

## DIRECT MEASUREMENTS OF VERTICAL SHEARS IN THE OPEN OCEAN

Direct measurements of the vertical gradients of horizontal water velocities in the open ocean have been made. The gradients, or vertical shears, have strong effects on ocean dynamic processes such as internal mixing, energy dissipation of currents, and the generation and persistence of turbulence. The measurements characterize the spatial and temporal variations of vertical shear and are a significant step forward in the ongoing effort to understand ocean dynamics.

### INTRODUCTION

In the fall of 1979, APL cooperated with the Naval Research Laboratory, the Naval Oceanographic Office, and several other defense agencies in an intensive at-sea test to study the dynamics of the ocean at various depths. One of APL's tasks was to measure vertical shears in the ocean. Vertical shear is the vertical gradient (rate of change) of horizontal water velocities; it occurs whenever the horizontal component of the flow velocity varies with depth. Ocean currents usually flow horizontally but can change rapidly in magnitude and direction from one depth to another, giving rise to a very complicated vertical shear profile that usually varies both in space and in time.

To understand the scope of the problem of characterizing ocean shear, one needs to know the spatial scales over which ocean currents exist. These scales range from thousands of kilometers to less than a meter. On the largest scale are the Gulf Stream and Kuroshio Current systems along the eastern shores of North America and Asia, respectively. These powerful currents, which attain speeds of several meters per second and span entire ocean basins, are produced by the combined effects of the zonal wind stress patterns, the Coriolis force, and the boundary effect of the continents themselves. Other large-scale currents include transitory surface flows generated during periods of strong winds and currents near the ocean floor caused by very cold, less saline water flowing toward the equator from the poles.

On a much smaller scale, current structures may vary rapidly as a function of space and time. The ocean consists of horizontal layers of different types of water masses. These layers are, in essence, made up of water of a nearly constant density that has sunk to a depth at which it is neutrally buoyant. Because warm water is less dense than cold water, a distinct cooling trend is always found in passing from the surface layers to deeper water. For example, near the interface between the "surface mixed layer" and the

region known as the "seasonal thermocline," one often sees large vertical shears. Within a water column, one also finds small-scale shears produced by a very intriguing type of current fluctuation: internal waves. They are distinct subsurface waves — with characteristic amplitudes and frequencies — that can travel hundreds of miles, have heights ranging from less than a meter to tens of meters, and have periods from less than an hour to more than a day. The causes of internal waves are not completely known, but evidence indicates that wind stress, wind-driven surface waves, and shears between different water masses (such as "mixed layer" to "seasonal thermocline" or the Gulf Stream to adjacent water) are possible sources.

The shear-related experiments performed during this sea test were designed to characterize the open-ocean spatial variations in vertical shear on scales of approximately 1000 m in depth and several kilometers in horizontal extent, at time scales ranging from a few minutes to many hours. These measurements of ocean current variability were made during a spatial coherence test and several time coherence tests. The spatial coherence test involved a rapid transit across the area of interest with profiles of current versus depth taken at predetermined intervals. The purpose was to obtain a picture of the current field and its gradient at a nearly fixed time. The temporal coherence tests involved taking a series of profiles of ocean current components at a single location. The time intervals between each profile were chosen so as to monitor the evolution of changes in the current profile over a variety of time scales.

### EFFECTS OF SHEAR ON OCEAN DYNAMICS

Since vertical shears have a strong effect on the mixing of one layer with another, on the energy dissipation of currents, and on the generation and persistence of turbulence, they represent an important parameter in ocean dynamics. The ocean is

generally characterized by relatively horizontal layers of constant temperature and density. Oceanographers quantify this stratification with a derived parameter, the Brunt-Väisälä frequency,  $N$ , defined as

$$N = \sqrt{\frac{g}{\rho} \frac{\delta\rho}{\delta Z}}, \quad (1)$$

where  $g$  is the gravitational constant,  $\rho$  is the density of seawater, and  $\delta\rho/\delta Z$  is the vertical gradient of density, excluding the compressional effects of pressure. Physically,  $N$  is the frequency at which a water particle will oscillate if it is displaced vertically from its neutrally buoyant depth. The stronger the density gradient (i.e., the larger  $N$  is), the more stable the water column is, i.e., the more resistant it is to vertical mixing phenomena. Vertical shear,  $S$ , tends to destabilize the water column; therefore, a useful quantity is the dimensionless ratio of stability to shear, called the Richardson number, defined as

$$Ri = N^2/S^2. \quad (2)$$

The probability of active turbulence, mixing, and distortion of internal waves decreases as  $Ri$  increases, and vice versa, making  $Ri$  an extremely important parameter in ocean processes.

## SYSTEMS FOR MEASURING OCEAN CURRENTS

Obtaining velocity and shear data required measurement systems capable of producing profiles of ocean currents over a large range of depth (e.g., 0 to 1000 m) in a short time. Until recently, such measurements could not be made. Underwater acoustic tracking ranges had been used to track slowly sinking instruments that emitted acoustic signals, and the position information thus generated could be differentiated to yield velocity and shear.<sup>1</sup> The greatest problem with this technique is that it requires the use of bottom-mounted acoustic hydrophones.

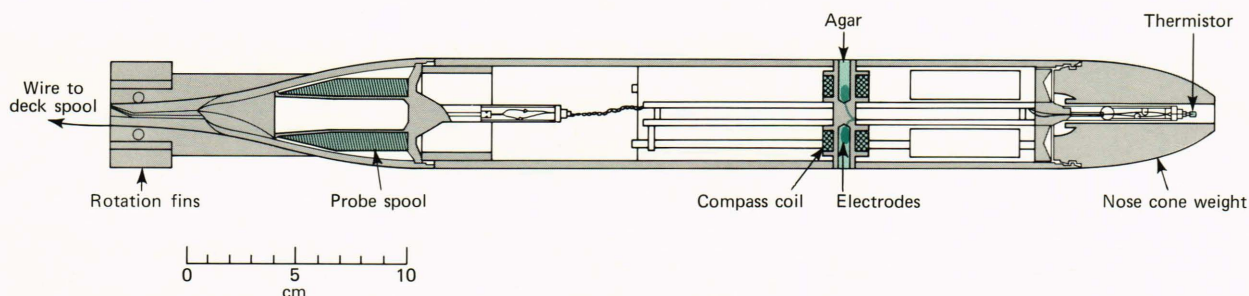
For our experiment, a newly developed instrument — the expendable current profiler (XCP) — was used to measure ocean current and shear patterns, producing a high resolution profile of relative

horizontal ocean currents down to 900 m in less than 4 min. In 1979, the XCP, designed and built by T. Sanford and R. Drever at the Woods Hole Oceanographic Institution,<sup>2</sup> was still in the prototype stage and only beginning to be produced in quantity. In spite of a lack of thorough testing of the instrument, its great potential to sample an entire water column in so short a time without the need for a tracking array or uncertain recovery procedures made the development of the XCP instrumentation and processing capability a high priority for this sea test. APL produced an XCP field data collection and calibration system that was built and used successfully during the experiment. Figure 1 shows the schematic diagram of an XCP.

### Principle of the Expendable Current Profiler

When an electrically conducting material (such as seawater) moves through a magnetic field, an electric field is generated in the material. The strength of the electric field is directly proportional to the strength of the magnetic field and the speed of the material traversing the field. This principle is used to measure ocean current velocities. The motion of the electrically conducting saltwater through the earth's natural magnetic field produces voltages between a pair of electrodes placed in the skin of the XCP. The XCP converts the electrode and compass-coil voltages to frequency modulated signals and transmits them by a thin wire link to a surface ship, where the data are displayed for quick-look data analysis and also are recorded on analog tape for post-test analysis.

An XCP cannot produce absolute values of current velocities because the electrodes only detect voltage variations caused by depth-dependent flows. To first order, the probe produces a velocity profile of the actual current velocity minus the average value of the current from the surface to the ocean floor, and unmeasured variations in the conductivity of the seawater and the underlying sea bottom cause additional second order corrections to the profile.<sup>3,4</sup> The XCP spins around the vertical axis as it descends, allowing a single pair of electrodes to measure voltages in more than a single vertical plane. The voltages can be converted to relative velocity components. Instantaneous probe orientation is established via a solenoid (compass coil) inside the instrument that



**Fig. 1—Schematic view of the expendable current profiler. The electrodes measure the voltage generated by horizontal ocean currents moving through the earth's magnetic field, and the compass coil gives probe orientation. The temperature sensor is located in the tip of the nose cone.**

produces a peak voltage when the electrodes are oriented east and west.

### Performance of the Expendable Current Profiler

The XCP performance characteristics have been experimentally determined by calibrations against accurately known sources of temperature and velocity versus depth. The results are summarized in Table 1. These values include the effects of system noise levels. For example, velocity components are sampled at 8 Hz, the rotation frequency of the probe. Based on a 4.8 m/s average fall rate, the vertical resolution would be 0.6 m. However, current versions of the XCP and its data collection system have system noise levels that degrade this value to 5 m. The same problem exists for the temperature sensor, which has an intrinsic thermistor time constant of 100 ms (corresponding, by itself, to 0.5 m resolution).

The velocity calibrations included comparisons with the APL acoustically tracked current profiler at the Naval tracking range in the Bahamas (AUTECH), as well as correlations between pairs of simultaneously dropped probes. Accurate temperature calibrations were performed by comparing temperature-depth profiles from a Neil Brown conductivity/temperature/depth (CTD) sensor to those produced by XCP's.

Table 1

PERFORMANCE CHARACTERISTICS FOR THE XCP.

Parameter	Accuracy	Resolution	Range	Vertical Resolution
Velocity	—	1 cm/s	0 – 450 cm/s	5 m
Temperature	0.1°C	0.02°C	-2 to +30°C	5 m
Depth	4% of depth	n/a	0 – 900 m	n/a

Note that velocity accuracy is undefined because of the undetermined constant offset.  
 Depth is calculated as  $d = d_0 + \bar{v}t + \frac{1}{2}\bar{a}t^2$ , where  $\bar{v}$  and  $\bar{a}$  are average fall rate and average acceleration.

### Supplementary Measurement Systems

In addition to the current profiling system, a CTD system was used. It is raised and lowered via a steel cable and provides high-quality ocean temperature, salinity, and density data. It can be used to produce time-series information by continuously raising and lowering the device, referred to as “CTD yo-yoing.” When used in this mode, the CTD can indirectly detect internal waves by measuring undulations in the constant density surfaces.

### Experiments Performed

Four separate experiments were performed, each designed to measure different aspects of the variability of horizontal ocean currents. The experiments included three time-series experiments and one L-pattern experiment. (An L-pattern experiment is a spatial coherence measurement wherein an L-shaped path is rapidly traversed while XCP's are deployed.)

### RESULTS

The CTD and XCP data from all four experiments have been processed to produce depth profiles of conductivity, temperature, relative horizontal current, and vertical shear. The data have also been used to produce various derived quantities such as profiles of the Brunt-Väisälä frequency and the Richardson number.

As mentioned above, two essential parameters to characterize ocean dynamics are the variations in vertical shear with time and location. The combined XCP/CTD data sets provide valuable information for measuring these quantities. Figure 2 shows vertical profiles of the east components of velocity from XCP's deployed in roughly the same location. The flow velocities range from 0 to 20 cm/s in amplitude and from 5 (the minimum resolvable increment) to 150 m in vertical extent. Differentiation of these profiles yields the shears, which range from 0 to about 4 cm/s-m. Notice that large features, such as those appearing at about 350, 600, 700, and 800 m, persist for several hours, whereas most velocity

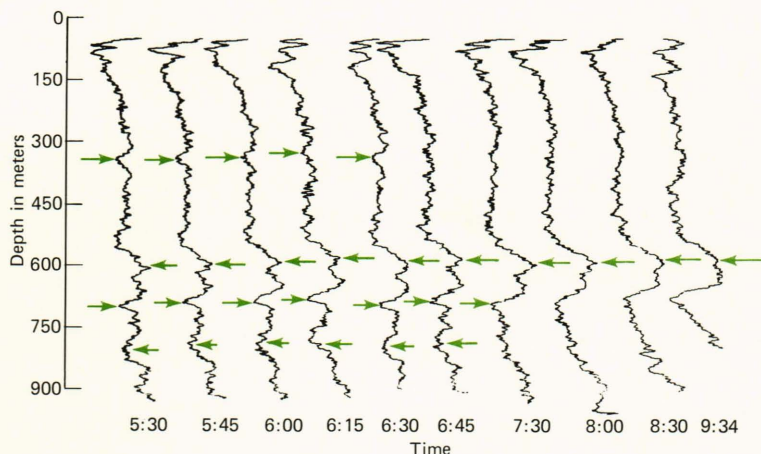


Fig. 2—Plots of east velocity profiles taken at one location during part of the current-meter time-series experiment. Each profile is separated by approximately 15 min in time. As indicated by the arrows, the largest velocity features persisted over several hours. These features are also to be seen in the north velocity profiles (not shown).

features with vertical scales between 10 and 30 m disappear (decorrelate) within an hour. Many of the velocity features are probably produced by internal waves passing through the test region.

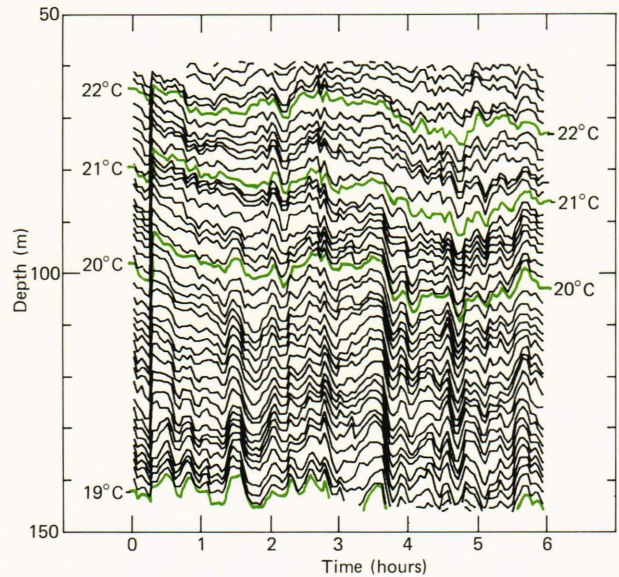
Another way of investigating temporal variability was to perform CTD yo-yos. Figure 3, produced by plotting the depth at which specific temperature values occurred during 108 CTD downcasts, clearly shows the displacement of temperature contours caused by internal wave activity. The most interesting aspect of the effect of the internal waves is the fact that the entire water column appears to oscillate as a solid body, suggesting that most of the energy is in the lowest vertical mode. The range of allowable internal wave frequencies is given by

$$f_1 \leq f \leq N, \quad (3)$$

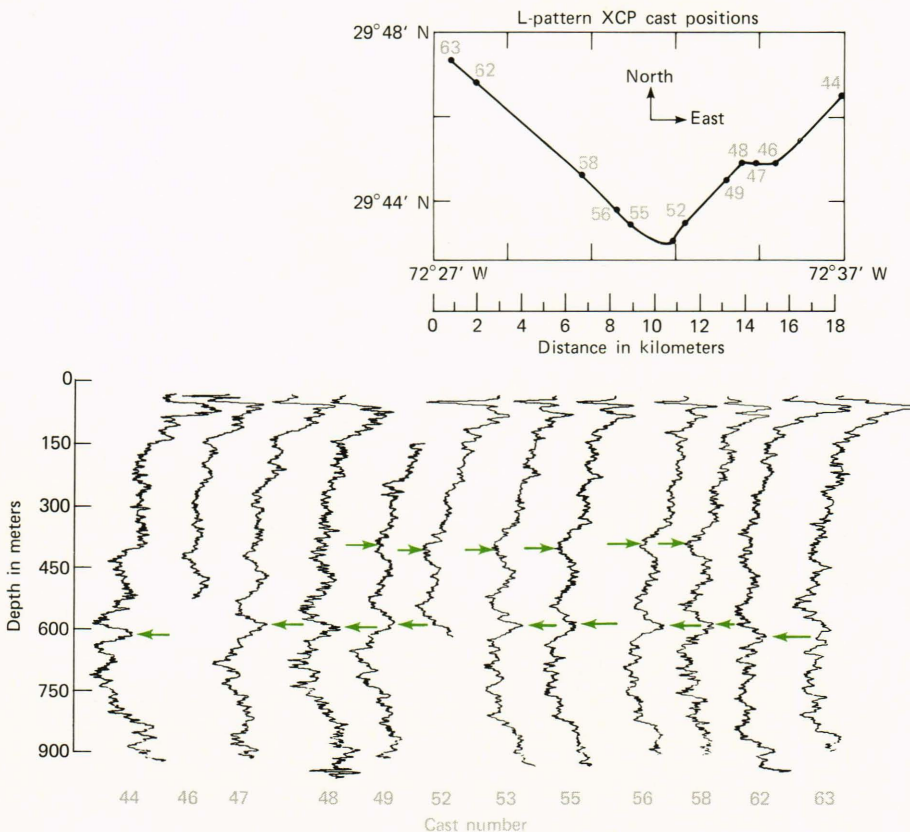
where  $f_1$  is the frequency at which unperturbed flows circulate under the influence of the local Coriolis force.<sup>5</sup>

To characterize the horizontal extent of vertical shear features requires simultaneous profiles of the ocean current at different locations. However, experimental constraints made it necessary to conduct this experiment with a single ship rapidly traversing a prescribed area while dropping XCP's at various locations. Assuming the transit time is small compared to the time scale of the features under consideration, one can compare the various profiles as though they were measured simultaneously. Figure 4

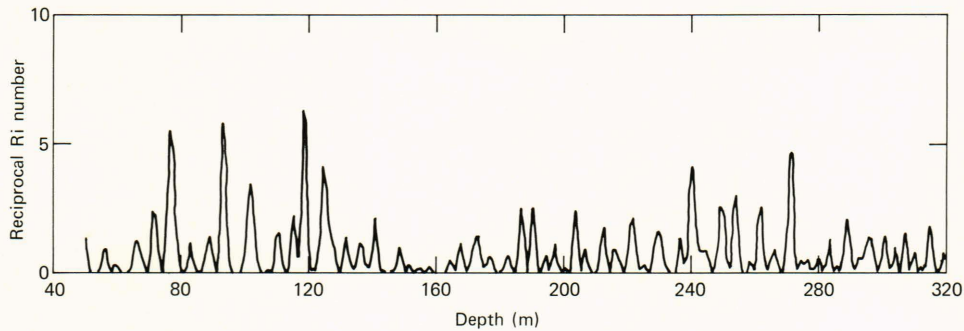
shows profiles of the east component of velocity from the L-pattern spatial experiment. As can be seen, the largest features persist over many



**Fig. 3—Temperature contours as a function of depth** obtained during a 6 h time-series experiment. Notice especially the high coherence in the vertical produced by high-frequency internal waves; vertical coherences frequently exceed 50 m. Temperature contours are plotted at 2 m intervals. (Figure and data processing courtesy of Dr. C. Johnson, Physical Dynamics, Inc.)



**Fig. 4—Profiles of east components of velocity** taken along an L-shaped path during a spatial coherence measurement. (The irregular spacing intervals are due to deletion of profiles from defective probes.) As indicated by the arrows, large velocity features are detectable over horizontal separations of several kilometers.



**Fig. 5—A typical plot of  $1/Ri$ . Regions of instability occur for  $1/Ri > 4$ . These may be caused by large vertical shears and/or low Brunt-Väisälä frequencies.**

kilometers. Features with scales between 10 and 30 m decorrelate spatially within 1 km.

XCP and CTD data have been combined to produce Richardson number profiles to characterize the degree of instability present in water columns. Because regions of zero shear exist,  $Ri = \infty$  is not uncommon; therefore, the reciprocal Richardson number,  $1/Ri$ , is more easily plotted. Figure 5 is a typical plot of this quantity. Unstable conditions exist whenever  $1/Ri > 4$ , caused either by large vertical shears or by very low Brunt-Väisälä frequencies. As can be seen, a number of unstable

regions are present. This result will have major implications for oceanographic modeling efforts.

## CONCLUSIONS

A first step in characterizing ocean dynamics has been successfully performed in obtaining open-ocean vertical shear data as a function of time and location. The results show definite effects of internal wave-generated features that can persist for up to several hours and over a horizontal extent of several kilometers for the largest events.

## REFERENCES

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