partially kept. The largest single difficulty continues to be that of discriminating between objects in the field of view.

Machines discriminate by means of what is called the gray scale—that is, the difference between the intensity of light reflected or transmitted from different parts of the image. Since most samples are not well-defined composites of one light and one dark phase, and since machines cannot yet discriminate between objects as the human eye does (by features such as shape, orientation, and relative positions), the objects to be measured often must be identified by the researcher before the machine can be put to use freely. Nevertheless, sophisticated automated image analyzing equipment (both commercial and custom-built) is being designed and used.

In the latter category, for example, at Northwestern University, Evanston, Illinois, J. E. Hilliard is completing an automated system for studying metallurgical specimens. Machines such as Hilliard's typically are built up from commercially available components, including microscopes, electronic image analyzing units, programmable minicomputers, television-type displays, keyboards, and magnetic tape storage units. At Northwestern, a movable stage permits scanning the brightness of the reflected light as a function of position on the specimen. The brightness is measured by a photodetector. The system provides for interaction between the machine and the scientist. If the constituents of a sample cannot be discriminated by the photodetector because their reflectivities overlap on the gray scale, the researcher can signal the identity of the constituent by means of switches. The inexperienced operator can, on request, receive instructions (via a high-speed video display) for operating the instrument. All the information needed to begin data-taking is elicited by means of a dialogue with the operator. The machine can then accumulate data and compute stereological parameters, such as volume fraction, boundary surface areas, line lengths, particle size distributions, and orientation distributions. In addition, a running estimate of the statistical variance is printed out, so that data-taking can be terminated when the results are sufficiently accurate.

At the National Cancer Institute, Bethesda, Maryland, L. E. Lipkin and his associates have built an automated system for analyzing autoradiographs. These preparations provide a measure of the magnitude and rate of nucleic acid synthesis in cells (cell kinetics). When a nucleic acid precursor (thymidine) is labeled with tritium, beta decay of the tritium exposes individual grains of a photographic film which overlays the specimen on a glass slide. Lipkin's group uses a television-type camera to scan the microscope image. The Cancer Institute experimenters also designed their machine to focus the microscope successively at different depths within the film emulsion (optical serial sectioning). And the system is programmed to discriminate between exposed film grains due to beta decay in the cell nucleus and other randomly exposed grains (background). However, the operator must still manually select the cell to be examined. Extensive in-house modifications of hardware components and about 80 percent of the system software are directed toward the goals of user convenience and acceptance.

For the most part, stereology is a tool science which is used in a rather routine manner by researchers in various disciplines whenever they have a problem requiring quantitative measurement of structure in three dimensions from two-dimensional samples. A few investigators, however, are pushing the present limits of stereology into nonroutine applications and into new theoretical and instrumental capabilities.—ARTHUR L. ROBINSON

Additional Reading

1. *Journal of Microscopy* **95**, Nos. 1 and 2 (1972). These issues comprise the Proceedings of the Third International Congress for Stereology.
2. E. E. Underwood, *Quantitative Stereology* (Addison-Wesley, New York, 1970).

Undersea Storms: Experiment in the Atlantic

Water in the upper part of the North Atlantic circulates clockwise around the ocean basin, driven by winds. The flow in at least some deeper reaches of the ocean is thought to move in the opposite direction, driven by temperature differences. But if the overall pattern of motion is fairly well understood, relatively little has been known about more local oceanic phenomena, particularly those of the open ocean, until a recent experiment that for the first time mapped an undersea storm or eddy.

The effort, called the Mid-Ocean Dynamic Experiment (MODE), involved oceanographers from a dozen universities in the United States and Britain, half a dozen research vessels, and a new generation of oceanographic research instruments (see box). In addition to providing what is in essence the first three-dimensional weather map of a patch of ocean—data that is proving useful to oceanographers who are attempting to construct numerical models of the oceans—the experiment has established the importance of eddies in ocean dynamics. Indeed, MODE scientists believe that the eddies play a central role in determining the circulation of the open oceans comparable to atmospheric cyclones and anticyclones (low and high pressure systems) in determining weather patterns. If so, then understanding how eddies transport heat, momentum, and trace constituents of seawater will be essential to predicting such things as climatic change and the dispersal of pollutants in the oceans.

The eddy that fortuitously appeared in the MODE experimental area (Fig. 1) last year is the only one to have been studied in detail, but its general characteristics are believed to apply to eddies in other parts of the ocean. Eddies are roughly circular flows about 200 kilometers in diameter. They extend vertically throughout the entire depth of the ocean, although the motion is three or five times as strong above the thermocline—the region of large temperature gradients that effectively divides the ocean into a warm, salty layer overlying a cooler and less salty body of water.

With velocities of 3 to 5 centimeters per second in deep water and 15 to 30 centimeters per second nearer the surface, an eddy has more kinetic energy than an atmospheric storm and lasts many times longer—60 to 80 days, or even much longer, some oceanographers believe. (The time and also the space scales of oceanic and atmospheric eddies are more nearly comparable in nondimensional units that take account of the different densities of air and water.) More significantly, the eddies are much more intense than atmospheric storms—their energy is 10 to 100 times as large as the mean flow of the open oceans, rather than comparable to the mean flow as in the case of atmospheric eddies. There is evidence that the oceanic eddies are far more common than atmospheric storms—MODE scientists found traces of other eddies bordering the storm on which their instruments were centered, suggesting that eddies occur closely packed (Fig. 2). And they seem to be a ubiquitous phenomenon. One of the MODE findings is that eddies are associated with vertical shifts in the position of the thermocline, so that it is possible to look at old hydrographic data and identify eddies from this feature. They have now been reported in the Pacific as well as in the Atlantic.

These results* have stimulated theoretical efforts aimed at understanding the dynamics of eddies in detail and ascertaining how and where eddies arise in the oceans. A popular hypothesis among oceanographers is that the eddies are generated by what is known as baroclinic instability. The central Atlantic contains a vast lens of warm, relatively light water at greater depths than would occur were the ocean in equilibrium, its presence marked by the gradual slope (downward to the west in the MODE region) observed in the warm water–cold water interface, the thermocline. This potentially unstable situation constitutes a store of potential energy large enough to drive the ocean circulation for many years, and the conversion of this potential energy to kinetic energy by one of several mechanisms is one potential source of eddies. Alternatively, a more localized instability may be the source of eddies—the strong Gulf Stream current, after it leaves the U.S. coastline, meanders across the Atlantic like an unstable jet of water, shedding large, ringlike vortices that some oceanographers believe may become eddies. Still other hypotheses propose winds, the radiation of energy by the meandering Gulf Stream, and the conversion of wave energy by reflection from continental boundaries or by interaction with topographic features on the sea floor as the sources of eddies.

The MODE data, originating from only one section of the ocean, are not sufficient to resolve the debate on the origin of eddies or to settle the question of how the eddies interact with the overall circulation pattern in the North Atlantic. But they have led to several new attempts at modeling the ocean, both local predictive models of the type used in weather forecasting, investigations of particular mechanisms in the open ocean, and models of the entire basin. W. R. Holland of the U.S. Commerce Department's Geophysical Fluid Dynamics Laboratory in Princeton, N.J., and, independently, A. Robinson of Harvard and Y. Mintz of the University of California at Los Angeles, have shown that it is possible to generate eddies by baroclinic instability in models of the entire basin.

Attempts to understand eddies are part of a general trend among theoretical oceanographers toward more realistic models of phenomena in the open ocean. Ten years ago the emphasis was on waves and the mechanisms by which they redistribute momentum and energy in the ocean. More recently, theoreticians have begun to grapple with the effects of bottom topography (as ocean-in-a-box models give way to models that include rough and sloping bottoms) and with stronger currents (nonlinear models, as opposed to linearized wave models), including eddies.

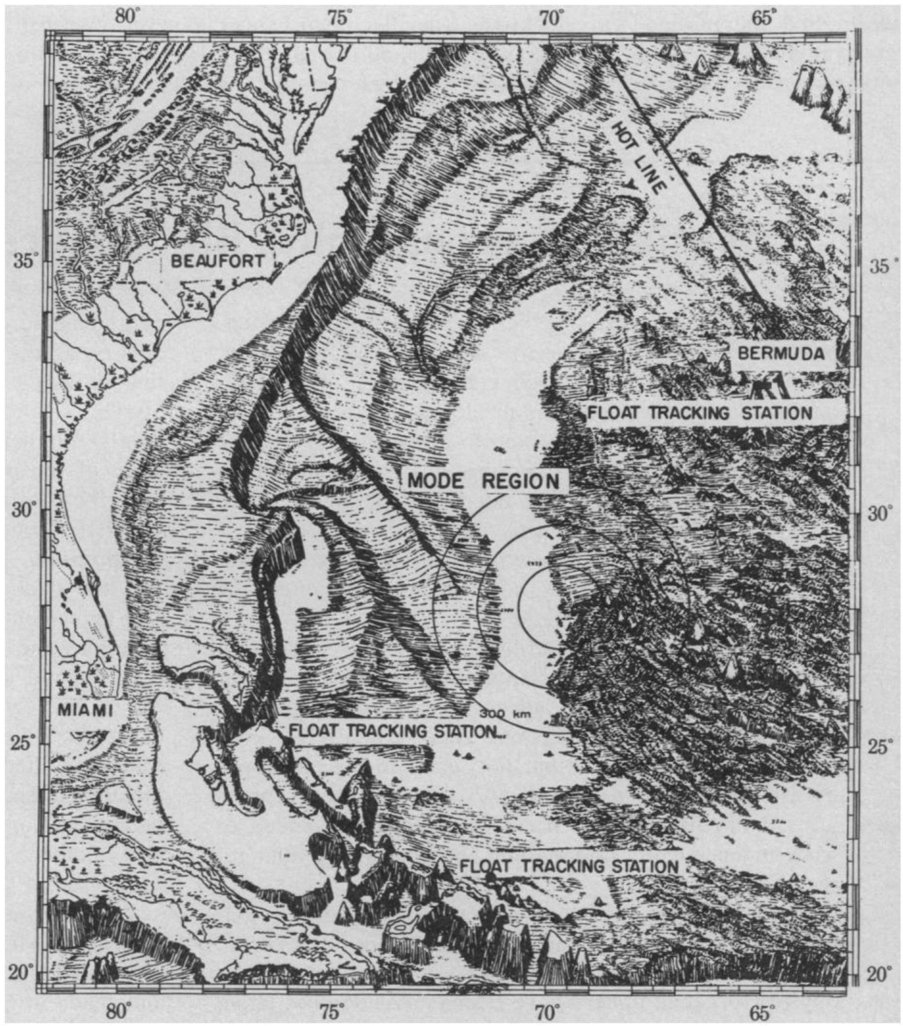
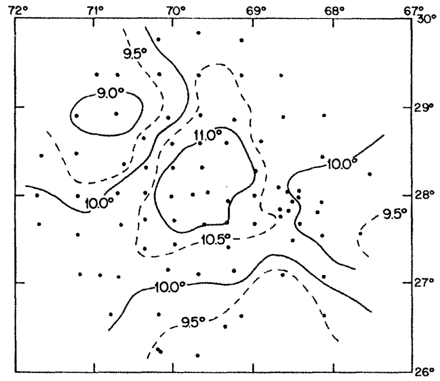


Fig. 1. Portion of the physiographic diagram of the North Atlantic (published by the Geological Society of America; copyright 1968 by Bruce C. Heezen and Marie Tharp). Concentric circles indicate the MODE experimental region between Bermuda and Miami. The ocean in this region reaches a depth of about 5 kilometers. The sea floor underlying the western half of the site is smooth, with rougher bottom topography to the east. The main experimental program was conducted between March and July 1973.

* Because many investigators have worked on the MODE program and have shared responsibilities and data, it is difficult to associate a particular result with any one investigator. The co-chairmen of the project were A. Robinson of Harvard University and H. Stommel of the Massachusetts Institute of Technology. In addition to scientists at those institutions, the program included investigators from the Woods Hole Oceanographic Institution, Yale University, the National Institute of Oceanography in Wormley, England, Nova University in Dania, Florida, the Johns Hopkins University, Scripps Institution of Oceanography, the Atlantic Oceanographic and Meteorological Laboratory of the U.S. Department of Commerce, University of Rhode Island, Columbia University, the universities of Hamburg and Gothenberg in West Germany, and the University of Hawaii.

Fig. 2. Lines of constant temperature (isotherms) plotted from temperature soundings (indicated by dots) at a depth of 800 meters, indicating a central eddy and the position of several surrounding eddies in the North Atlantic during the week of 7 May 1973. Temperatures are in degrees Celsius. Eddy currents were found to flow approximately parallel to the isotherms in a clockwise direction for the central (warm core) eddy, but counterclockwise for the neighboring cold core eddies. [Source: Woods Hole Oceanographic Institution]



The major contribution of MODE, however, has been the description of an eddy in sufficient detail that theoretical studies can proceed with more accurate numerical estimates for various properties. Data collected with moored temperature and current meters by W. J. Schmitz, Jr., of Woods Hole Oceanographic Institution and his colleagues show the main eddy quite clearly. Water in the center of the eddy was warmer than the surrounding ocean, and the motion was clockwise (anticyclonic). The eddy was slightly antisymmetric, elongated toward the north and south. The flow pattern for the most part paralleled lines of constant temperature, a correspondence common in atmospheric phenomena and implying a balance between pressure forces and the coriolis force due to the rotation of the earth. Below the thermocline, the eddy pattern became harder to see at increasing depths; data from the deeper instruments show smaller disturbances, not yet identified, in additicn to the eddy. The eddy remained centered over the network of instruments for nearly 2 months, then drifted slowly to the west, while a new eddy (this one with a cool core and rotating in the cyclonic direction) moved in from the east.

Submerged, free-swimming floats deployed by H. T. Rossby of Yale, J. C. Swallow of the Institute of Oceanographic Sciences in Wormley, Great Britain, and their colleagues provided additional information about the eddy and the surrounding ocean. The floats did move in an anticyclonic pattern, but they also showed the existence of some anomalies—one float midway between two current meters that were spaced about 60 kilometers apart was observed moving in exactly the opposite direction of the currents measured at the meters, possibly due to the rough topography of the ocean bottom underlying half of the MODE area. Indeed, the trajectories of floats at depths of 3000 meters or more showed the definite influence of bottom topography, according to Swallow. The floats proved very successful, and many are still being tracked nearly a year after the end

Physical Oceanography: Big Science, New Technology

Those who go to sea in the service of science participate in a tradition that reaches back at least a century. Despite the envy with which colleagues in other fields tend to view a deep sea suntan, doing research at sea is not an easy venture. In addition to becoming seasick, the oceanographer is, as one described it, "a prisoner for a month at a time on a small, noisy box." And there are the frustrations of instruments malfunctioning or disappearing altogether under the combined battering of wind, waves, and large fish, along with the corrosive effects of seawater and marine slime.

Oceanography is necessarily a somewhat cooperative enterprise, since a single ship must serve the needs of a variety of investigators. Indeed, the struggle to get ship time and to influence decisions about where the vessel will go is comparable to that for access to big telescopes by astronomers or to accelerators by high energy physicists. Nonetheless, most oceanographers have tended to work independently in designing and conducting their researches.

In recent years, however, under the prodding of federal granting agencies and with the incentive of problems that do not lend themselves to piecemeal attack, physical oceanographers have begun to undertake large, coordinated research programs. The MODE experiment (see accompanying article) is one of the first such ventures—and a largely successful one—into the arena of oceanographic big science, and it is thus interesting as an example of the genre. It has not been as large an effort, measured by either number of participants or dollars, as the huge experiment in tropical meteorology that is taking place this summer, but it is comparable. MODE established a reputation as one of the most tightly run field programs ever, much to the dislike of some of the participants. Detailed plans for the experiment were arrived at more or less by consensus, meaning that, according to one scientist deeply involved in the program, "on sticky points, we would take people into the back room and intellectually beat each other into agreement." The MODE scientists also pride themselves on the fact that theoreticians, often aloof from experimental efforts, played some role in helping to design and carry out this experiment. In fact the style of the experiment was distinctly flashy for an endeavor that was staffed almost entirely by academic scientists, and included leased telephone "hot lines" for communication, computers for day-to-day control of the operation, and many other paraphernalia of modern corporate organization.

The growing sophistication of oceanographers was evident in MODE in other ways too. The project displayed an awareness of public relations, for example, and made attempts to communicate with a broad audience rather than only with their oceanographic peers. An hour-long documentary on the experiment ("The Turbulent Ocean," recently shown nationally on public television) was produced with considerable assistance from MODE scientists.

of the main experiment. They show a westward drift, Rossby says, of about 1 centimeter per second.

Several different methods of measuring the vertical profiles of velocity and temperature gave very similar results, according to W. Richardson of Nova University in Dania, Florida. Among the findings is the difference between the profiles over smooth and rough ocean floors. The vertical distribution of currents measured over smooth bottoms changed drastically over rougher topography for reasons not yet understood. Another result concerns the distribution of energy in the eddy. The cold lower layer and the warmer surface layer of the ocean sometimes move as if independent of each other—the vertical profile of velocity parallels that of density. Some 80 percent of the eddy energy, according to T. Sanford of Woods Hole, is accounted for by this type of motion.

One of the more unexpected results from MODE did not, as it turns out, have anything to do with eddies. Pressure fluctuations were monitored at the sea floor by W. Munk of the Scripps Institution of Oceanography in La Jolla, California, H. Mofjeld of the Commerce Department's Atlantic Oceanographic and Meteorological Laboratory in Miami, and others, in the hope that high and low pressure systems corresponding to the eddies would be observable. After the large tidal fluctuations were subtracted, the pressure records did show sizable and regular low frequency variations. But they also showed a remarkable resemblance from one instrument to another over distances larger than the size of an eddy, an indication that whatever the cause of the fluctuations, it is probably not eddies. Comparison with the estimated pressure records at Bermuda, 1000 kilometers from the experimental site, suggest that the phenomena is at least of that scale. One possible cause, according to Munk, is the force of winds on the sea surface.

With MODE behind them, oceanographers are planning a larger experiment to be conducted in 1976 in cooperation with the U.S.S.R. and other countries. Some researchers believe that the experiment should focus on how eddies interact with each other and related local phenomena, in essence extending the mapping operation of MODE to a larger area and a longer period. Others believe that a more pertinent goal is to investigate how and where eddies are formed by taking data over a much larger geographical area; they believe that the collection of representative statistical information on the eddies may be more useful than a second, intensive study at this time. The debate is continuing, but what seems to be emerging is a compromise that will incorporate some of both approaches. Experiments on this scale take time to plan and carry out, and the theoretical work, despite renewed impetus, is not likely to resolve the remaining uncertainties about the open sea very quickly either. But awareness of the prevalence and intensity of undersea storms reflects a new perspective on what had been presumed to be the quiescent waters of the deep oceans.

—Allen L. Hammond

Perhaps the most significant measure of the coming of age of physical oceanography, however, is the blossoming of its research technology. MODE has been in many ways a test bed, in that the experiment allowed systematic intercomparisons, for a host of new instruments that have been under development during the last decade. It was in fact the availability of new instrumentation that made MODE and similar field programs possible. These new research tools include:

► Moored arrays—a network of current meters and temperature sensors attached at several depths to cables moored to the sea floor. The current meters provide direct measurements of velocities in the ocean, from high frequency wave motions to the more gradual variations of currents associated with an eddy, a considerable improvement in the traditional method of inferring velocities from temperature and salinity measurements. Techniques for deploying 5 kilometers of cable and anchoring it to a precise spot on the ocean floor are part of the experimental skills required for using moored instruments.

► Free-drifting floats—aluminum tubes that are neutrally buoyant at a particular depth in the ocean and hence free to follow where the current takes them. One type, the Sofar float, emits acoustic signals that can be tracked by shore stations up to 1800 kilometers away; a second type, the Swallow float, is tracked from on board ships. An early version of a Swallow float was the first to indicate in 1959 the presence of strong currents, now known to be eddies, in the deep ocean. The floats provide a record of current velocity measured following a patch of water (Lagrangian velocity) in contrast to the velocity measured by the fixed current meters (Eulerian velocity), a difference that is intriguing to theoreticians and may prove useful in tracking pollutants as well as eddies in the ocean.

► Shipboard and air-dropped profilers—freely falling probes that measure the average velocity of currents by one of several methods. The probes are tracked acoustically or by aerial photography of floats released while falling, or they measure electric fields induced in the water as it flows through the earth's magnetic field. Other probes record temperature and salinity profiles. The continuous profiles fill in the gaps between the measurements obtained at particular depths by moored instruments and floats.

► Bottom sensors—instruments that record temperature and especially pressure variations on the ocean floor. In principle much like the barometers that sense atmospheric high and low pressure systems, the sea floor gauges must be able to detect pressure variations as small as 2 centimeters of water in 5 kilometers, while separating out the larger variations due to tides.

The MODE experiment successfully demonstrated that these new research tools can be used in combination to study one piece of ocean in detail, but they will undoubtedly prove important to oceanographers in many individual applications as well. Indeed, "it would be disastrous," according to F. Bretherton, one of the MODE participants and the new president of the University Corporation for Atmospheric Research in Boulder, Colorado, "if the success of oceanographic big science persuades people that it is the only way to do things." The array of new tools and the MODE program are nonetheless impressive indicators of the capability for exploring how the ocean works.—A.L.H.