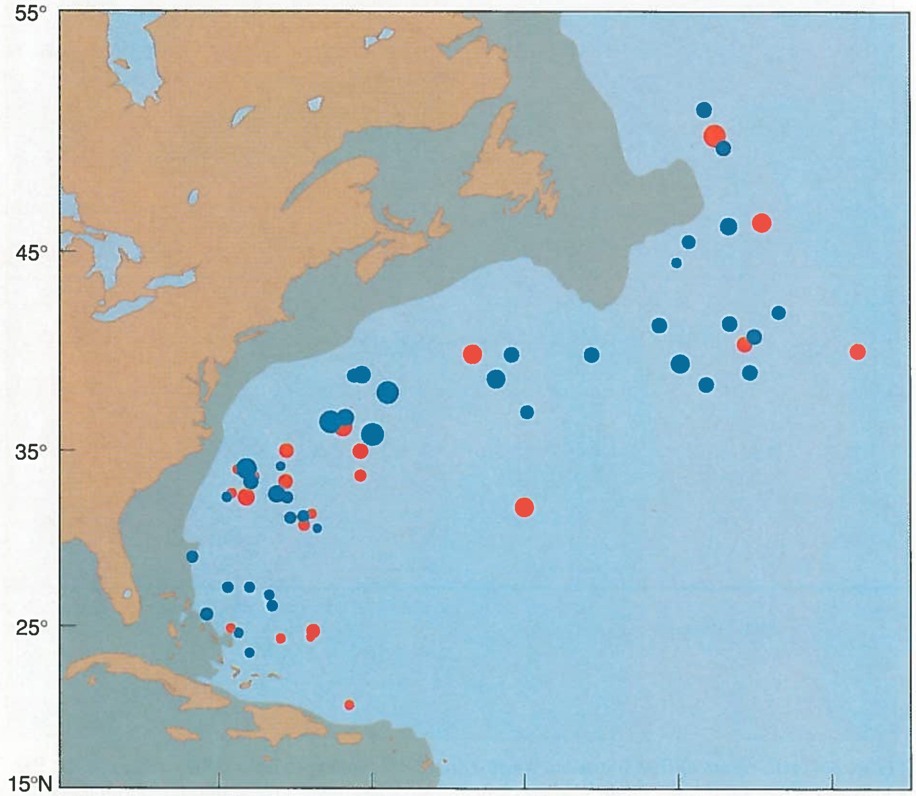

Figure 7. Actual distribution of clockwise- and counterclockwise-rotating eddies in the North Atlantic is revealed by floats drifting at a depth of 700 meters. For every two counterclockwise-rotating cold-core eddies *(blue)* in the western North Atlantic, there is a clockwise-rotating *(red)* eddy or anticyclone. The swirl speeds of the two types (indicated by the relative size of the dots) are similar. SOFAR floats have shown that surface measurements of eddy motion, which produce a distribution similar to that in Figure 6, fail to reveal many subsurface clockwise-rotating eddies southeast of the Gulf Stream. Whereas Figure 6 shows the eddies that would be expected at an instant in time, this map summarizes all eddies detected by floats since the 1970s.

average swirl speeds were around 35 centimeters per second at 700 meters, only a little less than Gulf Stream rings at the same depth. The average of all their swirl speeds and diameters proved to be similar to the Gulf Stream rings as well.

The float group's hypothesis, based on limited data, is that Gulf Stream anticyclones have a warm core made up of a thick layer of 18-degree-Celsius water in the shape of a lens. Underneath the lens, the main thermocline—the boundary between warm surface water and the colder deep waters—is depressed several hundred meters. The water swirls most rapidly near the center of the core *(Figure 8)*.

Because these anticyclones cluster in the northwestern Sargasso Sea near the Gulf Stream, the Stream or the deep layer of warm, 18-degree water adjacent to it may be their source. In the northwestern Sargasso Sea, the main thermocline is particularly deep, with a thick, nearly homogeneous layer of 18-degree water above. Detailed hydrographic surveys have revealed even deeper spots, usually next to the Stream and between Gulf Stream (cold-core) rings.

Anticyclones may form when parcels of 18-degree water separate from the thick layer next to the stream and move southward into a region where the 18-degree layer is thinner. Some numerical models *(Figure 5)* of Gulf Stream meanders show that anticyclones may form adjacent to cold-core rings, with the Stream providing the energy needed to form closed eddies. The models suggest it is possible that the two eddies could propagate together away from the Stream as a vortex pair.

If our hypothesis is correct, it might be that the cooling of the 18-degree water, which becomes deepest in the late wintertime, would lead to formation of the most energetic anticyclones in late winter near the Gulf Stream. Indeed, the inferred beginning of the longest tracked anticyclone is south of the Stream on March 10, 1983, just at the time when the vertically mixed layers were deepest. By combining data from two successive looping trajectories in close proximity, with similar rotation periods and swirl speeds, one anticyclone appears for 430 days *(Figure 9)*. This eddy's trajectory might even have been as long as 656 days if an earlier looper was in the same eddy. The looping characteristics were similar, but a 108-day gap makes the interpretation of a single eddy tentative.

This anticyclone's trajectory proved

to be particularly valuable because it passed through a current-meter array as it was being advected with the Gulf Stream in its later days. At 900 meters, the eddy's temperature was 4 degrees Celsius warmer than background water, and the maximum swirl speeds were 50 centimeters per second at a radius of 30 kilometers *(Figure 8)*. The inferred surface swirl velocity was 20 centimeters per second, and the diameter was 150 to 200 kilometers, depending on how the outer limit is defined.

The ultimate fate of Gulf Stream anticyclones is probably complete coalescence with the Stream, as is the case with Gulf Stream rings, but their opposite rotation could cause a different sort of interaction.

Meddies

In the eastern North Atlantic is found another type of eddy. Mediterranean water eddies—Meddies for short—form when warm, salty water from the Mediterranean Sea flows through the Strait of Gibraltar. Subsurface water in the Mediterranean is around 12 degrees Celsius and comparatively salty, at 3.8 percent. This dense water flows out beneath incoming, near-surface water, turns to the right and cascades down the continental slope to a depth of around 1,000 meters, where it reaches neutral buoyancy. This water flows westward to Cape St. Vincent, Portugal, where some of it turns and flows northward toward Cape Finisterre, Spain. As it flows, large pieces of the warm, salty water may meander, essentially bulging into the surrounding water in the way that a Gulf Stream meander does; the bulges may then pinch off to form Meddies that drift southwestward into the ocean interior. The westward and northward direction of the flow and the shape of the coastal meanders would lead to the development of a clockwise rotation.

Typical Meddies are around 800 meters thick and 100 kilometers in diameter. They contain about 0.08 percent more salt than surrounding ocean water, which corresponds to around 2 billion tons of salt per Meddy. The number of coexistent Meddies in the Canary Basin is unknown but may be around 25. Meddies are thought to be important in carrying salt away from the source in the Mediterranean near Gibraltar.

During the mid-1980s, subsurface floats provided the first long-term trajectories of Meddies, and their lifespans appear to be quite long. Three Meddies have been tracked, one for 821 days (a record for continuous eddy tracking), another for 8.5 months, and a third for 1.5 years. Extrapolating the average translation velocity back to the formation location near Cape St. Vincent, the first Meddy's full lifetime is estimated at four years. Meddy 2 apparently died catastrophically when it collided with seamounts after an estimated total lifetime of two and one-half years. Backtracking Meddy 3 gives a total life-span of four to seven years.

Meddies are long-lived because they rotate rapidly and translate slowly through the calm waters of the Canary Basin. All three had swirl speeds of around 30 centimeters per second and a rotation period of about five days. All three also translated south to southwest at 1 to 2 centimeters per second. Although the background water at 1,000 meters, where they drift, moves very little, the upper portions of Meddies lie within the generally southwestward flow of the subtropical gyre, which could explain the direction of their travel.

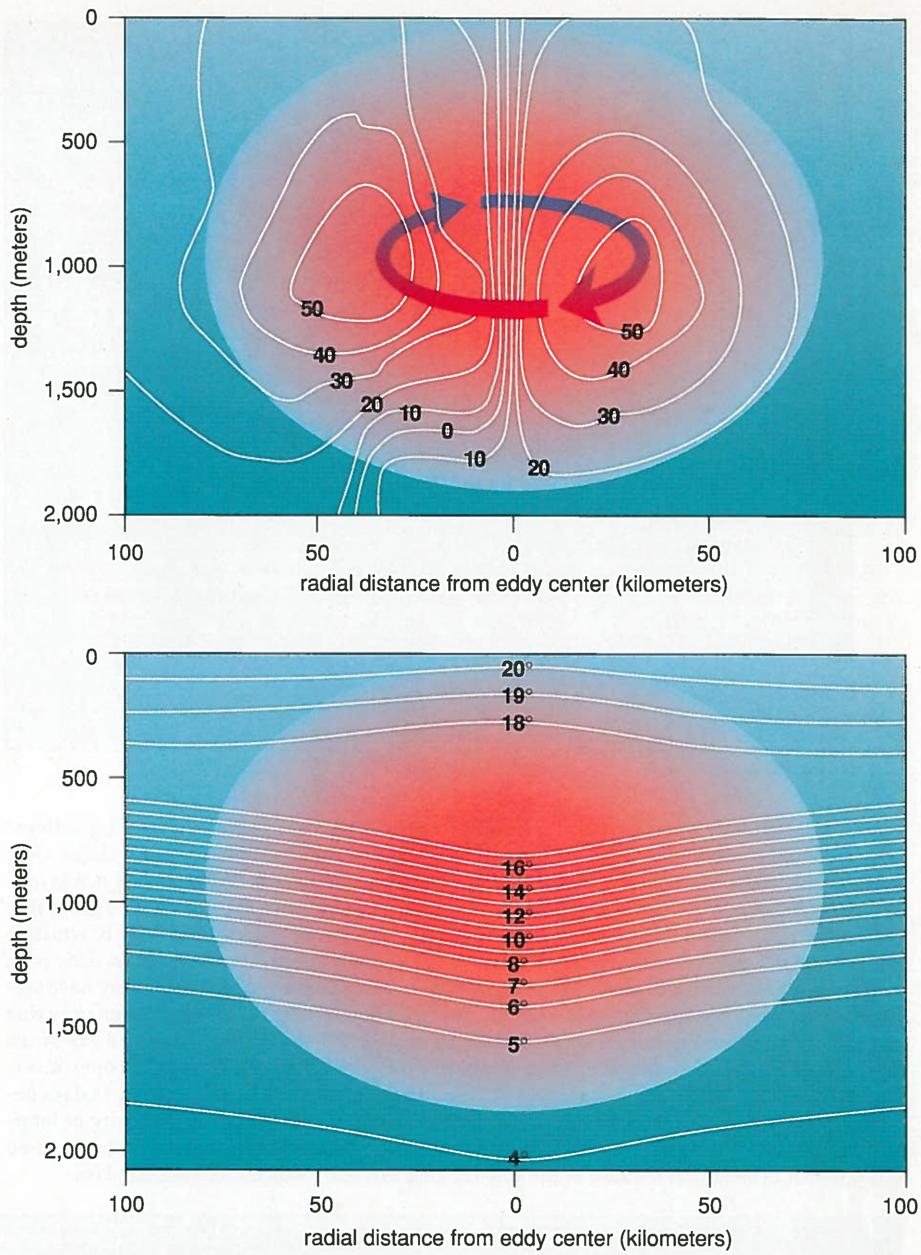

Figure 8. Maximum swirl speeds in Gulf Stream anticyclones occur well below the surface. A cross section showing velocity contours *(top)* (in centimeters per second) for the eddy tracked in Figure 9 reveals that the highest swirl speed was encountered at a depth of 900 meters and about 30 kilometers from the center. As the eddy passed through a current-meter array, water temperatures were also measured *(bottom)* in degrees Celsius. Because the surface temperature signal is relatively weak, a Gulf Stream anticyclone may not appear clearly on a satellite infrared image, yet the thermocline is depressed significantly below its core. The contours were based on data obtained by Bane, O'Keefe and Watts (1989).

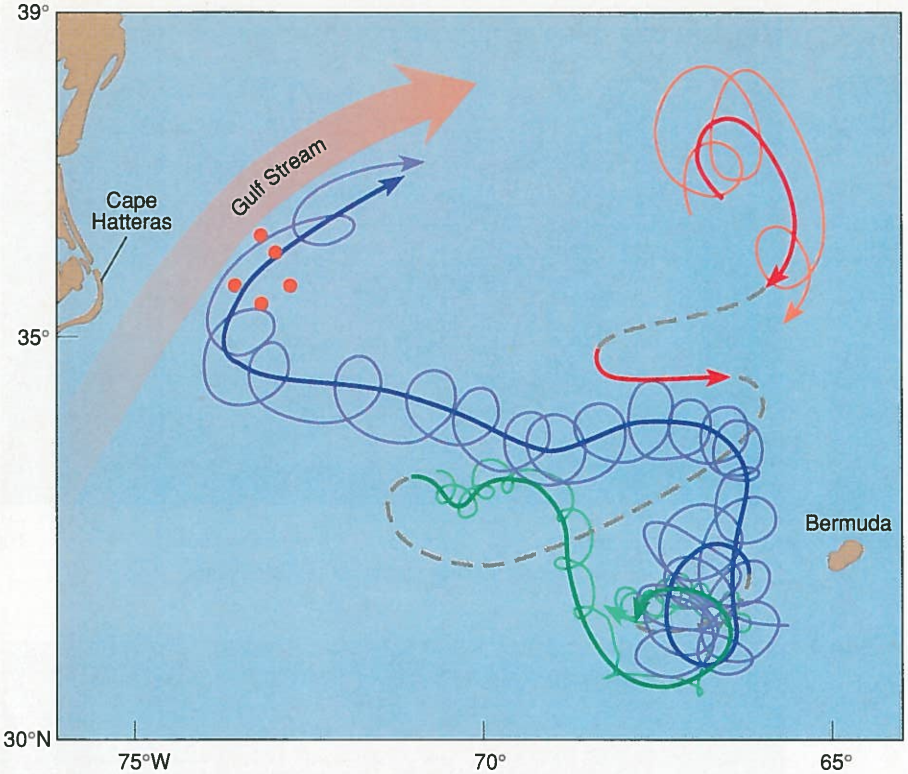

Figure 9. When only a few carefully selected float trajectories are plotted, interesting patterns may develop. Here the trajectories of three floats describe the possible path of a single Gulf Stream anticyclone. The dark-red line indicates the inferred path of the eddy as float A was continuously looping in it. The light-red line shows the actual trajectory of float A. The green line shows the part of the eddy's path that can be inferred from the trajectory of float B, which is shown in light green. Dark purple and light purple show, respectively, the inferred eddy path and the actual trajectory of float C. Dashed gray lines describe the path the eddy may have taken when no float was looping in it. Red dots show the location of the current-meter array that the eddy passed through *(see Figure 8)*. Looper A's track lasted 74 days, followed by a gap of 108 days when the float presumably was looping but for which data are missing. Looper B was tracked for 158 days. Looper C stayed with the eddy for 261 days. The short gap of 11 days between loopers B and C, their similar looping characteristics, and the close proximity of loops strongly suggest that loopers B and C were in the same eddy. If looper A was inside the same eddy, which is uncertain because of the 108-day gap, this eddy was tracked for 656 days.

In addition to the floats trapped in the three Meddies, four loopers were in less-salty, less-energetic, clockwise-rotating eddies in the same region. These eddies may be weaker brethren of Meddies, formed south of the Azores from meanders in the salty Mediterranean tongue. Although their salt gradient is estimated to be only about a quarter that of Meddies, they appear to be at least as numerous. They translate a little faster than Meddies and may also be important to salt and heat flux in the Mediterranean tongue.

Within about two years, the mechanisms of Meddy formation and their life histories should be much better understood. I will participate in a French research project that will track Meddies with RAFOS floats, surface drifters, current meters, shipboard measurements of temperature and salinity, and satellite altimetry and infrared images. We hope to learn how many Meddies coexist in the Canary Basin, what their trajectories are, and how long they live. A simultaneous research effort will track Mediterranean water from the Strait of Gibraltar to see where it does go and to better understand how and where Meddies form.

Retroflection Eddies

Our most recent float and surface-drifter data have characterized a fourth type of eddy. In the equatorial region of the South Atlantic, the North Brazil Current follows the Brazilian coast northwestward before turning sharply to the right between 5 and 10 degrees

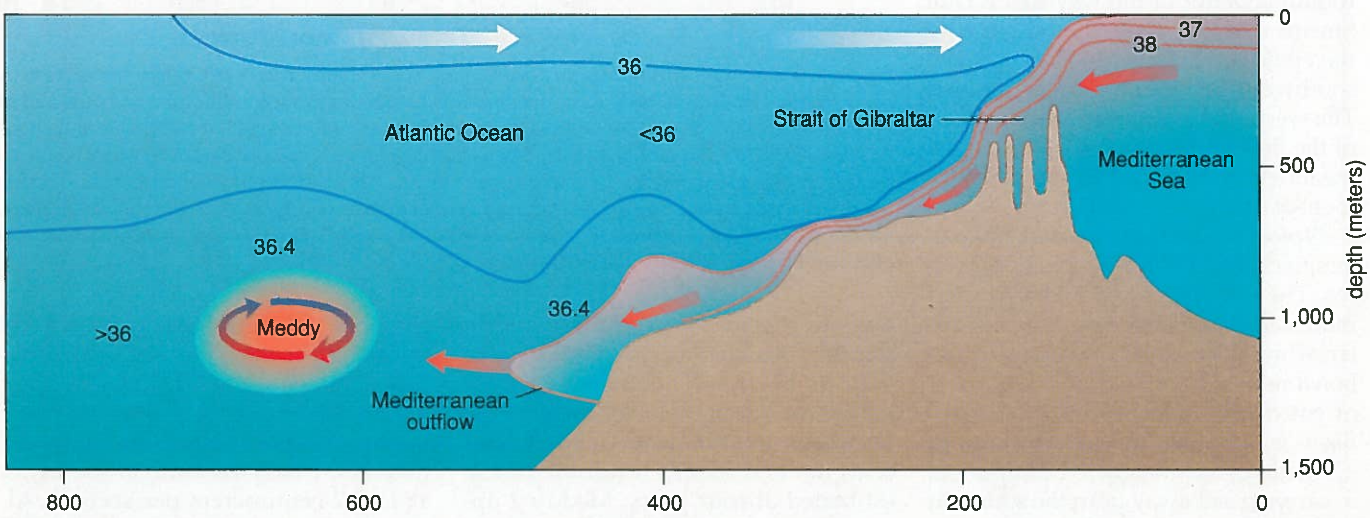

Figure 10. Eddies form when warm, salty Mediterranean water flows out of the Strait of Gibraltar beneath cooler incoming water and descends the continental slope. At around 1,000 meters, the salty tongue of Mediterranean water reaches neutral buoyancy with the surrounding ocean water and separates from the bottom. Pieces pinch off and drift southwestward in the Atlantic as clockwise-rotating lenses of salty, warm water that we call Meddies. Blue lines are contours of constant salinity (in practical salinity units, a measure based on conductivity), and white arrows indicate general water flow. (After Price et al. 1993.)

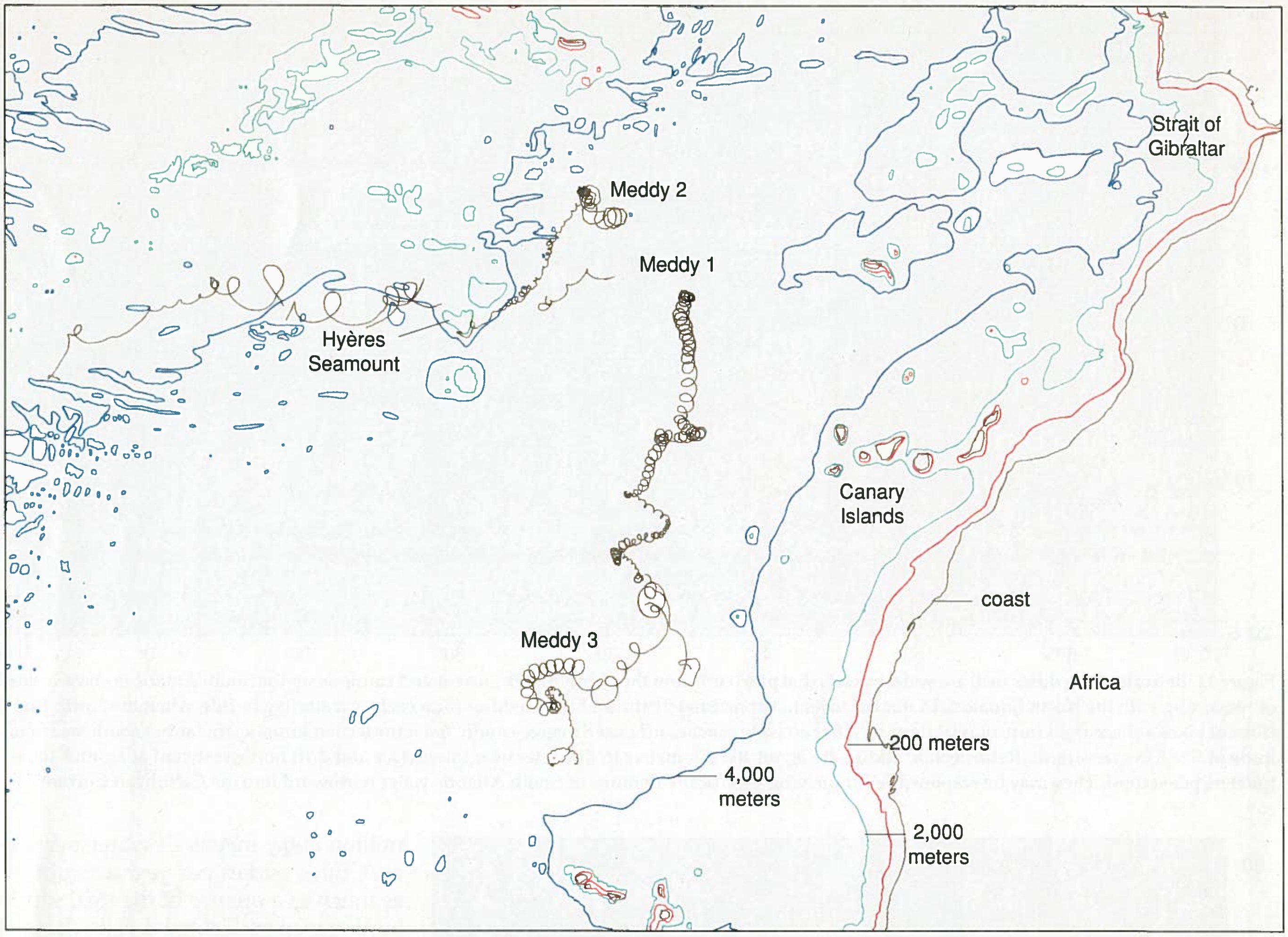

Figure 11. Three Meddies have been tracked for extended periods with SOFAR floats. Meddy 1 translated mostly southward and was repeatedly found and surveyed by listening to acoustic floats from shipboard. Four separate voyages tracked it to near-total decay off the coast of Africa *(bottom right)*. Meddy 2 translated more to the west and met a catastrophic end against Hyères Seamount. Meddy 3 was tracked for 552 days. A lifetime of four to seven years can be inferred by backtracking Meddies to their likely origin near Cape St. Vincent, Portugal, at least for the Meddies that do not hit seamounts. To the west of Hyères Seamount can be seen the tracks of anticyclones.

north latitude to cross the Atlantic as the North Equatorial Countercurrent.

In 1990, William E. Johns and his colleagues used satellite images to identify clockwise-rotating eddies that appeared to be breaking away from the North Brazil Current as it turned sharply to the east—much as a warm-core Gulf Stream ring forms from a meander. Johns then used current-meter data to show that these rings extended coherently down to 500 to 1,000 meters. Using satellite altimetry, Norbert Didden and Friedrich A. Schott observed that five such eddies translated up the coast from November 1986 to April 1989. Because they form as a result of a retroflection, or sharp change of direction, in a current, they are called North Brazil Current retroflection eddies.

Between 1989 and 1992 our Woods Hole group and another group working near the Amazon River launched and tracked surface drifters and subsurface floats, six of which became trapped in five different retroflection eddies. Looper trajectories suggest eddies with diameters of 250 kilometers or more, with swirl speeds as fast as 80 centimeters per second at the surface, dropping to 35 centimeters per second or less at 900 meters' depth. Diameter, along with velocity, decreases with depth, forming a sort of inverted cone of water moving through the background water. The available data suggest that roughly three such eddies form each year from July through March. They translate northwestward along the South American coast relatively rapidly, at a mean velocity of 10 centimeters per second, and seem to disintegrate when they encounter a 1,000-meter ridge between Barbados and Tobago.

An interesting question is whether retroflection eddies are carried northwestward by their own induced motion or ride on the Guyana Current. Surface drifters and historical ship drifts suggest that a continuous flow follows the coast to the Caribbean from January through June. From July through December, however, all surface drifters in the North Brazil Current have retroflected into the Equatorial Countercurrent. This observation contradicts historical ship drifts, which show a continuous northwestward current there. One possible explanation for this discrepancy involves retroflection eddies. The continuous current seen in ship-drift maps may be merely an artifact of averaging many years of velocity measurements on the inshore side of the mean path of eddies, where eddy swirl velocity is northwestward. The Guyana Current, if it exists at all during the months of July through December, is at least dominated by retroflection eddies.

Retroflection eddies appear to carry a significant volume of South Atlantic water northward in the North Atlantic, short circuiting the longer route around the gyres. Each eddy transports about a

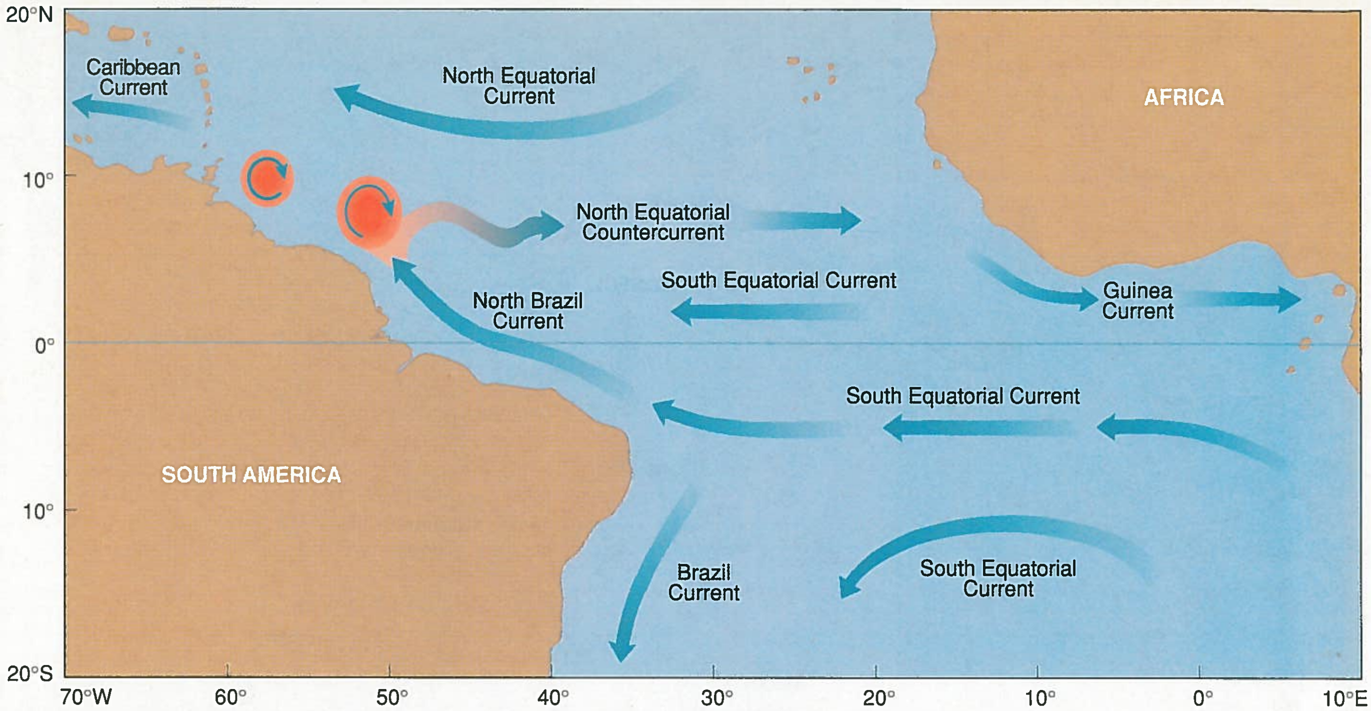

Figure 12. Retroflection eddies *(red)* are water parcels that pinch off from the North Brazil Current and continue up the South American coast instead of remaining with the North Equatorial Countercurrent. Approximately three of these eddies form each year starting in July, when the North Brazil Current takes a sharp right turn, or retroflection. After an eddy pinches off near 8 degrees north, the retroflection forms again farther south, near a latitude of 5 to 6 degrees north. Retroflection eddies are about 400 kilometers in diameter near the surface and drift northwestward at around 10 centimeters per second. They may be responsible for carrying significant amounts of South Atlantic water northward into the Caribbean Current.

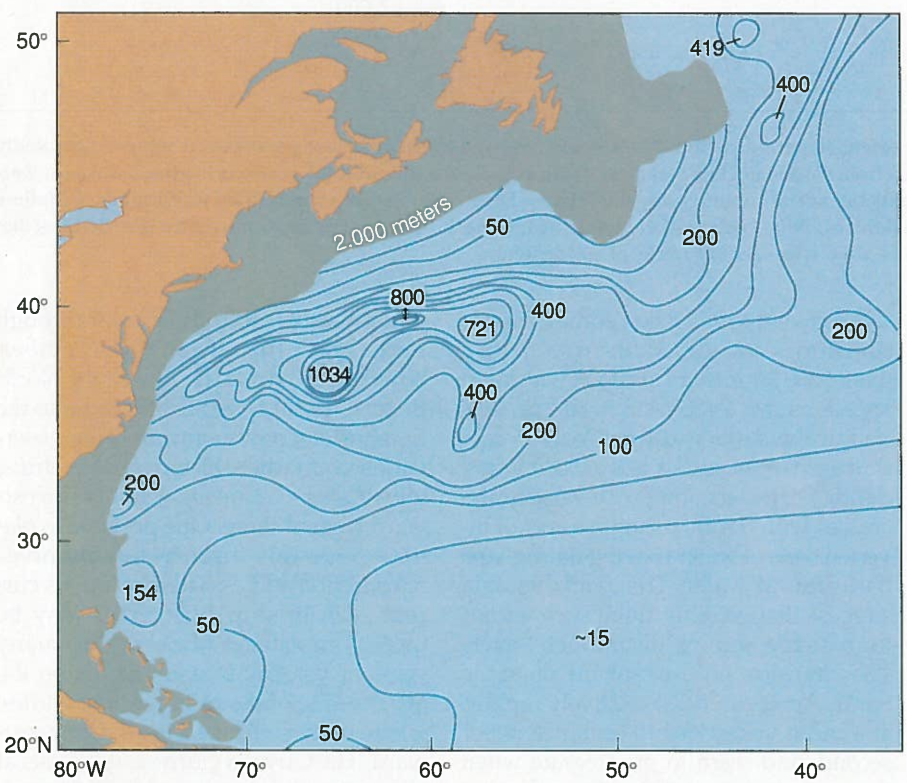

Figure 13. Kinetic energy of eddies was mapped by grouping individual 700-meter float measurements into bins. Contours *(blue)* of equal eddy kinetic energy (in centimeters squared per second squared) for the western North Atlantic are shown above. The highest values are in and near the Gulf Stream, owing to both discrete eddies and the Stream's energetic meanders. The lowest values are in the southern Sargasso Sea near 25 degrees north, 55 degrees west, the eddy desert. Eddy kinetic energy may be as much as eight times greater than background levels outside eddies in the western North Atlantic, and Meddies may be as much as 27 times as energetic as the relatively calm background water in the Canary Basin. (After Owens 1991.)

million cubic meters of water per second; three eddies per year account for as much as a quarter of the total south-north transport. Estimates place the total water exchange by upper layer currents into the North Atlantic at about 13 million cubic meters per second.

Eddy Kinetic Energy

North Atlantic float data are sufficient to allow mapping of the kinetic energy in moving masses of water and an estimate of the contributions eddies make to these values *(Figure 13)*. The highest eddy kinetic-energy values (the part of the total kinetic energy that can be attributed to eddies, or fluctuations from the average current) were along the Gulf Stream near 37 degrees north, 65 degrees west, where they were about 25 times higher than at the least-energetic location, near 25 degrees north, 55 degrees west in the Sargasso Sea. High eddy-kinetic-energy readings extended up into the Newfoundland Basin, where they were about 65 times higher than at the least-energetic location.

Because kinetic energy is proportional to the square of velocity, one might expect the swirling, traveling eddies to be important contributors to the kinetic-energy spectrum in the ocean. Indeed, looping trajectories were much more energetic than nonloopers. At 700 meters in the western Gulf Stream region, loopers were three times more energetic than nonloopers, which included the paths of floats in the Gulf Stream. In the Sargasso Sea west of the 50-degree latitude line and clear of the Stream, 700-meter loopers were five times more energetic than float trajectories in background water. In the Eastern Basin at 1,000 meters, loopers had eight times more eddy kinetic energy than background trajectories, and Meddies were most energetic, with one example reaching 27 times the background energy.

SOFAR floats have given us important insights into paths, velocities and lifetimes of eddies. From this we have inferred the contributions eddies make to mass, salt and heat fluxes in the North Atlantic. At least as important, however, are the surprising details of ocean dynamics they reveal. About half of the area in the Newfoundland Basin consists of eddies, perhaps caused by the way the Gulf Stream arcs around the Newfoundland Ridge.

More surprising, in the northwestern Sargasso Sea a large number of energetic anticyclones rival Gulf Stream rings in kinetic energy. In the Canary Basin, coherent lenses of salty Mediterranean water centered at a depth of 1,000 meters drift for years on end. Off the coast of Brazil, what has long been considered a coastal current may in fact be a series retroflection eddies—inverted, swirling cones that carry large amounts of South Atlantic water northward in the North Atlantic. SOFAR floats have given us a way to visualize these three-dimensional masses, revealing much that was unknown and, in some cases, utterly unexpected.

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"Certainly you can get a second opinion, or even a third."

Parental Favoritism toward Daughters

Why do the parents of some cultures invest more in the offspring of one sex than the other? A case study of the Kenyan Mukogodo offers an evolutionary explanation

Lee Cronk

The birth of a healthy child is greeted with great fanfare in almost every part of the world. But not every birth inspires a celebration. In many cultures, the birth of a girl is merely shrugged off by a couple hoping to produce a son. In others, the favoritism toward boys is so strong that parents may resort to infanticide, refusing to invest energy and affection in a daughter. The question this behavior raises has always been an intriguing one for anthropologists. Why would parents show such strong bias toward children of one sex?

Although there have been many studies of cultures that favor boy children, the question of sex-biased parental favoritism arose in a different way, and unexpectedly, in my own research a few years ago. My wife and I had been studying cultural change among the Mukogodo people of central Kenya. Because the Mukogodo had recently shifted from hunting and gathering to sheep and goat herding, the people had experienced a drastic change in their life-style. It seemed to be a perfect opportunity to study the adaptive responses of a small society during a rapid economic transition.

While we were conducting a census of the population, however, we discovered a curious statistic: A survey of Mukogodo births in the previous year showed that 32 girls had been born, but only 13 boys! Intriguingly, the biased sex ratio persisted for children under four years of age. As of 1986 there were 98 girls and only 66 boys less than five years old. Whereas most cultures around the world have roughly equal or slightly male-biased childhood sex ratios, the Mukogodo had veered in the opposite direction in a very big way. Could parental favoritism account for the Mukogodo's lopsided sex ratios? If so, why did they favor girls?

The anomalous sex ratio of the Mukogodo instigated a course of research that I have pursued to the present day. In the course of my investigation, I discovered that female-biased parental favoritism is very rare. A few instances are known, however, in such disparate countries as Pakistan, New Guinea, and the United States. In recent years these and other cases of sex-biased parental investment have become the focus of a great deal of research, especially from an evolutionary point of view. There is in fact a body of evolutionary theory that offers a biological explanation for the lopsided sex ratio among the Mukogodo, even though the same explanation may not hold true for other examples of unequal treatment of daughters and sons in human society. The theory asks the question: Could the tendency to favor daughters or sons in particular circumstances be the product of our species' history of natural selection?

Parental Investment

The mix of males and females among newborns in a sexually reproducing population tends to be roughly 50-50. There are species, however, that exhibit different sex ratios, and evolutionary biologists have attempted to explain these differences. One way that parents might modify the sex ratios of their offspring is to invest different amounts of energy in activities that promote an offspring's survival.

At first glance, favoring or neglecting some offspring would seem to be a nonadaptive response. Shouldn't a parent want to produce as many offspring as possible, of either sex? As with so many important issues in evolutionary theory, Charles Darwin was the first to attempt an explanation of sex-biased parental investment and the closely related problem of offspring sex ratios. In this case, however, Darwin soon decided that "the whole problem is so intricate that it is safer to leave its solution for the future."

The British biostatistician Sir Ronald A. Fisher offered the first convincing explanation of sex-biased parental investment. Fisher began with the observation that because every individual in a sexually reproducing diploid (duplicate chromosome) species gets half of its genetic material from its father and half from its mother, selection should favor parents who invest equally in sons and daughters. In this view a single unit of investment in an individual of one sex will have the same effect on a parent's fitness (measured in terms of grandchildren) as a unit invested in the other sex. If daughters and sons cost the same to rear to adulthood (and provide an equal payoff in terms of grandchildren), then this would lead to equal numbers of sons and daughters.

On the other hand, if daughters and sons do not cost the same, selection should favor greater production of the cheaper sex so that the overall parental investment in the sexes is equal. For example, if sons cost half as much to rear as daughters, then the equilibrium sex ratio for the population would be two males

Lee Cronk is assistant professor of anthropology at Texas A&M University. He received his Ph.D. in anthropology in 1989 from Northwestern University. He has received a Fulbright grant to spend this summer continuing his research among the Mukogodo, where he will be looking in detail at the effects of variations in parental behavior on children's health, nutritional status and development. Address: Department of Anthropology, Texas A&M University, College Station, TX 77843-4352.