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SOFAR Floats Give a New View of Ocean Eddies

Philip L. Richardson

There is something wonderful about a subsurface float trajectory. It provides a visualization of water parcel movement in the interior of the ocean that is available from no other technology. Sound Fixing And Ranging (SOFAR) floats are freely drifting, acoustically tracked subsurface floats. During the last 18 years, American scientists have obtained 230 SOFAR float trajectories in the North Atlantic. Most trajectories are so convoluted, however, that it is difficult to see patterns, and we must calculate statistics of the velocity field and plot maps of mean velocity and eddy kinetic energy to obtain an overview. These maps tend to obscure individual eddies and other details of the flow field, and we must return to the plots of individual floats to see them.

Recently I have explored the float data set to learn about discrete eddies in the ocean, in particular their distribution, number, paths, interactions, sizes, and speeds. Because the float data are so numerous, we can piece together eddy patterns at different depths over a large part of the North Atlantic. Some striking patterns emerge.

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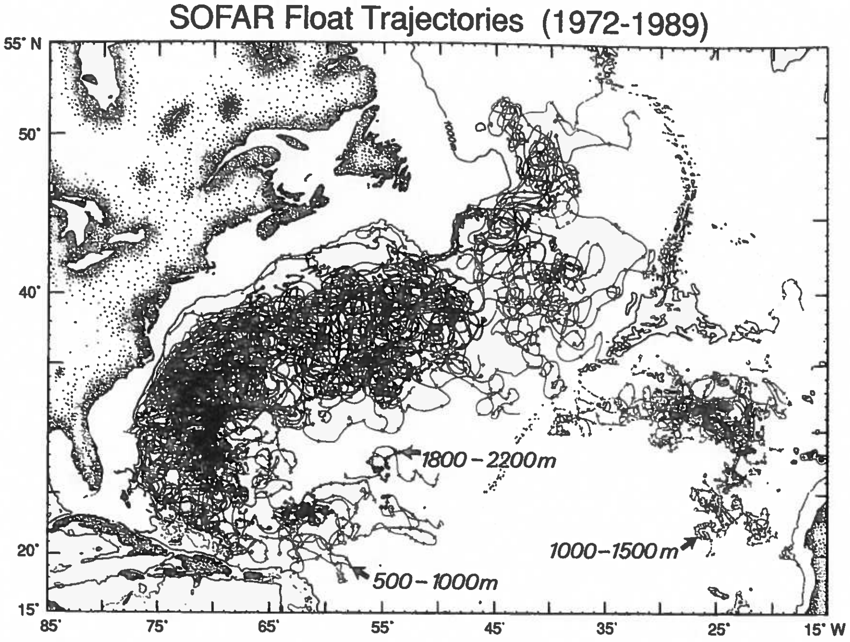
Float Trajectories

Beginning in the early 1970s, SOFAR floats were used in a series of experiments to explore and study specific ocean features, regions, and depths. Over the years the lifetime of the average float has increased, from a few days to a current world record of nine years. At present there are over 240 SOFAR float-years of data in the North Atlantic at depths from 700 to 2,000 meters. Additional data sets being recorded continuously at an accelerated rate are a truly great resource for ocean circulation studies.

A summary figure on the next page showing the accumulated float trajectories reveals where the data were measured and conveys some idea of regional differences and the complexities of water movement. Details of the flow field are difficult to see in the figure because of the tangled appearance, which is a measure of the time variations of the ocean, or, more simply, ocean eddies. Parcels of water move in very complex patterns that must be seen to be believed. Colors represent

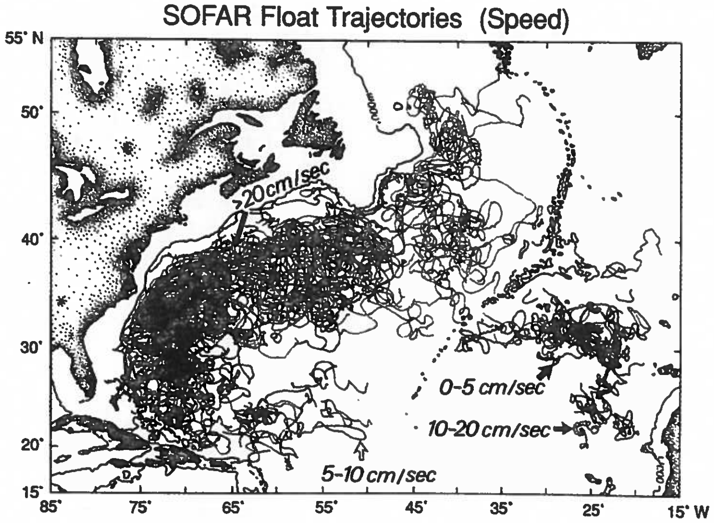


North Atlantic SOFAR float trajectories are easily recognized using color coding to signify float depths. Red denotes floats near 700 meters; green, near 1,300 meters; and blue, near 2,000 meters. Arrowheads indicate 30-day intervals along the trajectories. Most trajectories exist in and south of the Gulf Stream.

velocities in the figure below: Red indicates the fast-moving Gulf Stream, Gulf Stream rings, and the Stream's fast extension into the Newfoundland Basin. Blue and black identify the slow-moving waters of the Sargasso Sea. Float velocities recorded in eddies tend to be faster than those in nearby background floats.

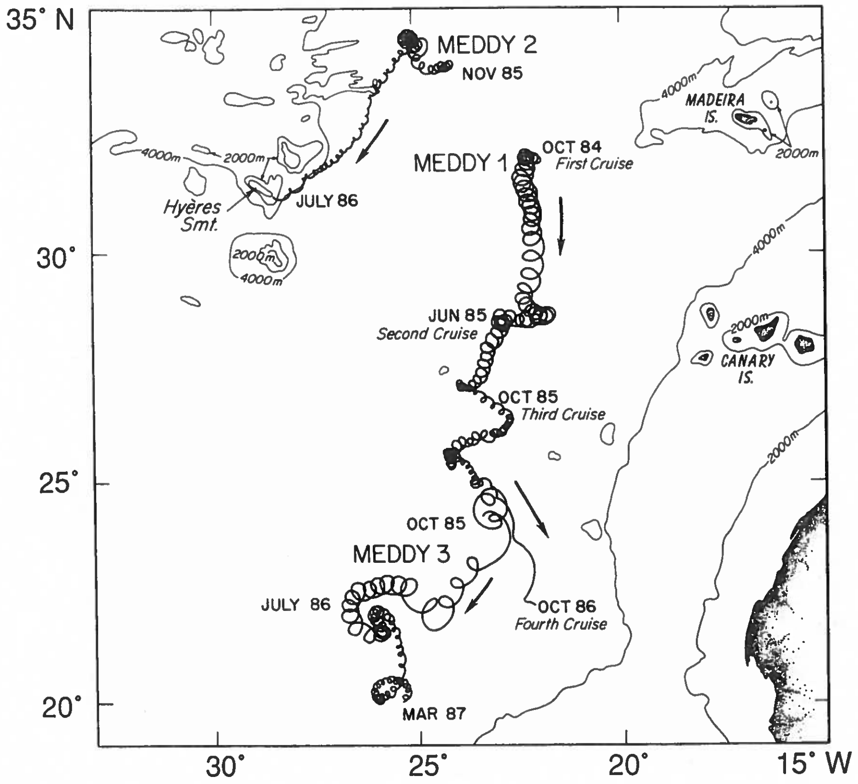
Discrete Eddies

Eddies can be thought of as ocean weather; they are analogous to the atmospheric high- and low-pressure cells seen in daily weather maps. The diameter of discrete ocean eddies is typically a few hundred kilometers. The current swirling around eddy centers reaches several knots, and



In this summary of SOFAR float trajectories, colors signify float velocities. Red shows floats drifting faster than 25 centimeters per second; green, 10 to 25 centimeters per second; blue, 5 to 10 centimeters per second; and black, less than 5 centimeters per second. One knot equals approximately 50 centimeters per second. The color patterns reveal the fast-moving (red) Gulf Stream, its rings on either side, and its extension into the Newfoundland Basin. Slowest moving waters (blue-black) are in the Sargasso Sea near 25°N, 50°W.

is usually much larger than average currents. Eddies are important to study because they give clues to ocean dynamics and help identify sources and sinks of energy. They are thought to be dynamically significant in driving the mean flow in regions of high eddy energy. Although the presence of discrete subsurface ocean eddies has been known for many years, detailed information about eddy life cycles and movement through the ocean has remained elusive because of the difficulty in measuring continuously flowing eddies.

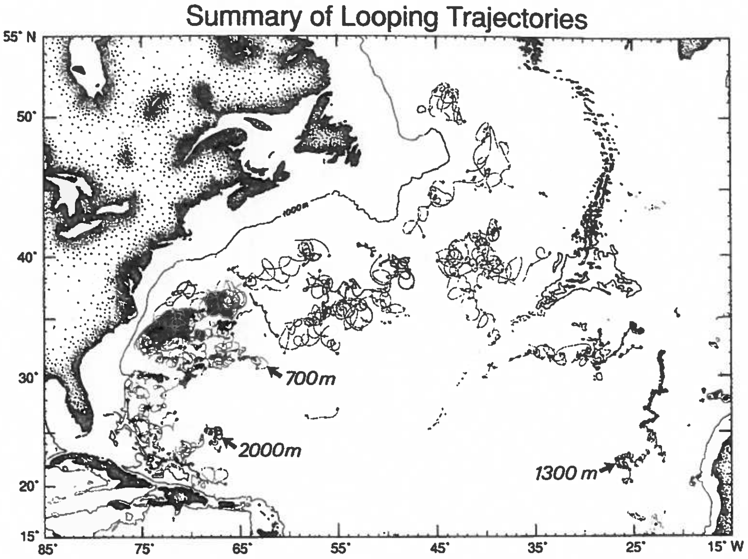


Float Trajectories in Meddies

The paths of three salty Mediterranean water eddies (Meddies) in the Canary Basin are illustrated by the SOFAR float trajectories. Meddy 1 was tracked for over two years during 1984 to 1986 with five floats as it drifted 1,090 kilometers southward with a mean velocity of 1.8 centimeters per second. Four shipboard surveys revealed the nearly total decay of Meddy 1 by gradual mixing processes. Meddy 2 drifted 530 kilometers southwestward with a mean velocity of 2.3 centimeters per second until it collided with Hyeres Seamount (when the two floats in it abruptly stopped looping). Meddy 3 drifted 500 kilometers southwestward for a year and a half at 1.1 centimeters per second The float loops are clockwise, and reveal solid-body rotation rates of four to six days for these Meddies.

Many floats were trapped in the strong flow around discrete eddies and looped around the eddy centers as the eddies moved through the ocean. Some of these floats looped long enough to reveal interesting eddy trajectories and eddy properties, such as rotation direction and rate. This unique float information provides a new picture of the behavior of subsurface eddies in the ocean.

Three Mediterranean water eddies (Meddies) were tracked in the Eastern Atlantic for long time periods. One float tracked an eddy for 114 loops over 821 days. This long-lasting eddy was measured by ship (with conductivity/temperature/depth or CTD profiles) several times during its life as it drifted southward and slowly decayed. This Meddy can be seen in the figure above located near 22°W between 22° and 32°N. Another of these Meddies was observed to crash into some tall undersea mountains where it disintegrated (near 31°N, 28°W). The third Meddy drifted southwestward for a year and a half.


Summary of Looping Trajectories

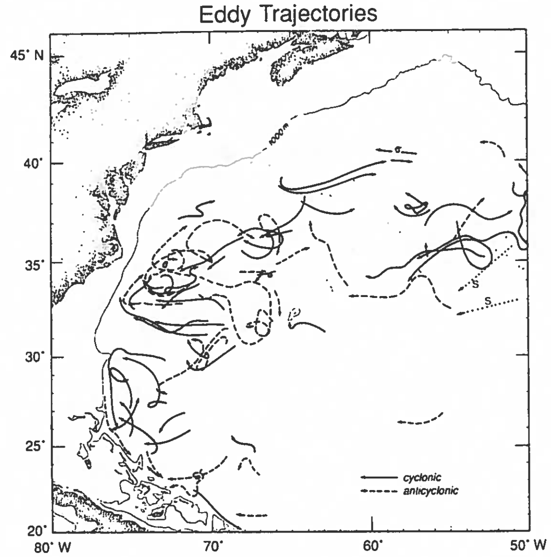
Float trajectories that consist of two or more consecutive loops in the same direction imply the presence of discrete eddies. Overall, 15 percent of float trajectories are loopers. Higher percentages exist at 700 meters in the Newfoundland Basin (47 percent), and in and south of the Gulf Stream (20 percent). A low percentage (about 4 percent) occurs at 2,000 meters and in the southern Sargasso Sea.

To learn more about ocean eddies, I systematically studied all looping trajectories (loopers) looking for patterns. The first task was to look carefully at each float trajectory and identify looping portions within discrete eddies. I defined loopers as floats making at least two consecutive loops and identified 119 separate ones. Occasionally an eddy trapped more than one float, which reduced the number of different eddies involved to 104.

The highest density of loopers occurred at 700 meters in the Newfoundland Basin and south of the Gulf Stream. In the Newfoundland Basin approximately half (47 percent) of all possible trajectories are loopers, implying that half of that area consists of closely packed eddies. This was reinforced by the individual float trajectories observed there; floats seemed to jump from one eddy into another with little time between. One float looped there for 560 days in seven different eddies, the most sampled by any float. In the Gulf Stream region approximately 20 percent of the trajectories were loopers. The percentage of loopers decreased dramatically with depth to around 4 percent at 2,000 meters in the vicinity of the Stream.

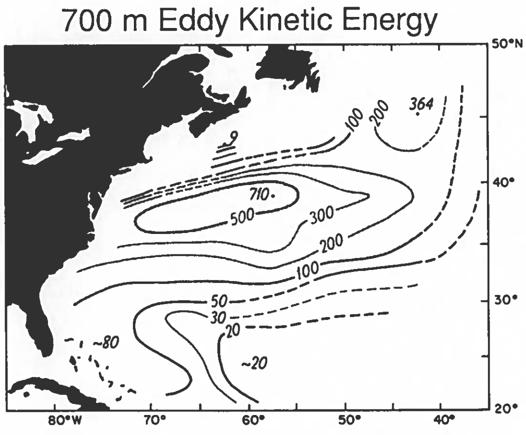
It is interesting that overall nearly 50 percent of the loopers rotated clockwise and 50 percent rotated counterclockwise. However, the distribution of rotation direction varied enormously in the North Atlantic. Almost all loopers in the East Atlantic at 1,100 meters rotated clockwise, presumably because they were all formed in a similar way from the salty tongue of Mediterranean water emanating from the Straits of Gibraltar. The best examples are the Meddies, but three other slower-rotating eddies were also observed. Offshore of the Gulf Stream and in the Newfoundland Basin only one out of three or four loopers rotated clockwise. This was probably due to the many strong counterclockwise-rotating eddies or rings that pinch off there from Gulf Stream meanders.

Trajectories of the eddies were visually estimated from the looping float trajectories and are summarized in the top figure on page 27. Eddies generally (but not always) drift southwestward at a rate of 1 to 3 kilometers per day. This seems to hold true for eddies in the East Atlantic, in the interior Newfoundland Basin, and south of the Gulf Stream. A noticeable exception is in or very close to the Stream, and its northward extension in the Newfoundland Basin, where eddies appear to be advected downstream in the Stream. A second exception is close to the western boundary (south of 30°N), where several eddies drifted southward, presumably advected by a southward boundary current there.



Trajectories of discrete eddies may be inferred visually from looping floats in the western North Atlantic (shown in the previous figure). Two record holders for length of time tracked are a warm core eddy (A) tracked for 431 days (over 40 loops) by two different floats, and a cold core Gulf Stream ring (B) tracked for 361 days (26 loops). Solid lines indicate counterclockwise (cyclonic) eddies, dashed lines are clockwise eddies.

These discrete eddies identified in float trajectories are being studied in greater detail to learn more about their characteristics and their role in the general ocean circulation. A clearer view of the complex patterns of ocean motion is revealed by the float data. Statistical summaries of mean velocity and eddy kinetic energy are used to help describe the flow field and create and improve models of the general circulation. The float data, combined with current meter records and hydrographic profiles, help us determine the mean circulation in the Gulf Stream system.



This contoured map of eddy kinetic energy at 700 meters is based on grouping individual velocity measurements in 2° latitude by 5° longitude boxes. Dashed contours indicate gaps in the 2-by-5 grid. High values greater than 500 centimeters squared per second squared (centimeters^2/second^2) are centered in the Gulf Stream, with an extension into the Newfoundland Basin. Relatively high values of 80 centimeters^2/second^2 are located along the western boundary south of 30°N. Values around 20 centimeters^2/second^2 are centered in the region surrounding 25°N, 50°W, the eddy desert.

Present and Future Float Experiments

Presently the "float group"* at the Woods Hole Oceanographic Institution (WHOI) is doing two experiments. One is a feasibility study of float tracking in the Arctic under ice. Ice reduces tracking range, and there are very few current measurements for this area. We intend to measure the general circulation. The other is a study of cross-equatorial water exchange between the North and South Atlantic. We obtain float trajectories to investigate the large-scale meridional transport of water, northward across the equator in the upper 1,000 meters, and southward in the North Atlantic deep water. We seek to measure, for the first time, paths of water in the vicinity of the equator, and to observe the extent to which water can freely cross the equator in swift, deep, western-boundary currents. We have recently obtained the first data and are processing them to plot the first subsurface trajectories in the Tropical Atlantic. Preliminary trajectories of 1,800-meter floats reveal a narrow (100-kilometer-wide) current flowing swiftly (25 centimeters per second) southward, adjacent to the continental slope off north Brazil.

Future studies of the float group will include using Bobber floats during 1991 to 1993 to measure characteristics of newly formed and subducted water in the Canary Basin, and also to measure horizontal dispersion in the thermocline as part of the World Ocean Circulation Experiment (WOCE) Tracer Release Experiment. Also during WOCE, a detailed study of the deep circulation in the Brazil Basin will be made using RAFOS floats (SOFAR spelled backwards). Work in the Mediterranean Outflow to identify how it disperses in the Atlantic, and further studies in the Tropical Atlantic are planned.

Float groups at other institutions are also active.** American scientists are obtaining and studying float trajectories in the Gulf Stream, the South Pacific, east of the Bahama Islands, and in the Circumpolar Current. French scientists are obtaining trajectories of the Arctic, and also tracking floats in the Gulf Stream extension over the Mid-Atlantic Ridge. British scientists have measured deep trajectories in the Canary and Iberian Basins. German scientists are beginning float experiments in the Mediterranean water off Iberia, and Japanese scientists have begun a new program to obtain trajectories in the Philippine Sea. As these groups continue to collect and pool exploratory float data, we will be able to create worldwide maps of trajectories, mean velocities, and eddy statistics. The next 10 years will be a very exciting time for ocean scientists. We expect some big surprises.

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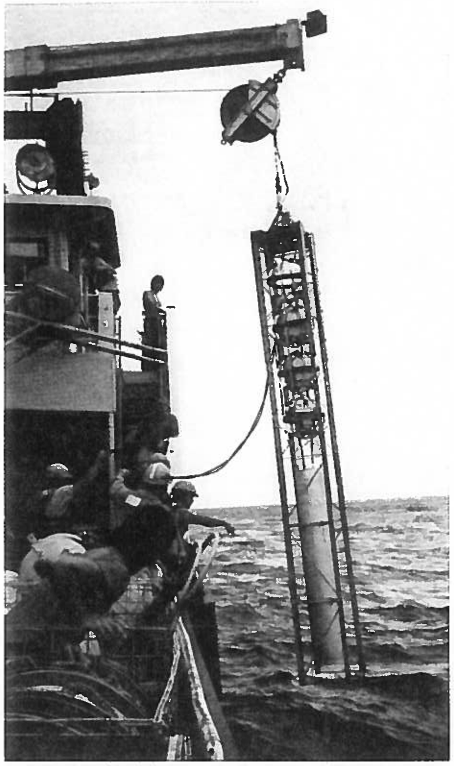
Early SOFAR Float Development

Starting 25 years ago SOFAR floats were developed by Doug Webb, at WHOI, and Tom Rossby, originally at Massachusetts Institute of Technology, and later at Yale University. Two major difficulties needed to be overcome: putting sufficient sound into the ocean for long-range signaling, and extracting the sound from the ocean, for tracking. A neutrally buoyant float capable of transmitting large amounts of acoustic energy and operating unattended for long periods of time at great pressures was required. Gaining access to military listening stations, extracting the received signals, and triangulating on the float were other problems that had to be solved. Webb led the float development, and Rossby planned the tracking. The result was the SOFAR float.

Modern SOFAR floats are neutrally buoyant aluminum or glass pressure housings that are ballasted to drift deep within the ocean. Some of the floats that drift the deepest (greater than 3,000 meters) are constructed from glass spheres. The floats emit a low-frequency acoustic signal (250 hertz) that sounds like a boat whistle. The sound travels horizontally through the ocean in an acoustic waveguide where the speed of sound is minimal (typically near 1,000 meters in the Sargasso Sea), and is received by undersea listening stations at ranges of a few thousand kilometers. Differences in the signal arrival times at the stations are used to calculate distances and to triangulate the float positions.

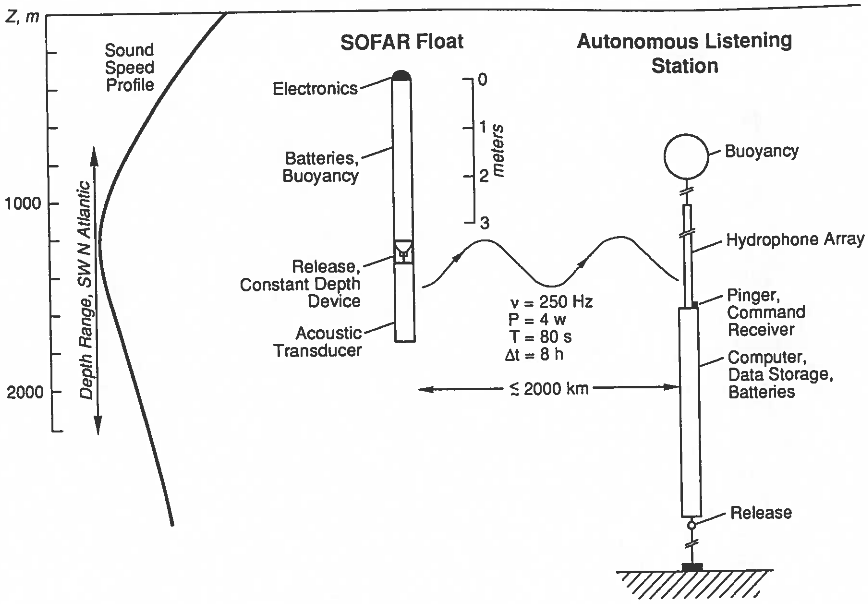


A 3,500 meter SOFAR float was launched from R/V Oceanus in January 1989 on the Atlantic equator. Glass spheres (pressure housings) contain electronics and batteries, and can withstand the enormous pressure of a 3,500 meter depth. The aluminum tube is the acoustic resonator, which produces a 250 Hertz signal once per day for tracking. The float is released from its rigid cage after it is lowered below the sea surface. This is one of the 48 floats, some aluminum and some glass, launched in the Tropical Atlantic to measure cross-equatorial currents. An array of six moored listening stations is recording data from these floats over a four-year period.

Recent Float Developments

Over the years, new developments have radically changed some aspects of subsurface acoustic floats, adding new capabilities. Early floats were tracked with landbased Military Impact Landing Stations, which precluded studying trajectories in the Gulf Stream and other areas far from shore. In 1977, the Autonomous Listening Station was developed at WHOI by Al Bradley and Jim Valdes. These stations, which can be moored anywhere in the ocean, made float tracking possible worldwide, at least wherever a deep sound channel occurs. We are still using some of the original autonomous listening stations, which have worked remarkably well (with over a 90 percent success rate). New autonomous listening station versions that are smaller, lighter, and easier to use have been incorporated in freely drifting tracking stations and mobile ice stations in the Arctic. These listening stations telemeter data back to us via orbiting satellites allowing us to receive the data in real time. The moored versions remain submerged, recording data for as long as two years. This moored system is cost effective, but makes us wait for what seems like an extremely long time to see float trajectories and to diagnose problems.

SOFAR floats have been greatly improved with microprocessors, better clocks, louder signals, and automatic ballasting control. Float lifetimes of four to five years are almost routine now. A new version, the SOFAR Bobber float, developed by Doug Webb (now at Webb Research Corporation) and Jim Price (at WHOI), repeatedly oscillates or bobs between selected isotherms to follow a specific layer of water. These will soon be used in the Subduction and WOCE Tracer Release Experiments. In 1984 Tom Rossby developed the RAFOS float, a smaller, less expensive float that "listens" to moored sound sources and at the end of its drift, surfaces and reports data back home or to the lab via satellite. A newer version of the RAFOS float developed by Rossby is being tested at WHOI by Breck Owens and Jim Valdes for use in WOCE. Modifications of this float are in progress at the University of Rhode Island and WHOI to make it rise periodically to the surface, report data back, and then return to its prescribed depth and continue its mission. Louder and more



A neutrally buoyant, freely drifting SOFAR float and a moored autonomous listening station is illustrated schematically. The floats transmit acoustic signals that are received and recorded by the listening stations. Tracking consists of triangulating on the position of a float, using the time delays of the signals received at several listening stations. RAFOS floats reverse the process by receiving the signals transmitted by moored sound sources. At the end of their missions these floats surface and radio their data to orbiting satellites. (Courtesy of Jim Price.)

powerful sound sources to further increase tracking range are also being developed by Tom Rossby.

Russ Davis of the Scripps Institution of Oceanography (SIO) and Doug Webb have recently developed a multiple "pop-up" float called the Autonomous LAgrangian Circulation Explorer (ALACE) that is not acoustically tracked. This float drifts at a preselected depth and periodically pops up to the surface where its position is calculated by orbiting satellites. Approximately 50 surfacings over a lifetime of five years are projected. The first few trajectories from ALACE floats are now being received from the Southern Ocean. ALACE floats present a good option for use where maintaining an acoustic tracking array is logistically difficult and, therefore, too expensive.

A remarkably innovative development by Doug Webb will make possible a smart and much more active float than we have seen before. Named after Joshua Slocum, the first person to sail singlehanded around the world, the new device, called Slocum, is actually a self-propelled undersea vehicle (see *Oceanus*, Winter 1989). Six times a day, it harnesses the thermal stratification of the ocean to dive to a preselected depth, return to the surface, report its findings, and receive new instructions by satellite. A Slocum glides horizontally both on the way down and up, and it can control its own direction. If the Slocum is successful, a fleet of these devices could one day monitor the ocean as weather balloons now monitor the atmosphere. On April 24, 1995, the 100th anniversary of the start of Joshua Slocum's voyage, we hope to send the first Slocum vehicle off on a world-circling trip of its own. It will not follow the same route, however, because the Straits of Magellan and other shallow passages would be impossible for the Slocum vehicle to negotiate.

Technical Difficulties

The successes we have had with floats have been accompanied by many serious problems that continually jeopardized our studies. Since most SOFAR floats are left to drift passively and are not recovered, it is difficult to diagnose their problems. Frequently we recovered data and saw problems in one batch of floats many years after they were launched and, sad to say, after even more of the same type of float had been launched. Problems have included failed transducers, vibration-induced electronic failures as power was increased, changed (degraded) electronic components, leaky batteries that caused electrochemical fires and explosions, and more recently, now that microprocessors are in use, slight but disastrous glitches in software that resulted in curtailed or failed missions. Thoroughly checking each float and sound source seems to be the obvious solution, but testing for the typical multiyear float lifetime is very expensive and time consuming. When funds to build instruments come late, thereby setting back delivery times and reducing time to prepare floats to meet inflexible ship schedules (especially for studies where different research groups work together on a joint experiment), checking each float becomes impossible. The more advanced and complicated the floats and the larger the experiments, the more difficult it is to adequately test the floats—and the more we worry. Another recent problem is obtaining necessary clearances to launch floats and moorings within the national waters of other countries. Long lead times required for clearance applications and the imposition of inflexible conditions make working within 200 miles of land a real headache. However, as we look back over the last 20 years and review the wonderful collection of ocean current trajectories, the successes more than outweigh the failures and difficulties.

> ***One of the biggest problems we now have is attracting bright graduate students to the field.***

It may seem surprising, but one of the biggest problems we now have is attracting bright graduate students to the field, to analyze the new float data in innovative ways and extract a better understanding of dynamic ocean processes. Fruitful analysis of float data is not easy, and new techniques need to be developed. I think the rich data sets we are obtaining will attract creative new scientists and we will start to see the data used in exciting new ways. I expect we will find that our present analyses have only scratched the surface of our SOFAR float data set.

Philip L. Richardson is a Senior Scientist in the Department of Physical Oceanography, Woods Hole Oceanographic Institution. He is director of the center of derelict drifters and phantom floats (Phil calls it CODDAPHT).

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*The WHOI float group consists of five scientists: Amy Bower, Breck Owens, Jim Price, Phil Richardson, and Bill Schmitz, who work together on a variety of scientific problems and share resources.

**Tom Rossby (University of Rhode Island) recently obtained float trajectories in the upper layer of the Gulf Stream, and with Steve Riser (University of Washington) has obtained deep float trajectories in the South Pacific. Keavin Leaman (University of Miami) obtained trajectories east of the Bahama Islands, and Russ Davis (Scripps Institution of Oceanography) has launched ALACE floats in the Circumpolar Current.