POLYMODE: Exploring the Undersea Weather

Ocean circulation may be dominated by turbulence in the form of undersea eddies

Within the ocean it does not rain. But a citizen of the lost city of Atlantis would still have to contend with the vagaries of undersea weather. Circulating eddies—undersea storms—travel generally westward across the North Atlantic and bring water winds up to tens of centimeters per second to buffet an area a couple of hundred kilometers in diameter for several months at a time. Within an eddy, the water might be similar to water from another part of the ocean; pollutants, nutrients, organisms, salt, and heat can be carried long distances by eddies.

New data from a nearly completed project are helping oceanographers to unravel the mysteries of undersea weather, to categorize eddies, to understand how they are formed, and to determine how they interact with the currents—the prominent features of ocean circulation. The elusive goal is the prediction of undersea weather, with its benefits for the military, fisheries, meteorology, and shipping. Understanding the details of ocean circulation is vital to knowing the fate of any wastes—toxic or nuclear—that may be disposed of at sea.

Early in this decade two experiments revealed that ocean circulation is intricate and involves turbulence in the form of undersea eddies. The two experiments were the 1970 Soviet Polygon (Russian for "proving ground") and the American-British MODE (Mid-Ocean Dynamics Experiment) conducted in 1973. In fact, MODE probed one undersea storm (*Science*, 19 July 1974, p. 244) in great detail. Finding the MODE eddy whetted the appetites of oceanographers for more information about the detailed patterns and fluctuations of ocean circulation.

But MODE and Polygon were exploratory experiments, and although they were huge by oceanographic standards—MODE involved six ships, two aircraft, and researchers from 15 institutions—they were not big enough to answer in detail the questions they raised about the types of eddies, their role in ocean circulation, and their geographic distribution. A bigger experiment was needed and invited U.S.-Soviet cooperation, then very much in vogue, to pull it off. POLYMODE was conceived, funded, and born.

"The difference between MODE and POLYMODE is the difference between an afternoon tour of a foreign capital and living there for a month," says Henry Stommel of the Woods Hole Oceanographic Institution, cochairman of the U.S. POLYMODE Organizing Committee.* POLYMODE includes a broad theoretical program and several major experiments to probe the circulation in different regions of the North Atlantic for 8 to 18 months over a period of 5 years.† The last instruments are due to come out of the water this fall.

Field studies for POLYMODE were designed by experimentalists and theorists working together, with the theoreticians having a major say in determining where experiments were done and what sorts of data were gathered. One POLYMODE effort, the Local Dynamics Experiment, centered 400 kilometers west of Bermuda, is very much a theoretician's experiment and was designed to a large extent by James McWilliams of the National Center for Atmospheric Research. Data collection was tailored to the equations that describe fluid motions in the ocean, with several parameters—temperature, pressure, salinity, and current velocity—being measured at closely spaced sites and at frequent intervals to ensure that the gradients can be calculated accurately.

In pursuit of one POLYMODE goal, the researchers have found and described several more "species in the eddy zoo." Eddies are typed according to their properties, such as size, strength, temperature, and water chemistry. The MODE eddy has become a standard for comparison. It was about 200 kilometers in diameter, lasted probably several months, and the water within it was slightly warmer than the water outside. The velocity of water swirling clockwise about the center of the eddy ranged from 3 to 5 centimeters per second in deep water to 15 to 20 centimeters per second near the surface.

An intense, cyclonic (counterclockwise rotating) eddy, only 50 kilometers in diameter, was found last summer during the Local Dynamics Experiment. According to Bruce Taft of the University of Washington, the water within this eddy was strikingly different from water outside: it was not very salty and was similar to water normally found north of the Gulf Stream, off the U.S. coast. In addition, the eddy was noticeable only in deep water. It had no signature above the thermocline—the boundary between warm, salty surface water and cold, less saline deep water, where the temperature decreases rapidly with depth.

Taft conjectures that this eddy was a drastically reworked Gulf Stream ring, a type of eddy that forms when a meander in the Gulf Stream is cut off (*Science*, 28 October 1977, p. 387). Rings south of the Gulf Stream contain water from north of the current and vice versa. But rings are typically much larger than the small eddy, and they are usually stronger above the thermocline than below it.

Another kind of small eddy, containing anomalously cold water, was observed during the local experiment. However, this eddy was obvious only in and above the thermocline; it could not be detected in deep water. Both the small eddies moved toward the southwest, along tracks that nearly paralleled each other. But the shallow eddy—found 1 month after the deep one and farther north—traveled 1 1/2 times faster than the deep one, and, according to McWilliams, both were much speedier than any eddy previously observed in the region.

Eddies larger than the MODE eddy have been found in other areas of the oceans. Some, called Gulf Stream extension rings or "big babies," appear to be roughly 500 kilometers in diameter. These eddies haunt the central North Atlantic, outside the POLYMODE survey area, and tend to contain water very

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*Major U.S. POLYMODE investigators are affiliated with several institutions, including Charles Stark Draper Laboratories, Harvard University, Massachusetts Institute of Technology, National Center for Atmospheric Research, Nova University, National Oceanographic and Atmospheric Administration, Oregon State University, Scripps Institution of Oceanography, U.S. Naval Academy, University of California at Los Angeles, University of Miami, University of Rhode Island, University of Washington, and Woods Hole Oceanographic Institution.

†The POLYMODE field areas are northeast, southeast, and west of Bermuda; 700 kilometers east of Martinique; and on both sides of the Mid-Atlantic Ridge near 28°N.

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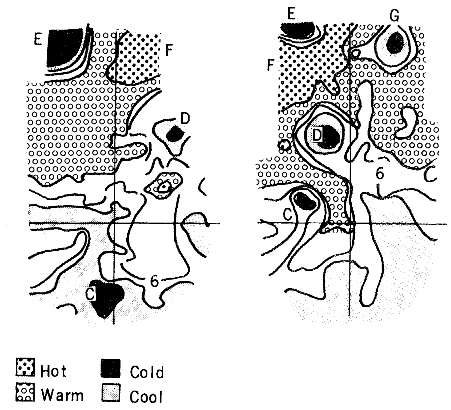
Complicated interactions among several eddies show up in these undersea weather maps from the Soviet survey area between 26°N and 34°N, centered on 70°W. The depths to the 15°C isotherm are contoured. In the 2½ months between maps, warm eddy F has oozed west around nearly stationary cold eddy E. Cold eddy D has moved west, while eddy C traveled north. [Source: Soviet and American POLYMODE researchers]



much colder or warmer than is typical for that region. In addition, there are clues that eddies up to 1000 kilometers in size exist in some parts of the Pacific.

It is possible that part of a very large eddy was observed during the Local Dynamics Experiment. "The strongest feature we saw when we were out there was considerably larger in scale than the 200-kilometer diameter survey region," says Taft. He was describing a seemingly linear flow pattern which moved northwest out of the survey area during the second half of the survey.

The pattern developed or moved into the area while the research ship was in port for 10 days having its generator repaired. Taft and co-workers hope the origin and nature of the feature will be apparent on the records made by instruments moored in the study area at the time. Those instruments are being retrieved this summer.

A Taste of Satellite Oceanography

From experiments such as MODE and POLYMODE oceanographers have learned that the oceans are so active that brief surveys of small patches of sea have not revealed the full picture of ocean circulation. Although POLYMODE has contributed enormously to the characterization and understanding of undersea storms called eddies, oceanographers are still a long way from being able to predict the undersea weather. For prediction, oceanographers must know where particular eddies are and where they are going. Yet there are not enough ships, equipment, or scientists to monitor the entire ocean continuously.

The short reign last summer of Seasat, a satellite devoted to watching the oceans, demonstrated that satellites may be part of the answer.* A satellite with Seasat's capabilities can get the data needed to monitor the major features of undersea weather. Eddies deflect the sea surface, causing it to be higher or lower than normal. With data from Seasat's altimeter, Robert Cheney of the Goddard Space Flight Center detected, for example, one very strong eddy, known as Cold Ring 4, in which the sea surface was depressed 60 to 65 centimeters. Since Seasat's altimeter proved accurate to 10 centimeters, even weaker eddies such as midocean eddies with sea surface deflections of less than 20 centimeters could be monitored in principle. Carl Wunsch of the Massachusetts Institute of Technology says that one could watch these eddies "by comparing nearly identical passes of a satellite with an altimetric system (including corrections for factors such as tides, weather, and orbit error) accurate to 5 centimeters."

Seasat examined nearly the entire area of the oceans every 3 days, although it could measure the height of the sea surface only directly below the flight path. In light of Seasat's abilities, some oceanographers dream about the detailed coverage they could get with a few satellites simultaneously surveying the oceans with an accuracy equal to or better than Seasat's.

But at the moment there are no such satellites, and oceanographers would be happy with one. Says Wunsch, "sea-surveying satellites are a very valuable tool for the future." However, it appears that the future will not come until at least 1985—the earliest date another satellite dedicated to monitoring the oceans can be launched.—B.K.H.

*For additional reading on Seasat, see *Science*, 29 June 1979, pp. 1405-1424.

Many eddies show up on the undersea weather maps produced from data obtained by the Soviet POLYMODE team. Some individual eddies appear on several of the maps, and the eddies even can be observed interacting. The maps record the evolution of the circulation pattern in an area centered 200 kilometers south of the Local Dynamics Experiment. While some oceanographers expect these maps to be valuable for testing undersea weather prediction models, others are disappointed. There are gaps up to 2 weeks long in the "continuous" record, and some of the maps cover only part of the large survey area.

Originally the Russians and Americans planned to have the mapping and the Local Dynamics Experiment occur in the same place, as the two types of studies provide complementary data sets: one covers a large area for 15 months, and the other covers a small area in detail for a few months. The location of the studies was the subject of considerable debate; ultimately the itinerary for the Soviet ships had to be planned before the Americans had selected the site for their study, scheduled to start nearly a year after the mapping.

Some generalizations about ocean eddies are being made, although as yet too few have been made to serve as a firm basis for forecasting the undersea weather. The impressive thing, according to Curtis Collins, program manager of the International Decade of Ocean Exploration, the National Science Foundation agency sponsoring POLYMODE, is that eddies are highly variable. "Some float with the mean flow, while others appear to travel upstream. Some are shallow, some are deep, and others penetrate the entire water column." Eddies even seem to have different roles in different regions of the oceans. However, if the details are elusive, some broad outlines of the eddy picture are emerging.

"We now have solid evidence that eddies can carry anomalous water properties over great horizontal distances with little change or dilution by the surrounding water," says Thomas Rossby of the University of Rhode Island. This evidence was obtained by using special devices, called sofar (sound fixing and ranging) floats, which travel along with the water at a particular depth, say 700 or 1300 meters. If at least two "listening stations" receive the acoustic signals transmitted by a float, then the position of the float can be determined. According to Rossby, floats have been trapped in eddies for several months, and some floats consequently follow tortuous, loopy paths. By sampling the water near one trapped float, oceanographers got clues that the water in that eddy, for instance, came from near the African coast.

The floats also revealed that ocean flow is very disorderly. Floats dropped very near each other may be widely dispersed within a few months, or they may travel in formation. Floats released at the same place a few months apart may head in radically different directions.

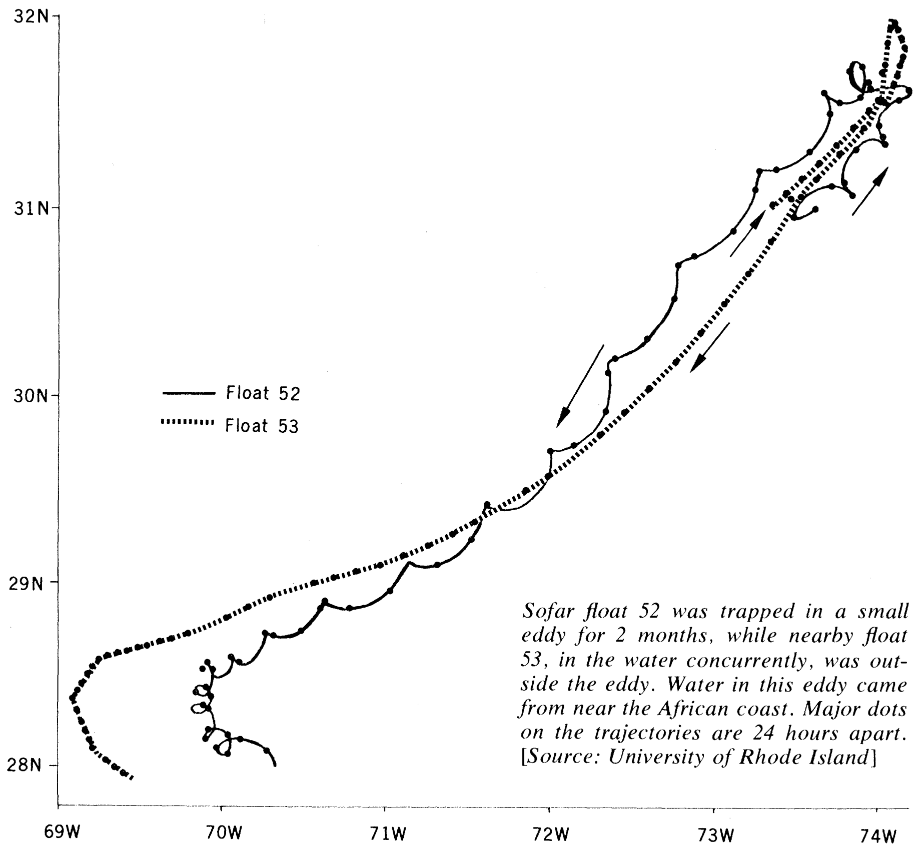
With experiments in several areas of the North Atlantic, POLYMODE researchers have explored some of the geographic variability of eddies. Generally the eddies are strongest—have largest kinetic energy—near the Gulf Stream. The energy of the eddies decreases with distance from that current. Researchers are quick to point out that this does not mean that eddies are formed near the current and travel away from it: eddies and eddy energy need not travel in the same direction.

In most cases eddies are weaker near the ocean bottom than they are near the surface or in the thermocline. POLYMODE researchers report that this vertical gradient in strength is less pronounced where the eddies are energetic than it is where they are weak. According to Lee-lueng Fu and Carl Wunsch of MIT, the eddy energy is nearly zero just above the ocean bottom where the seafloor topography is rough, such as near the Mid-Atlantic Ridge.

Peter Niiler and Thomas Keffer of Oregon State University observe that far from the Gulf Stream the ocean flow, even in deep water, may fluctuate in response to varying winds. Furthermore, in their study area 700 kilometers east of Martinique, Niiler suspects "the fluctuating motions may be more wavelike than eddylike." In contrast with eddies, wavelike features do not transport water masses. Niiler's suspicion cannot be confirmed until the data are analyzed fully.

POLYMODE theorists have not been waiting idly for the field data to be obtained and processed. They have been cultivating the models of ocean circulation that were developed at the time of MODE. These models borrowed heavily from assumptions and techniques developed over the past half-century by theoreticians studying turbulence and the earth's other large fluid body—the atmosphere.

According to Allan Robinson of Harvard, cochairman of the U.S. POLYMODE Organizing Committee, the MODE models "contain elements that will be part of our permanent understanding of the oceans, because the models are tied to and validated by field data." In the last 5 years the models have been modified to come closer to real ocean conditions. No longer are computer oceans always square boxes with smooth bottoms. But, says Robinson, "the models are not yet models of the real ocean." However, faster, large computers have made it possible to model the oceans in more detail, with grid points in the numerical ocean close enough together to resolve eddies—40,000-square-kilometer blemishes in 4-million-square-kilometer model oceans. Eddies that develop in the new computer models are similar in size and longevity to real eddies. And the strength of computed eddies is comparable to that observed in the field.



Sofar float 52 was trapped in a small eddy for 2 months, while nearby float 53, in the water concurrently, was outside the eddy. Water in this eddy came from near the African coast. Major dots on the trajectories are 24 hours apart. [Source: University of Rhode Island]

Theorists are trying to use the superficially successful models to learn more about ocean flow, including aspects that are difficult (if not impossible) to measure in the field. For instance, computer oceans can be studied in their entirety for a period corresponding to many years. The results of such studies, if correct, are discouraging to the experimentalists. The models suggest that even a large, long experiment, such as POLYMODE, is not large enough or long enough to sample truly representative or average ocean flow conditions.

The problem is that values averaged over a limited amount of time or over a subregion of the ocean may not equal the long-term or full-ocean average. William Holland of the National Center for Atmospheric Research suggests that measurements should be made over at least 3 to 4 years to reflect long-term conditions. Ed Harrison of MIT finds that the energy budget in no subregion of a numerical ocean represents the energy budget averaged over the whole ocean. Thus, "symbiotic interaction between modeller and experimenter becomes a necessity," says Robinson.

Oceanographers are trying to use the models to determine how the eddies interact with the large-scale circulation. Harrison says that the models give no definitive answer. Different models disagree, and at the root of the disagreement are assumptions that vary from model to model. As yet there is no a priori reason to favor one set of assumptions over another.

These questions notwithstanding, oceanographers are enthusiastic about what they have learned from POLYMODE and related studies of the Atlantic circulation conducted by French, British, German, and Canadian marine scientists. Eddies now are recognized to play an important role in ocean flow nearly everywhere. Although undersea weather prediction is not likely to be achieved in the near future, oceanographers now have an idea how a great variety of undersea storms behave.

—Beverly Karplus Hartline