EPSONDE: An Instrument to Measure Turbulence in the Deep Ocean

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(Invited Paper)

***Abstract*—EPSONDE is a tethered free-fall profiling system used to obtain temperature microstructure and velocity turbulence data to a depth of at least 1500 m. EPSONDE, which carries a variety of slow and fast sensors, is deployed on a loose kevlar multiconductor cable by a specialized wire-handling system. Data are transmitted from this underwater unit (1792 samples per second) to a shipboard system which includes a dedicated microcomputer for data logging and on-line data processing. The performance of this system will be demonstrated by discussing a study of turbulent mixing processes in a lens of Mediterranean water (a MEDDY) found at a depth of 1000 m in the Canary basin. These studies indicate that turbulent kinetic energy dissipation may be an important mechanism in determining the decay and lifetime of a MEDDY.**

I. Introduction

OCEANOGRAPHERS use measurements of temperature and velocity microstructure to infer rates of vertical diffusion of heat and mass in the ocean. These rates are important to our understanding of mixing in the ocean, including local questions such as nutrient regeneration in regions of biological productivity, and to questions related to large-scale circulation. In this paper I will present the major features of a unique microstructure profiler, EPSONDE, designed at the Bedford Institute of Oceanography. I will illustrate its use in the field study of a deep salt lens found in the Canary basin.

The energy in a turbulent field may be measured by assuming that in equilibrium, turbulent energy generation is balanced at small scales by viscous dissipation. By measuring all of the variance in velocity at these small scales, one is able to calculate the turbulent kinetic energy dissipation, ϵ (W/kg). Instruments used to measure turbulent microstructure are therefore designed to measure the smallest length scales of fluctuation in velocity in the ocean. Similarly, temperature fluctuations caused by straining the mean temperature field by turbulence must also be determined to small scales. These cutoff scales are determined by viscosity and thermal diffusivity, respectively. The velocity cutoff scale for a turbulent field with energy ϵ (W/kg) and viscosity ν (m^2s^{-1}) is given by

$$\lambda_v = 2\pi(\nu^3/\epsilon)^{1/4} \quad \text{m.} \tag{1}$$

Similarly for temperature, the cutoff scale for molecular diffusivity D(m^2s^{-1}) is

$$\lambda_T = 2\pi(\nu D^2/\epsilon)^{1/4} \quad \text{m.} \tag{2}$$

For the mixed layer with a typical value of $\epsilon \approx 10^{-6}$ W/kg (where $\nu = 1.3 \times 10^{-6}\ m^2s^{-1}$ and $D = 1.4 \times 10^{-7}\ m^2s^{-1}$), $\lambda_v = 0.75$ cm, and $\lambda_T = 0.25$ cm. In the deep ocean where ϵ may be 10^{-10} W/kg these values are $\lambda_v = 7.5$ cm and $\lambda_T = 2.5$ cm.

For an instrument traveling through the water at a speed V, these cutoff length scales correspond to frequencies $f_{ci} = V/\lambda_i$. An instrument designed to measure to these small scales must have sensors which are small enough physically (compared to λ_i), have a fast enough response time, and must be sampled faster than f_{ci}. The vehicle must be hydrodynamically quiet with high signal-to-noise electronic circuitry.

Energy dissipation, ϵ, is obtained from EPSONDE by measuring the turbulent velocity fluctuation profiles (or velocity microstructure time series) using velocity shear probes. From power spectra derived using these profiles (and Taylor's hypothesis) one obtains the total variance in the velocity shear field, $\overline{(\partial u/\partial z)^2}$ s^{-2}. The dissipation is given by

$$\epsilon = 7.5\nu\overline{(\partial u/\partial z)^2} \quad \text{W/kg.} \tag{3}$$

Similarly, at the same time temperature microstructure measurements allow one to estimate the temperature gradient variance, $\overline{(\partial T'/\partial z)^2}$ °C^2m^{-2}. The vertical diffusivity is then given by

$$K_T = 3D\frac{\overline{(\partial T'/\partial z)^2}}{(\partial \bar{T}/\partial z)^2} \quad m^2s^{-1} \tag{4}$$

where $(\partial\bar{T}/\partial z)$ is the mean temperature gradient. If, for example, there is a distribution of a scalar quantity such as nutrients, $P(z)$, this vertical diffusivity would cause a vertical nutrient flux $K_T\partial P/\partial z$ kg $m^{-2}s^{-1}$.

II. EPSONDE Profiler and Deck Unit

EPSONDE was designed as an instrument capable of measuring the smallest fluctuations in the turbulent velocity field and the temperature field in the ocean to depths of at least 1500 m. At the same time, it measures the large-scale temperature and salinity fields. Data are available in real time for presentation and analysis.

The EPSONDE profiler is shown in Fig. 1. It is a 2.4 m long pressure tube, 0.14 m in diameter, with a leading reduced

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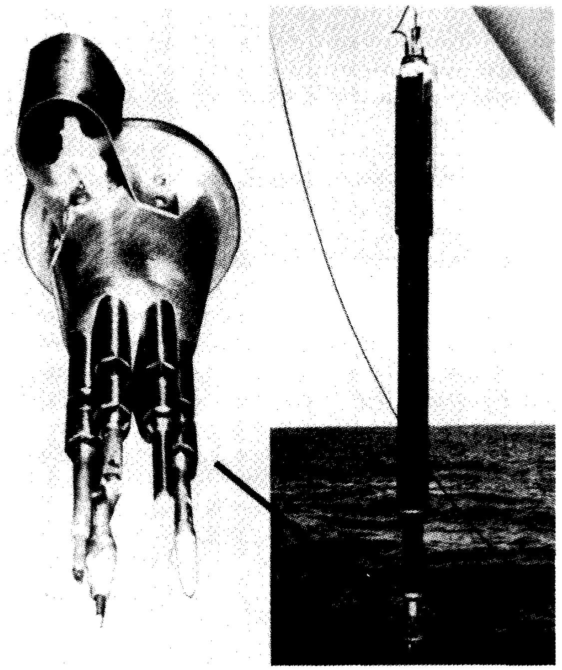

Fig. 1. The EPSONDE profiler is shown being deployed from the *CSS Hudson*. Probes to measure turbulent microstructure are at the lower end. The sensors: conductivity, temperature, platinum thin-film, fast thermistor, and two velocity shear probes are shown in the inset.

diameter tube containing preamplifiers and sensor input electronics. At the leading end of EPSONDE are strings which hold the microstructure sensors well ahead of the vehicle flow blockage. These sensors are shown in the inset photo of Fig. 1. The vehicle is designed to have a strong righting moment in order to keep it vertically stable. The net buoyancy is 0.5 to 0.8 kg negative to provide a drop speed in the range of 0.5 to 1.0 ms^{-1}.

The following summarizes the principal measurements obtained with EPSONDE:

1) CTD parameters are measured using a strain gage pressure transducer, a Neil Brown conductivity sensor, and a thermistor sampled at 32 Hz using a 14-bit conversion system.
2) Temperature microstructure is measured using a) a fast thermistor (Thermometrics FP07 with 7 ms time constant) sampled at 32 Hz and, as well, the differentiated signal from the same sensor sampled at 128 Hz; and b) a DISA platinum thin film sensor (2 ms time constant) sampled at 32 Hz and the differentiated signal (from which the temperature gradient is derived) sampled at 256 Hz. The noise levels for these two are respectively equivalent to approximately 5 μ°C and 50 μ°C RMS over a bandwidth of 1 to 10 Hz.
3) Velocity microstructure is measured using a shear probe built at the Bedford Institute. It works on the principle of lift on an axisymmetric airfoil caused by an off-axis turbulent fluctuation and sensed by a piezoceramic crystal. The sensor was designed and adapted for ocean use by Osborn and Siddon [1] and is described in detail by Osborn and Crawford [2]. Many vertical profilers use a version of this sensor. The differentiated signal from this sensor (which gives the velocity shear) is sampled at 256 Hz. The cutoff for the sensor is about 2 cm, and the vehicle and noise level correspond to $\epsilon \approx 10^{-10}$ W/kg.
4) A variety of engineering and diagnostic signals such as instrument tilt and battery voltage are measured.

Signal flow is summarized in the block diagram of Fig. 2. Preamplifiers and other low-noise electronic circuits are in the leading small tube close to the sensors in order to minimize noise. This compartment is protected so that if it is flooded it will not flood the rest of the instrument. In the main body of the vehicle are contained a battery power module and a section with circuitry to perform signal conditioning such as differentiation, filtering, and range scaling or amplification. The final module in the underwater unit is an analog multiplexer accepting seven channels sampled at 256 Hz. Two are submultiplexed at half-speed (four channels at 128 Hz) and two are submultiplexed at one eighth speed (16 channels at 32 Hz). Thus, up to 23 channels of data are selected and converted to digital format, ID bits and synchronization bits are added, and the data are transmitted to the surface deck unit using a standard USART transmitter–receiver pair at a speed of 38.4 kbaud.

The data link to the surface is a four-conductor kevlar multiconductor cable. It has been used in lengths as long as 2000 m, which is near the maximum length for telemetry at our current bit rate. Longer cables are unlikely to be used in any event because of the difficulties these present in the tethered-free-fall method of deployment (which will be described later).

In the deck unit the data are received, formatted into 16-bit words with appropriate ID bits, and computer logged. Data are also converted back to analog form and are recorded on multichannel graphic recorders for diagnostic purposes during a profile.

An INTEL 310/40R multibus computer has been used as a dedicated data logger using a specialized DMA controller. Software for the computer with an associated array processor is presently being developed to do spectral analysis and other on-line calculations concurrently.

III. Instrument Deployment

EPSONDE is a free-fall instrument, negatively ballasted to fall at a speed of about 0.5 to 1.0 ms^{-1}. The instrument drops, trailing a slightly negatively buoyant tether line which is fed out faster than the rate at which the instrument separates from the ship. The normal operating technique for this as well as other tethered free-fall instruments is with the ship broadside to the prevailing wind and wave field so the ship does not overrun the loose cable. Operating the ship in a more normal station-keeping mode is impractical with a free-floating loose line as the line and instrument may get under the ship, where hull projections are likely to snag the line with potentially disasterous consequences such as instrument loss. The maximum deployment depth is therefore dependent on the drift

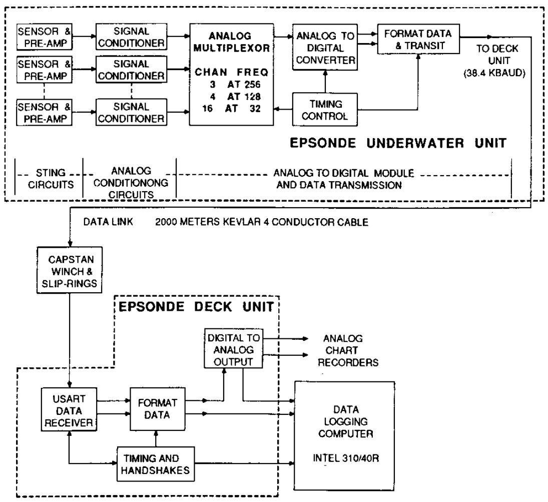

Fig. 2. The EPSONDE microstructure profiling system is shown. It includes the profiler, the cable-handling system, the deck unit, and the data-logging computer.

speed of the ship relative to the water speed and direction throughout the whole column sampled. Depending on conditions, one may achieve a depth as little as 35 percent or as high as 90 percent of the length of cable used.

This tethered-free-fall method of profiling and the use of multiconductor kevlar cable (0.3 cm diam) have required the design of a specialized winch–capstan cable handling system. During free-fall deployment, the cable is injected into the water by a capstan which is operator controlled to keep the tether line loose. During recovery, a winch with a 0.6 m diameter by 0.5-m-wide drum winds the kevlar in layers of about 300 m. Thus, for even a 2000 m cable there are only six or seven layers and therefore the cable does not become buried and damaged. A special sheave block was designed by Greifeneder and Oakey [3] to recover cable safely from angles 0 to 70° in the vertical and ±90° in the horizontal, which may occur with the ship drifting broadside and with EPSONDE advected by large shears as it profiles.

Using this cabling system we have been able to obtain successive profiles to 200 m every 10 minutes for periods of hours to obtain many realizations of the intermittent turbulent field in the mixed layer and upper pycnocline. This allows us to obtain much better sampling statistics than would be possible using free-fall profilers which must be recovered after each drop. In an experiment in the Canary basin under nearly ideal weather conditions we were able to profile to greater than 1500 m to study a deep salt lens of Mediterranean origin. This study is described in detail in the next section in order to illustrate the field use of EPSONDE.

IV. MEDDY Field Study

High-salinity warm water outflows the Mediterranean basin and mixes with less saline cooler water as it sinks. Some of this water forms large lenses of water at 1000 m which move into the Canary basin and occasionally are caught in the large-scale circulation of the North Atlantic and have been found in the westward basin [4]. These lenses or Mediterranean eddies (MEDDY's), of the order of 100 km diameter and 600 m thick at a depth of 1000 m, are about 1 PSU more saline than their surroundings and are several degrees warmer. MEDDY's may represent a very significant mechanism for the transport of heat and salt in the North Atlantic. For this to be possible, they must live for one to several years.

A study of the life history of a MEDDY [5] was started in the fall of 1984 when one was found and surveyed by Armi from the Scripps Institute of Oceanography using a CTD to estimate its heat content and total energy. In June 1985, we relocated the same MEDDY using the *CSS Hudson* from the Bedford Institute of Oceanography by tracking SOFAR acoustic floats set by Armi in the previous cruise. Again, the total energy and heat content were measured by extensive CTD surveys so that the rate of energy and heat loss between the two cruises might be estimated. In our study in June, we were able to estimate the "instantaneous" energy dissipation using EPSONDE and compare it to the observed energy loss from the large-scale decay of the lens.

A CTD temperature section, stations 209 to 224 at approximately 5 km spacing from near the center of the MEDDY along a radius to about 45 km from the center, is shown in Figs. 3 and 4. Temperature profiles are shown as thin solid lines displaced to correspond to the geographic location. The heavy solid line is the 11°C temperature contour. Within this contour is the "anomalous" water which is the lens or MEDDY. Clearly, as one goes further from the center there is more temperature structure. Well away from the MEDDY (stn. 224) there are only remnants of the MEDDY water. Overlaid on Fig. 3 are vertical profiles of temperature microstructure corresponding to the simultaneous CTD profiles. There is a large increase in structure above and below the MEDDY compared to the interior. The edges of the MEDDY are regions where there is enhanced mixing. Values of vertical diffusivity, K_T, on the underside of the MEDDY are as high as $K_T = 5.0 \times 10^{-4}$ m^{2}s^{-1} compared to typical values in the upper 500 m of 2 to 5 $\times$ 10^{-5} m^{2}s^{-1}.

In Fig. 4 velocity microstructure profiles are overlaid on the temperature profiles. The most intense values of dissipation, ϵ, are in the upper 500 m. Examining the signals from 600 m to 1400 m nevertheless reveals consistently more velocity signal near the edges than in the middle of the MEDDY. Most dissipation values within the core of the MEDDY have $\epsilon \leq 5 \times 10^{-10}$ W/kg (where the noise level is 2×10^{-10} W/kg). Only in regions of the MEDDY near its edge do values become greater than 10^{-9} W/kg. One may estimate the total rate at which the MEDDY is losing energy to viscous dissipation by integrating the dissipation, ϵ, found in sections such as shown in Fig. 4. Preliminary estimates of the rate of energy loss due to viscous dissipation using EPSONDE during the study of the June 1985 cruise is 2.1×10^6 W. The total MEDDY kinetic and potential energy at the time of the June 1985 survey was approximately 4×10^{13} J. (Hebert [6]). This would be dissipated at the observed viscous dissipation rate in a time of the order of one year. Although the generation of this turbulence at the MEDDY periphery is not clearly understood, the MEDDY was significantly decreased in size in one year. It

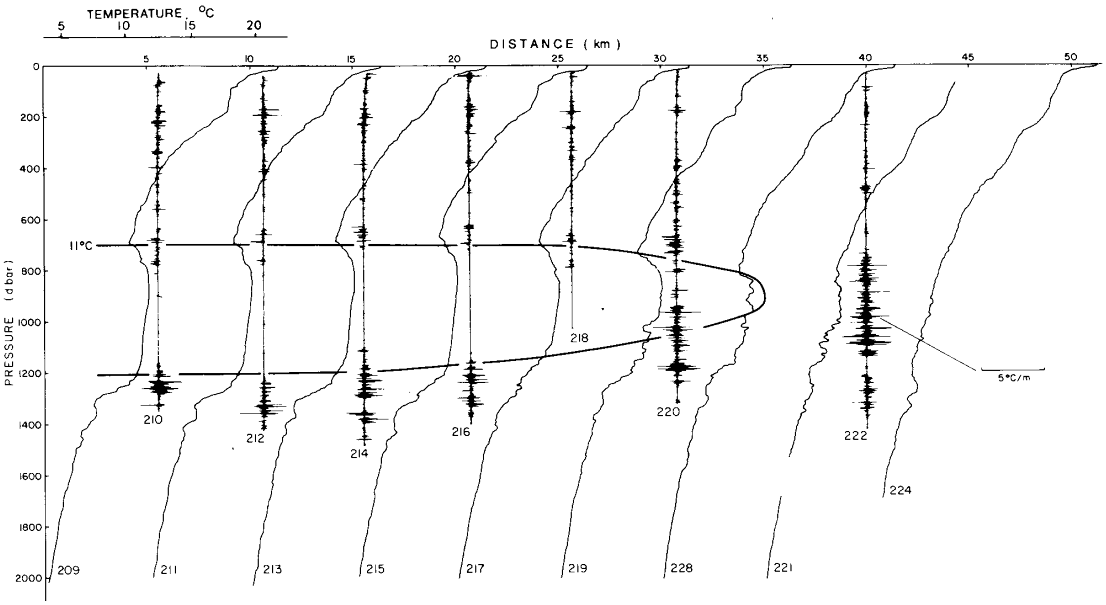

Fig. 3. Temperature microstructure profiles in a MEDDY. Successive temperature profiles (thin lines) at 5 km spacings from the center of the MEDDY are shown. The heavy line is the 11°C contour. Temperature microstructure profiles are overlaid. Most of the structure is at the MEDDY edges.

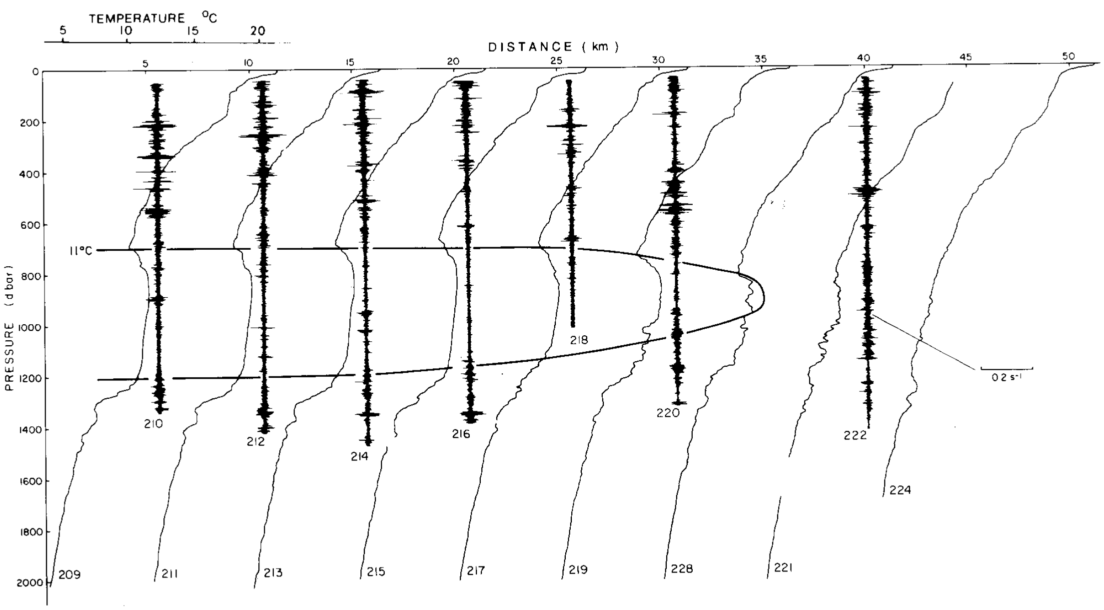

Fig. 4. The velocity microstructure profiles in the MEDDY are overlaid on the CTD temperature profiles as in Fig. 3. There is more velocity microstructure at the edges of the MEDDY than in the interior.

is clear, therefore, that dissipation at centimeter scales must be considered in the energetics of this 100-km-diameter feature of the ocean.

Only with a specialized vertical profiler such as EPSONDE can these deep-ocean mixing processes be studied.

References

[1] T. R. Osborn and T. E. Siddon, "Oceanic shear measurements using the airfoil probe," in *Third Biennial Symp. on Turbulence in Liquids* (University of Missouri-Rolla), 1973, pp. 41-45.

[2] T. R. Osborn and W. R. Crawford, "An airfoil probe for measuring velocity fluctuations in the water," in *Air Sea Interactions: Instruments and Methods,* F. W. Dobson, L. Hasse, and R. Davis, Eds. New York: Plenum, 1980, pp. 369-386.

[3] W. B. Greifeneder and N. S. Oakey, "A multi-roller sheave block for use with Kevlar oceanographic conductor cables," *Sea Technology,* July 1987.

[4] S. E. McDowell and H. T. Rossby, "Mediterranean water: An intense mesoscale eddy off the Bahamas," *Science,* vol. 202, pp. 1085-1087, 1978.

[5] L. Armi, D. Hebert, N. Oakey, J. Price, P. Richardson, T. Rossby, and B. Ruddick, "The history and decay of a Mediterranean salt lens," *Nature,* to be published.

[6] D. L. Hebert, "A Mediterranean salt lens," Ph.D. dissertation, Dalhousie Univ., Halifax, N.S., 1988.

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After graduating, he spent three years as a research associate at Texas A and M University, College Station, TX. Since 1970 he has been a research scientist in physical oceanography in the Ocean Circulation Division at the Bedford Institute of Oceanography, Dartmouth, N.S. One of his principal interests has been the study of turbulent mixing processes in the ocean and the relationship of these processes to larger-scale oceanic processes. As part of this program, he has developed instruments and sensors to measure oceanic microstructure, of which the profiler EPSONDE is the most recent. He has led several oceanographic cruises studying mixed-layer turbulence, frontal mixing processes, mixing in the equatorial undercurrent, and deep ocean mixing in a MEDDY and has published his findings in a number of oceanographic journals.