MESOSCALE OCEANOGRAPHIC MAPPING

In the early fall of 1979, APL collaborated with other agencies (the Defense Advanced Research Projects Agency, the Naval Research Laboratory, the Naval Oceanographic Office, and the Naval Ocean Research and Development Activity) in an extensive at sea experiment that involved collecting a large body of oceanographic data. To attain the objective of the experiment, it was necessary to make numerous measurements of the physical properties of the ocean that might affect the detectability of submarines. L. J. Crawford and R. W. Eakle of APL's Submarine Technology Division served as chief test scientist and chief test conductor, respectively.

The experiment was conducted in two different marine environments: on the instrumented range at the Navy's Atlantic Undersea Test and Evaluation Center at Andros Island and in an area of the open ocean northeast of the Bahamas. The passage of hurricane David and the threat of other hurricanes made it necessary to delay the beginning of the experiment, to condense some of the tests, and to reorder the sequence of test events. Despite the disruption, the experiment was highly successful.

Six ships of various types and two aircraft—all highly instrumented—were involved in the experiment. The instrumentation and data-processing systems employed were more advanced (technically or functionally) than those used in previous tests. One functional advance was the use of air-dropped, expendable bathythermographs (AXBT's), which measure water temperature as a function of depth, to aid in selecting a suitable ocean test site within the larger area being considered.

OCEAN AXBT SURVEYS

To understand the atmospheric conditions in a given locale, it is necessary to characterize the overall weather pattern of atmospheric jets, fronts, and storms surrounding that locale. Similarly, to understand ocean structure and properties in a small area, analogous nearby oceanographic "weather" systems must first be known. The oceans of the world are continually in motion, exhibiting large jets (such as the Gulf Stream), frontal regions, and rotating low and high pressure systems (eddies) that are now recognized as commonplace oceanographic features. Just as air can be warm or cold and calm or turbulent inside or near atmospheric systems, so can significant variation of oceanic conditions be expected to accompany those anomalies that constitute an oceanographic weather system. The ensuing spatial and temporal variations in currents, density, temperature, and wave activity can affect measurements in many oceanographic experiments, making the interpretation of test results difficult. Areas exhibiting gross manifestations of those anomalies had to be avoided if the objective of the experiment was to be attained.

The mapping of anomalies is a task that requires measurements on the mesoscale, that is, on a horizontal spatial scale of the order of 50 to 500 km. As with atmospheric systems, appreciable flows (currents) are typically associated with the anomalies. Direct measurements of current have been made in the U.S. and International Mid-Ocean Dynamics Experiments, but they are very expensive because of the extensive moored systems that must be deployed in order to obtain sufficient detail. An alternative characterization technique that is more economical and appropriate was needed for this experiment.

Large atmospheric flows or oceanographic currents occur only in response to density and pressure gradients. In the ocean, water temperature is related to density, and large currents are related to horizontal temperature gradients. This interrelationship of water movement with pressure, density, temperature, and Coriolis force is known as the principle of geostrophic balance. As a result of that principle, oceanographic currents may be deduced from spatial temperature measurements. For example, large jets such as the Gulf Stream are associated with horizontal thermal variations of over 10°C; the same can be true of large rotating eddies. Thus, thermal maps of the ocean can be used to describe oceanic weather systems just as maps of barometric pressure can be used to describe atmospheric weather systems.

AXBT MAPPING TECHNIQUE

Mapping of the mesoscale variability of the ocean requires measurements taken over an area of hundreds of thousands of square kilometers. Typically, a descending oceanographic instrument is deployed from a single point at the surface of the ocean. While descending, it continuously senses a selected ocean parameter as a function of depth. For example, ship-deployed devices, such as conductivity-temperature-depth (CTD) probes or XBT's, can be used to survey an area of the size stated above, but several days of ship time may be required to map it adequately. During that period, the thermal structure of the region may change so much that the survey results do not accurately represent the surveyed area.

In contrast, large ocean regions can be sampled adequately in a relatively short time through the use of airborne instrumentation. Figure 1 illustrates the deployment of an AXBT to take vertical temperature profiles. The AXBT is deployed from an aircraft traveling at about 250 kt at an altitude ranging from a few hundred to several thousand feet. After ejection from the aircraft, the instrument is stabilized by a parachute for entry into the water. A radio transmitter is then deployed and the temperature probe is released from the float. Probe data are telemetered to and recorded in the aircraft. At present, AXBT's provide ocean thermal structure data to depths of approximately 400 m, deep enough to resolve most mesoscale features. Recent refinements in AXBT design promise higher resolution and measurements to depths greater than 750 m.

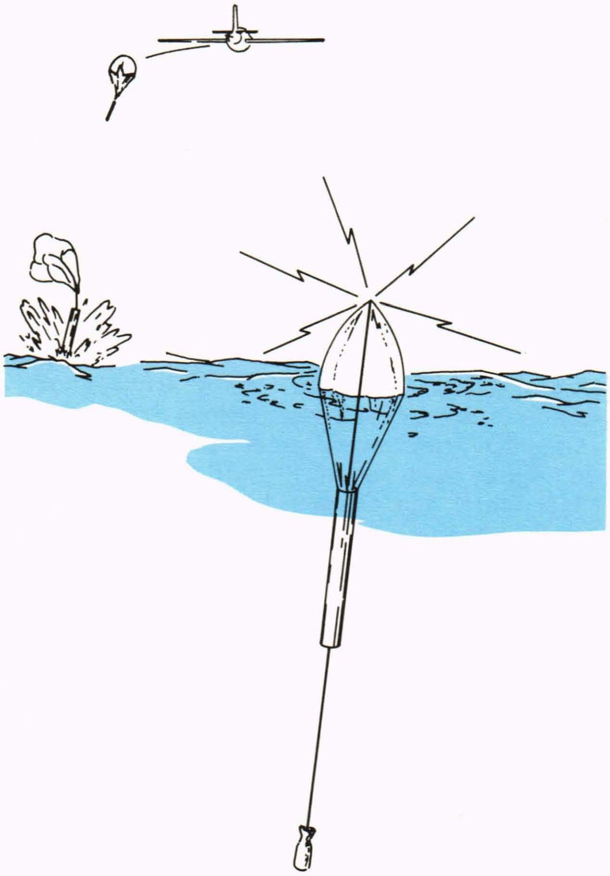

Fig. 1—Air-dropped AXBT deployment. Temperature probes are dropped from an airplane in a predetermined pattern. Data on temperature as a function of sensor depth are telemetered to the airplane.

RESULTS

A typical AXBT thermal recording taken during this experiment is illustrated in Fig. 2. This profile illustrates typical upper ocean stratification encountered in the Sargasso Sea. A weakly stratified mixed layer is observed close to the surface, where the water temperature is nearly constant (isothermal). The depth of this layer depends on the season. During the cold, stormy winter months, very deep mixing can occur, and the resultant mixed layer may deepen to hundreds of meters. Immediately below this layer is a steep temperature gradient that represents the seasonal thermocline. Here, the gradient shows the effects of summer heating; it may be completely eroded as the ocean cools and mixes during the winter months. Below that layer is the weaker thermal cooling that characterizes the deeper ocean regions.

To survey the area, AXBT's were dropped in a regular grid with spacing of about 40 km. Interpolative techniques were applied to obtain a statistically best estimate of the temperature structure throughout the area. The resulting data were then contoured to show isotherms at selected depths. Any large system, such as a frontal region or an eddy, shows up as a region of high thermal variability.

Figure 3 illustrates a map of the ocean thermal structure at 350 m depth. Asterisks indicate the

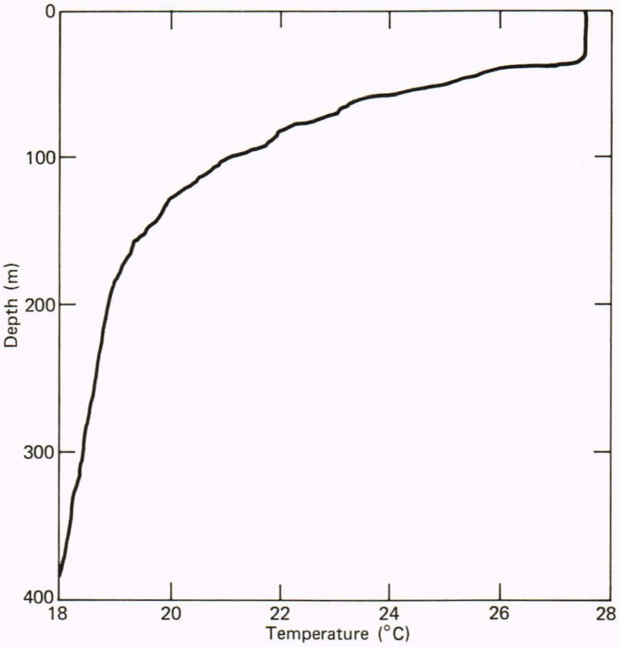

Fig. 2—Sample AXBT trace. Temperature versus depth profile in the Sargasso Sea during summer. The mixed layer extends to about 30 m, followed by the steep gradient of the seasonal thermocline, and then by the cooler water that characterizes deeper ocean regions.

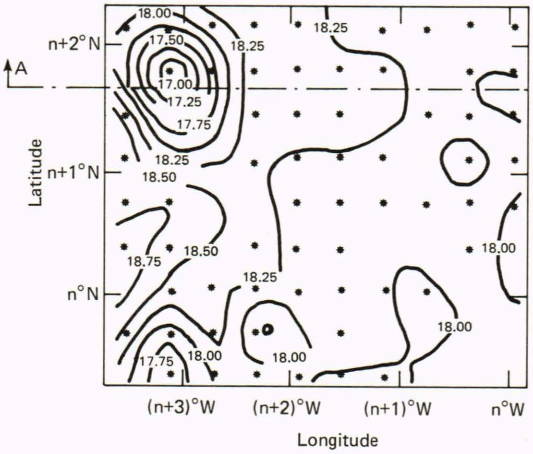

Fig. 3—Temperature contours at 350 m. Asterisks represent temperature measurements at approximately 40 km intervals. Temperature contours are shown at 0.25°C intervals. A strong temperature anomaly is apparent at top left. A-A′ indicates the section shown in Fig. 4.

positions of the AXBT's, and the contour lines represent horizontal isotherms at 0.25°C intervals. About one day of aircraft operations was required to survey this area of 120,000 km^2. Most of the area is thermally quiet; the wide spacing of the isotherms indicates small horizontal thermal gradients. However, in the western part of the area, a large cold anomaly is illustrated by the area of closed, nearly concentric contours. As a result of geostrophic balancing, such a cold water mass would have large counterclockwise rotating currents associated with it, analogous to the conditions attending an atmospheric low pressure system. This anomaly represents a cold-core cyclonic eddy, a feature that has been recognized as commonplace in ocean climatology. An eddy of this sort can originate from an instability in a large system such as the Gulf Stream: a current meander may break away and form a rotating eddy having a diameter of 100 to 500 km. Currents as strong as 5 kt can be associated with such eddies, which can travel through the ocean for periods as long as several years.

The effect of such a feature on ocean stratification is illustrated in Fig. 4, a west-east vertical section through the eddy. In the right-hand side of Fig. 4 (corresponding to the eastern part of Fig. 3), only small variations in the depths of the isotherms are observed. The mixed layer is indicated by the lack of any thermal variation in the top 40 m. The seasonal thermocline produces the close spacing of isotherms from 40 to about 100 m, followed by the weaker stratification below that depth. The generally horizontal orientation of the isotherms in this region indicates no significant large-scale activity. The small undulations in isotherm depth may be the result of tidal or internal waves within the ocean.

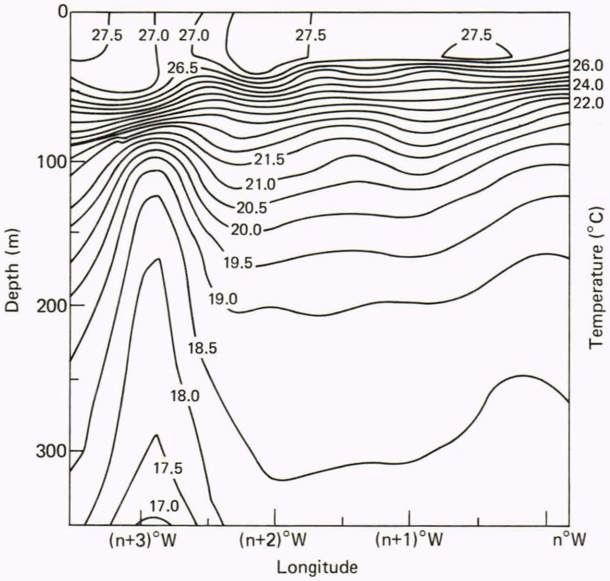

Fig. 4—Example of vertical temperature structure at a selected latitude (n + 1.75)°N. Constant temperature contours in degrees centigrade are plotted versus depth and longitude. A subsurface cold water anomaly is indicated near longitude (n + 3)°W. No significant horizontal temperature variations were visible to a depth of 50 m. Therefore, surface temperature observations would not have shown the anomaly.

In contrast, a strong eddy is evidenced by a significant upheaval of the isotherms in the western region. The cold center of the eddy results in an upward displacement of the lower isotherms by more than 200 m, an effect that extends upward to a depth of about 75 m. Above that depth, however, little thermal structure is evident, so that the eddy would be thermally invisible at the surface. The width of the feature appears to be about 140 km, and it can be expected to extend to depths of over 2000 m based on past observations of eddy structure at greater depths. The nearly symmetric displacements of the isotherms about a central axis, together with the nearly circular isotherms of Fig. 3, indicate that the eddy is a large dome-shaped mass of rotating water. Results of surveys made on different dates indicate that the eddy was moving at a rate approaching 10 km per day.

The air-drop technique permitted a rapid and accurate thermal characterization of a large ocean area to be made. Through interpolative contouring techniques, significant oceanic anomalies were identified and their effect on ocean stratification determined.

ROBERT F. HENRICK
Submarine Technology Division