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Shear and Richardson number in a mode-water eddy

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ABSTRACT

Measurements of stratification and shear were carried out as part of the EDDIES tracer release experiment in mode-water eddy A4 during the summer of 2005. These measurements were accomplished using both shipboard instrumentation and a drifting mooring. A strong relationship between shear intensity and distance from the center of the eddy A4 was observed with the shipboard ADCP. Diapycnal diffusivity at the SF_6 tracer isopycnal prior to and during the release was estimated from the drifting mooring to be $2.9 \times 10^{-6}\,m^2\,s^{-1}$. Diffusivity increased by an order of magnitude to $3.2 \times 10^{-5}\,m^2\,s^{-1}$ during the period of the final tracer survey in early September, which was similar to the value estimated from the tracer analysis for the whole experiment ($3.5 \times 10^{-5}\,m^2\,s^{-1}$, [Ledwell, J.R., McGillicuddy Jr., D.J., Anderson, L.A., 2008. Nutrient flux into an intense deep chlorophyll layer in a mode-water eddy. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2008.02.005]].

1. Introduction

A tracer release experiment using sulfur hexafluoride (SF_6) was performed in the summer of 2005 (Ledwell et al., 2008) as part of the EDDIES field program to study nutrient fluxes and biogeochemical cycles in the Sargasso Sea. EDDIES was carried out to test the hypothesis that eddy-induced upwelling changes community structure and increases biological productivity and export of carbon from the euphotic zone. One goal of the tracer release was to estimate diapycnal diffusivity within the mode-water eddy A4 over a 1.5-month period. The SF_6 was injected on an isopycnal $\sigma_\theta = 26.255\,kg\,m^{-3}$, which was at a depth between 80 and 100 m near eddy center.

Microstructure measurements have often been carried out in conjunction with previous tracer releases in the open ocean to provide an independent method of estimating diffusivity (Ledwell et al., 1993; Toole et al., 1994; Ruddick et al., 1997; Schmitt et al., 2005). Dissipation rates of turbulent kinetic energy and temperature variance were measured in each of these experiments. Diapycnal eddy diffusivities of buoyancy and temperature estimated from these dissipation rates were compared with the diffusivity of the passive tracer. Also measured were shear and gradients of temperature, salinity and density, at the scales of gradients directly forcing the mixing events. This strategy made it possible to test relations between dissipation rates and diffusivities and to develop relationships between the statistics of gradients at 10-m scale and diffusivities. It is important that such measurements be made with any study of diapycnal mixing in order to interpret the experiment, to place it in dynamical context and to compare with other mixing experiments. Comparisons of diffusivity derived from dissipation measurements with those estimated from SF_6 tracer releases have tended to agree within a factor of 2 in past experiments. Such comparisons must take into account double diffusive effects (St. Laurent and Schmitt, 1999) as well as temporal and spatial bias in the dissipation sampling (Ledwell et al., 2000). Comparisons of tracer-based and dissipation-based estimates of diffusivity will continue to be valuable; however, no microstructure data were collected in this field program.

In order to place the tracer results for diapycnal mixing in context of gradients at relatively accessible scales, it is possible to use the relation of energy dissipation to 10-m shear found by Gregg (1989; see also Polzin et al., 1995). In this parameterization the dissipation is proportional to the ratio of the mean value of 10-m shear to the fourth power of the 10-m shear given by the Garrett and Munk spectrum (GM spectrum, Garrett and Munk, 1972, 1975). The dissipation is also proportional to the square of the buoyancy frequency. The Osborn relation can be used to estimate the diffusivity of density from dissipation (Osborn, 1980). The background diffusivity obtained from these formulas for the GM spectrum and shear level is approximately $5 \times 10^{-6}\,m^2\,s^{-1}$. It should be noted that the scale of 10 m is larger than the scale of actual shear instabilities.

The Gregg parameterization depends on a model of the flux of energy to higher vertical wave numbers in the internal wave spectrum characteristic of the stratified open ocean. It will probably not apply where the open-ocean internal wave spectrum does not exist. For example, MacKinnon and Gregg (2003a) report

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a very different relation between dissipation and shear and stratification for a site on the continental shelf. It also must be considered that diapycnal mixing in mode-water eddies could be more active than in cold eddies because of trapping of near-inertial waves (Kunze, 1985; Lee and Niiler, 1998).

Mack and Schoeberlein (2004) used an 80 m towed thermistor-conductivity chain in combination with a shipboard 150 kHz ADCP to estimate Richardson number, *Ri*, in the seasonal thermocline of the Sargasso Sea. Their results showed a statistically significant coincidence of scalar activity with low 10 m *Ri*. They also state that there is strong evidence for Kelvin–Helmholtz shear instability but no single critical *Ri* was identified.

Ship-based measurements of shear and stratification during the EDDIES field program are presented in this paper along with an alternative method using a drifting mooring.

2. Methods

2.1. Shipboard ADCP and CTD

The R/V *Oceanus* had two hull-mounted RDI acoustic Doppler current profilers (ADCP), the first a narrowband 150-kHz system and the second, the Ocean Surveyor (OS) 75-kHz system. The narrowband data are available for cruises OC415-1, OC415-3 and OC415-4, while the OS system was operational for OC415-2, OC415-3 and OC415-4. The narrowband data were processed in 5 min averages for depth bins of 4 m. The OS data were processed in 5 min averages for 10-m bins. Vertical shear was calculated using a first-order differencing technique. There is a loss in shear variance due to both the first-order differencing process and the Bartlett filter applied to the sampling scheme of the RDI ADCP. MacKinnon and Gregg (2003b) suggest a correction factor of 1.5 based on spectra of observed shear and the details of the filter transfer function.

The shipboard ADCP also was used to estimate the position of the center of the eddy. A daily-mean position was identified by locating the local minimum in depth-averaged currents in objectively analyzed maps of the ADCP data. Eddy center estimates were also informed by the trajectories of drogued drifters.

Shipboard CTD data were collected with a Sea-Bird model 911*plus* on a 24-bottle rosette. These data were processed into 1-dbar bins using standard Sea-Bird protocols. A total of 214 CTD profiles were acquired on R/V *Oceanus* during the four legs of this field program; of those, 107 profiles met the criteria of being collected within 50 km of the center of eddy A4 as well as having data to at least 100 m depth. Buoyancy frequency was computed for each profile using the seawater toolbox for MATLAB (Morgan, 2003).

For the estimation of gradient Richardson number, *Ri*, each CTD profile within 50 km of the center of eddy A4 was matched with the closest 5 min ADCP profile. This is the most appropriate matching as the analysis of the CTD data was done using the downcast in the upper 200 m of the water column and, therefore, these data were collected within several minutes of the start of the CTD cast. *Ri* is computed as the buoyancy frequency squared divided by shear squared from the ADCP. Representative *Ri* profiles for each leg of the field program were derived by computing the median of the combined individual profiles.

The absolute vorticity, relative plus planetary vorticity (ζ+f), of the eddy over the depth interval of 80–120 m was computed for OC415-4 using the shipboard ADCP. This depth interval was chosen as representative of the depth of the SF_6 tracer. Velocities were binned in 5-km intervals from the center of the eddy. Assuming rigid body rotation at rate Ω in each of the 5-km bins, the relative vorticity is calculated as 2Ω. The vorticity was then normalized by dividing by the Coriolis frequency, f, at 30°N.

The mean 4-m shear (10 m for OC415-2) in two layers (0–50 and 80–120 m) was calculated for each leg of the field program as a function of distance from the center of A4. These results were determined by binning the ADCP data in 10-km intervals and are based on over 14,000 individual profiles. Mean *Ri* was estimated in 20-km intervals as a function of distance from A4 center for these two layers using the method described above to generate mean profiles for each cruise.

2.2. SeaHorse mooring

The SeaHorse is an autonomous profiler comprised of a surface buoy, 1/4″ jacketed wire, suspended weight (or mooring anchor in moored applications) and a positively buoyant instrument package (Hamilton et al., 1999). This field experiment represented the first deployment of SeaHorse in a drifting mode. The SeaHorse profiler (Fig. 1) ratchets down the wire using a one-way clamping mechanism as the buoy follows the surface waves, and then smoothly slides up the wire as its instruments make measurements. This design reduces the coupling between the surface float and the SeaHorse profiler during its ascent. This utilization of surface wave energy for profiling enables the mooring system to dedicate battery resources to the instrument payload. For the deployments in this experiment the SeaHorse was set to cycle every 60 min. It was estimated that with this cycle interval the profiler might not have enough time to complete its descent along the mooring wire in very calm sea conditions, but that in most sea states this period should be sufficient. The mooring was designed for the SeaHorse to profile starting at 200 m depth and ascending to approximately 5 m below the surface. The ascent rate of the profiler is adjusted by changing the system buoyancy and was about 0.4 m s^{-1} for this experiment.

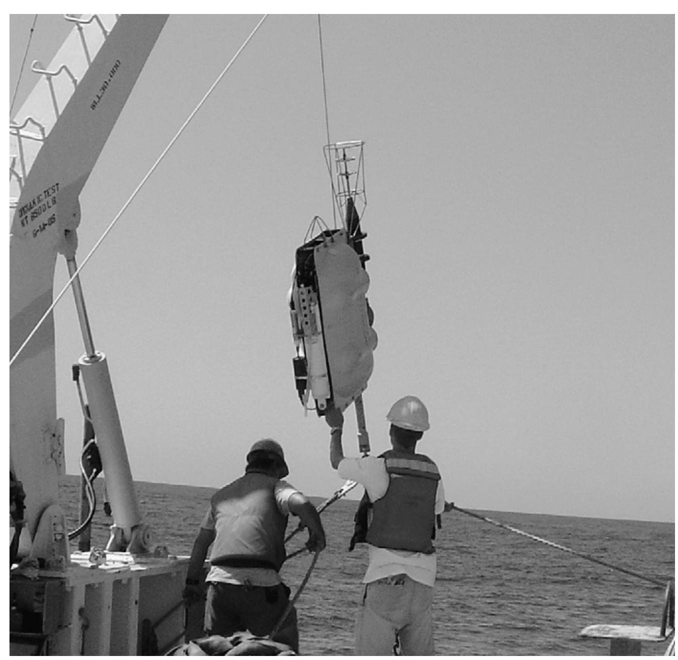

Fig. 1. SeaHorse profiler being recovered on R/V *Oceanus* in September 2005 as it rests on the bottom stopper of the mooring wire. The Sea-Bird 19plus CTD and WetLabs WetStar fluorometer are on the near-side of the profiler. The MAVS current meter is on the far-side with the sensor head extending above the SeaHorse.